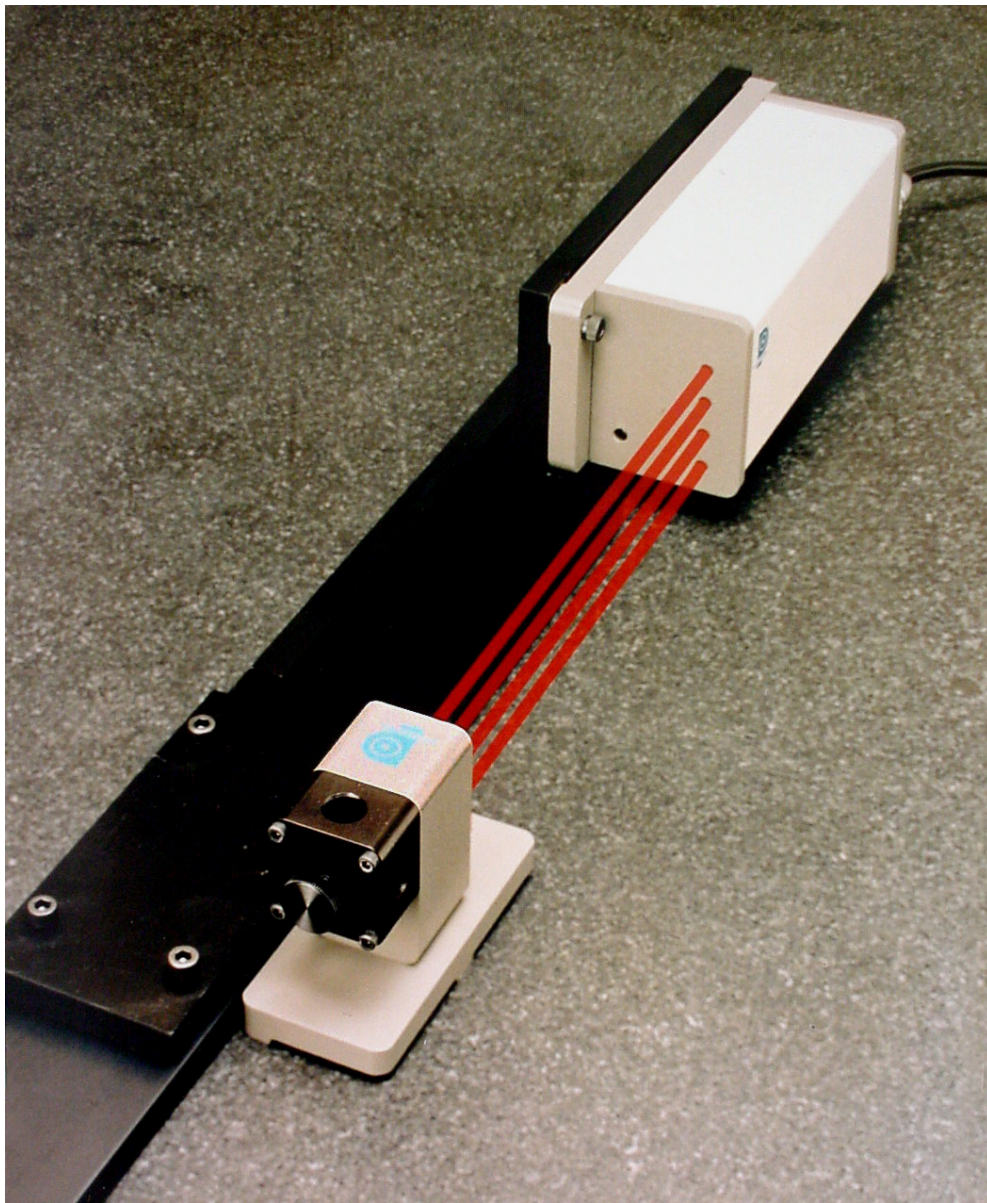


Laser Doppler Displacement Meter™ Laser Measurement System

User's Guide



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This device is patented – U.S. Patents 4,715,706; 5,116,126; 5,394,233; 5,471,304 and 5,724,130 with other patents pending.

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CONGRATULATIONS

Congratulations on your purchase of a measurement system, built around Optodyne's Laser Doppler Displacement Meter (LDDM™). This system offers an unprecedented combination of price, performance, and ease of use, made possible by the integration of state-of-the-art electronics and optics. Several different applications built around the LDDM™ are possible. The components in your system including this manual, have been carefully designed to best serve your specific application.

This manual is divided into the following three parts:

1. Introduction

2. Application

3. Appendix

The Introduction will familiarize you with the LDDM™ system quickly. The Application section gives you step-by-step instructions on how to install and operate your LDDM™ system for the specific applications that were intended for it. The Introduction and Applications sections should be read completely before using the LDDM™. The Appendix contains detailed explanations and reference material on topics related to the LDDM™. Information in this section is not normally needed for day-to-day operation.

For technical assistance, please call Optodyne's Service department at: (310) 635-7481, or write to:

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Part I. INTRODUCTION

1.0 Before we begin

1.1 Safety Precautions

This device is a Safety Class I system. It has been designed and tested according to IEC Publication 348, "Safety Requirements for Electronic Measuring Apparatus." This product is also a Class II Laser Product conforming to Federal Bureau of Radiological Health Regulations 21 CFR 1040.10.

Warning: This equipment generates, uses, and can radiate radio frequency energy and if not installed and used in accordance with the instructions found in this manual, it may cause interference to radio communications. Temporarily allowed by current regulations the equipment has been tested for compliance within the limits for Class A computing devices pursuant to Subpart J of Part 15 of FCC rules, which are designed to provide reasonable protection against such interference. Operation of this equipment in a residential area is likely to cause interference. The user at his own expense, will be required to take whatever measures that may be necessary to correct the interference.

Warning: Do not clamp the Laser Head Module at any point other than the base plate. To do so can damage the unit.



Warning: There is high voltage in both the Laser Head Module and the Processor Module. When the covers of these modules are removed, the operator is exposed to high voltage.

1.2 Patent

This device is patented - U.S. Patents 4,715,706, 5,116,126, 5,394,233, 5,471,304, 5,724,130, 6,498,653 and 6,519,043 with other patents pending.

1.3 Unpacking and Inspection

As soon as you have unpacked the system please check for the following components:

1. Processor Module
2. Laser Head Module
3. Display Module
4. Retroreflector
5. Cable Assemblies
6. AC Power Cord
7. User's Guide
8. Options
9. Accessories and Software

Please check the condition of all components. Fill out the Warranty Registration, section 5.0, and return it to Optodyne, Inc., at the address shown on the cover page of this manual. All equipment should be tested as soon as it is received in accordance with the installation instructions, page 3.2. If any component fails to operate properly or is damaged in any way, a warranty claim should be filed with the carrier. A full report of the damage should be filed with the claim agent, and a copy made available to Optodyne, Inc., Service Department. Optodyne will then advise you of the disposition of the equipment and arrange for its repair or replacement. Include model number and serial number when corresponding about this equipment for any reason.

If a warranty claim is necessary, please provide detailed information concerning equipment type, serial number, nature of the problem, etc. Send the claim to the Optodyne Service Department at the address at the front of this manual. Instructions for the disposition of the equipment will be returned to you. When ordering replacement components from the factory, always give the type and serial number of the equipment and the values, tolerances, ratings and Optodyne designation of all electrical components required. Please refer to the Parts List where applicable.

2.0 General Information

2.1 Product Description

The Laser Doppler Displacement Meter, referred to herein as LDDM™, is an instrument system which measures displacement to an accuracy of one part in one million (1 ppm). A laser is positioned on the axis along which the target moves. The laser beam is returned by a reflector mounted on the axis along which the target moves. The reflected beam is detected near the laser source: the original and reflected beams run parallel, adjacent paths. After detection the displacement information is calculated and sent to a digital display for read-out or to an external controller for closed loop applications. LDDM™ is fully compatible with TTL systems. When the control loop is closed, full automatic control is accomplished. Other control data interfacing methods are also available.

The LDDM™ instrument system consists of four components; a Laser Head Module, Retroreflector, Processor Module and a Display Module or Notebook computer as shown in Fig. 2-1, LDDM™ System Block Diagram.

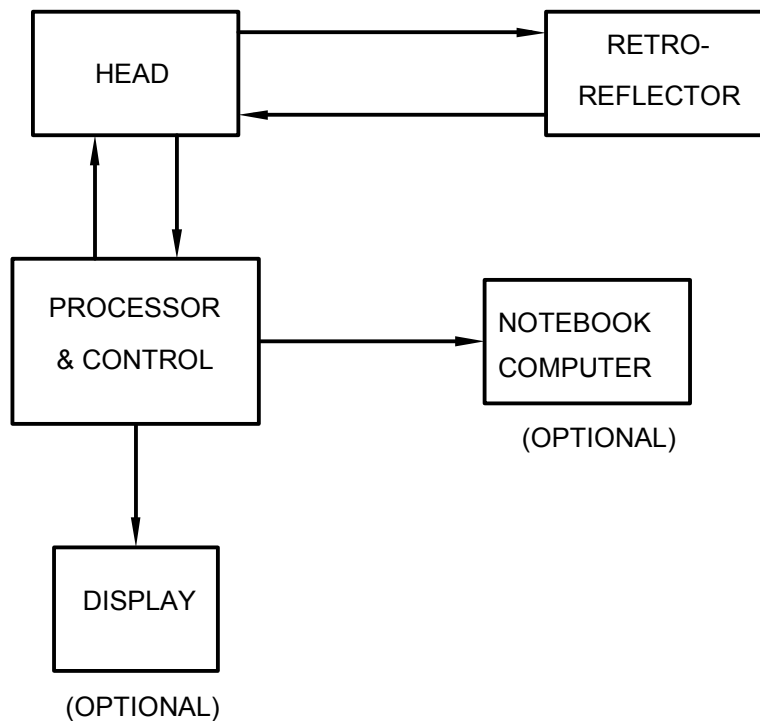


FIG. 2-1 LDDM SYSTEM BLOCK DIAGRAM

The following is a general description of these four components:

Laser Head Module:

The Laser Head Module houses a HeNe laser source, an electro-optic assembly and a photodetector which functions as a receiver. A compact and stable HeNe laser is used as the light source. In a manner similar to the well known Doppler Radar, the output light beam is chirped and the Doppler shift of the return light beam is measured by optical heterodyne technique. The displacement measurement is determined by the laser frequency, speed of light, and the Doppler shift. See Fig. 2-2, Laser Head Module, Physical Layout, and Fig. 2-6, Laser Head Module, Block Diagram.

Retroreflector:

The Retroreflector serves as a cooperative target. It is a corner cube, which reflects the laser beam back to the receiving aperture on a path displaced from, but parallel to the input beam, regardless of the angle of incidence. The use of a corner cube reflector provides significant advantages. Its alignment during installation is not critical in that it may rotate during measurements. See Fig. 2-3 Retroreflector, Physical Layout.

Processor Module:

The Processor Module provides power for the Laser Head Module, electro-optics, analog and digital signal processors and the output interfaces. It also provides signal processing, calibration alignment and output signal conditioning. The Processor Module contains a phase-demodulator board, a microprocessor board, an EO-device driver, a laser power supply, and a DC power supply. The signal from the photodetector is processed by the phase-demodulator and converted to standard TTL pulses. These up/down pulses are counted and converted to English or Metric units by a microprocessor. The result is sent to the display module. See Fig. 2-4, Processor Module, Physical Layout and Fig. 2-7, Processor Module, Block Diagram. Other interfaces such as RS-232C, automatic temperature and pressure compensation, quad-detector, up/down pulses and AquadB square waves are available.

Display Module:

The Display Module (or notebook computer) shows the displacement for one or two axes of motion. Either inches or centimeters are displayed on the dual 10 digit displays. Reset can be done by remote control or by a push-button on the display panel. The display is controlled by the microprocessor. It can display X-axis, Y-axis, signal intensity, error messages, and other information. See Fig. 2-5, Display Module, Physical layout and Fig. 2-8, Display Module, Block Diagram. A notebook computer with standard RS-232 interface can be used to

replace the display module. DOS or Windows software are available for data collection and analysis.

2.2 Theory of Operation

LDDM™ monitors the displacement of the objective or target, from an initial position where the display is zeroed, to any final position within the range of the instrument. Displacement is shown continuously as the target moves. At the final position, the displacement of the target is displayed. The sign of the displayed number indicates positive or negative displacement. Once set up the system operates without further adjustment.

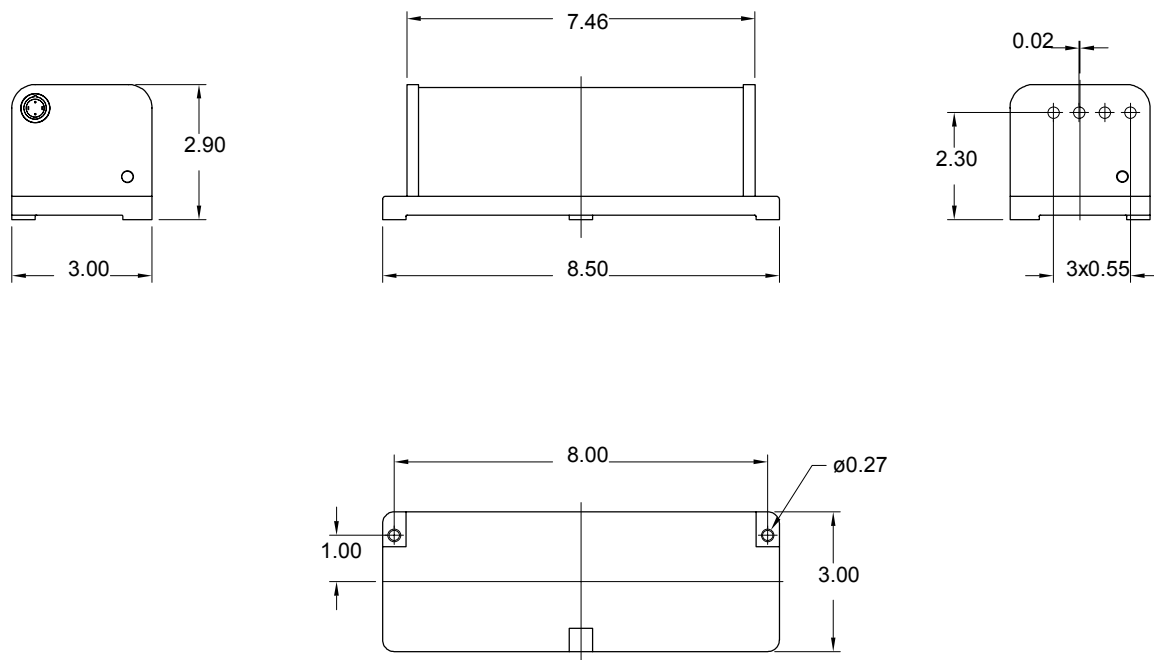


FIG. 2-2 LASER HEAD MODULE
OUTLINE & MOUNTING DIMENSIONS

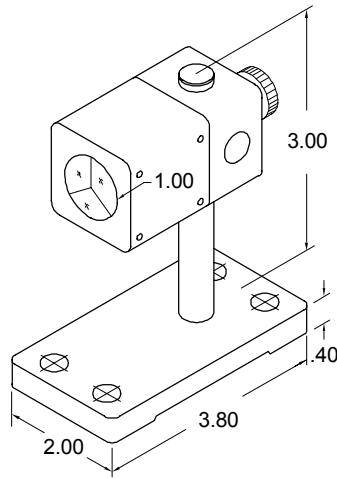
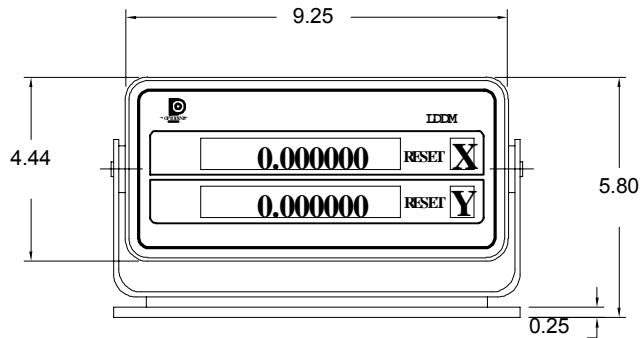


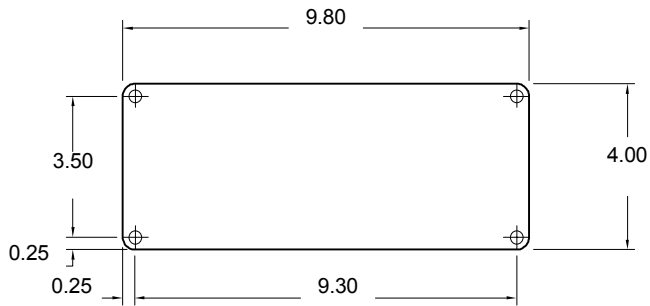
FIG. 2-3 RETROREFLECTOR AND HOLDER



FIG. 2-4 PROCESSOR MODULE
OUTLINE DIMENSIONS



FRONT VIEW



BASE MOUNTING

FIG. 2-5 DISPLAY MODULE, PHYSICAL LAYOUT

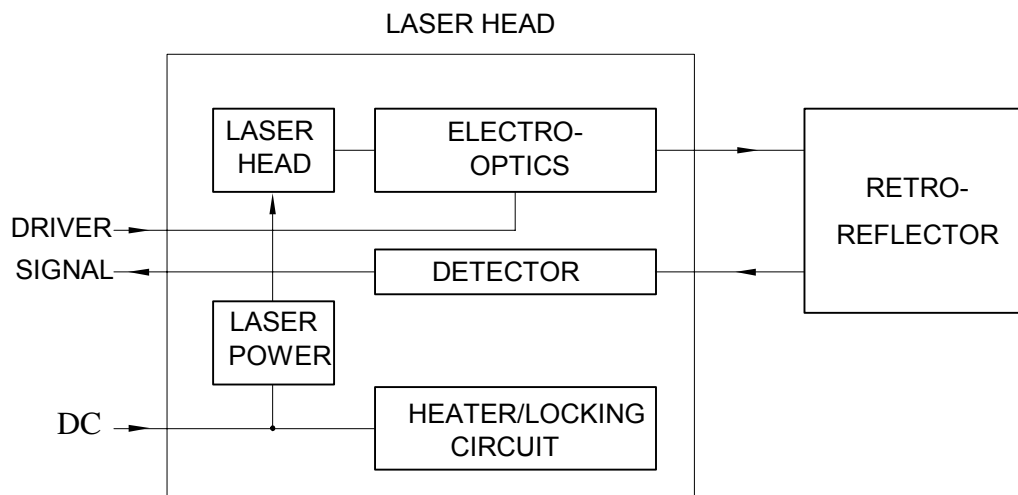


FIG. 2-6 LASER HEAD MODULE, BLOCK DIAGRAM

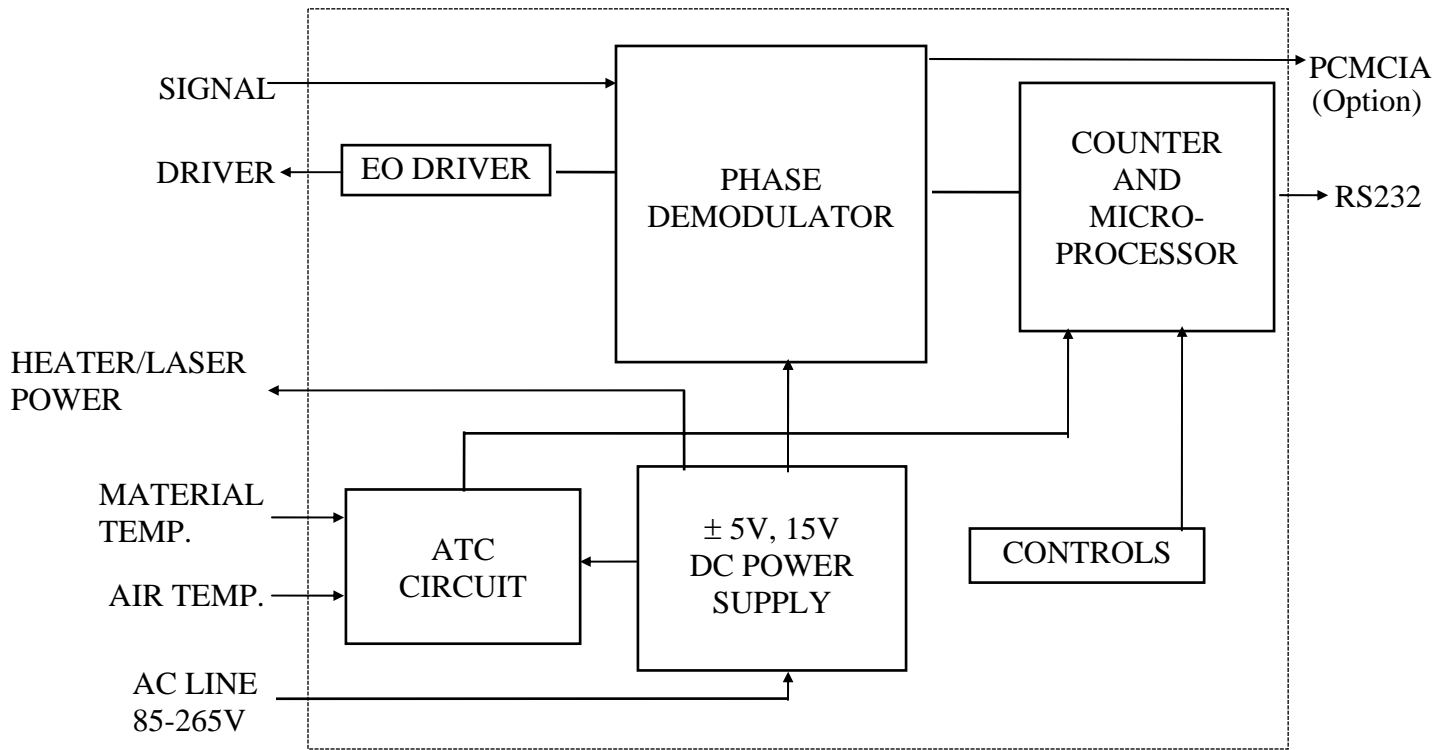


FIG. 2-7 PROCESSOR MODULE, BLOCK DIAGRAM

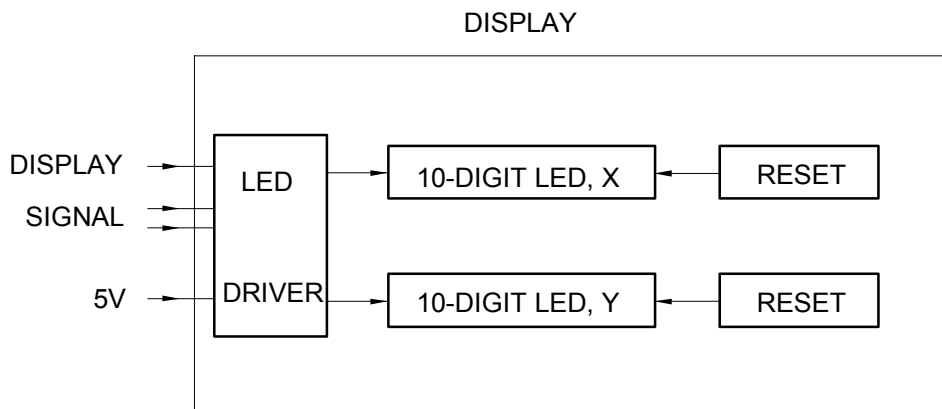


FIG. 2-8 DISPLAY MODULE(Option), BLOCK DIAGRAM

LDDM™ uses an electro-optical device which detects the Doppler shift of a laser frequency caused by a moving target to measure displacement with a high degree of accuracy. The range may be from a few microns to several meters. Other precision displacement measuring devices use interferometric techniques, requiring a sophisticated and bulky laser. This approach calls for critical, time consuming alignments, and causes additional expense. LDDM™ is based on the principles used in radar. Its construction is simpler, less costly, more rugged and much easier to use than a conventional interferometer.

The frequency of the reflected laser beam is shifted by the motion of the Retroreflector and is proportional to its velocity. The phase shift is proportional to the displacement. A phase-detector is used to sense the phase shift. For each half wavelength of displacement a counter is incremented. A microprocessor is used to read the counter and the phase angle, and converts them to inches or centimeters.

The Doppler frequency shift can be expressed as:

$$\Delta f = (2f/c) \Delta v$$

or:

$$\Delta \theta = 2 \pi (2f/c) \Delta z$$

Where Δf and $\Delta \theta$ are the frequency and phase shift and Δv and Δz are the velocity and displacement respectively, of the Retroreflector. The variable f is the frequency of the laser, and c is the speed of light.

A counter is used in conjunction with the phase detector to record the number of half-wave lengths, $\lambda/2$, detected. A microprocessor reads the counter and the phase angle, converts them to output units, and controls the 10-digit display. Compensation for changes in the speed of light due to temperature, pressure and humidity variations is programmable.

As shown in Fig. 2-6, the laser frequency is chirped by an electro-optic device and is then sent to the Retroreflector. Light returned from the Retroreflector is detected by a photodetector. Power for both the laser and the electro-optics driver comes from the Processor Module. Detected signals are sent to the Processor Module.

2.3 Technical Specification

	Standard	Optional	Units
Laser Stability:	0.1	0.01	ppm
Resolution:	1	0.05	μin
	0.01	0.0012	μm
Range:	0-120	0-2400	inches
	0-3	0-60	meters
Axes:	one	two	
Rate (max.):	72	144	inch/sec.
	100	200	meters/min.
Outputs:	Up/Down or serial BCD, A quad B square wave, computer interface, RS-232C		

Operating Environment: Temperature - 60 to 90 °F (15° to 32°).

Altitude: 0 to 10,000 feet

Humidity: 0 to 95 percent (non-condensing)

Components:	Width in (mm)	Height in (mm)	Length in (mm)	Weight lb (kg)
Laser Head Module	3 (76.2)	2.75 (69.85)	8.5 (216)	2.5 (1.37)
Retroreflector	Φ1.0 (25.4)		0.75 (19)	0.6 (0.27)
Processor Module	9.3 (236.2)	3.5 (88.9)	9 (228.6)	8.5 (3.86)
Display Module (optional)	9.3 (236.2)	5 (127)	2.5 (63.5)	4.0 (1.8)

Interconnection

Cables: Number 2 Length 12 ft (3.6m) (other lengths available)

Power Requirements: 85-265 VAC, 50-60HZ, 100W

Note: Specification may change without notice.

3.0 Operation

3.1 General Applications

Applications for LDDM™, MCV-2000 laser system fall into five categories: calibration and compensation of linear displacement errors, calibration and compensation of volumetric positioning errors (displacement errors, straightness errors, angular errors and squareness errors), calibrate and compensation of rotary table, calibrate of surface plates, and check circular contouring accuracy for servo tuning and structure vibration.

There is a wide range of calibration requirements where the high accuracy and ease of use characteristics of LDDM™ can be advantageously employed. These measured positioning errors can be used by the controller to compensate the errors and improve the machine performance.

When employed as a calibration tool, the LDDM™'s lightweight, portability, and simplicity of setup and operation, are advantages which you will appreciate. The LDDM™ is also often mounted permanently in a calibration setting whereby production or laboratory parts and instruments are cycled through the calibration fixture.

LDDM™ is ideally suited as a position monitor. When mounted on a machine tool or X-Y position machine, it integrates well with standard operating practices in providing improved accuracy and ease of use over a long period and without requiring maintenance or recalibration. LDDM™ can be used as a component for real time, feedback loop control in many applications such as:

- X-Y Stages
- Pattern generators
- Steppers and aligners
- Magnetic and optical disk drives
- Diamond point turning machines
- Precision machine tools
- CNC machines
- Coordinate measuring machines

LDDM™ can be installed as a component in a position control system. Its characteristics of ruggedness, stability and high accuracy allow it to perform in a superior manner within the feedback loop.

3.2 Installation and Checkout

The LDDM™ system is extremely easy to set up and operate. The Laser Head, placed on the axis of interest, is mounted in a fixed position. The Retroreflector should be rigidly mounted onto the moving objective or target. The final position

of these two components is determined by targeting the laser beam while moving the objective. There is no limitation on the location of the Processor Module within the limits of its two interconnecting cables; one to the Laser Head Module, the other to the Notebook; and its AC power cord.

Mount the Laser Head Module at the two mounting holes near the two ends. The laser head may be secured to a work surface in any fashion that will not generate and transmit excessive mechanical stresses to the Laser Head Module.

After the Reflector is mounted onto the target/objective, and the Laser Head Module is in place, attach the cables between the Laser Head Module and the Processor Module. Locate and mount the notebook computer and interconnect it with the Processor Module using the second cable. Plug the Processor Module into an AC power source.

Turn on the power switch located on the Processor Module. After approximately five seconds, the laser will start up and a red beam of light can be detected from the center hole on the Laser Head Module.

Caution: Do not look directly into the laser beam hole to detect the laser light beam. Instead, position a piece of white paper in front of the hole until a visible spot can be seen on the paper.

LDDM software instruction

There are 2 types interface between the Notebook PC and the LDDM processor module, one is serial interface through the com port and the other is USB human interface. All the software is stored in a CD-ROM. Click on "Setup" to install the software to your Notebook PC.

Serial interface through Com Port

1, Using RS-232 port on your Notebook PC

Boot the Notebook PC first with the RS-232 cable disconnected. Turn on the LDDM processor, connect the RS-232 cable, and start the LDDM program. If the LDDM program couldn't find the interface, check the "device manager", and "Com Port" to make sure the Com Port is available. Also, make sure all the cables are connected properly and reset the Processor by turn-off the power and turn-on again. Many times, the problem is caused by a bad (poor contact) RS-232 cable or poor connection.

2, Using USB port with RS-232/USB converter

Make sure the driver for the RS-232/USB converter is installed. Connect the RS-232/USB converter to the Notebook PC, turn-on the LDDM processor, connect the RS-232/USB converter to the RS-232 port and start the LDDM program. If the LDDM program couldn't find the interface, check the "device manager", and "Com Port" to make sure other device, such as external mouse, is not using the same com port. Sometimes, the external mouse has to be disabled. Also, make sure all the cables are connected properly and reset the Processor by turn-off the power and turn-on again. Many times, the problem is caused by a bad (poor contact) RS-232 or USB cable or poor connection.

Direct USB human interface

Make sure the laser head and ATC sensors are connected to the processor. Connect the USB cable between the Notebook PC and the LDDM processor. Start the LDDM program. For Windows Vista, use "Run as administrator". If the LDDM hardware is not connected and you want to do analysis, there is a popup screen stating: "Report missing USB device, Yes or No". Click on No, the main menu will be displayed and click "analysis" to perform data analysis. If all the LDDM hardware is connected, the main menu will be displayed, otherwise a popup screen stating: "Linear USB data device not connected. Continue? Yes/No". Click Yes to continue and No to exit.

For some Notebook PC with too many USB ports, the voltage becomes marginal or too low, an external USB hub with power should be used. Go to "device manager" and click on "Human Interface Devices". There should be 6 lines of HID-compliant device and 6 lines of USB Human Interface Device. If any of these are missing or with a yellow exclamation mark on the corner, external USB hub with power should be used. The PC screen will show the Digital Display. When the system is properly aligned, the intensity reading should read more than 80%, depending on the processor module and the laser head. When the beam is completely blocked, the intensity should read less than 10%. The system is operable at any reading above 20%, but for more reliable operation it should be above 80%.

If the laser does not start, turn the laser power switch off and then on again. If the laser still will not start after a few minutes see section 4 of this manual. Adjust the positions of the Laser Head Module and the Retroreflector so that the return beam is visible on the Laser Head Module front plate. Continue to adjust these two components until the spot of the return beam does not move while the objective, with the Retroreflector mounted on it, is moved over the desired range of measurement. Finally, move the Retroreflector so that the return beam enters the receiver aperture. Move the corner cube in the lateral direction until at the maximum intensity. Then move the corner cube to the full extreme of the travel while monitoring the monitor. If the number falls below 20% at a certain location, realign the corner cube for the largest intensity possible at that location and then move the corner cube down the rail while monitoring the monitor for the

maximum. After the unit is properly aligned, it will be able to travel the complete length of the rail with little change in the intensity. Click the reset to reset to zero. The LDDM™ system is now ready to use. (For more details see Section 7.5).

Even when the Retroreflector is stationary, the displacement readings will be affected by vibration, noise, variations in humidity, variations in barometric pressure and variations in temperature. These changes will affect the accuracy of the laser system as follows, approximately:

As a rule of thumb, temperature increase of 1°F is equivalent to a wavelength increase of 0.5 ppm, which is equivalent to 0.5 μin per inch of distance measured. A barometric pressure increase of 0.1 in. Hg is equivalent to a temperature decrease of 2°F or 1 μin per inch distance measured. A relative humidity increase of 30% RH is equivalent to a temperature decrease of 1°F or 0.5 μin per inch of distance measured.

However, usually the material thermal expansion is the dominant factor. For example, the thermal expansion coefficient of steel is 7.6 ppm/°F which corresponds to a 7.6 μin per inch of distance measured for each 1°F of temperature change. For further discussion see Section 7.7 and Appendix H.

3.3 Displacement Measurement

If installation and check out have been followed as described in section 3.2, the laser beam will be aligned parallel to the linear motion of the Retroreflector over the displacement range of interest. To operate the system, simply turn the Power switch, which is located on the front panel of the Processor Module, to the ON position. Reset the Display Module to zero with the reset button. The system is now ready to start measuring displacement. The system will function immediately after turning power on. However, ultimate accuracy is achieved only after a warm-up period of 15 to 30 minutes during which the laser locks its frequency. The indicator light on the back of the laser head will light after the frequency is locked.

As the Retroreflector moves, the X axis display will show displacement. The value displayed will constantly change as the Retroreflector moves. When motion stops, the display will show the displacement of the Retroreflector at its current position. If motion resumes, the display will again constantly change to show each instantaneous position of the moving Retroreflector. If the Retroreflector moves back to its original position, where the display was zeroed, the display will again show zero displacement. If the Retroreflector moves closer to the Laser Head Module than it was at the point of zero, then displacement will be displayed with a minus sign to indicate a negative displacement. For further details see Section 7.8.

4.0 Maintenance

4.1 Troubleshooting

The following paragraphs describe several diagnostic situations which the end user should be aware of in order to assure constant and reliable operation from the LDDM™ system:

No laser beam:

Turn off the power switch. Check the cable connector and make sure it is pushed in all the way. Turn on the power again and make sure that the indicating light above the switch is illuminated. If there is no laser beam after 30 seconds, turn the power off and on again. If there is still no laser beam after a few tries, return both the Laser Head Module and the Processor Module for factory diagnosis.

Intensity less than 20%:

This is an indication that the return beam is not properly aligned or that cables are not properly connected. Check all cables and connectors, and realign the Retroreflector. If this problem persists return the system for factory diagnosis.

4.2 Preventive Maintenance

There is no preventive maintenance required for the LDDM™. The system is designed to operate for an extended time without attention. The laser tube has an estimated life of 20,000 operating hours. Replacement of this tube is indicated by either no laser beam or a frequent flashing "R" on the display and is accomplished by returning the Laser Head Module to the factory. Please contact your local sales office to identify nominal charges associated with this repair when done out of warranty. During the warranty period, repairs must be done by Optodyne in order to maintain the warranty. The cases of both the Laser Head Module and the Processor Module are sealed with foil seals to prevent tampering. The **BREAKING OR REMOVING OF THESE SEALS VOIDS THE WARRANTY.**

After the warranty expires, Optodyne strongly recommends that subsequent defective components be returned to the factory for authorized service. Special tools, test equipment and know-how are required to evaluate LDDM™ component performance and to match replacement parts to maintain optimum system performance to specifications.

It is recommended that the LDDM™ be sent back to Optodyne Service Department annually for maintenance service and calibration. An extended warranty of up to three years is also available.

5.0 Warranty and Certification

5.1 Warranty

Optodyne, Inc., warrants that each new instrument which it manufactures and sells is free from defects in material and workmanship under recommended use and service conditions. Liability under this warranty is limited to servicing or adjusting any unit returned to the factory for that purpose and replacing any defective parts thereof. If a problem is limited to a single module, it is preferred that only the defective module be returned to Optodyne. This warranty is effective for one year from the date of delivery and to the original purchaser only. When the unit is returned (transportation charges prepaid by the original purchaser) and when upon examination, it is found to be defective, if the fault has been caused by misuse or abnormal conditions of operation, repairs will be billed at cost. In this case, an estimate will be submitted before the work is started. Optodyne, Inc. shall not be liable for damages by reason of failure of the instrument to perform properly or for any consequential damage. This warranty does not apply to any unit that has been subject to neglect, accident, misuse, improper operation or that in any way has been tampered with, altered or repaired by any person other than an authorized Optodyne personnel or to any unit whose serial number has been altered, defaced or removed.

Exclusive Remedies: The remedies provided herein are the buyer's sole and exclusive remedies. Optodyne, Inc., shall not be liable for any direct, indirect, special, incidental or consequential damages, whether based on contract, tort or any other legal theory.

5.2 Certification

Optodyne, Inc. certifies that this product meets its published specification (see [section 2.3](#)) at the time of shipment from the factory.

5.3 Calibration

The fundamental accuracy of the LDDM™ is based upon the wavelength stability of the laser used in the system. This wavelength has been measured to be 632.81934 ±0.0005 nm (24.914154 μin) at ambient conditions defined as follows:

Temperature:	68° Fahrenheit
Pressure:	29.90 inches of mercury
Relative Humidity:	40%

A calibration constant of 80275.65 counts per inch has been programmed into the microprocessor within the Processor Module. Recalibration service is available from Optodyne, Inc., for a nominal charge. A certificate of calibration

which is traceable to the National Institute of Standards and Technology, NIST, will be provided upon request. Optodyne is accredited to ISO/IEC17025 by L.A.B. The certificate number is L-1085.

SPECIAL THREE-YEAR LIMITED WARRANTY FOR MODEL V

Optodyne, Inc. warrants that each new Model V instrument which it manufactures and sells is free from defects in material and workmanship under recommended use and service conditions. Liability under this warranty is limited to servicing or adjusting any unit returned to the factory for that purpose and replacing any defective parts thereof. In the case that a problem is limited to a single module, it is preferred that only the defective module be returned to Optodyne. This special warranty is effective for three years from the date of delivery and to the original purchaser only. At the end of the first and second year, the unit should be returned for calibration. A service fee of \$750.00 and transportation charges will be charged to the original purchaser for each calibration. The warranty will be voided, if the original purchaser fails to return the unit for calibration. When the unit is returned (transportation charges prepaid by the original purchaser) and found to be defective upon examination, if the fault has been caused by misuse or abnormal conditions of operation, repairs will be billed at cost. In this case, an estimate will be submitted before the work is started. Optodyne, Inc. shall not be liable for damages by reason of failure of the instrument to perform properly or for any consequential damage. This warranty does not apply to any unit that has been subject to neglect, accident, misuse, improper operation or that in anyway has been tampered with, altered or repaired by any person other than an authorized Optodyne personnel or to any unit whose serial number has been altered, defaced or removed.

Exclusive Remedies: The remedies provided herein are the buyer's sole and exclusive remedies. Optodyne, Inc. shall not be liable for any direct, indirect, special incidental or consequential damages, whether based on contract, tort or any other legal theory.

Warranty Registration

Please complete this sheet as soon as the system is unpacked and return it to Optodyne, Inc. at the address shown below. Registration establishes the warranty period and enables Optodyne to keep you informed of product changes or upgrades.

End user's name: _____		
Title: _____	Dept.: _____	
Company: _____	Phone Number: () _____	
	ext.: _____	
Address: _____		
City: _____	State: _____	ZIP: _____
Date of Purchase: _____		
Model Number: _____		
Laser head	Processor	Display
S/N: _____	S/N: _____	S/N: _____
Description of intended use or application:		

Mail to:
Optodyne, Inc.
1180 Mahalo Place
Compton, CA 90220

or FAX to 310-635-6301.

Part II. APPLICATIONS

6.0 LDDM™ Measurement System

6.1 Introduction

The characterization of machine movement is extremely complex. For each axis of motion, there are six degrees of freedom as shown in Fig. 6-1. The six degrees of freedom are:

1. Linear displacement
2. Pitch
3. Yaw
4. Roll
5. Vertical straightness, and
6. Horizontal straightness

These (6) variables are used to characterize the movement of a carriage traveling on a pair of ways.

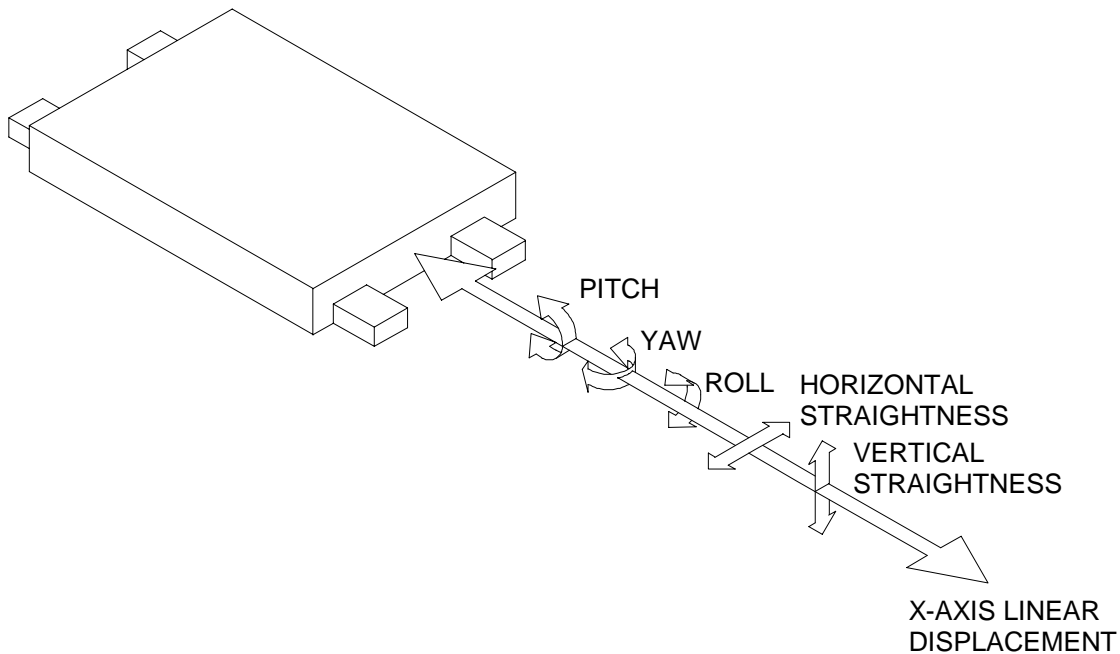


FIG. 6-1 LINEAR MOTION WITH SIX DEGREES OF FREEDOM

Squareness and parallelism of travel between two axes characterize how these two axes are positioned relative to each other as shown in Fig. 6-2. Each of these characteristics contributes to positioning accuracy and precision at any point within the machine's work zone. All of these measurements (except roll) can be made with the LDDM™/Laser Measurement System. It is a portable and compact measuring system designed to calibrate CNC machine tools, coordinate measuring machines, linear measuring devices, XY-Tables, etc. The LDDM™ can calculate the following measurements:

- a. Displacement (linear distance) [see Section 7]
- b. Pitch, Yaw and Straightness (angular method) [see Section 8]
- c. Surface Flatness [see Section 9]
- d. Squareness, Parallelism and Straightness [see Section 10]
- e. Velocity, Acceleration and Vibration [see Section 11]
- f. Rotary Table [see Section 12]

For all of these measurements a laser head, a retroreflector, a processor module and a display module or a notebook PC will be needed. In addition, you may want a small computer (IBM compatible computer), software and various accessories. A listing of the hardware needed for each measurement is provided in Table 6-1.

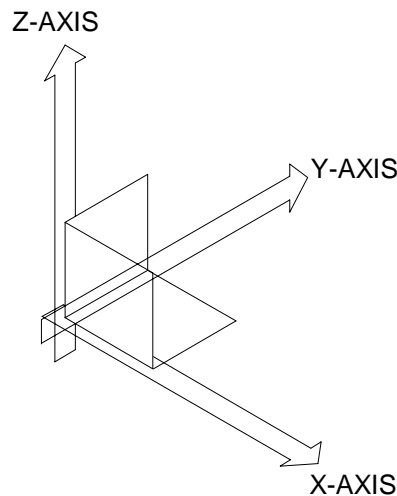


FIG. 6-2 SQUARENESS BETWEEN AXES

Hardware, P/N	Linear Displacement	Pitch,Yaw & Straight- ness	Surface Flatness	Squareness Parallelism & Straightness	Velocity, Acceleration Vibration	Rotary Table Calibration	Circular Contour
Laser head, Standard, L-101	✓			✓			
Laser head, Dual- Beam, L-104	✓	✓	✓	✓		✓	✓
Laser head, Single- Aperture, L-102					✓		
Retroreflector, Standard, R106	✓			✓			
Retroreflector, Dual, R103		✓	✓			✓	
Retroreflector, Ø0.5in, R102					✓		
Processor Module, Standard, P-111	✓				✓		
Processor Module, 2-Channel, P210		✓	✓	✓			✓
Display Module, D101/ Notebook PC	✓	✓	✓	✓	✓	✓	✓
Direct IBM PC Interface, PC1					✓		
Metrology Software ("S" denotes DOS)							
W-102	✓						
W-103		✓	✓	✓			
W-104				✓			
W-105						✓	
S106S					✓		
S107					✓		
W500LB							✓
W500PC							✓
Accessories							
90° Beam Bender, LD-15	✓			✓	✓		
Optical Square, LD-16				✓			
Surface Flatness Kit, LD-24			✓				
Alignment Kit, LD-32		✓					
Quad-Detector, LD-42				✓			
Straight Edge for Flatness, LD-43			✓				
Rotary Stage, LD-53						✓	
IBM PC Portable Computer					✓		
Optical Adapter LD-69DB							✓
6" Flat Mirror LD-71							✓
PC Card & Cable ICP5-1000							✓

Table 6-1 List of Hardware Versus Measurement

6.2 Hardware, Options and Accessories

For a general description of the laser head, retroreflector, processor module and display, see section 2.1.

6.2.1 Laser Head

L-101 standard dual-aperture laser head

This laser head houses the laser tube which produces the laser beam used in the measurement calculation. It also contains an Electro-optical modulator, a photo-detector and a heater. One aperture is at the exit of the laser beam and the other aperture is for the return beam from a retroreflector. Typical dimensions of the laser head are shown in Fig. 6-3.

L-104 Dual-Beam laser head

This dual-beam laser head emits two laser beams. Both beams are reflected back by two retroreflectors mounted on a rigid base (dual retroreflector). There are two photo-detectors. One detects the displacement of the center laser beam, and the other detects the difference in displacement between the center beam and the right-hand-side beam. Hence, both linear displacement and angular displacement of the dual-retroreflector can be measured simultaneously. The dimension of this laser head is the same as the dual-aperture laser head. A front view and a back view of this laser head is shown in Fig. 6-4.

6.2.2 Processor Modules

P-111, Standard Processor Module

This processor module provides power for the laser head, electro-optics, analog and digital signal processor, and output interfaces. The resolution is 1 μ in. Available options are the RS-232 interface, IBM PC direct interface, automatic temperature and pressure compensation, and quad-detector interface. A typical dimension of the processor module is shown in Fig. 6-5.

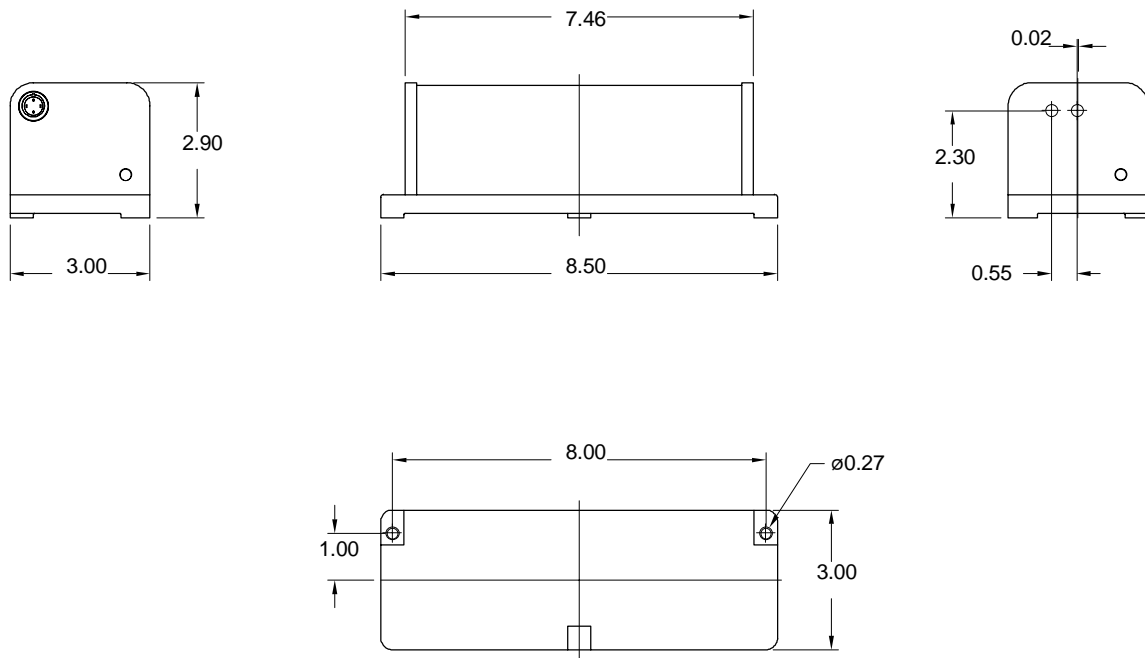


FIG. 6-3 LASER HEAD MODULE (L-101 Dual - aperture)
 OUTLINE & MOUNTING DIMENSIONS

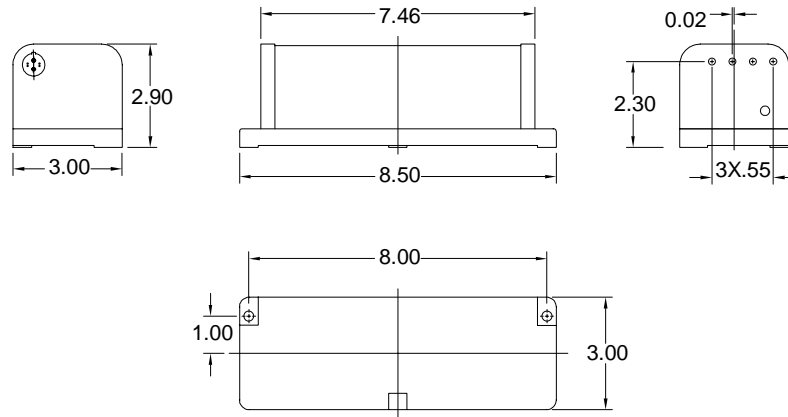


FIG. 6-4 LASER HEAD MODULE OUTLINE (L-104 Dual - beam)
& MOUNTING DIMENSIONS



FIG. 6-5 PROCESSOR MODULE
OUTLINE DIMENSIONS

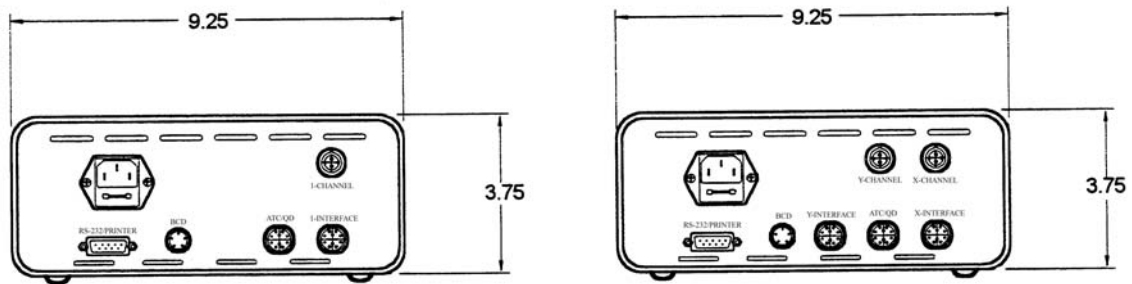


FIG. 6-6 REAR VIEW OF PROCESSOR MODULE

P-210 2-channel Processor Module

This processor module is the same as the P-101, but additionally includes the capability of processing two signal channels (when used with the dual-beam laser head). The resolution is 1 μ in. The quad-detector interface, ATC interface and RS-232 interface are all included. The dimensions of all processor modules are identical. The rear panels of P-111 and P-210 are shown in Fig. 6-6.

6.2.3 Retroreflector and Flat Mirror

The retroreflector serves as a cooperative target. It is a corner cube, which reflects the laser beam back to the receiving aperture on a path parallel to the input beam regardless of the angle of incidence. The standard retroreflector has a diameter of 1 in. For a single aperture laser head, you may use a smaller, say \varnothing 0.5 in. retroreflector. For long distances, you may use a larger, say \varnothing 2.5 in. retroreflector. The dimensions of a dual retroreflector, \varnothing 0.5 in. retroreflector and \varnothing 0.25 in. retroreflector are shown in Fig. 6-7. For the single aperture laser head, it is possible to use a first-surface flat mirror as a target. However, the flat mirror has to be aligned such that the reflected beam is parallel to the incident beam to within 30 arcsec. It is noted that the laser beam is non-polarized (random polarized), special coatings are not necessary and any flat first surface mirror can be used to steer the laser beam with any incident angle. Precise interferometer optical components will easily work with the LDDM™. However, less precise and therefore less expensive components may be used with the LDDM™ without sacrificing measurement accuracy and precision.

6.2.4 Display Module (optional)

The display module shows the displacement for one or two axes of motion. Either inches or mm can be displayed on the dual 10 digit displays. Reset or switch modes can be entered by pressing the X and/or Y buttons on the display panel. Various modes of display are controlled by the microprocessor firmware. See Appendix C for details.

6.2.5 Computer Interfaces

There are three types of computer interfaces, one is through an RS-232 bus, the second one is through a direct interface card, which is inserted into an IBM PC compatible computer extension slot and the third is through a PCMCIA interface card. The RS-232 bus transmits all the information shown on the display at 9600 Baud, 8-bit with 1 parity bit and 1 stop bit. Also, the computer can send command code to the processor module to reflect different modes of display. For more details see Appendix E. The IBM PC direct interface card is a half-size card with ADC and counters. The inputs to the interface card are up count, down count, analog phase signal and error signal. Demonstration software is provided to display the displacement on the computer monitor. The PCMCIA interface card can be inserted into notebook PC with a PCMCIA slot. The inputs are up count, down count, digital phase signal and error signal. A photograph of an PCMCIA card and cable is shown in Fig. 6-8.

6.2.6 Automatic temperature and pressure compensation

The ATC probe consists of an air temperature sensor, an air pressure sensor, and a material temperature sensor. The ATC electronics consist of a power supply to the probe and ADC to convert analog signal to digital signal. Two types of electronics are available. One is installed in the processor module (ATC) and the other is inserted into the IBM PC computer extension slot (ATCC). For ATC, the air temperature and air pressure readings are used to correct for velocity of light changes. The corrected displacement is shown on the display. The material temperature reading is transmitted through an RS-232 bus to the computer. The user needs to key in the material thermal expansion coefficient to calculate the correction factor (MTE) for the material thermal expansion. For ATCC, the air temperature and air pressure are used to calculate the correction factor needed for any velocity of light change. The material temperature is used to calculate the material thermal expansion. For a detailed description and calibration procedure, see Appendix H. A photograph of the ATC probe, and ATCC card and probe is shown in Fig. 6-9.

6.2.7 Quad-detector

In calculating squareness and parallelism measurements, a quad-detector is used to measure the centroid of the laser beam. The quad-detector is a large

area photodetector cut into four quadrants as shown in Fig. 6-10. If the laser beam shines at the center of the quad-detector, the signal strength from the four detectors will be the same. If the beam is to the left, 1 and 3 will have higher output than 2 and 4. Similarly if the beam is to the top, 1 and 2 will have a higher output than 3 and 4. A typical quad-detector with mount is shown in Fig. 6-11.

6.2.8 Beam bender and optical square

The output laser beam is random polarized. Hence any first-surface flat-mirror can be used to reflect the laser beam to any desired direction. A beam bender is a flat mirror used to reflect the laser beam 90° from the incident beam. Two fine threaded screws are turned to adjust the mirror angle, or for fine tuning the output laser beam direction. With this beam bender, the laser beam is easily aligned to be parallel to the travel of the bed or table. A typical 90° beam bender is shown in Fig. 6-12. An optical square is a penta-prism, as shown in Fig. 6-13, such that the output laser beam is always 90° from the incident laser beam, irrespective of the angle of the penta-prism. Hence, an optical square can be used to generate a reference laser beam perpendicular to the incident laser beam. It is used to check squareness and parallelism. A typical optical square is shown in Fig. 6-14.

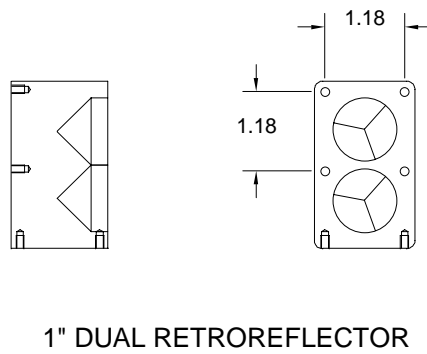
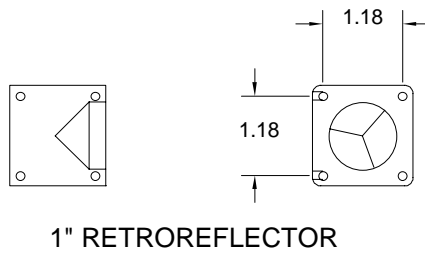
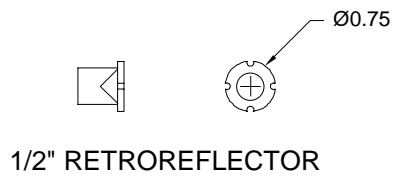


FIG. 6-7 OUTLINE & MOUNTING DIMENSIONS OF RETROREFLECTOR



Fig. 6-8 Photograph of PCMCIA Interface Card and Cable

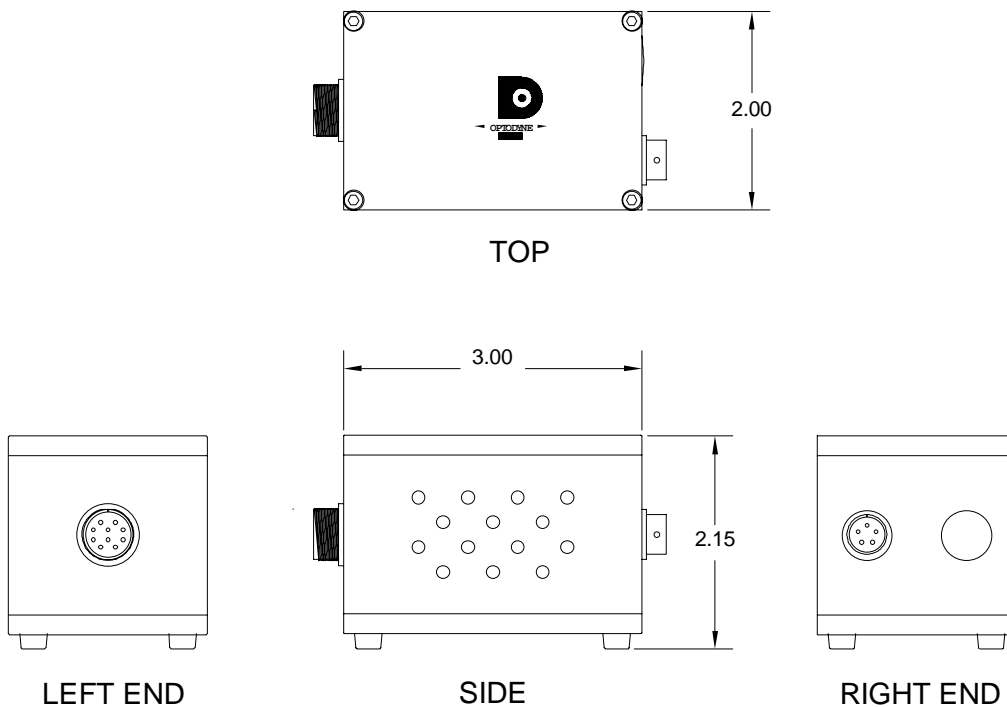


FIG. 6-9 ATC SENSOR

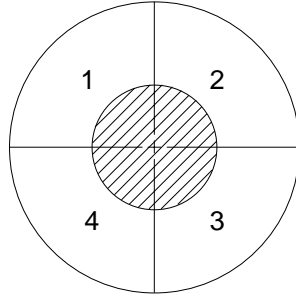


FIG. 6-10 SCHEMATIC OF QUAD-DETECTOR

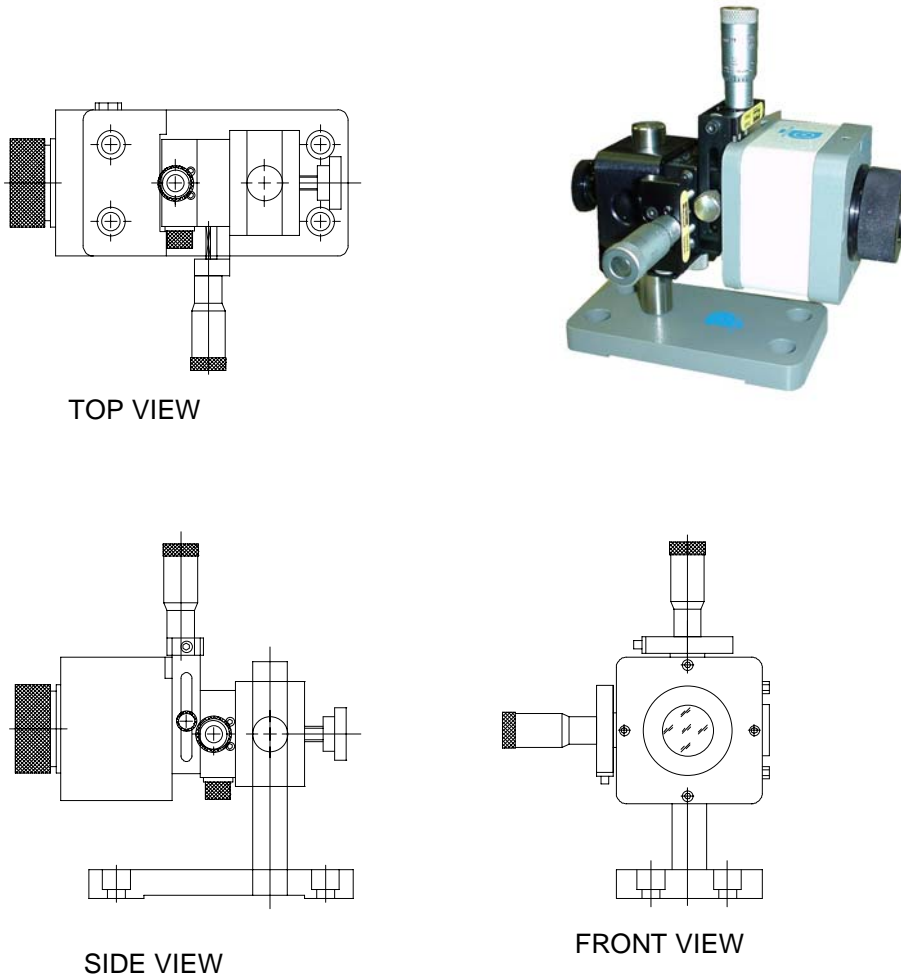


FIG. 6-11 QUAD-DETECTOR WITH MOUNT

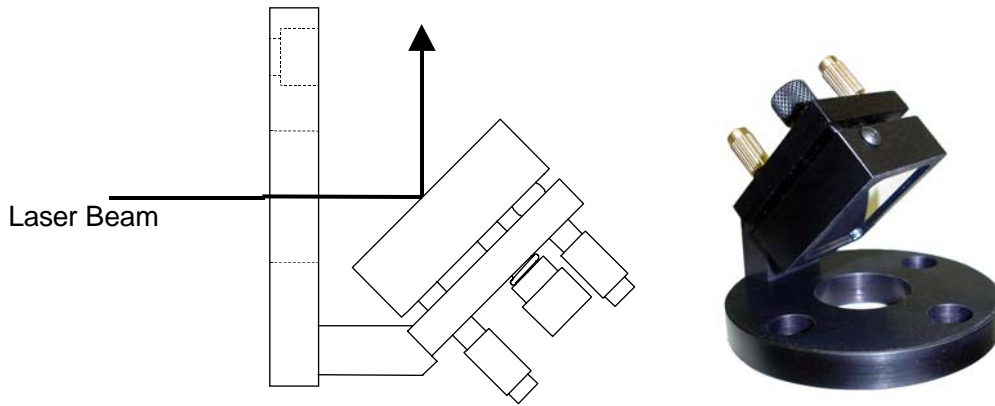


FIG. 6-12 90° BEAM BENDER

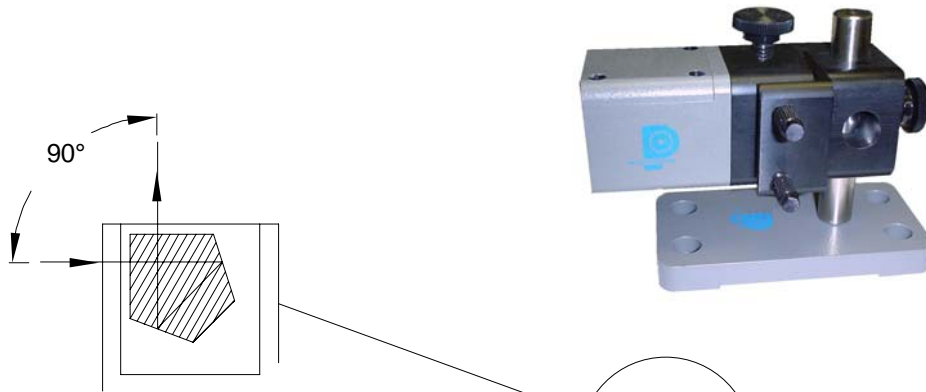
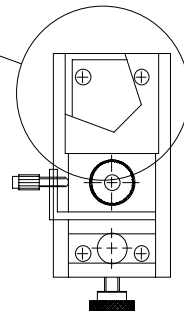
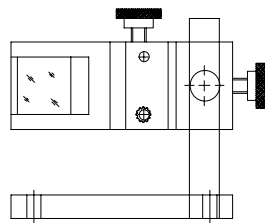


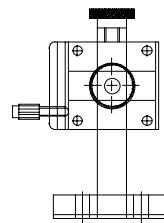
FIG. 6-13 SCHEMATIC OF A PENTA-PRISM



TOP VIEW



LEFT VIEW



FRONT VIEW

FIG. 6-14 OPTICAL SQUARE WITH MOUNT

6.3 Calibration and Compensation of CNC machines and CMM machines

The use of CNC machines and CMM machines can result in significant productivity gain and better quality control. However, these machines also require greater accuracy. Hence, frequent acceptance testing and periodic calibrations become necessary and important. A complete check of the machine specifications would include measurement of the linear position error of each axis, pitch and yaw angles, straightness, squareness and parallelism. However, after the acceptance test, periodic measurement of the linear position error and the repeatability could reveal most of the machine tool problems.

Also, many machine controllers can provide compensation for repeatable errors on each axis of motion. These repeatable errors, caused by the inaccuracy of machine ways, lead screws, or encoders, may change after wear and settling. The LDDM™ laser measurement system can be used to generate a new compensation file and re-calibrate the machine tool position accuracy.

Using the metrology program, various mean values and statistical fluctuations can be calculated based on the definition of National Machine Tool Builders Association (NMTBA) used in USA and the definition of the German VDI/DGQ3441 used in Europe. NMTBA uses "Error-band" and "Non-repeat" to define the machine accuracy, while VDI/DGQ3441 uses "P", "Ps", "Pa" and "U" to define the machine accuracy.

ISO uses accuracy, "A", averaged reversal value, " \bar{B} " and repeatability in the forward and reverse directions, "R⁺" and "R⁻" to define the machine accuracy.

For the B5 and B89 standard, the position error is defined as the LDDM™ reading - target position. The accuracy is the maximum averaged position error in the forward direction minus the maximum averaged position error in the reverse direction. The maximum reversal error is the maximum difference between the averaged forward position error and the averaged reverse position error at the same point.

"Error-band" is the difference between the most-positive 3σ points.

"Non-repeat" is the difference between the positive 3σ and negative 3σ limits at the point at which this difference is the greatest.

"P" indicates error band.

"Ps" indicates the maximum positional scatter, which is equal to two times the value of the largest difference between the average value for one direction of travel and the associated 3σ line.

"Pa" indicates a quantity which is analogous to "error-band", but is based on the difference between the most-positive and the most-negative average error.

"U" indicates the maximum backlash.

"A" indicates the machine accuracy.

"B" indicates the reversal value

"R" indicates the repeatability (forward = +, reverse = -.)

Typical plots based on the NMTBA standard and the VDI/3441 standard are shown in Fig. 6-15 and Fig. 6-16 respectively. Typical ISO and B5 plots are shown in Fig. 6-17 and 6-18. Current machine tool calibration standards, such as ISO-230-2(1977), ASME B5.54 and ASME B5.57 are all available.

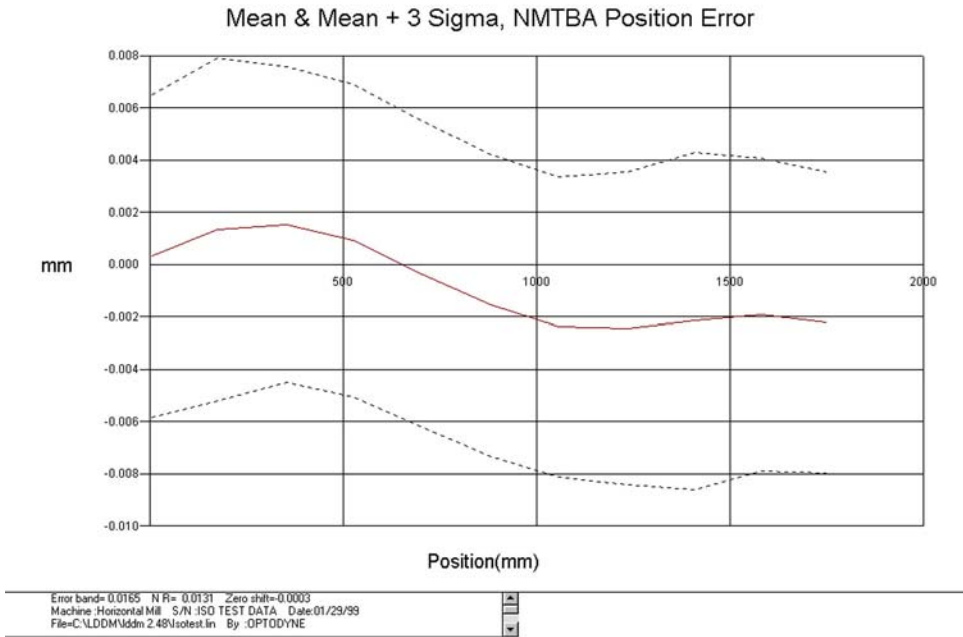


FIG. 6-15 AVERAGED POSITION ERROR PLOT BASED ON THE NMTBA STANDARD. THE SOLID LINE IS THE AVERAGED POSITION ERROR AND THE DOTS ARE THE 3-SIGMA POINTS.

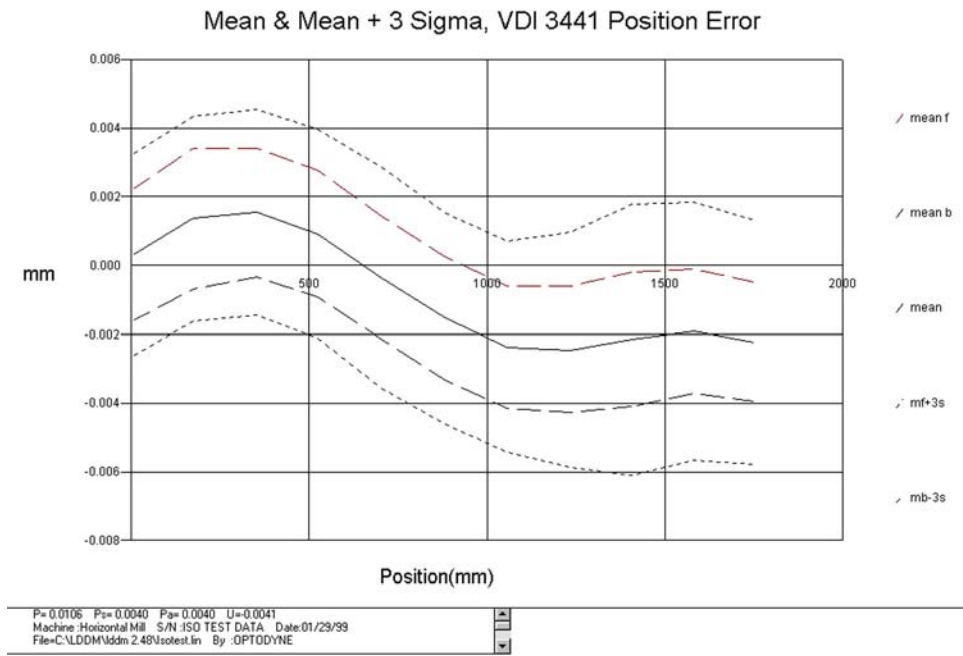


FIG. 6-16 AVERAGED POSITION ERROR PLOT BASED ON THE VDI/3441 STANDARD. THE TOP AND BOTTOM SOLID LINES ARE THE AVERAGED POSITION ERROR IN THE FORWARD AND BACKWARD DIRECTION, RESPECTIVELY. THE MIDDLE SOLID LINE IS THE MEAN VALUE. THE DOTS ARE THE 3-SIGMA POINTS.

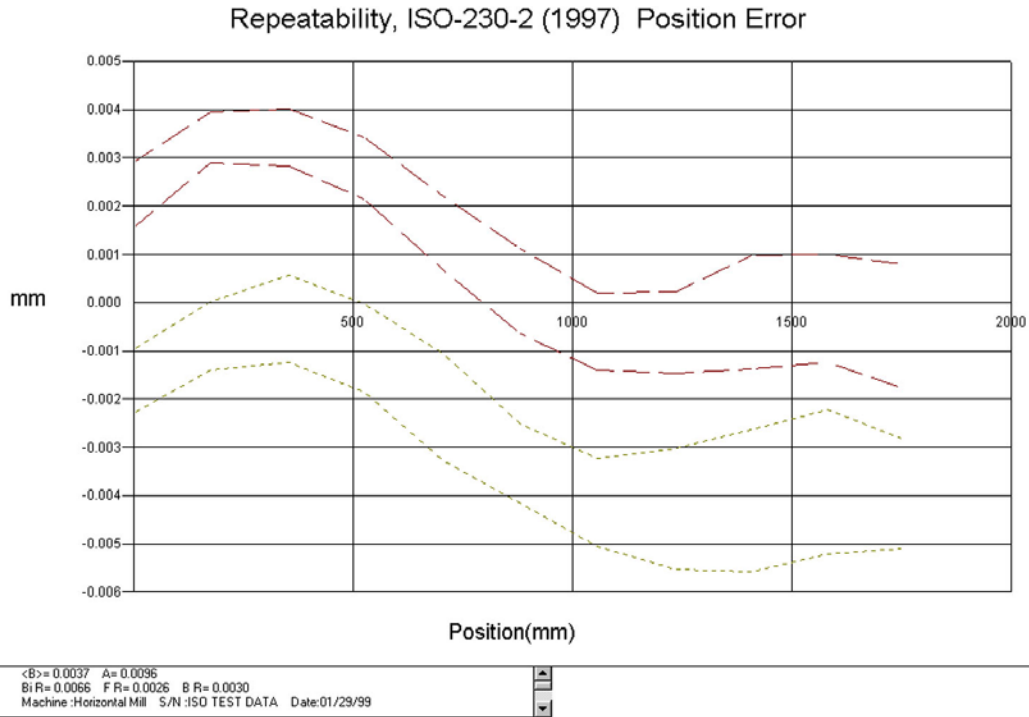


FIG. 6-17a ISO REPEATABILITY

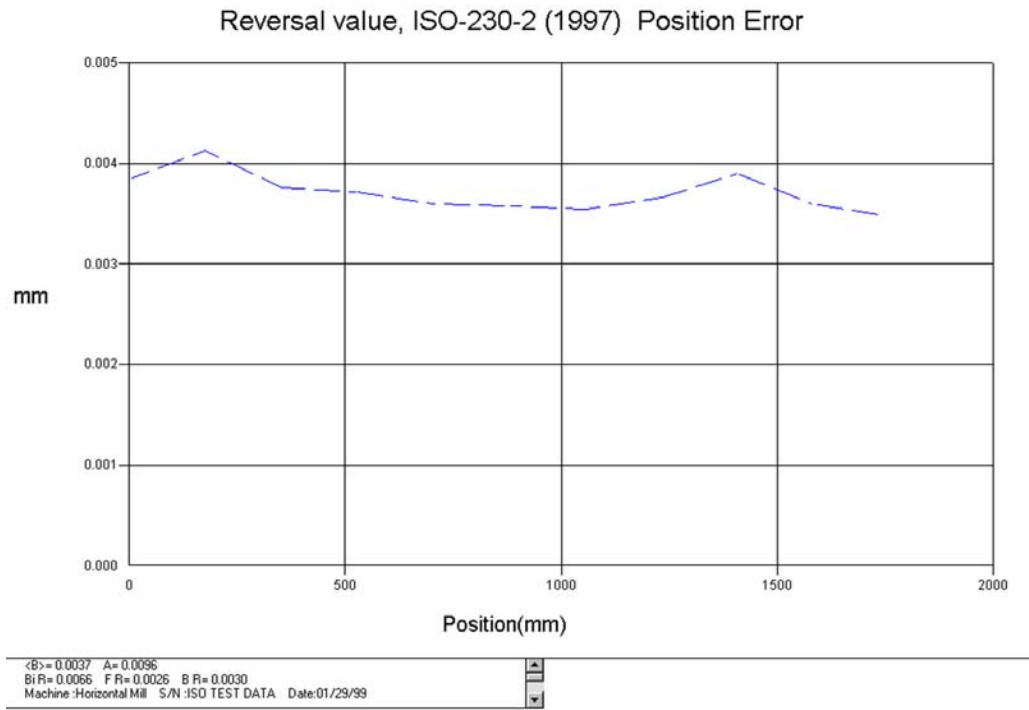
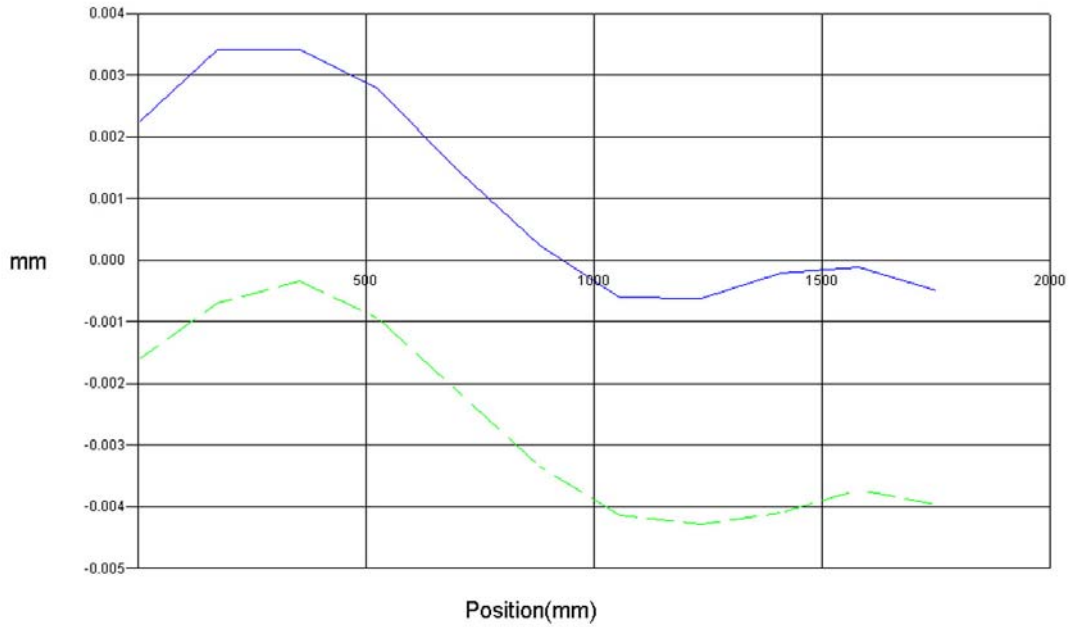


FIG. 6-17b ISO REVERSAL VALUE

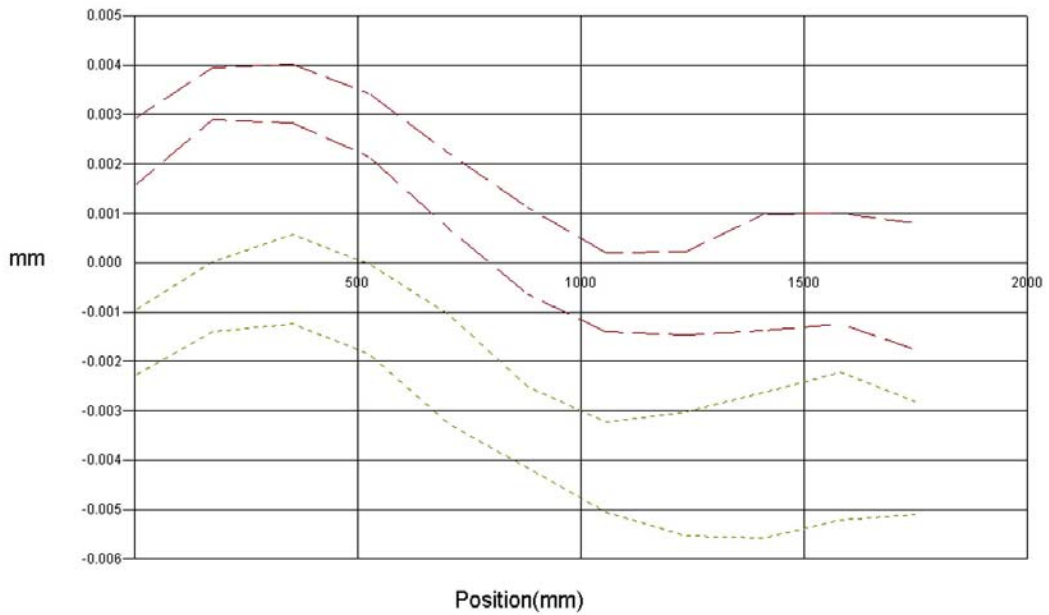
Mean Error, ISO-230-2 (1997) Position Error



= 0.0037 A= 0.0096
 Bi R= 0.0066 FR= 0.0026 BR= 0.0030
 Machine: Horizontal Mill S/N: ISO TEST DATA Date: 01/29/99

FIG. 6-17c ISO MEAN

Repeatability, ASME B5.57 Position Error



= 0.0037 A= 0.0096
 Bi R= 0.0066 FR= 0.0026 BR= 0.0030
 Machine: Horizontal Mill S/N: ISO TEST DATA Date: 01/29/99

FIG. 6-18 B5 STANDARD ERROR PLOT

7.0 Displacement Measurement

7.1 Introduction

The LDDM™ CNC Calibration Package is designed to calibrate CNC machine tools, CMMs (Coordinate Measuring Machines), and other precision measurement machines and stages.

Based on the LDDM™, Optodyne's innovative Dopplometry technology has broken through the technological barrier of bulky, cumbersome laser heads, time consuming set-up and alignments, and costly measurement methods. Optodyne's CNC Calibration Package allows for a large misalignment tolerance making it possible to setup the package and have it operational in a matter of minutes.

7.2 Hardware Required

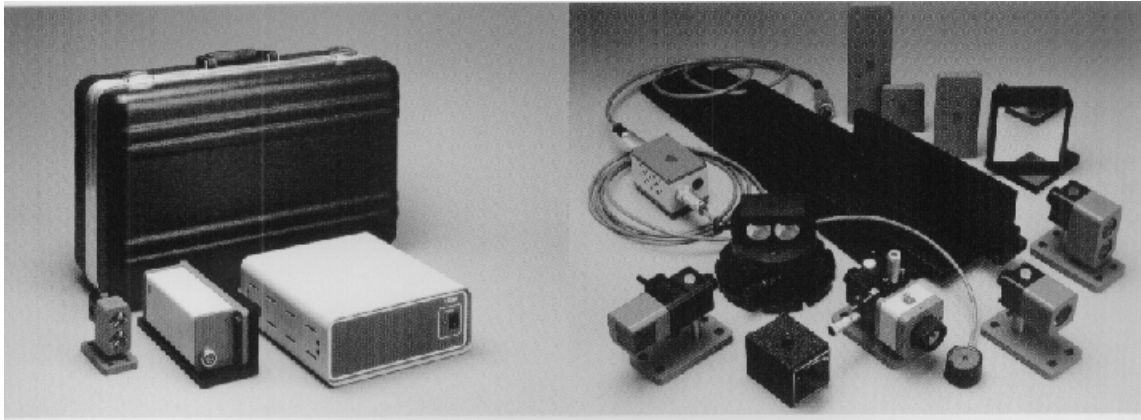
The basic hardware and software required for linear calibration are listed below:

a. Dual Aperture Laser Head	L-101
b. Processor Module with RS-232 Interface	P-111
c. Display Module or Notebook PC	D-101 or LTC
d. Ø1" Retroreflector	R-106
e. Metrology/Analysis Program	S-102R, W-102
f. 90° beam Bender (Ø1")	LD-15
g. Magnetic Base	LD-03
h. Adapter Platform	LD-14
i. 12 ft Cable Set	LD-21

The following optional hardware is also available:

Carrying Case	LD-20
Notebook PC computer	LTC
Automatic temperature compensation	IATC(IATCC)

Some of the hardware is shown in Fig. 7-1.



CALIBRATION HARDWARE
FIG. 7-1

7.3 Operating Specifications

Accuracy: The laser stability at an atmospheric pressure of 29.9 in Hg and an air temperature of 68°F is 1 $\mu\text{in}/\text{ft}$. At other pressures and temperatures, the measurement accuracy depends upon the velocity of light compensation and the material thermal expansion correction. With manual compensation and correction, the accuracy depends upon the accuracy of the measured air temperature, air pressure, and the material temperature. With automatic temperature and pressure compensation (IATC), an accuracy of $\pm 12 \mu\text{in}/\text{ft}$ could be achieved. For more detailed discussion on accuracy see Appendices H and J.

Resolution: Standard resolution is 1 μin (0.01 μm).

Maximum Velocity: 72 inch/sec (1800 mm/sec)

Measurement Range: Up to 100 ft (30 m) (optional 200 ft)

Temperature Range: 60°F to 90°F or (15.5°C to 32°C)

7.4 Reference Material

Appendix C, Description of microprocessor control and firmware

Appendix H, ATC and Calibration

Appendix J, Accuracy

7.5 Installation and Alignment

7.5.1 Important Considerations

1. Check that all cables are firmly connected before connecting the power cable and switching the power switch to the on position.
2. Always mount the laser head on a stationary part and the retroreflector on a moving part. Never use a tripod to mount the laser head. The tripod may introduce an error. For example, on most CNC machine tools, the spindle is moving in the Z-direction and the bed is moving in X- and Y-direction. Hence, when calibrating the X- and Y-direction, mount the laser head on the spindle (or near the spindle by a magnetic hold) and the retroreflector on the bed. Then to calibrate the Z-direction, mount the laser head on the bed and the retroreflector on the spindle. However, for most CMM machines, the bed is fixed and the spindle is moving in X-, Y-, and Z- directions. Therefore, always mount the laser head on the bed and mount the retroreflector on the spindle or the moving carriage.

CAUTION! Never turn on the spindle of the CNC while either the laser or retroreflector are mounted there. This could cause injury to the operator and/or damage to the equipment.

3. When installing the laser head, make sure that the laser beam coming out from the 90° beam bender will travel in the direction of the displacement measurement.
4. Vibration and loose connections must be minimized by proper mounting. Make sure that all supports and cables are completely stationary. A spindle, for example, must be secured by a brake so it will not rotate.
5. The output laser beam and the retroreflector must be aligned properly such that the beam intensity is above the minimum requirement (4 bars) along the entire measurement path.

7.5.2 Installation

Install the 90° beam bender to the front of the laser head by the beam bender adapter (LD-15B) and the adapter platform (LD-14DB) as shown in Fig. 7-2. Four mounting positions are possible. For pointing in the left or right direction, use only one screw. Make sure both exit beam and return laser beam are covered by the steering rectangular mirror inside the 90° beam bender. To mount the laser head to the spindle, you may use the spindle mount adapter (Fig. 7-3) or the magnetic holder (Fig. 7-4). The retroreflector and holder (Fig. 7-5) can be mounted on the bed or on a magnetic holder (Fig. 7-6). Make sure all screws are tight and the surface of the magnetic holder is free of grease. Various other mounting techniques are shown in Fig. 7-7, Fig. 7-8, and Fig. 7-9.

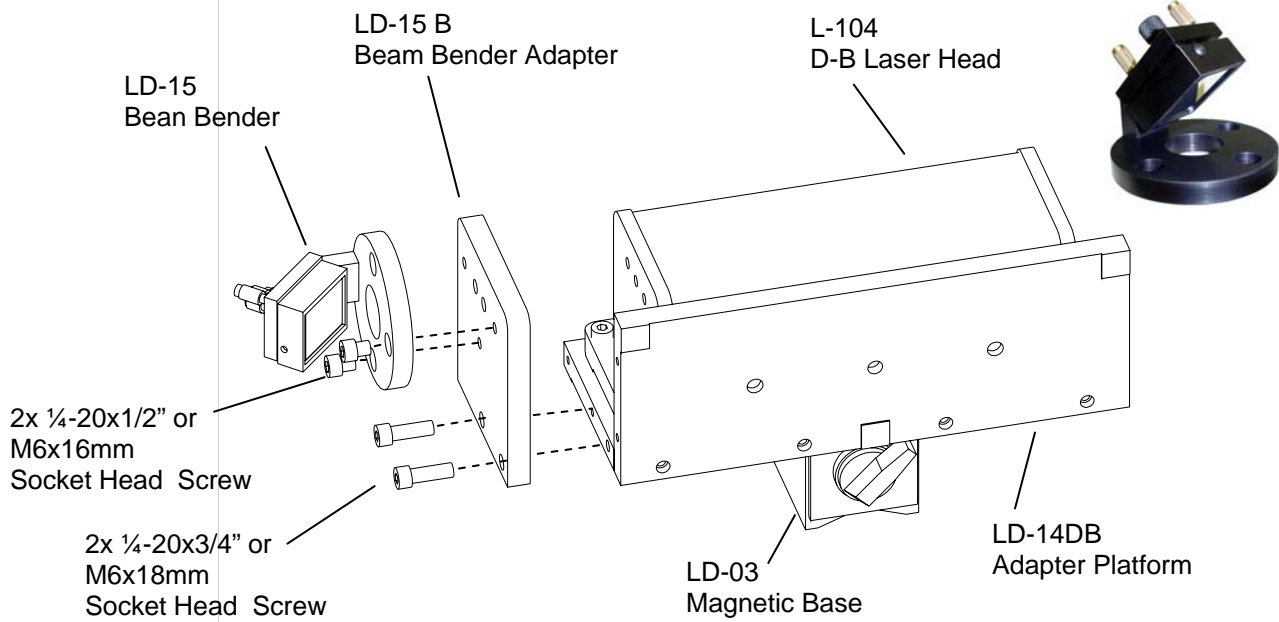


FIG. 7-2 Installation of 90° BEAM BENDER (LD-15)

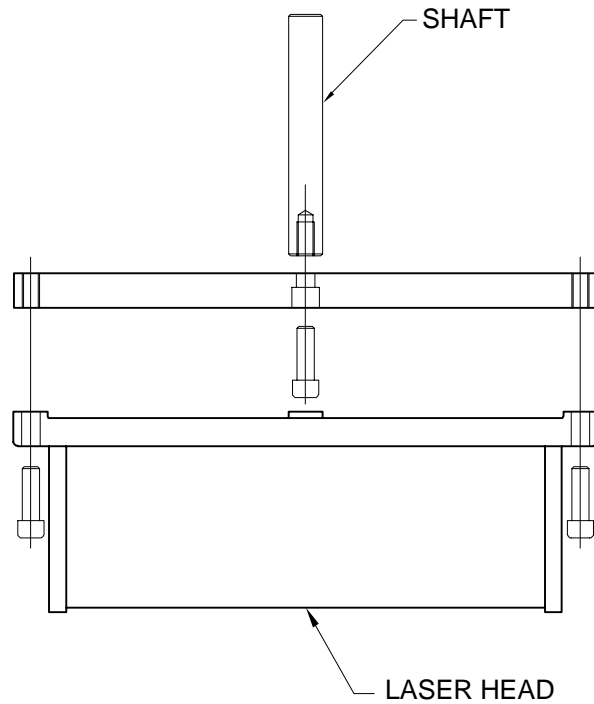


FIG. 7-3 SPINDLE MOUNT ADAPTER

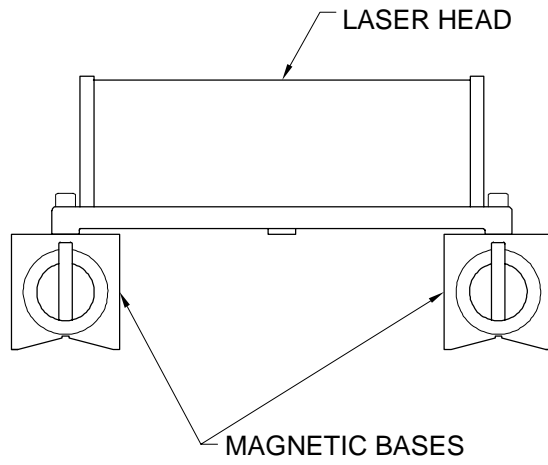


FIG. 7-4 LASER HEAD MOUNTED ON MAGNETIC BASES

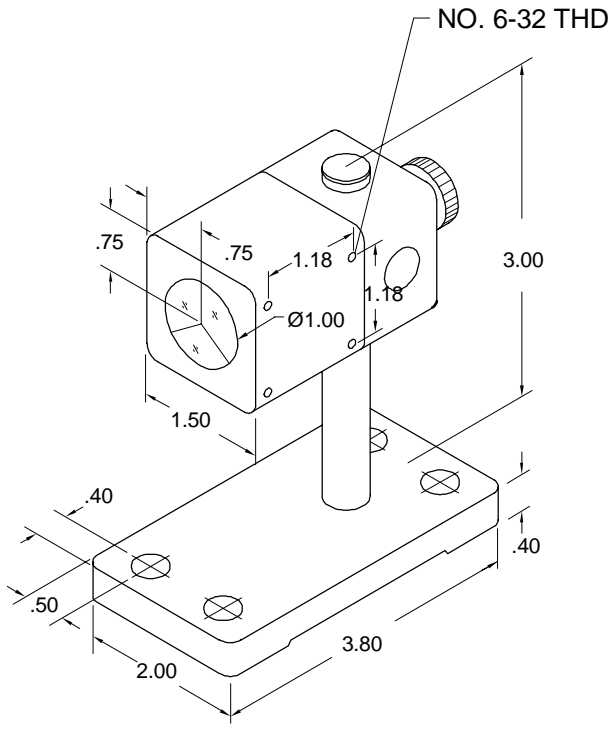


FIG. 7-5 RETROREFLECTOR AND HOLDER

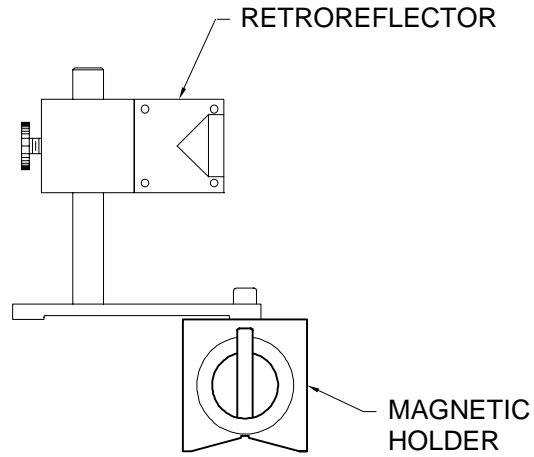


FIG. 7-6 RETROREFLECTOR
MOUNTED ON MAGNETIC HOLDER

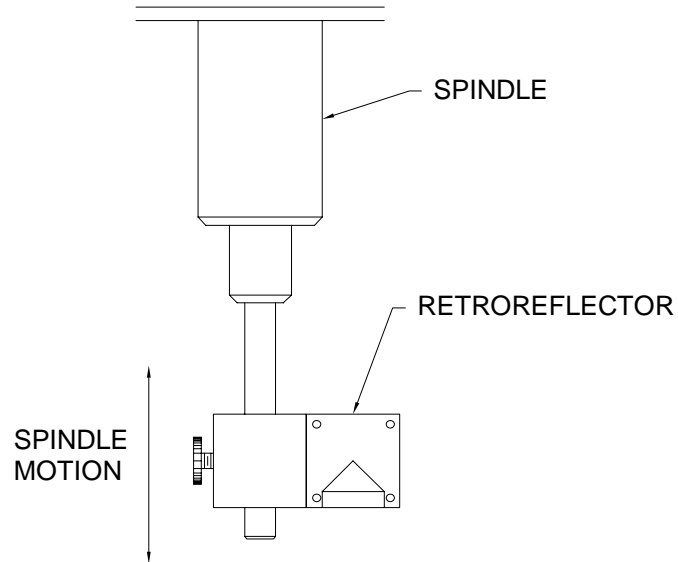


FIG. 7-7 RETROREFLECTOR
MOUNTED ON A SPINDLE

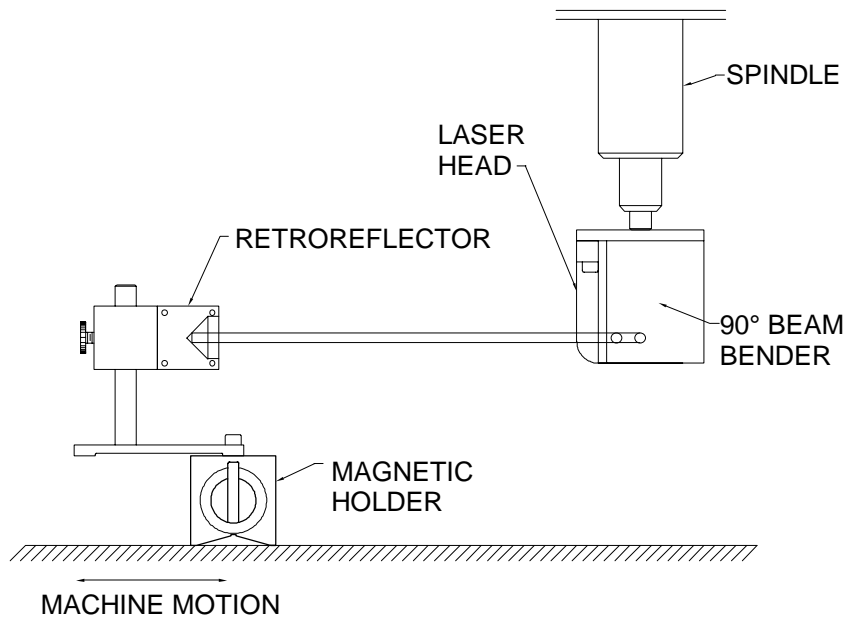


FIG. 7-8 LASER HEAD MOUNTED ON A SPINDLE

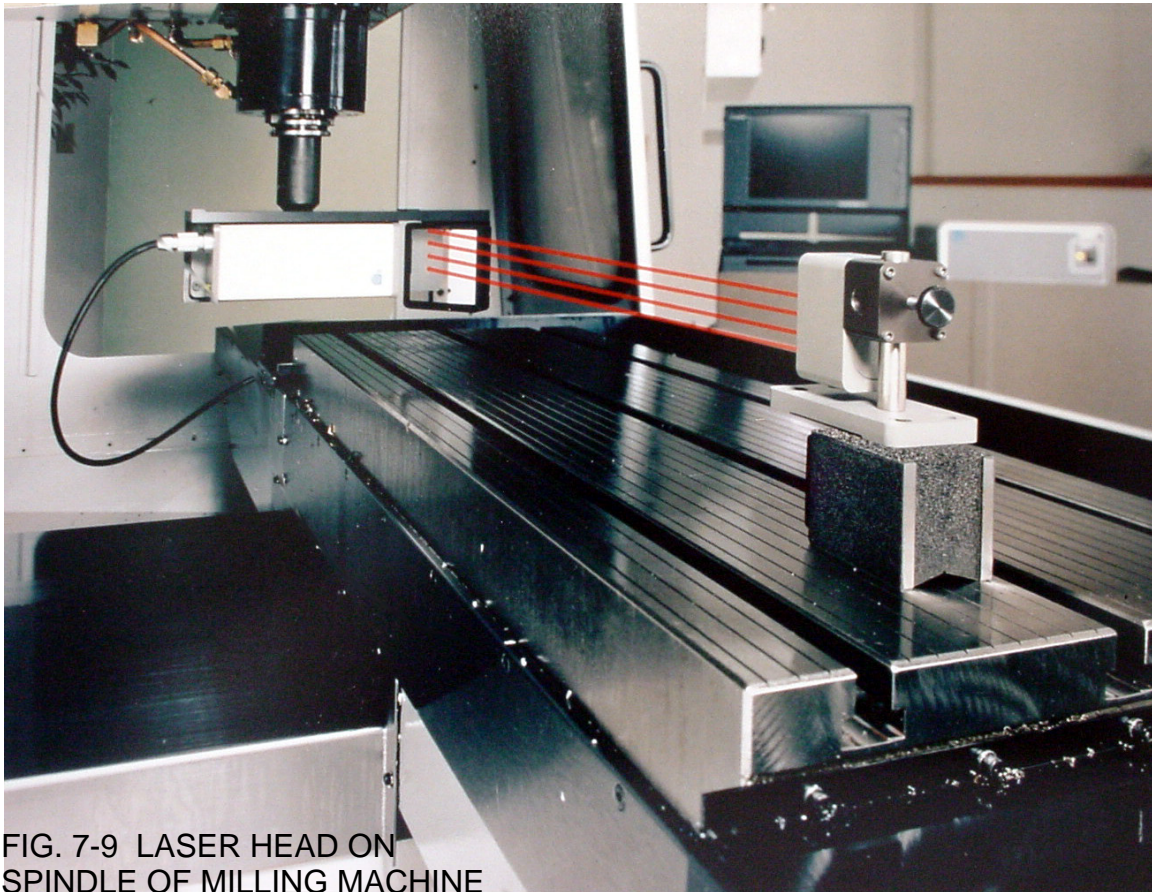


FIG. 7-9 LASER HEAD ON SPINDLE OF MILLING MACHINE

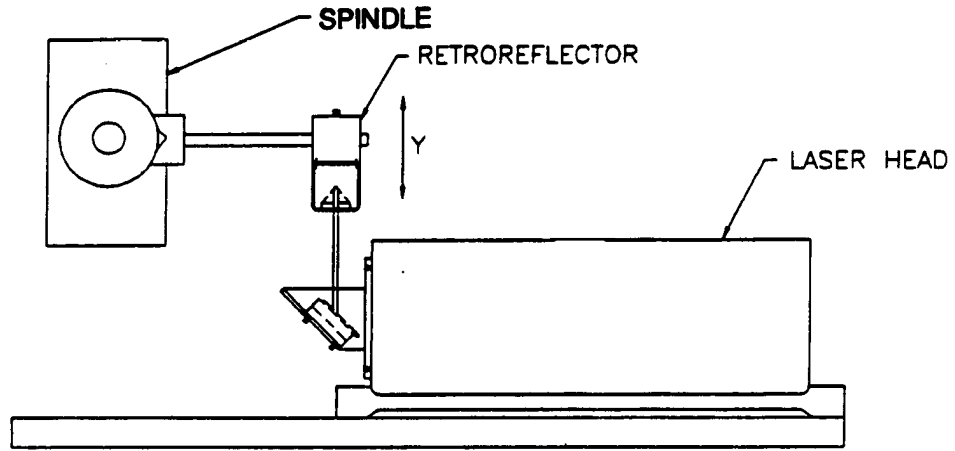
7.5.3 Description

1. Decide which axis of travel you want to measure, which part is moving and which part is stationary for this axis of motion. It is noted that the movable part of the machine may depend on the axis you are measuring. That is, the X-axis movable part may not necessarily also be the Y-axis or Z-axis movable part. (See Fig. 7-10, 7-11, 7-12).
2. Mount the laser head on the stationary part, and the retroreflector on the moving part. Move the movable part of the machine to the starting point or the end point, then mount the retroreflector as close to the laser head as possible.
3. Adjust the laser head or the 90° beam bender such that the output beam is parallel to the direction of travel. (See Section 7.5.4 Alignment Procedure).
4. Move the retroreflector perpendicular to the laser beam direction such that the return beam enters the receiving aperture of the laser head.
5. Move the movable part from the starting point to the end and make sure that the beam intensity is above the minimum requirement along the entire measurement path.
6. Now the laser is aligned and ready to do the measurement. If you are using a computer to collect data, please load the appropriate software. If you are not using a computer, press X-reset on the display module to change the measurement mode (see Appendix C for a detailed description of the various different modes) and to reset the X-display to zero.
7. If you are using automatic temperature and pressure compensation, place the air temperature and pressure sensor near the laser beam path and the material temperature sensor near the lead screw or the machine bed.

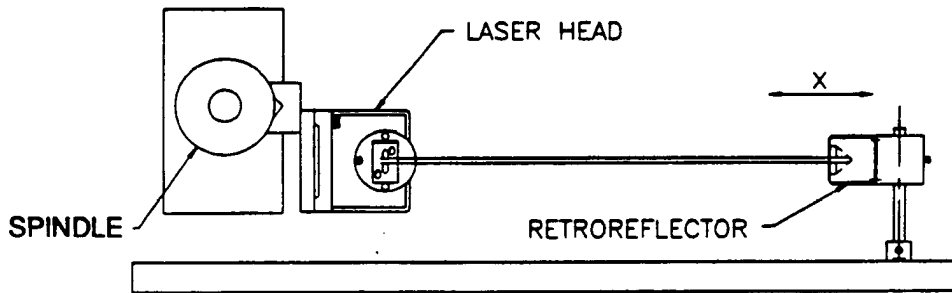
7.5.4 Alignment Procedure

1. Make sure the Laser beam is parallel to the stage travel by using a magnetic cross or masking tape as a target.

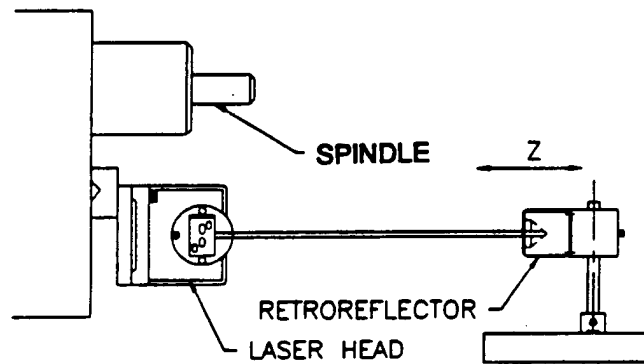
- A) When the target is near the laser head, move the cross to the center of the beam.
 - B) When the target is away from the laser head, move the laser beam to the center of cross, by steering the beam.
 - C) Repeat A and B until the laser beam is parallel to the stage travel.
2. Move the retroreflector, not the laser beam, to be certain that the return laser beam is centered in the receiving aperture and the intensity reading is maximum.
 3. Move the stage in and out and make sure the intensity reading remains maximum. Otherwise, repeat steps 1 and 2. Sometimes the intensity readings are maximum at two ends, but lower in the middle. Move the retroreflector to the location where the intensity reading is at the minimum, then move the retroreflector laterally (do not steer the laser beam) until the intensity is at the maximum at that location.



CALIBRATION IN Y AXIS



CALIBRATION IN X AXIS



CALIBRATION IN Z AXIS

FIG. 7-10 CALIBRATION OF HORIZONTAL MILLING CENTER

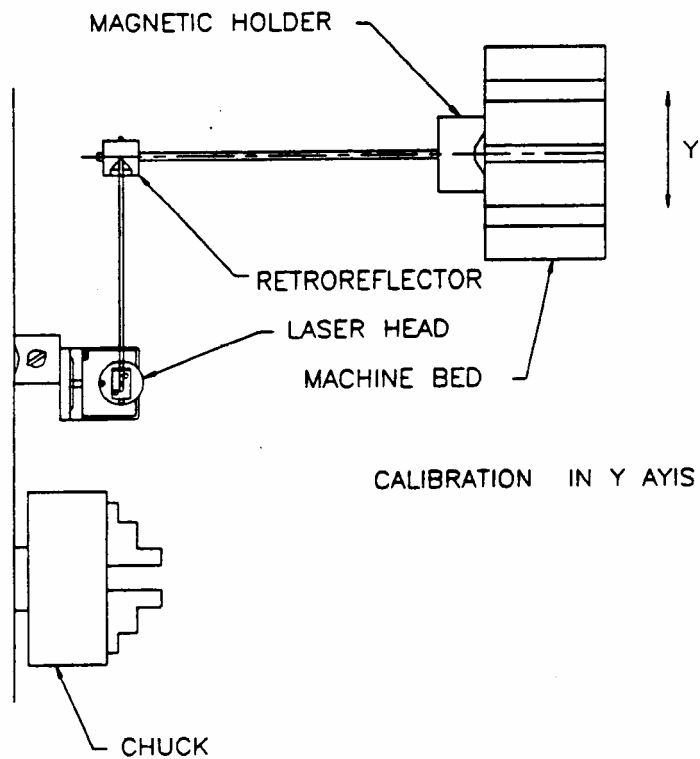
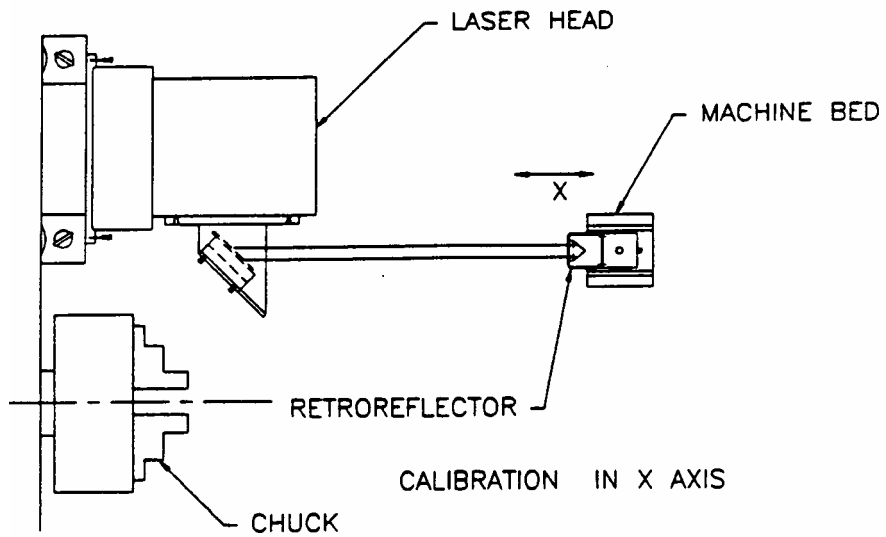
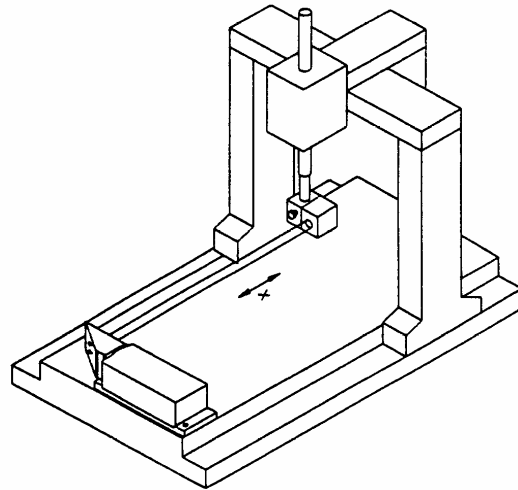
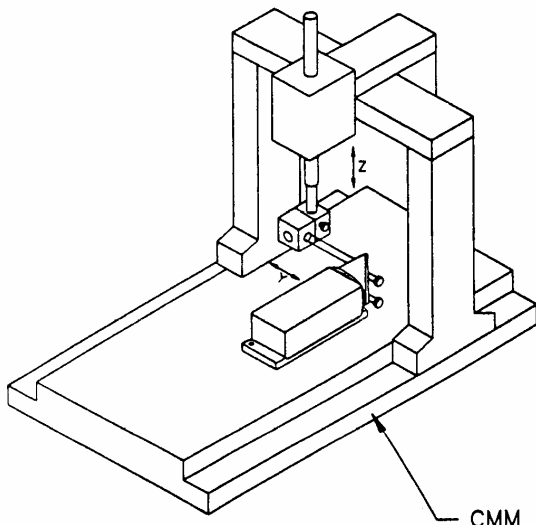


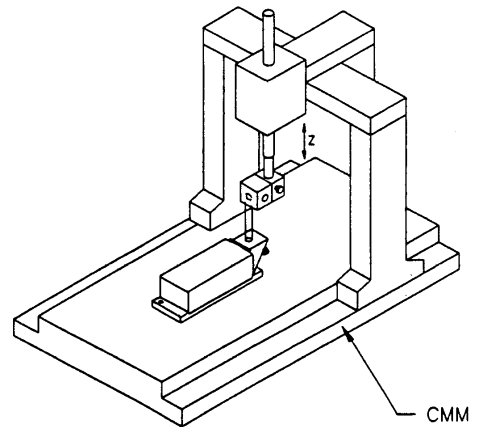
FIG. 7-11 CALIBRATION OF TURNING CENTER



X-AXIS



Y-AXIS



Z-AXIS

FIG. 7-12 CMM CALIBRATION

7.6 Software Description

The Metrology program is used to determine the positioning accuracy of machine tools, coordinate measuring machines, XY-stages, or any other linear measuring device. The calibration system utilizes an extremely sensitive LDDM™ to detect any positioning errors. After the LDDM™ is attached to the device to be calibrated, the device is operated to exercise a typical calibration procedure, and the LDDM™ senses any discrepancies from a theoretically perfect measurement. The discrepancies are recorded for later analyses and data reduction to produce correction factors for the device to be calibrated. The LDDM™ is supported by an IBM PC with special Metrology software to direct the operator through the setup and execution of measurement procedures. Data can be printed in tabular or graphic forms. For more details, see the software manual.

7.7 Accuracy and Error Sources

Displacement measurements are accurate within the following tolerances depending on the speed of light compensation and operating temperature. Assume at a standard condition, i.e. 68°F 29.9 inHg, and 40% relative humidity, the accuracy is ± 1 ppm. For example, the error is ± 12 μin for a total travel of 12 inches. The LDDM™'s displacement accuracy depends on a correct system setup and operation combined with accurate utilization of atmospheric pressure, air temperature, humidity and material temperature data.

The following are some potential measurement errors, and how they affect displacement measurements. The LDDM™ has a stability of 0.1 ppm. All of the following measurement errors add to this value. The sources of error in displacement measurement are:

1. Measurement of atmosphere pressure, air temperature and humidity to determine the speed of light.
2. Material temperature measurement, the material temperature may be higher or lower than the air temperature. The difference may be as large as the actual variation in room temperature.
3. Mis-alignment between machine travel and laser measurement axis. This is the cosine error, which is equal to $(1 - \cos x)$ where x is the mis-alignment angle.
4. Mechanical vibration and stress of the retroreflector and the laser head.

These errors are common to all laser interferometers.

The sum total of all the errors listed above determines the overall accuracy of the laser measurement system in your application. (More details in Appendix J).

7.8 Taking a Measurement

1. Decide which axis you are going to measure, from which starting point to which end point, and the increment per stop. Key in all the variables and pertinent information into the computer.
2. For automatic data collection, program your machine controller with the specific increment per stop, total number of stops (or total travel), and the speed. The dwelling time at each stop should be longer than (6) seconds.
3. Set up the LDDM™ by following the instructions in Section 7.5.

4. Set up computer and load the appropriate software by following the instructions in Section 7.6 or the software manual.
5. All the software is menu-driven; follow the instructions on the monitor.
6. Move the machine to the starting point.
7. Reset the LDDM™ reading, press the start key. Then move the machine to the first stop.
8. For automatic data collection the computer will wait (5) seconds after the machine is stopped and then automatically record the LDDM™ reading. For manual data collection, after the machine is stopped, wait (5) seconds then press "c" to record the LDDM™ readings.
9. Continue to move the machine to the next stop and repeat step 8.
10. Repeat step 9 until the 'end' point. This is done for single-direction measurement.
11. For bi-directional measurement, move the machine about 0.5 inch further, stop, wait (6) seconds, then return to the 'end' point, stop, wait (6) seconds and repeat step 8 for the return travel.
12. After all data has been collected, you may print the data in table format or plot in graphic form. After exiting the data collecting program, you may use data analysis software to analyze the data and print out the result.

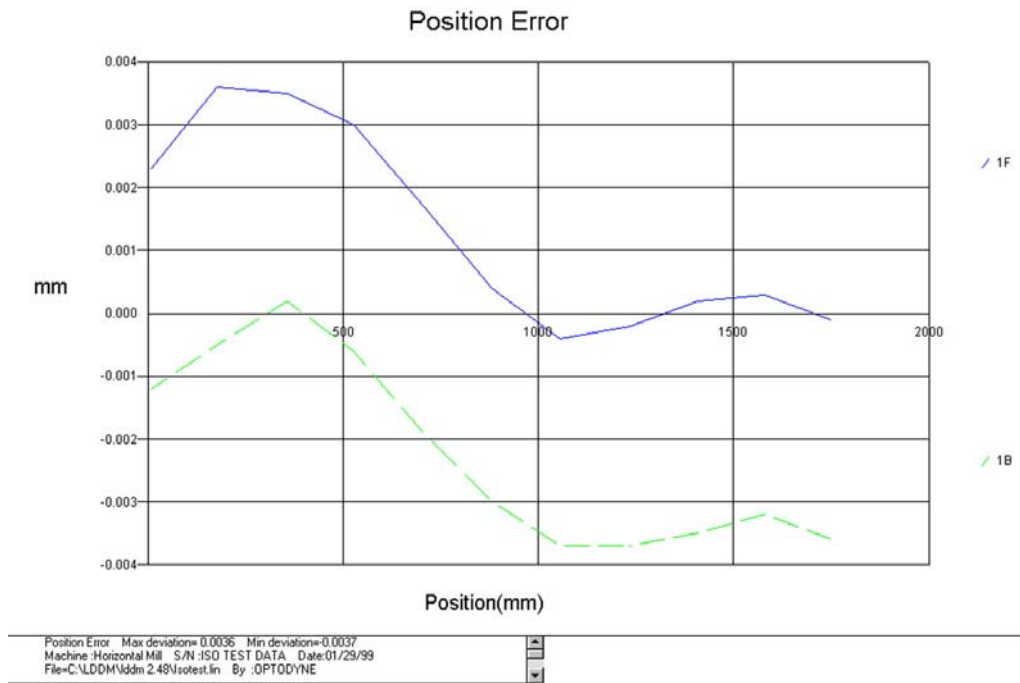


FIG. 7-13 POSITION ERROR PLOT OF A SINGLE RUN

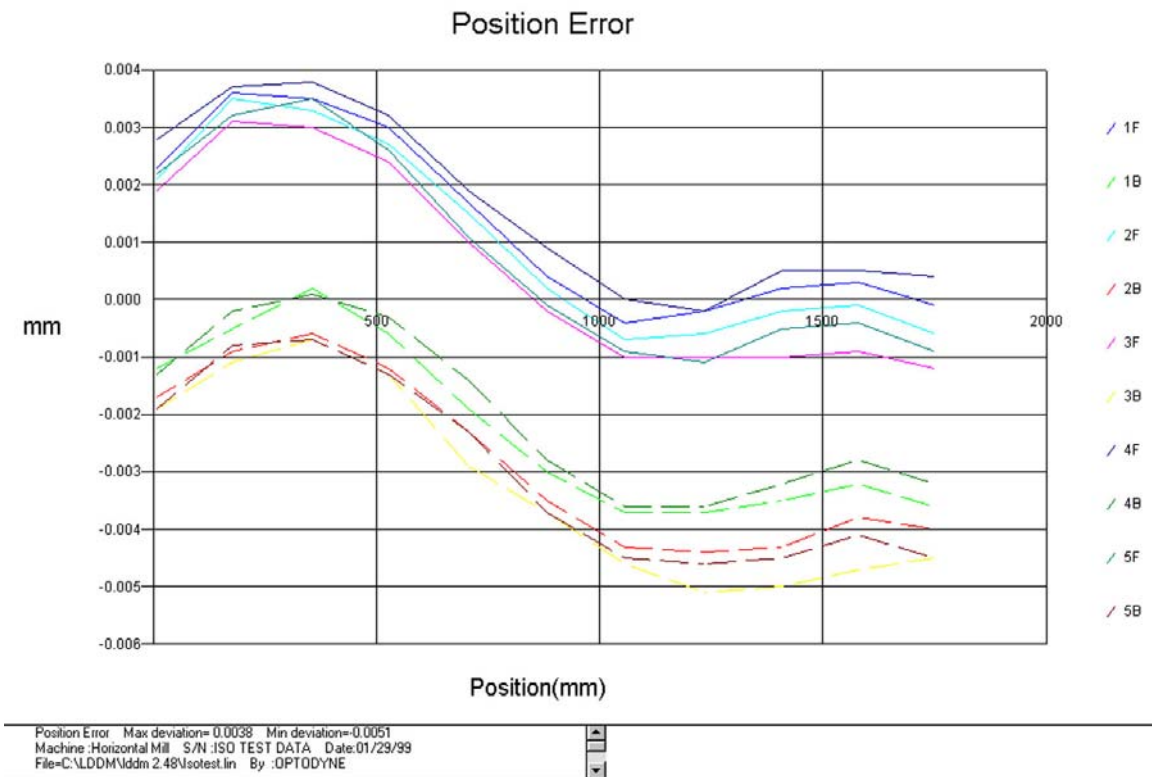
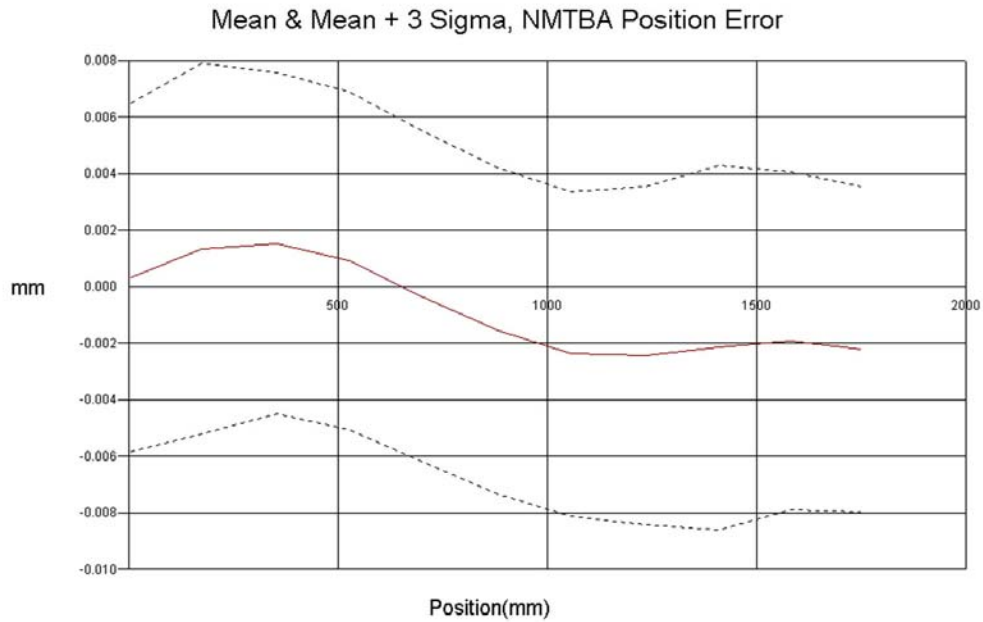
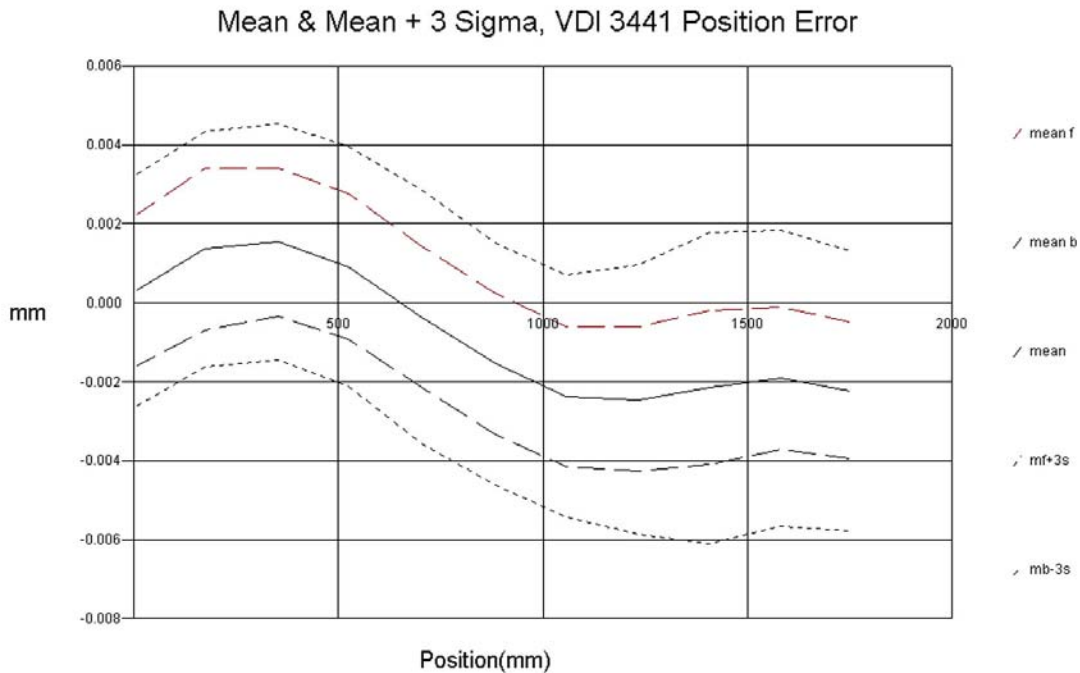


FIG. 7-14 POSITION ERROR PLOT OF (5) RUNS



Error band= 0.0165 N R= 0.0131 Z zero shift= -0.0003
 Machine : Horizontal Mill S/N : ISO TEST DATA Date: 01/29/99
 File=C:\LDDM\ddm 2.48\isotest.lin By : OPTODYNE

FIG. 7-15 AVERAGED POSITION ERROR PLOT BASED ON THE NMTBA STANDARD



P= 0.0106 Ps= 0.0040 Pa= 0.0040 U= 0.0041
 Machine : Horizontal Mill S/N : ISO TEST DATA Date: 01/29/99
 File=C:\LDDM\ddm 2.48\isotest.lin By : OPTODYNE

FIG. 7-16 AVERAGED POSITION ERROR PLOT BASED ON THE VDI/3441 STANDARD

7.9 Description of a Measurement

After a measurement is completed, the data can be analyzed by the analysis software. The output of a typical measurement on a horizontal milling machine is shown in Figs. 7-13, 7-14, 7-15 and 7-16. The measurement here was on the Y-axis, bi-directional, 100 mm increment, 600 mm total travel and 7 runs. Figure 7-13 is an individual plot, and Fig. 7-14 is a group plot of all 7 runs. The vertical axis is the position error and the scale is 0.01 mm. The horizontal axis is the machine position and the scale is 600 mm. The filename, "630921.dat" is shown on the top-right corner. The corresponding position error table is printed as shown in Table 7-1 and in Table 7-2. The machine type, serial number, date and operator are shown in the left column above the data. Air temperature, material temperature, air pressure and humidity are shown in the right column above the data. MTE is the multiplication factor for the correction of material thermal expansion. There is a total of 7 runs, and Table 7-1 shows run number 1. "LDDM" is the direct reading without correction for material thermal expansion and "LDDM corrected" is the corrected reading for material thermal expansion. The corrected reading is equal to the LDDM™ reading multiplied by the MTE. The deviation is equal to the corrected LDDM™ reading minus the target position. The maximum, minimum and mean are the maximum value of the deviation, the minimum value of the deviation, and the averaged value of the deviation, respectively.

For the NMTBA (National Machine Tool Builders Association) standard, the plot is shown in Fig. 7-15, and the data is shown in Table 7-3. The solid line is the averaged deviation over 7 bi-directional runs. The dot above and below the solid line is the mean value plus and minus the 3σ , respectively. At the bottom of the plot, the machine model, "HMC 630P", the serial number, "87630921", the date of the measurement, "2-18-89" and the operator, "Bob Griffin", can be seen in the left column. The increment size, "100 mm", number of points per run, "6", number of runs, 7, direction "+" and "-" (forward and backward) and the axis and location, "Y" are shown in the center column. The right column shows the error band, 0.012494 mm, the non-repeat, 0.011334 mm and the zero off-set, 0.000018 mm. In Table 7-3, the "mean deviation" is the averaged deviation over both forward and backward for 7 runs. The "3-Sigma" is the 3σ value calculated over both directions for 7 runs. The "X (Ave) + 3-Sigma" and "X (Ave) - 3-Sigma" are the mean deviation plus 3σ and the mean deviation minus 3σ , respectively. The "averaged mean deviation" is the averaged value of mean deviations at each position. The "Averaged 3-Sigma" is the averaged value of 3σ at each position. The "Zero shift" is the mean value of the error-band.

For the VDI/3441 standard, the plot is shown in Fig. 7-16 and the data is shown in Table 7-4. The top and bottom solid lines are the mean position error in the forward direction and backward direction respectively. The middle solid line is the mean value of the top and bottom solid lines. The dots above and below

the solid lines are the forward mean value plus the averaged 3σ and the backward mean value minus the averaged 3σ , respectively. The reversal error, "U" is 0.003523 mm. The positional uncertainty, "P" is 0.009056 mm, the positional scatter, "Ps" is 0.006456 mm and the positional deviation, "Pa" is 0.003026 mm. In Table 7-4, the forward data and the backward data are averaged separately. The averaged 3σ is the averaged value between the forward 3σ and the backward 3σ . For further definition of these parameters see Section 6.9.

For the ISO standard, the plots are shown in Fig. 7-17, 7-18, and 7-19. Figure 7-17 shows the repeatability. The solid lines are forward direction and dotted lines are the reverse. The accuracy, "A" is 0.009072 mm. The averaged reversal value "B" is 0.001973 mm. The repeatability in the forward direction, "R+" is 0.003113 mm, the reverse direction, "R-" is 0.003401 mm and in both directions, "R" is 0.006461 mm. The data is shown in Table 7-5.

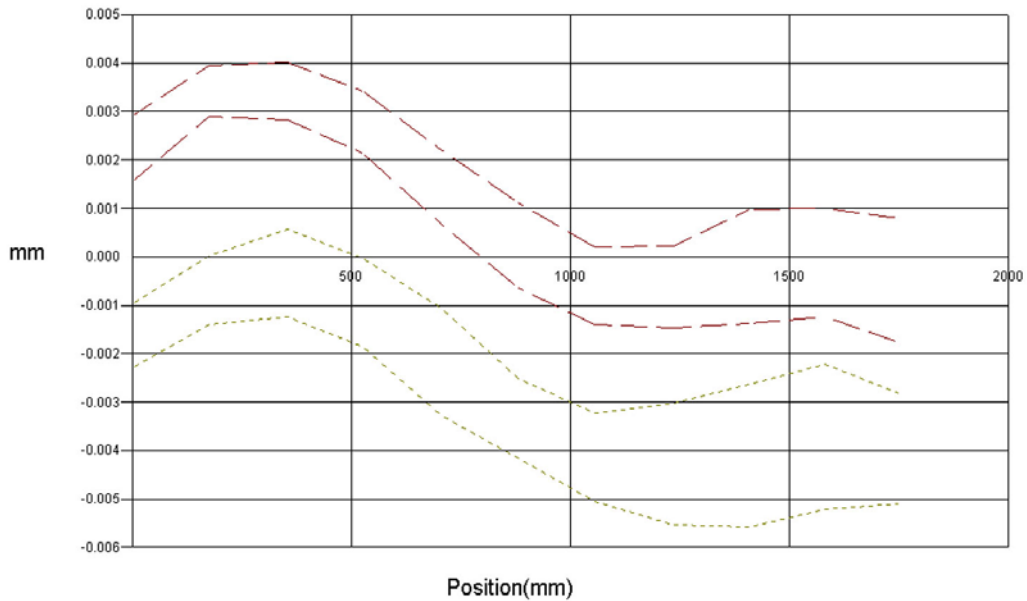
For the B5 and B89 standard, the position error is defined as the LDDM™ reading - target position. The accuracy is the maximum averaged position error in the forward direction minus the maximum averaged position error in the reverse direction. The maximum reversal error is the maximum difference between the averaged forward position error and the averaged reverse position error at the same point. A plot is shown in Fig. 7-20 where the solid line is in the forward direction and the dotted line is in the reverse direction. The Accuracy is 0.805130 and the maximum reversal error is 0.003527. The data is shown in Table 7-6.

7.10 Generating a Compensation File

Many machine tool controllers can provide compensations for repeatable position errors on each linear axis of motion. To generate a new compensation file, first set the compensation to zero and set the LDDM™ laser measurement system to measure the position error at an increment corresponding to the compensation file requirement. Second, use the metrology software to collect position error data and to generate a position error table. Third, key in the new compensation file based on the position error table. Finally, use the LDDM™ laser measurement system again to measure the position error with the new compensation file to make sure that the position errors have been compensated. Otherwise, the machine may have large non-repeatability.

For some standard machine tool controllers, software is available to convert the measured error table to a compensation file and load the compensation file through an RS-232 port to the controller.

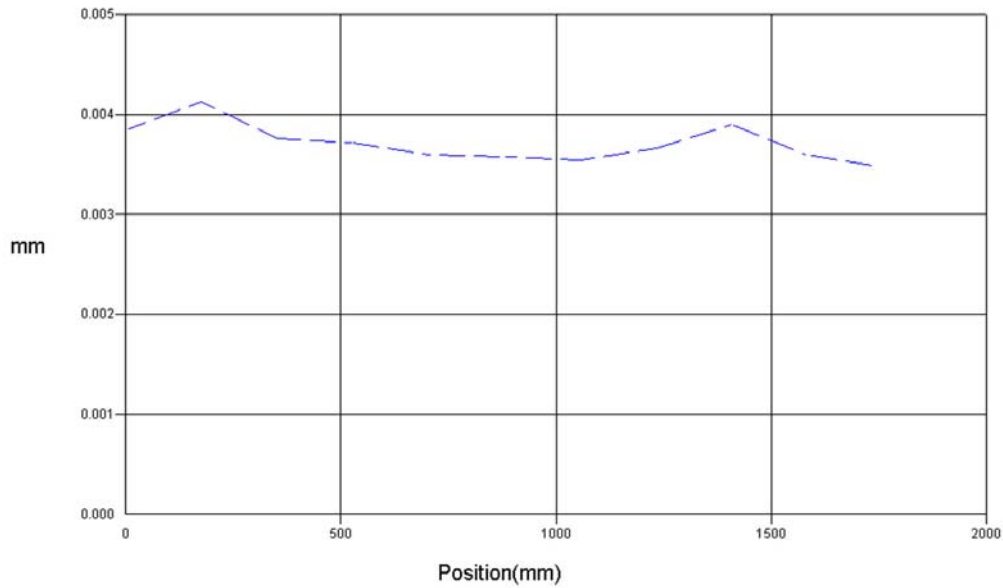
Repeatability, ISO-230-2 (1997) Position Error



= 0.0037 A= 0.0096
 Bi R= 0.0066 FR= 0.0026 BR= 0.0030
 Machine :Horizontal Mill S/N :ISO TEST DATA Date:01/23/99

FIG. 7-17 ISO REPEATABILITY

Reversal value, ISO-230-2 (1997) Position Error



= 0.0037 A= 0.0096
 Bi R= 0.0066 FR= 0.0026 BR= 0.0030
 Machine :Horizontal Mill S/N :ISO TEST DATA Date:01/23/99

FIG. 7-18 ISO REVERSAL VALUE

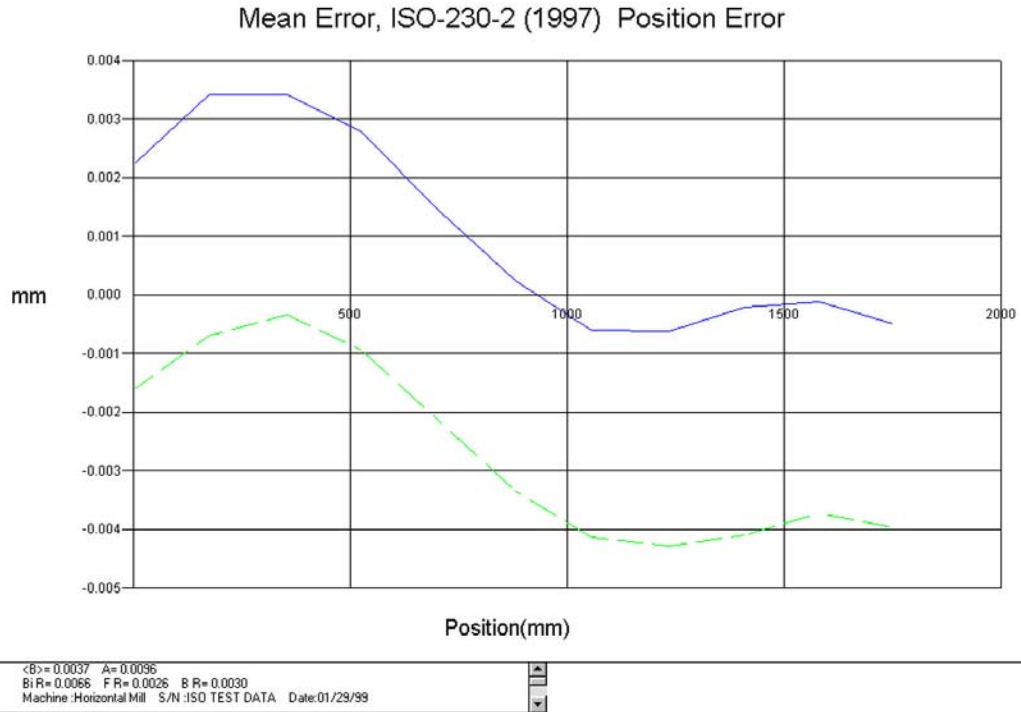


Fig. 7-19 ISO MEAN UNIDIRECTIONAL DEVIATION

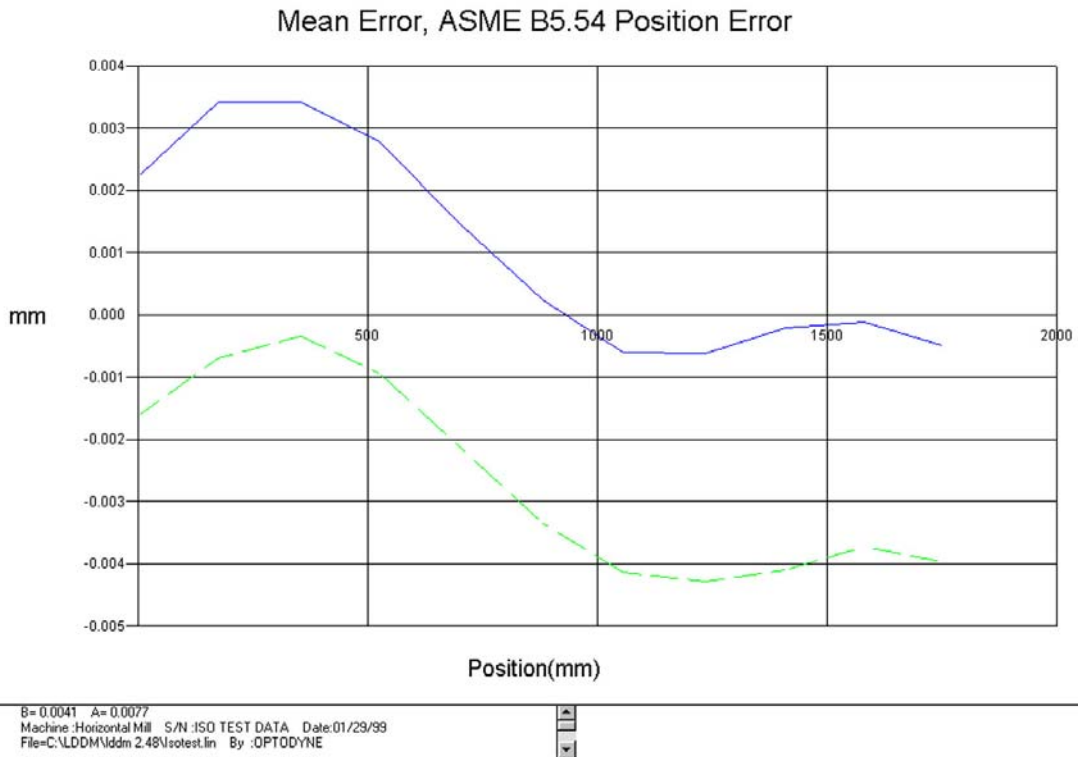


FIG. 7-20 B5 STANDARD ERROR PLOT

Position Measurement, Error Analysis (mm) File=C:\LDDM\lddm 2.48\lsoctest.lin Date :
Machine :Horizontal Mill S/N :ISO TEST DATA By :OPTODYNE
Start Position: (6.711, 0, 0) End Position: (1750.92, 0, 0)
Total Travel = 1744.209 Points = 11 No of Runs= 5
Pressure: 753.58 Humidity: 50.00 Air Temp: 20. Material Temp: 20. MTE = 1.0
Max Error: 0.0036 Min Error: -0.0037 Mean: -0.0005

Position,mm	Run #1
6.711	0.0023
175.077	0.0036
353.834	0.0035
525.668	0.0030
704.175	0.0017
881.868	0.0004
1055.89	-0.0004
1234.304	-0.0002
1408.462	0.0002
1580.269	0.0003
1750.92	-0.0001
1750.92	-0.0036
1580.269	-0.0032
1408.462	-0.0035
1234.304	-0.0037
1055.89	-0.0037
881.868	-0.0030
704.175	-0.0019
525.668	-0.0006
353.834	0.0002
175.077	-0.0005
6.711	-0.0012

Table 7-1 Linear Measurement Data for One Run

Position Measurement, Error Analysis (mm) File=C:\LDDM\lddm 2.48\lsoctest.lin Date :01/29/99
Machine :Horizontal Mill S/N :ISO TEST DATA By :OPTODYNE
Start Position: (6.711, 0, 0) End Position: (1750.92, 0, 0)
Total Travel = 1744.209 Points = 11 No of Runs= 5
Pressure: 753.58 Humidity: 50.00 Air Temp: 20. Material Temp: 20. MTE = 1.0
Max Error: 0.0038 Min Error: -0.0051 Mean: -0.0008

Position,mm	Run #1	Run #2	Run #3	Run #4	Run #5
6.711	0.0023	0.0021	0.0019	0.0028	0.0022
175.077	0.0036	0.0035	0.0031	0.0037	0.0032
353.834	0.0035	0.0033	0.0030	0.0038	0.0035
525.668	0.0030	0.0027	0.0024	0.0032	0.0026
704.175	0.0017	0.0015	0.0010	0.0019	0.0011
881.868	0.0004	0.0002	-0.0002	0.0009	-0.0001
1055.89	-0.0004	-0.0007	-0.0010	0.0000	-0.0009
1234.304	-0.0002	-0.0006	-0.0010	-0.0002	-0.0011
1408.462	0.0002	-0.0002	-0.0010	0.0005	-0.0005
1580.269	0.0003	-0.0001	-0.0009	0.0005	-0.0004
1750.92	-0.0001	-0.0006	-0.0012	0.0004	-0.0009
1750.92	-0.0036	-0.0040	-0.0045	-0.0032	-0.0045
1580.269	-0.0032	-0.0038	-0.0047	-0.0028	-0.0041
1408.462	-0.0035	-0.0043	-0.0050	-0.0032	-0.0045
1234.304	-0.0037	-0.0044	-0.0051	-0.0036	-0.0046
1055.89	-0.0037	-0.0043	-0.0046	-0.0036	-0.0045
881.868	-0.0030	-0.0035	-0.0037	-0.0028	-0.0037
704.175	-0.0019	-0.0023	-0.0029	-0.0014	-0.0023
525.668	-0.0006	-0.0012	-0.0013	-0.0003	-0.0013
353.834	0.0002	-0.0006	-0.0007	0.0001	-0.0007
175.077	-0.0005	-0.0009	-0.0011	-0.0002	-0.0008
6.711	-0.0012	-0.0017	-0.0019	-0.0013	-0.0019

Table 7-2 Linear Measurement Data for Seven Runs

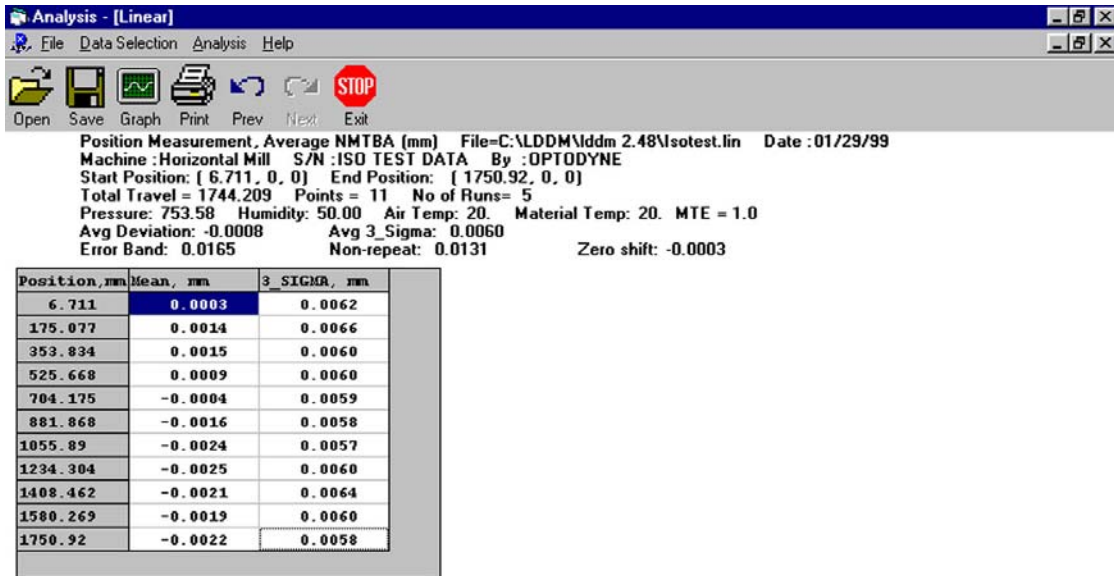


Table 7-3 Linear Measurement Data for the NMTBA Standard

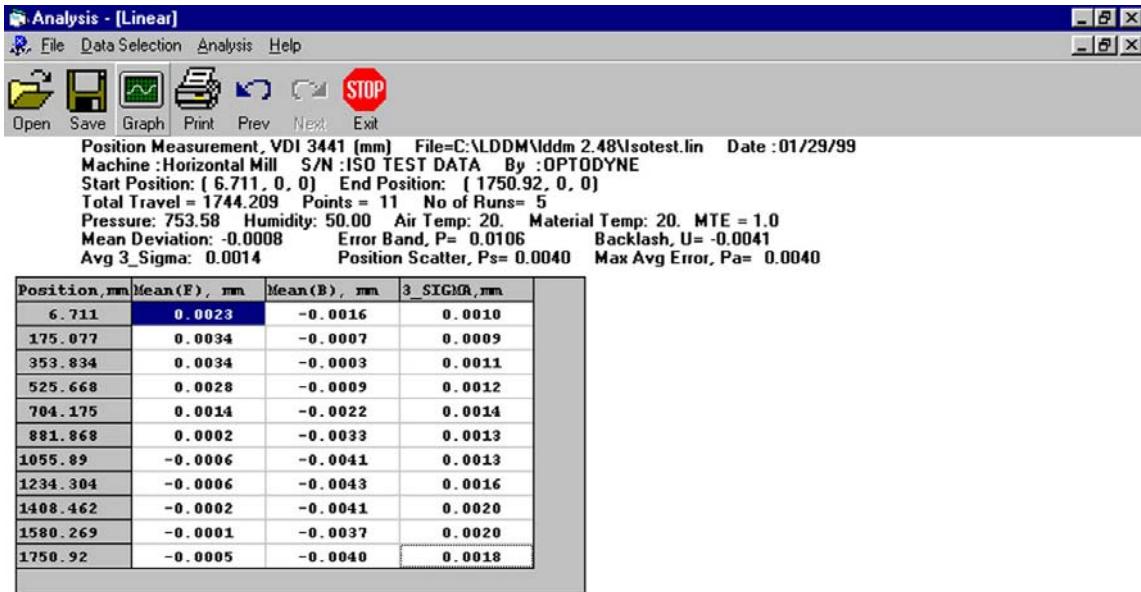


Table 7-4 Linear Measurement Data for the VDI/3441 Standard

Analysis - [Linear] File Data Selection Analysis Help

Open Save Graph Print Prev Next Exit

Position Measurement, ISO-230-2 (1997) (mm) File=C:\LDDM\lddm 2.48\isotest.lin Date : 01/29/99
 Machine : Horizontal (Go to the Previous screen) DATA By : OPTODYNE
 Start Position: (6.711, 0, 0) End Position: (1750.92, 0, 0)
 Total Travel = 1744.209 Points = 11 No of Runs= 5
 Pressure: 753.58 Humidity: 50.00 Air Temp: 20. Material Temp: 20. MTE = 1.0

Position, mm	Mean, mm	2_SIGMA, mm
6.711	0.0023	0.0007
175.077	0.0034	0.0005
353.834	0.0034	0.0006
525.668	0.0028	0.0006
704.175	0.0014	0.0008
881.868	0.0002	0.0009
1055.89	-0.0006	0.0008
1234.304	-0.0006	0.0009
1408.462	-0.0002	0.0012
1580.269	-0.0001	0.0011
1750.92	-0.0005	0.0013
1750.92	-0.0040	0.0011
1580.269	-0.0037	0.0015
1408.462	-0.0041	0.0015
1234.304	-0.0043	0.0013
1055.89	-0.0041	0.0009
881.868	-0.0033	0.0008
704.175	-0.0022	0.0011
525.668	-0.0009	0.0009
353.834	-0.0003	0.0009
175.077	-0.0007	0.0007
6.711	-0.0016	0.0007

Reversal value, B= 0.0041 (at point=1)
 Mean reversal value, = 0.0037
 Range mean bidirectional positional deviation,
 M=0.0040
 Systematic deviation of positioning, E=
 0.0040 (0.0034, -0.0006) (Forward),
 0.0039 (-0.0003, -0.0043) (Backward),
 0.0077 (0.0034, -0.0043) (Bi-directional).
 Repeatability of positioning, R=
 0.0026 (at point=10) (Forward),
 0.0030 (at point=9) (Backward),
 0.0066 (at point=8) (Bi-directional).
 Accuracy, A=
 0.0058 (0.0040, -0.0018) (Forward),
 0.0061 (0.0006, -0.0056) (Backward),
 0.0096 (0.0040, -0.0056) (Bi-directional).

Table 7-5 Linear Measurement Data for the ISO Standard

Analysis - [Linear] File Data Selection Analysis Help

Open Save Graph Print Prev Next Exit

Position Measurement, ASME B5.54 Standard (mm) File=C:\LDDM\lddm 2.48\isotest.lin Date : 01/29/99
 Machine : Horizontal Mill S/N : ISO TEST DATA By : OPTODYNE
 Start Position: (6.711, 0, 0) End Position: (1750.92, 0, 0)
 Total Travel = 1744.209 Points = 11 No of Runs= 5
 Pressure: 753.58 Humidity: 50.00 Air Temp: 20. Material Temp: 20. MTE = 1.0
 Max Reversal = 0.0041 Accuracy, A= 0.0077

Position, mm	Mean, mm
6.711	0.0023
175.077	0.0034
353.834	0.0034
525.668	0.0028
704.175	0.0014
881.868	0.0002
1055.89	-0.0006
1234.304	-0.0006
1408.462	-0.0002
1580.269	-0.0001
1750.92	-0.0005
1750.92	-0.0040
1580.269	-0.0037
1408.462	-0.0041
1234.304	-0.0043
1055.89	-0.0041
881.868	-0.0033
704.175	-0.0022
525.668	-0.0009
353.834	-0.0003
175.077	-0.0007
6.711	-0.0016

Table 7-6 Linear Measurement Data for the B5.54 Standard

7.11 Measurement Along a Body Diagonal

In the “Methods for Performance Evaluation of Coordinate Measuring Machine”, ASME B89.1.12M-1990, a measurement along a body diagonal is required. This measurement can easily be achieved with a diagonal mirror (LD-51) and a diagonal mount with retroreflector (LD-58A).

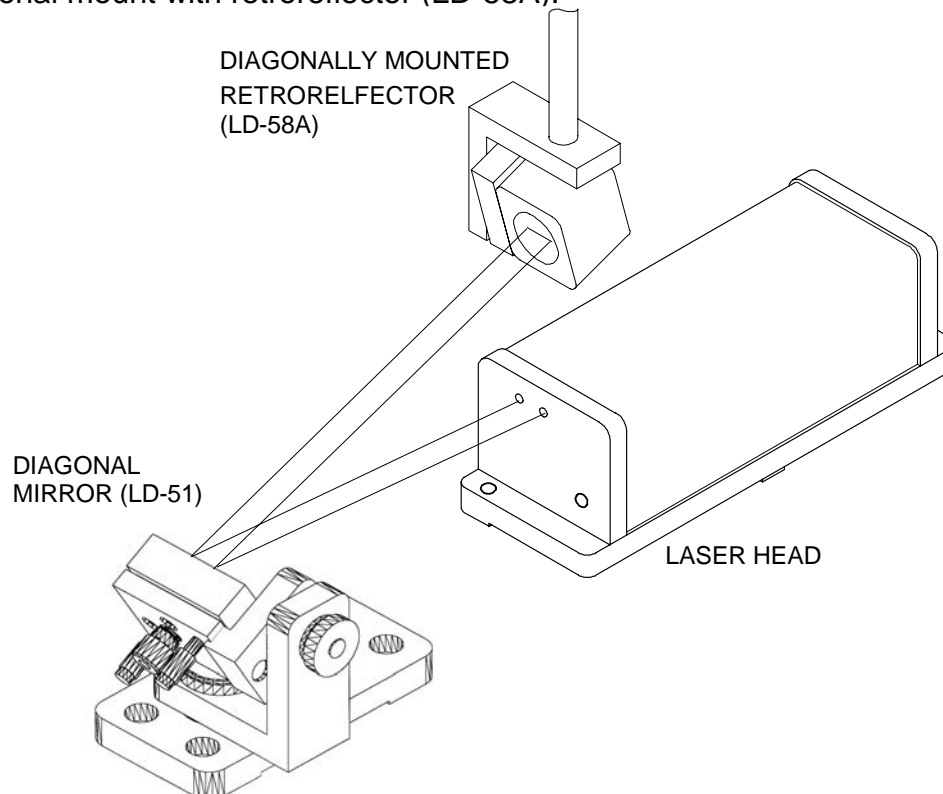


FIG. 7-21 BODY DIAGONAL MEASUREMENT

As shown in Fig. 7-21, the LDDM™ laser head is stationary, the diagonal mirror reflects the laser beam in the diagonal direction and the diagonal mounted retroreflector reflects the beam back to the laser head. The diagonal mounted retroreflector is attached to the spindle, which is moving in the diagonal direction. First, align the laser beam to the diagonal direction and parallel to the retroreflector motion. Then move the retroreflector such that the reflected beam enters the receiving aperture. Specify the initial position (x_0, y_0, z_0) the end position (x_1, y_1, z_1), and the number of steps, in the software and follow the instruction on the monitor, same as the linear measurement.

7.12 Data Files

The data file is in stored ASCII format when it is collected. A third party software spreadsheet program can be used to process and analyze the data files generated by the LDDM™ system.

7.13 Velocity and Acceleration Measurement

The dynamic measurement program can be used to collect both velocity and acceleration data of a machine tool. This program can collect data from 1 data point per 1000 seconds up to 5 data points per second. A total of 5000 data points can be recorded in a data file. After the displacement data is collected, it can be differentiated once to obtain velocity and differentiated again to obtain acceleration. The results can be printed in tables or plotted as a graph as shown in Table 7-7 and Figs. 7-22 through 7-24. Figure 7-22 is a plot of the displacement vs. time. The sampling rate is 1 data per second with a total of 50 points. The velocity is shown in Fig. 7-23, and the acceleration is shown in Fig. 7-24. The output data is shown in Table 7-7.

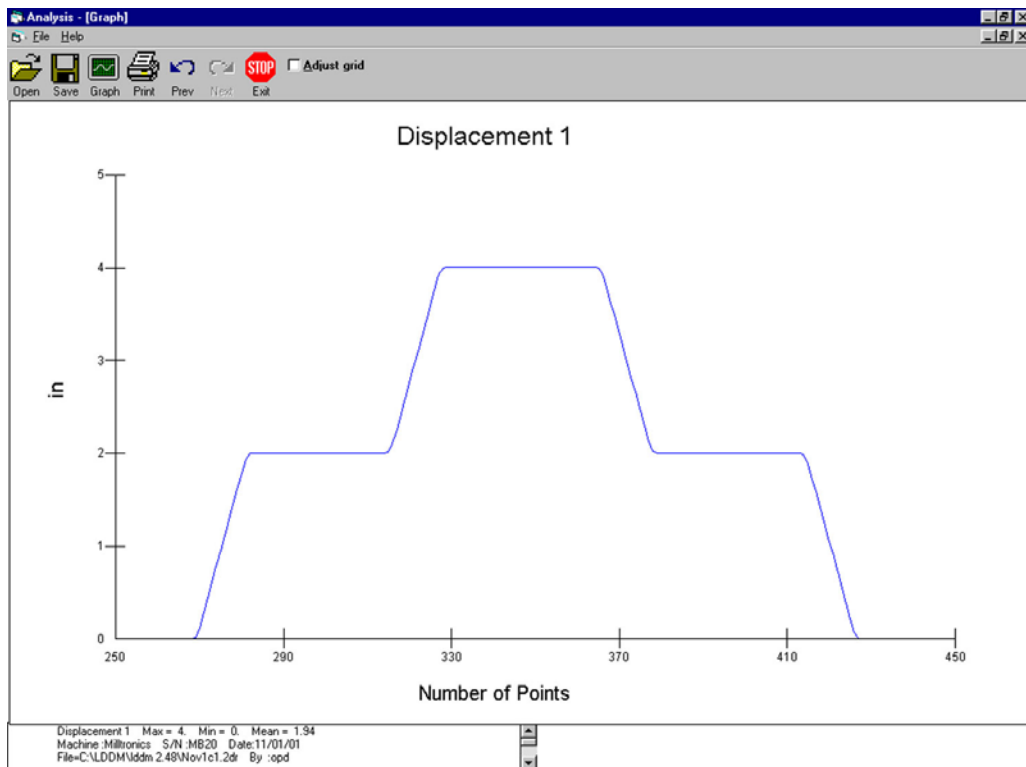


FIG. 7-22 POSITION PLOT

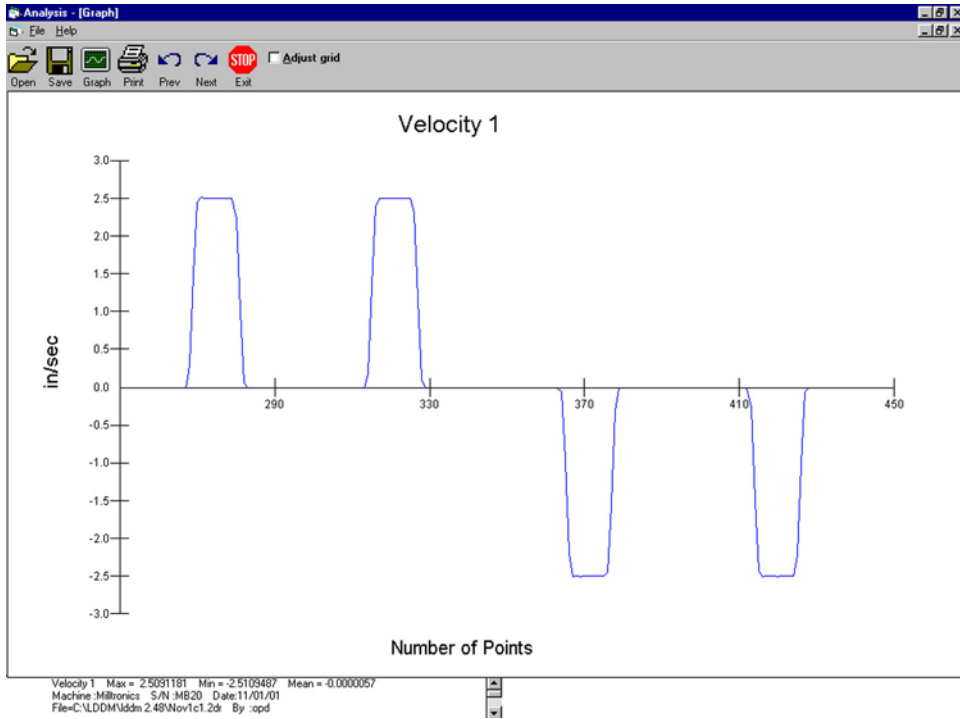


FIG. 7-23 VELOCITY PLOT

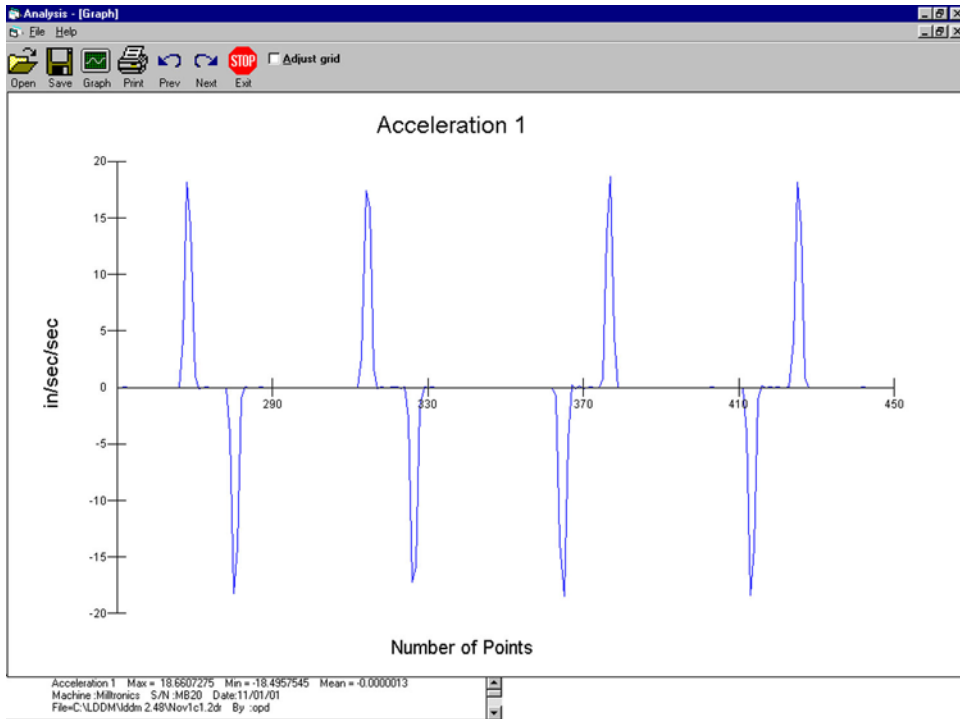


FIG. 7-24 ACCELERATION PLOT

Analysis - [2D Time Base]

File Data Selection Analysis Help

Open Save Graph Print Prev Next Exit

Acceleration 1 (in) File=C:\LDDM\lddm 2.48\Nov1c1.2dr Date : 11/01/01
 Machine : Milltronics S/N : MB20 By : opd
 Comments = o4006
 Measurement Plan = XY Measurement Direction = Y
 Rotation = Clockwise Start Position = 0 (in)
 Total Points = 465 Feedrate = 100 in/minute Sampling rate: 15/sec
 Max: 182.3084385 Min: -168.9181620 Mean: -0.0000006

Data Point	Displacement 1	Velocity 1	Acceleration 1
260	0.0003576	-0.0001343	0.0016200
261	0.0003486	-0.0000263	0.0010515
262	0.0003468	0.0000438	-0.0009630
263	0.0003498	-0.0000204	0.0025830
264	0.0003484	0.0001518	-0.0050805
265	0.0003585	-0.0001869	0.0037655
266	0.0003461	0.0000642	-0.0029340
267	0.0003504	-0.0001314	4.2701910
268	0.0003416	0.2845480	18.1822335
269	0.0193115	1.4966369	14.2440435
270	0.1190913	2.4462998	0.9422745
271	0.2821779	2.5091181	-0.1337475
272	0.4494525	2.5002016	-0.0224655
273	0.6161326	2.4987039	0.0459840
274	0.7827128	2.5017695	-0.0186135
275	0.9494975	2.5005286	-0.0036780
276	1.1161994	2.5002834	-0.0009195
277	1.2828849	2.5002221	-0.0247440
278	1.4495664	2.4985725	-0.0195315
279	1.6161379	2.4972704	-4.1566335
280	1.7826226	2.2201615	-18.2647845
281	1.9306334	1.0025092	-14.0954505
282	1.9974673	0.0628125	-0.9547125
283	2.0016548	-0.0008350	0.0170355
284	2.0015991	0.0003007	-0.0034155
285	2.0016192	0.0000730	-0.0026280
286	2.0016240	-0.0001022	-0.0083205
287	2.0016172	-0.0006569	0.0158535
288	2.0015734	0.0004000	-0.0081900
289	2.0016001	-0.0001460	0.0010950
290	2.0015904	-0.0000730	0.0019710
291	2.0015855	0.0000584	0.0003060
292	2.0015894	0.0000788	-0.0021015

Table 7-7 Dynamic Measurement Data

8.0 Pitch, Yaw and Straightness Measurement

8.1 Introduction

The LDDM™ Flatness and Angle Measurement Package is designed to measure pitch or yaw angle, straightness (angular method) and surface flatness (see section 9). It incorporates a specially designed LDDM™ Dual-beam laser head which measures both the linear and angular displacement of the dual-retroreflector. With a 2-channel processor module, both the linear and angular displacement can be measured simultaneously. The vertical straightness can be obtained by integrating the pitch angle measured along the travel. Similarly, the horizontal straightness can be obtained by integrating the yaw angle measured along the travel. For more discussion on this technique, see Appendix K. A notebook computer (or any IBM PC compatible computer) can be used to collect data and plot the pitch or yaw angles and vertical or horizontal straightness.

8.2 Hardware Required

Dual beam laser head	L-104
Processor module with RS-232 Interface	P-210
Dual retroreflector	R-103
Alignment kit (flatness and angle)	LD-32A
Adapter platform for dual-beam head	LD-14DB
Surface flatness kit	LD-24
12 ft cable set	LD-21
Angular measurement program	S-103R
Options:	
Notebook PC Computer	LTC
Automatic Temperature Compensation	IATC
Carrying case	LD-20C
Special straight-edge	LD-43

8.3 Operating Specification

<u>Accuracy:</u>	Linear displacement	$\pm 12 \mu\text{in/ft}$ ($\pm 1 \mu\text{m/m}$)
	(see Section 7.3.)	
	Angular displacement measurements are accurate within $\pm 0.2\%$ of displayed value ± 0.1 arcsec.	
<u>Resolution:</u>	Linear displacement	$1 \mu\text{in}$ ($0.01 \mu\text{m}$)
	Angular displacement	0.2 arcsec
<u>Maximum distance:</u>	Linear displacement	32 ft, 66 ft. optional (9.6 m, 20 m optional)
	Angular displacement	16 ft, 30 ft. optional (4.8 m, 9 m optional)
<u>Range:</u>	Linear displacement	32 ft (9.6 m)
	Angular displacement	$\pm 10^\circ$

8.4 Reference Material

Appendix C. Description of Microprocessor Control
Appendix H. ATC and Calibration

8.5 Installation and Alignment

8.5.1 Important Considerations

1. Make sure all cables are firmly connected before connecting power cable and switching the power switch on.
2. Always mount the laser head on a stationary part and retroreflector on a moving part. Never use a tripod to mount the laser head. The tripod may introduce error.

3. When installing the laser head, make certain the laser beam coming out from the 90° beam bender will travel in the direction of the displacement measurement.
4. Vibration and loose connections must be minimized by proper mounting. Make sure that all supports and cables are completely stationary. A spindle, for example, must be secured by a brake so it won't rotate.

CAUTION! Never turn on the spindle of the CNC while either the laser or retroreflector are mounted there. This could cause injury to the operator and/or damage to the equipment.

5. The output laser beam and the retroreflector must be aligned properly so that the beam intensity is above the minimum requirement (0.20 or 5 bars) along the entire measurement path.
6. For angular displacement measurement, the sign is very important. Make sure the starting-point of the dual retroreflector is always near the dual-beam laser head and moving away from the laser head.

8.5.2 Installation

Attach the dual-beam laser head to the adapter plates and the dual-reflector to the reflector holder as shown in Fig. 8-1. This is for pitch angle measurement. For yaw angle measurement, rotate the laser and the retroreflector 90° as shown in Fig. 8-2. When the spindle of the machine is moving, mount the laser head on the table and the retroreflector on the spindle as shown in Fig. 8-3. When the table of the machine is movable, mount the laser head on the spindle. Attach the shaft to the adapter plate before mounting the laser head to the adapter plate and the retroreflector on the table as shown in Fig. 8-4. In some situations, for example when the table is not flat or the spindle is tilted, you may need an alignment kit (LD-32A) to align the laser beam parallel to the travel. For pitch angle measurement attach the alignment kit in front of the dual-beam laser head as shown in Fig. 8-5a. For yaw angle measurement, attach the alignment kit to the other side of the adapter plate as shown in Fig. 8-5b. A typical setup for Z-axis measurement is shown in Fig. 8-6. Please note that using a 2-channel processor module, both the linear displacement and the pitch angle (or yaw angle) can be measured simultaneously. However, using a standard processor module, you may measure the linear displacement first, switch the cable to angular detector and then measure the pitch angle (or yaw angle) without realignment.

8.5.3. Description

1. Decide which axis of travel you want to measure, which part is moving and which part is stationary for this axis of motion. It is noted that the movable part of the machine may depend on the axis you are measuring. That is, the X-axis movable part may not necessarily also be the Y-axis or Z-axis movable part (see Fig. 7-10, 7-11, 7-12).
2. Mount the laser head on the stationary part, the retroreflector on the moving part. Move the movable part of the machine to the starting point or the end point, then mount the retroreflector as close to the laser head as possible.
3. Adjust the laser head or the alignment mirror such that the output beam is parallel to the direction of travel.
4. Move the retroreflector perpendicular to the laser beam direction so that both return beams enters the respective receiving apertures of the laser head.
5. Move the movable part from the starting point to the end and make sure that the beam intensity is above the minimum requirement along the entire measurement path.
6. Now the laser is aligned and ready to do the measurement. If you are using a computer to collect data, please turn on the computer and load the appropriate software. If you do not use a computer, press X-reset on the display module to change the measurement mode (see Appendix C for detailed description of the various different modes) and to reset the X-display to zero.
7. If you are using automatic temperature and pressure compensation, locate the air temperature and pressure sensor near the laser beam path and the material temperature sensor near the lead screw or the machine bed.

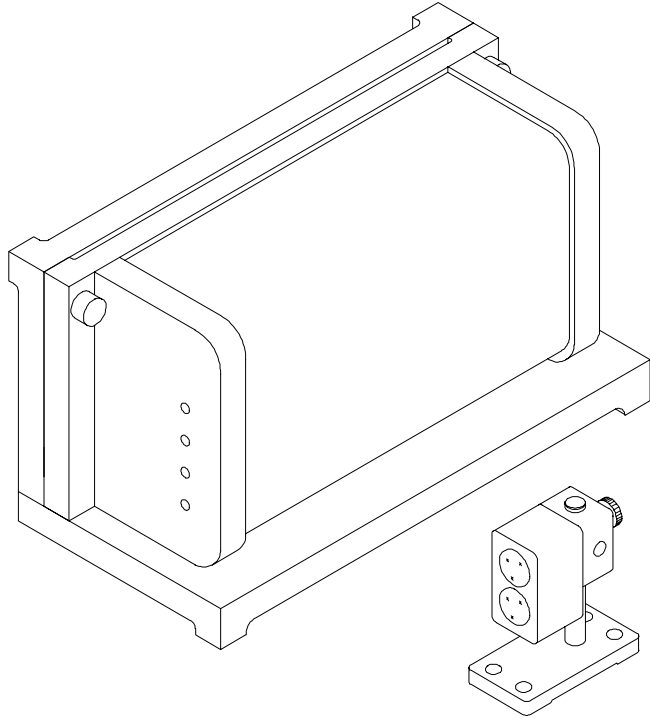


FIG. 8-1 DUAL-BEAM LASER HEAD AND
DUAL-RETROREFLECTOR FOR
PITCH ANGLE MEASUREMENT

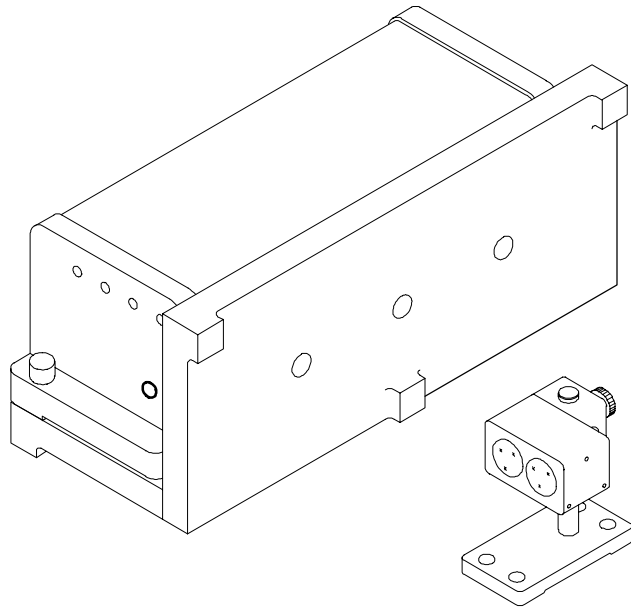
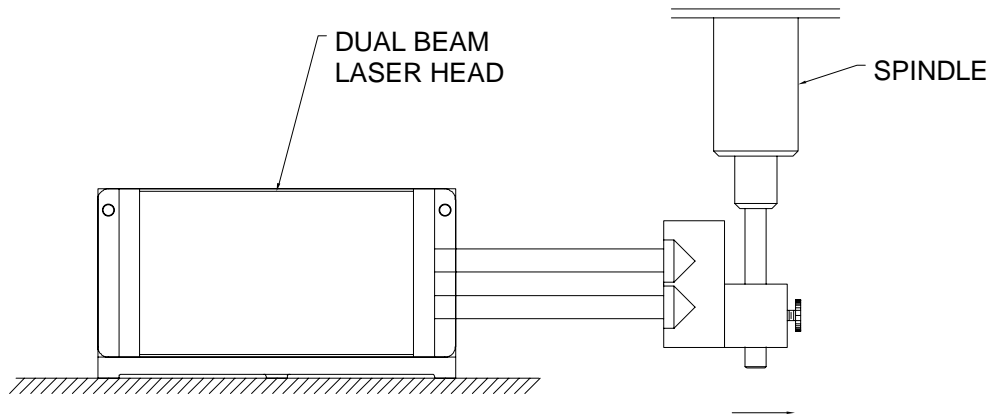
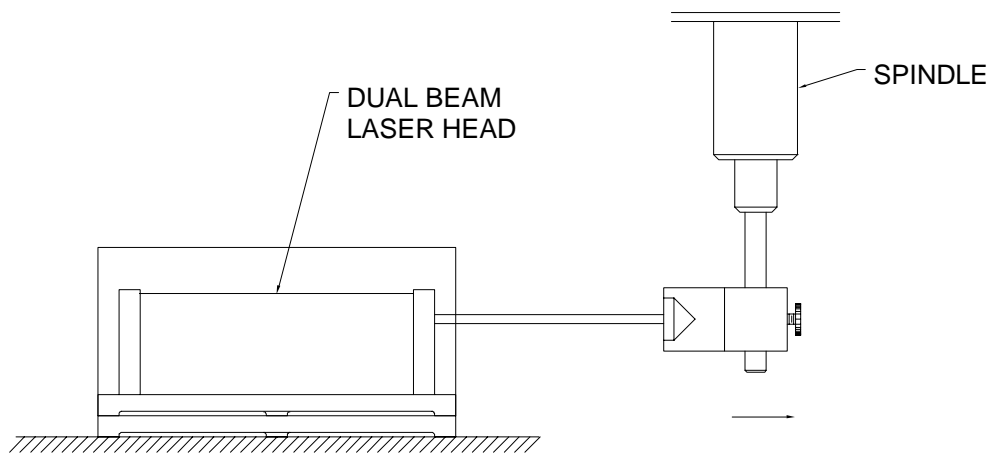


FIG. 8-2 DUAL-BEAM LASER HEAD AND
DUAL-RETROREFLECTOR FOR
YAW ANGLE MEASUREMENT

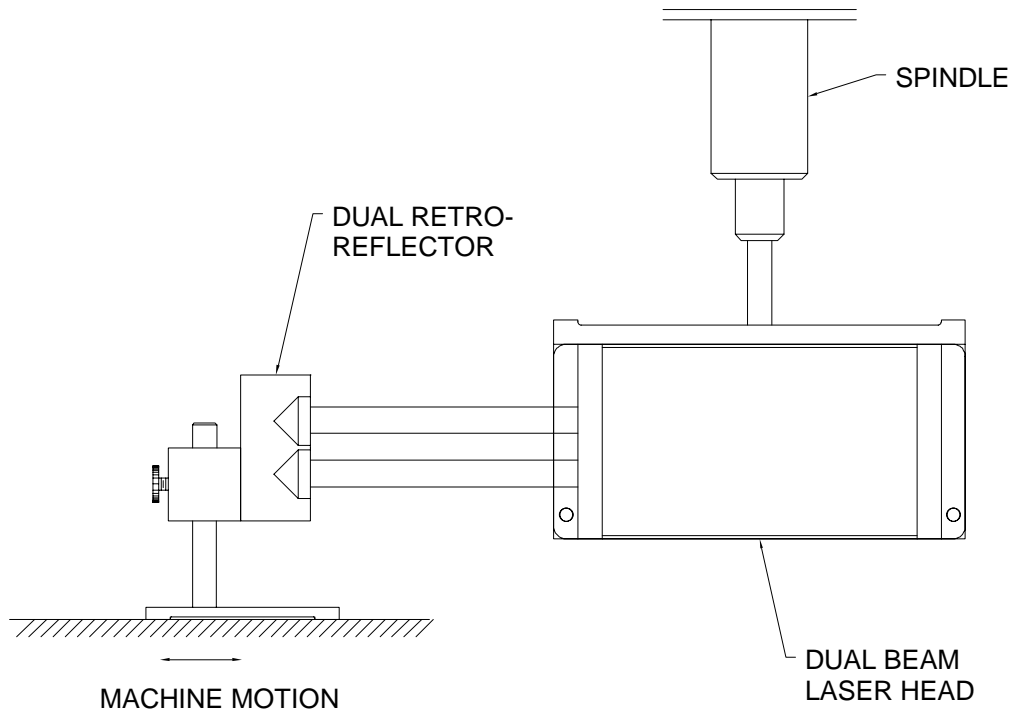


PITCH MEASUREMENT, TABLE MOUNT

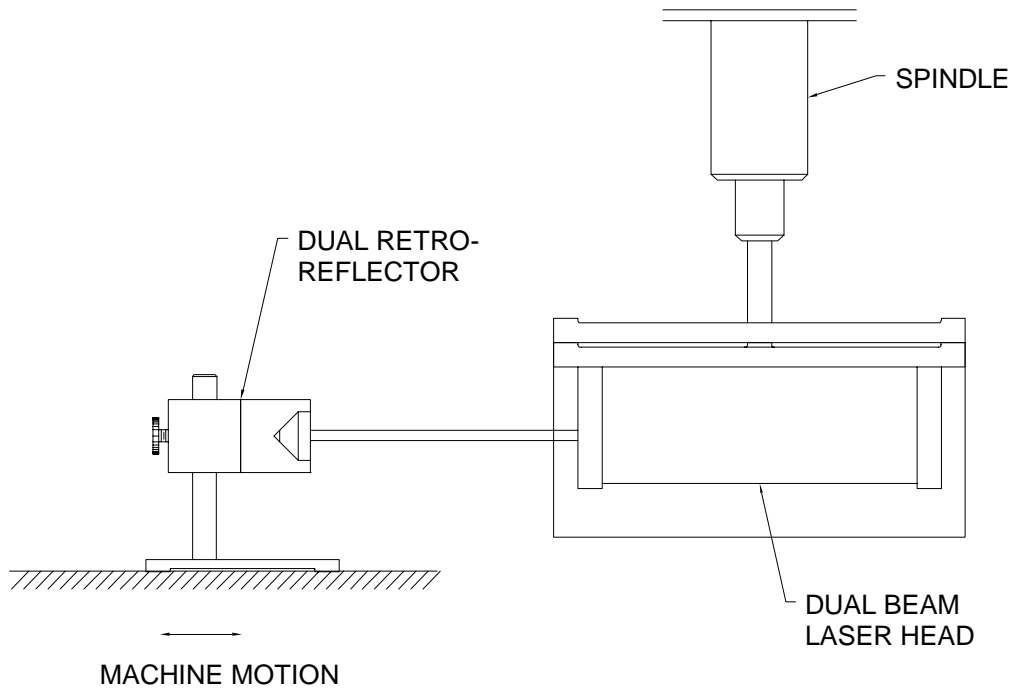


YAW MEASUREMENT, TABLE MOUNT

FIG. 8-3



PITCH MEASUREMENT, SPINDLE MOUNT



YAW MEASUREMENT, SPINDLE MOUNT

FIG. 8-4

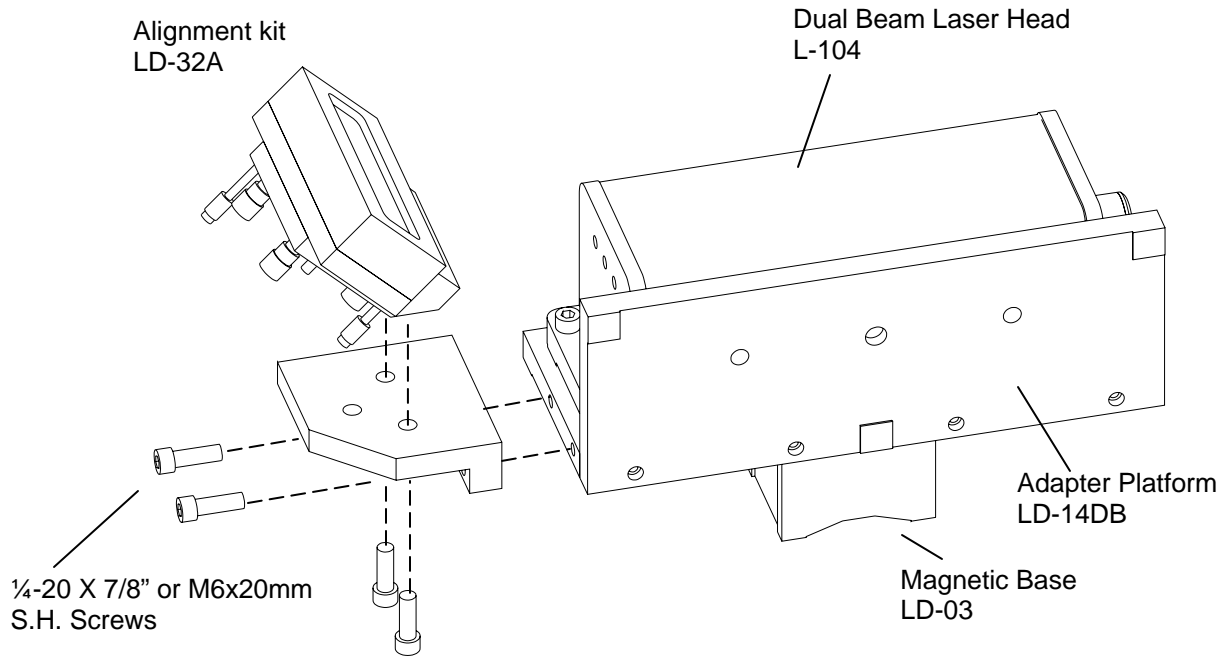


FIG. 8-5a Pitch Measurement with an Alignment kit (LD-32A)

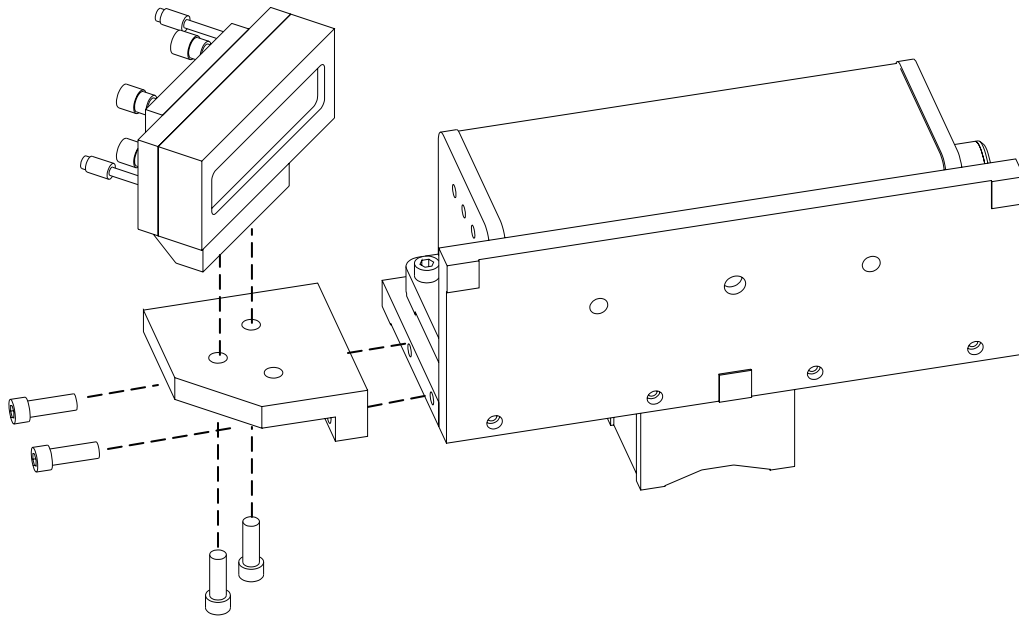


FIG. 8-5b Yaw Measurement with an Alignment kit (LD-32A)

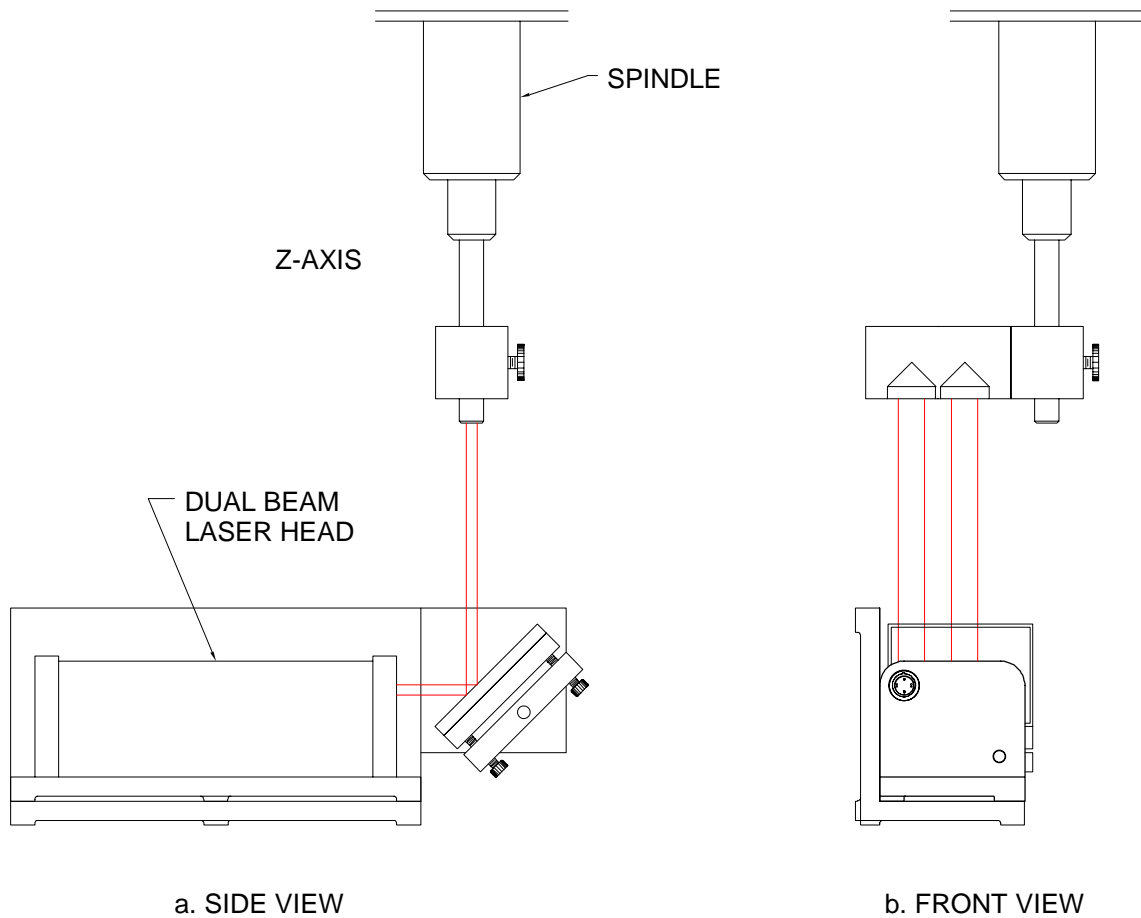


FIG. 8-6

8.5.4 Alignment Procedure

1. Make sure the two output laser beams are in the vertical plane for pitch angle measurement and in the horizontal plane for yaw angle measurement.
2. Make sure the Laser beam is parallel to the stage travel by using a magnetic cross or masking tape as a target.
 - A) When the target is near the laser head, move the cross to the center of the beam.
 - B) When the target is away from the laser head, move the laser beam to the center of cross, by steering the beam.
 - C) Repeat A and B until laser beam is parallel to the stage travel.

3. For pitch angle measurement, with table mount, move the dual retroreflector, not the laser beam, so that the top laser beam is returned by the top retroreflector to the center of the top receiving aperture with the intensity reading at maximum. The lower laser beam should be returned by the lower retroreflector to the center of the lower receiving aperture with the intensity reading at maximum. Otherwise, rotate the laser head or the dual retroreflector slightly. Please note that for standard processor module, when the linear-detector is connected, the Y display shows the signal intensity of the product of the top laser beam and the lower laser beam. For a 2-channel processor module, when both the linear-detector and angular-detector are connected, the number of bars on X is proportional to the signal intensity of the top laser beam and the number of bars on the Y display is proportional to the signal intensity of the product of the top and lower laser beam.
4. Move the stage in and out and be sure (check) that the intensity reading is at maximum. (See Section 7.5.4).

8.6 Software Description

See Section 7.6 and the software manual.

8.7 Accuracy and Error Sources

See Section 7.7.

For pitch or yaw angle measurement, the angle is derived by the difference in displacement of the two retroreflectors. Hence, the speed of light compensation and the mis-alignment error (cosine error) are negligible. The major sources of error are:

1. The distance between the two retroreflectors may change. If this distance changes during a measurement, the measurement results will be incorrect. This distance will change if the temperature of the dual retroreflector's housing changes during a measurement results will be incorrect. This distance will change if the temperature of the dual retroreflector's housing changes during a measurement.
2. For an angle larger than 1° , the large angle correction must be made, i.e., corrected angle = $\arcsin(\text{displaced angle})$.
3. Excessive roll motion of the dual retroreflector may create error.

4. The temperature gradient or air turbulence in the room will diffract the laser beam. To minimize this effect, avoid a large temperature difference between the machine and the air, and use a statistical average technique to reduce the air turbulence effect. For more discussion, see Appendix H.

8.8 Taking a Measurement

1. Decide which axis you are going to measure, from which starting point to which end point, and what the increment per stop is. Key in all this information into the computer.
2. For manual data collection, you need to program your machine controller with the specific increment per stop, total number of stops (or total travel) and the speed. Minimum dwelling time at each stop should be 3 seconds.
3. For on-the-fly data collection, you need a dual-channel processor module. Program your machine controller with speed no more than 1 ips.
4. Set up the LDDM™ by following the instructions in Section 8.5.
5. Set up the computer and load the appropriate software by following the instructions in Section 7.6 or the software manual.
6. All of the software are menu-driven, just follow the instructions on the monitor.
7. Move the machine to the starting point.
8. Reset the LDDM™ reading, press the start key, then move the machine to the first stop (for on-the-fly measurement, move the machine continuously to the end point).
9. Move the machine to the next stop and repeat step 8.
10. Repeat step 9 until the end point.
11. After all the data have been collected, if a printer is connected, you may print the data in table format or plot in graphic form.

12. You may plot the data in angle (pitch or yaw) with the units in μrad or arcsec, or integrate the angular data to plot as straightness in units of inches. Here, the straightness plot assumes the initial angle or slope is equal to zero.
13. The adjusted straightness is defined as rotating the straightness measured in step 12 by an angle, such that the deviation at both the starting point and end point is zero.
14. Typical plots of pitch angle in arcsec (1 run), pitch angle in arcsec (7 runs), straightness and adjusted straightness are shown in Figs. 8.7, 8.8, 8.9 and 8.10 respectively, and their data is shown in Table 8.1.

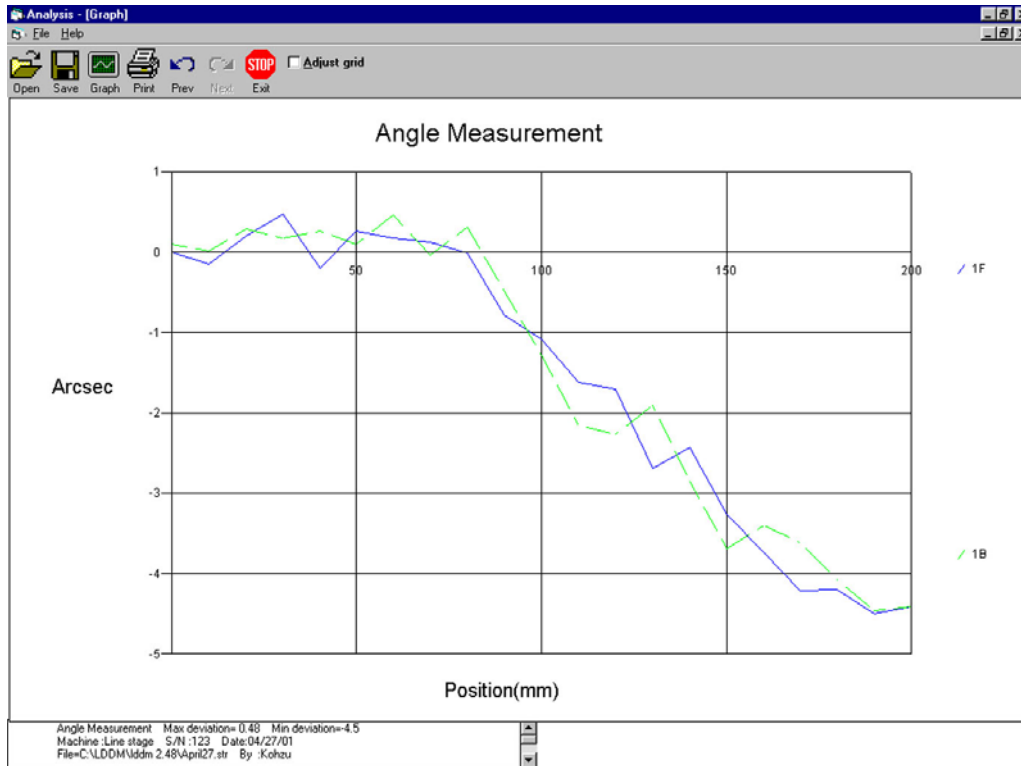


FIG. 8-7 PLOT OF MEASURED PITCH ANGLES IN ARCSEC vs. POSITION

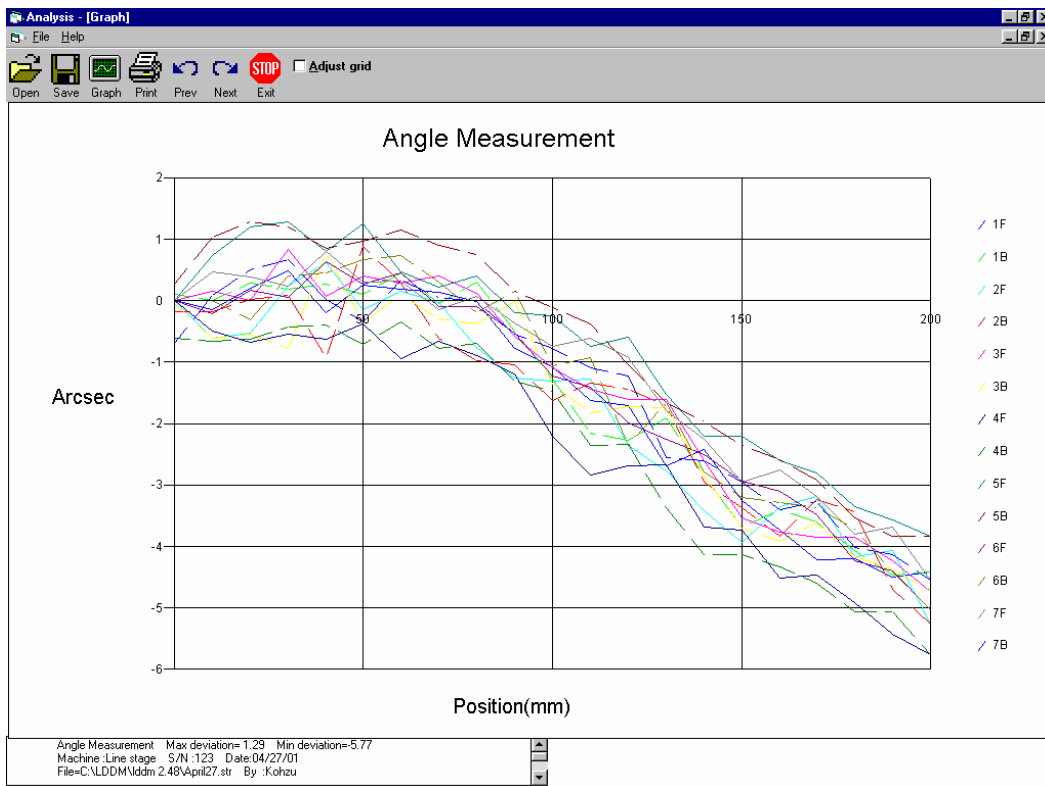


FIG. 8-8 PLOT OF MEASURED PITCH ANGLES IN ARCSEC vs. POSITION, 7 RUNS



FIG. 8-9 STRAIGHTNESS PLOT, VERTICAL DEVIATIONS IN INCHES vs. POSITION

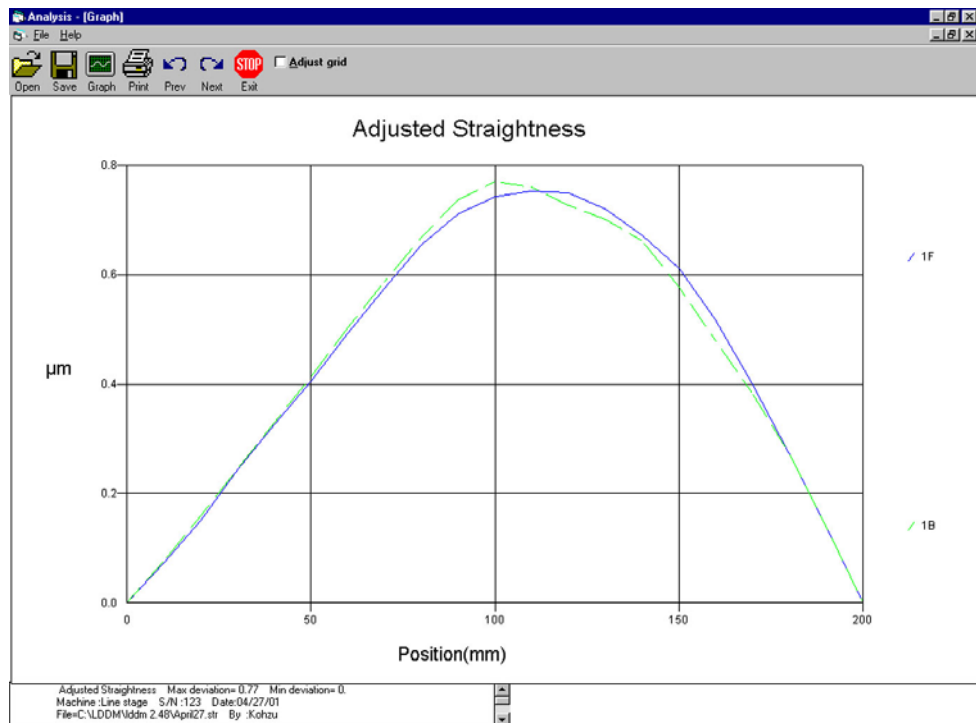


FIG. 8-10 ADJUSTED STRAIGHTNESS PLOT, VERTICAL DEVIATIONS IN INCHES vs. POSITION

Analysis - [Straightness]

File Data Selection Analysis Help

Open Save Graph Print Prev Next Exit

Adjusted Straightness, Error Analysis (µm) File=C:\LDDM\lddm 2.48\April27.str Date: 04/27/01
 Machine: Line stage S/N: 123 By: Kohzu
 Start Position: (0, 0, 0) End Position: (200, 0, 0) Laser Head Sep: 27.94
 Total Travel = 200 Points = 21 No of Runs = 7
 Pressure: 760. Humidity: 50.00 Air Temp: 20. Material Temp: 20. MTE = 1.0
 Max Error: 0.795 Min Error: 0. Mean: 0.424

Position,mm	Run #1(µm)	Run #2(µm)	Run #3(µm)	Run #4(µm)	Run #5(µm)	Run #6(µm)	Run #7(µm)
0.0	0.	0.	0.	0.	0.	0.	0.
10.0	0.073	0.07	0.072	0.101	0.055	0.066	0.067
20.0	0.151	0.127	0.144	0.185	0.14	0.136	0.143
30.0	0.243	0.205	0.233	0.268	0.238	0.213	0.214
40.0	0.327	0.31	0.324	0.352	0.326	0.301	0.295
50.0	0.405	0.405	0.404	0.44	0.414	0.394	0.378
60.0	0.492	0.49	0.489	0.52	0.494	0.482	0.449
70.0	0.576	0.577	0.574	0.594	0.548	0.562	0.509
80.0	0.655	0.643	0.655	0.669	0.601	0.629	0.562
90.0	0.712	0.678	0.713	0.731	0.644	0.685	0.611
100.0	0.743	0.7	0.741	0.761	0.672	0.713	0.639
110.0	0.754	0.721	0.748	0.752	0.685	0.721	0.661
120.0	0.75	0.717	0.742	0.73	0.69	0.71	0.679
130.0	0.72	0.677	0.733	0.713	0.677	0.679	0.669
140.0	0.672	0.612	0.7	0.671	0.624	0.635	0.627
150.0	0.611	0.518	0.619	0.604	0.555	0.574	0.556
160.0	0.518	0.426	0.511	0.517	0.476	0.499	0.473
170.0	0.401	0.351	0.395	0.412	0.383	0.411	0.384
180.0	0.274	0.257	0.276	0.297	0.271	0.295	0.27
190.0	0.14	0.142	0.149	0.159	0.141	0.157	0.144
200.0	0.	0.	0.	0.	0.	0.	0.
190.0	0.14	0.162	0.138	0.151	0.152	0.163	0.143
180.0	0.273	0.28	0.263	0.285	0.298	0.295	0.273
170.0	0.384	0.361	0.369	0.408	0.421	0.401	0.382
160.0	0.48	0.453	0.47	0.513	0.521	0.497	0.476
150.0	0.577	0.548	0.573	0.606	0.607	0.589	0.563
140.0	0.661	0.622	0.651	0.695	0.679	0.668	0.63
130.0	0.702	0.655	0.68	0.766	0.733	0.71	0.687
120.0	0.728	0.652	0.682	0.793	0.765	0.742	0.711
110.0	0.761	0.64	0.687	0.795	0.766	0.756	0.7
100.0	0.77	0.633	0.682	0.777	0.744	0.738	0.678

TABLE 8-1a STRAIGHTNESS MEASUREMENT DATA

Analysis - [Straightness]

File Data Selection Analysis Help

Open Save Graph Print Prev Next Exit

Angle Measurement, Error Analysis (Arcsec) File=C:\LDDM\lddm 2.48\April27.str Date: 04/27/01
 Machine: Line stage S/N: 123 By: Kohzu
 Start Position: (0, 0, 0) End Position: (200, 0, 0) Laser Head Sep: 27.94
 Total Travel = 200 Points = 21 No of Runs = 7
 Pressure: 760. Humidity: 50.00 Air Temp: 20. Material Temp: 20. MTE = 1.0
 Max Error: 1.29 Min Error: -5.77 Mean: -1.95

Position,mm	Run #1(Arcsec)	Run #2(Arcsec)	Run #3(Arcsec)	Run #4(Arcsec)	Run #5(Arcsec)	Run #6(Arcsec)	Run #7(Arcsec)
0.0	0.	0.	0.	0.	0.	0.	0.
10.0	-0.15	-0.61	0.15	-0.49	0.73	-0.21	0.47
20.0	0.2	-0.52	0.01	-0.67	1.2	0.17	0.38
30.0	0.48	0.24	0.03	-0.55	1.28	0.05	0.24
40.0	-0.2	0.61	0.07	-0.63	0.8	0.63	0.81
50.0	0.26	-0.15	0.41	-0.38	1.25	0.27	0.31
60.0	0.18	0.16	0.29	-0.95	0.47	0.45	0.32
70.0	0.13	-0.03	0.4	-0.66	0.22	-0.09	-0.15
80.0	-0.01	-0.76	0.12	-0.9	0.41	-0.1	0.07
90.0	-0.78	-1.26	-0.58	-1.19	-0.19	-0.53	-0.36
100.0	-1.08	-1.31	-1.1	-2.21	-0.24	-1.22	-0.75
110.0	-1.62	-1.28	-1.44	-2.03	-0.75	-1.4	-0.62
120.0	-1.7	-2.36	-1.61	-2.69	-0.59	-1.99	-0.93
130.0	-2.69	-2.78	-1.6	-2.67	-1.53	-2.25	-1.79
140.0	-2.43	-3.41	-2.6	-3.68	-2.21	-2.5	-2.25
150.0	-3.26	-3.94	-3.54	-3.74	-2.2	-2.93	-2.96
160.0	-3.74	-3.95	-3.77	-4.52	-2.6	-3.1	-2.75
170.0	-4.21	-3.19	-3.05	-4.46	-2.01	-3.48	-3.19
180.0	-4.2	-4.17	-3.05	-4.92	-3.36	-4.24	-3.8
190.0	-4.5	-4.07	-4.24	-5.43	-3.56	-4.39	-3.69
200.0	-4.41	-5.26	-4.73	-5.77	-3.03	-5.03	-4.55
190.0	-4.41	-5.26	-4.73	-5.77	-3.03	-5.03	-4.55
180.0	-4.46	-4.7	-4.36	-5.07	-3.84	-4.42	-4.13
170.0	-4.07	-3.43	-4.16	-5.06	-3.54	-3.72	-4.02
160.0	-3.61	-3.23	-3.62	-4.6	-2.92	-3.37	-3.27
150.0	-3.4	-3.03	-3.92	-4.33	-2.58	-3.29	-3.4
140.0	-3.69	-3.37	-3.71	-4.13	-2.36	-3.2	-2.95
130.0	-2.85	-2.96	-2.05	-4.14	-1.98	-2.79	-2.6
120.0	-1.9	-1.71	-1.74	-3.37	-1.65	-2.56	-2.54
110.0	-2.27	-1.45	-1.73	-2.34	-1.05	-2.36	-1.23
100.0	-2.16	-1.94	-1.03	-2.36	-0.37	-0.92	-1.09
90.0	-1.28	-1.62	-1.35	-1.48	-0.11	-1.06	-0.77

TABLE 8-1b ANGULAR MEASUREMENT DATA

8.9 Description of a Measurement

After a measurement is completed, the data can be analyzed by the same software. The output of a typical measurement on a milling machine is shown in Fig. 8.7 to 8.10, and the data is shown in Table 8.1. The measurement here was on the x-axis with 0.5 in. increments, and 12 in. total travel. Fig 8.7 is the pitch angle in μrad vs. distance and Fig. 8.8 is the same pitch angle in arcsec vs. distance. Fig. 8.9 is the straightness vs. distance, where the initial slope is zero. Fig. 8.10 is the adjusted straightness vs. distance, where the deviation at both the start point and end point are zero. The measurement increment, total points, maximum or minimum angle or deviation and axis of motion are shown on the bottom of each plot.

In Table 8.1b, the first column is the run number, the second column is the point number, the third column is the position, the fourth is the direct LDDM™ reading at each position, fifth is the angle in μrad (LDDM™ reading \times 1,000,000/Beam Separation), sixth is the angle in arcsec (angle in $\mu\text{rad}/4.82$), seventh is the straightness ($S_n = S_{n-1} + \text{LDDM}^{\text{TM}} \text{ reading} \times \text{Increment}/\text{Beam Separation}$), and the eighth is the adjusted straightness ($S'_n = S_n - n \times (S_e/N_{e1})$), where N_e is the total number of points and S_e is the deviation at the end point.

8.10 Effect of Air Turbulence on Straightness Measurement Techniques

For comparison, the existing techniques, laser interferometry and the alignment laser are briefly described. Basically, the interferometer splits the laser beam into two component parts, with each part leaving the interferometer along a specific, precisely-controlled path by a Wollaston prism. Each beam from the straightness reflector consists of a pair of front-surface plane mirrors, rigidly mounted such that they reflect each beam back along its incoming path to the interferometer. Initially, the two paths from the interferometer to the reflector have some length relative to each other. If the straightness reflector is moved laterally, the relative length of the two beams will change. This change indicates a non-straightness. The alignment laser technique is based on the fact that a HeNe laser produces an intense beam of red light which is a straight line of the greatest accuracy in vacuum. Attach a target with a quad-detector, which is a large area photodetector cut into four quadrants. If a laser beam shines at the center of the quad-detector, the output from the 4 detectors should be the same. However when the quad-detector is moved toward the left, the detectors on the right should have higher output than the detectors on the left. The difference in the detector output is proportional to the lateral displacement of the quad-detector. This is also true in the case where the quad-detector is moved up and down. Hence the laser beam center position can be determined.

The Laser Doppler Displacement Meter consists of a dual-beam laser head, a dual-retroreflector and a 2-axis processor module. It can be used to measure both the linear position and pitch or yaw angle of the dual-retroreflector. Using a

notebook computer, local slopes at each increment can be collected automatically. The straightness can be determined by integrating the measured local slopes.

All of the above three techniques are extremely accurate in a vacuum. However, in atmospheric conditions, the speed of light changes with air density (or pressure) and humidity. Particularly, the air turbulence and the temperature gradient will affect the measurement accuracy. Detailed analysis on the effect of air turbulence is very complex. For illustration purpose, discussed here is a simple model based on Komogrov's turbulence model. Assume the turbulence is generated by shear flows with temperature gradients. Various sizes of vortex are generated by the shear flow. You may imagine vortices as glass beads of various sizes and density gradients. When a laser beam passes through these glass beads, it may bend in various different directions like a random walk process.

For order of magnitude estimation, assume the dominate effect is due to vortex of the size of the laser beam diameter. Assume the temperature difference is 5°C, the diameter of the vortex is 5 mm. If the total beam path is 1 m, the diffraction by each vortex is about 5 μ rad and the total diffraction over one meter is about 70 μ rad. Assume a temperature gradient of 5°C/m, the deflection is about 5 μ rad. Hence, the accuracy of the alignment laser technique is limited to 70 μ rad over one meter. Of course, statistical averaging can be used to improve the accuracy. As compared to the laser interferometer technique and LDDM™, beam deflection only causes a cosine error and the actual measurement is the difference in displacement divided by the beam separation. Hence, for the same atmospheric condition above, the angular error is only 7 μ rad instead of the 70 μ rad shown above.

In conclusion, comparing these three techniques, the laser interferometer technique provides high resolution and accuracy, but it is extremely difficult to use and very expensive. The alignment laser technique is relative easy to use, but the resolution and accuracy may not be enough. Only the LDDM™ technique provides both high resolution and easy use.

9.0 Surface Flatness Measurement

9.1 Introduction

The surface flatness measurement is based on the Moody method which calculates the surface flatness deviation from the measured angular displacements and the length dimension of the foot-spacer. The package described in Section 8 plus a set of (3) foot-spacers and the surface flatness software are best suited for the calibration of surface plates. With a 2-channel processor module, both the linear and angular displacement can be measured simultaneously. Hence the angular displacement data can be collected at every 2 inches (or other increments depending on the size of the foot-spacers used) automatically on the fly in a single stroke. Using a specially designed straight-edge (LD-43), the time consuming alignment is eliminated. The result can be plotted either as an isometric plot, or as a numeric plot.

9.2 Hardware Required

See [Section 8.2](#)

9.3 Operating Specification

Accuracy: 2 μin $\pm 0.2\%$

Resolution: using 2" foot-spacer, 2 μin , (0.02 μm)
using 4" foot-spacer, 4 μin , (0.04 μm)
using 6" foot-spacer, 6 μin , (0.06 μm)

Reference Plane Accuracy: The uncertainty of the flatness measurement is bounded by two parallel planes separated by:

$$\Delta = 0.12F^2 \mu\text{in}$$
$$(\Delta = 0.03M^2 \mu\text{m})$$

Where F = length of the surface diagonal in feet and M = length of the surface in meters.

Measurement Uncertainty: The closure errors 7 and 8 indicate the measurement uncertainty. Large closure errors may be caused by large lateral offset which displace the retroreflector more than ± 0.05 inch from the beam path in any direction.

Maximum Distance: 16 ft. (4.8 m)

9.4 Reference Material

See Section 8.

9.5 Installation and Alignment

9.5.1 Important Considerations

See Section 8.5.1

9.5.2 Installation

Attach the dual-beam laser head to the special straight-edge (LD-43) and the dual-retroreflector to the foot-spacer (select one of the 3 standard sizes 2" (50 mm), 4" (75 mm) and 6" (150 mm) as shown in [Fig. 9-1](#) and [9-2](#). The length of measurement divided by the foot-spacer length should be greater than 10. Make sure that the center line of the dual-retroreflector is perpendicular to the base plate. (You may check this by rotating the dual-retroreflector slightly along the vertical axis; the LDDM™ reading should only change slightly; less than the accuracy you need.) Otherwise, adjust the three mounting screws on the base to make it perpendicular. Adjust the two mounting screws on the laser head so that the laser beam is parallel to the surface. If you do not have a special straight-edge, you may use the alignment kit (LD-32) discussed in [Section 8.5.4](#).

9.5.3 Description

1. To measure flatness of a surface you will have to draw a "grid" on it and make measurements along each edge and diagonal of this grid. A typical grid map is shown in [Fig. 9-3](#).
2. For each line measured:
 - A) You will initially position the dual retroreflector at the 'start' point of the line.
 - B) Position the laser head (mounted on the straight-edge) in front about ½" of the dual retroreflector.
 - C) Align the straight-edge parallel to the line.
 - D) Move the dual-retroreflector from the 'start' point to the 'end' point of the line and make sure the beam intensity reading is above the minimum required.
 - E) You are ready to take a measurement. Always start the retroreflector near the laser head and move it away from the laser head.

9.5.4 Alignment Procedure

If you are using the alignment kit, see Section 8.5.4. If you are using a special straight-edge, make sure the laser beam is parallel to the surface, and that no further alignment is required.

9.6 Software Description

See [Section 7.6](#) and the software manual.

9.7 Accuracy and Error Sources

See [Section 8.7](#)

Clean the measurement surface thoroughly. A build-up of dust or dirt on the measuring surface can cause error in your flatness measurement.

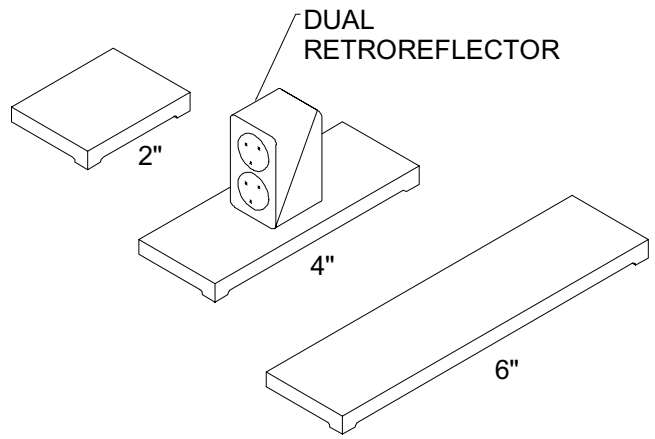


FIG. 9-1 DUAL RETROREFLECTOR AND FOOT SPACER

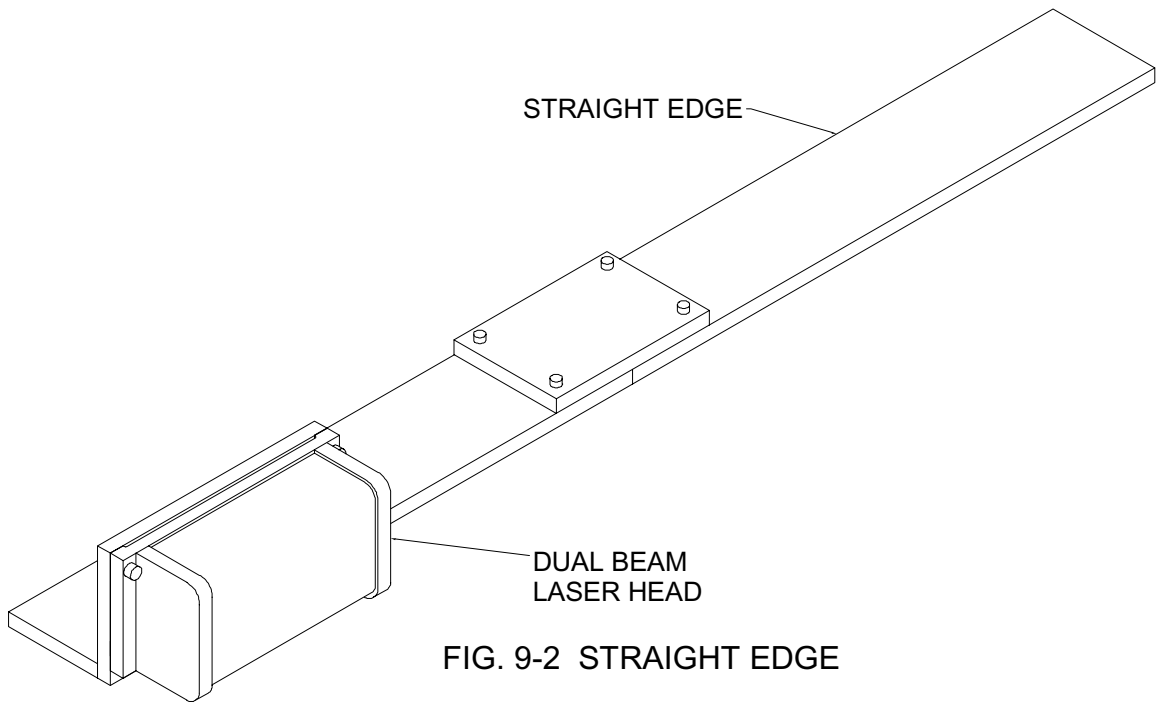


FIG. 9-2 STRAIGHT EDGE

9.8 Taking a Measurement

1. Install and align the laser ([Section 9.5](#)).
2. Draw a "map" of the surface plate. The map should be drawn on a sheet of paper with highlights located on the surface plate itself with a lead pencil. Take care not to put markings directly on the grid lines, since the equipment must be free to slide on the granite surface along these lines. The grid system must contain the eight basic lines, as shown in [Fig. 9-3](#).

The length of each line in this grid should be an even integer ("2", "4", etc.) multiple of the length of the footspacer. For a very large Surface Plate, you will probably want to use a larger foot-spacer, since measurement points will be determined by end-to-end positioning of the foot-spacers. There should also be a 3 inch (7.5 cm) margin between the outside of the grid and the edge of the Surface Plate on all sides.

3. Boot computer and load the appropriate software. (See [Section 7.6](#) or the software manual).
4. The software is menu-driven; follow the instructions on the monitor.
5. For a specific measurement "line" on the surface plate, place the dual retroreflector, with an appropriate foot-spacer, at the starting point and near the center of the line. Place the laser head, mounted on the straight-edge, about 0.5 inch in front of the dual retroreflector. Align the straight-edge so that it is parallel to the measurement "line". Move the dual retroreflector from the starting-point to the 'end' point and make sure that the beam intensity is above the minimum requirement. Place the dual retroreflector at the 'starting' point. For automatic data collection (you need a 2-channel processor module) press the starting key and smoothly move the dual retroreflector along the straight-edge from the 'starting' point to the 'end' point. The angular data will be recorded automatically. Follow the instructions on the monitor and move to the next measurement "line". During the measurement make sure not to press the straight-edge too hard. This may deflect the laser beam direction.
6. Repeat step 5 until all of the "lines" have been measured.
7. For manual data collection, stop the dual retroreflector at every 2" (or at other increments), then press the space bar to record the angular data.
8. Continue step 7 until all data points have been collected on the "line".

9. Repeat steps 7 and 8 until all (8) "lines" have been measured.
10. A suggested routine for a measurement is shown in [Fig. 9-4](#).
11. The data can be collected in any sequence or direction. Just follow the instruction on the monitor to select a measurement "line" and direction. Make sure you always start the dual retroreflector near the laser head and move away from the laser head.
12. You may re-measure any "line" by repeating the measurement.
13. After all data has been collected, you may print the data in table format or plot an isometric or numeric plot. A typical output data is shown in [Fig. 9-5](#).

9.9 Description of a Measurement

After a measurement is completed, the data can be analyzed by the analysis software. The output of a typical measurement on a surface plate is shown in [Fig. 9.5a](#) and b, and the data is printed in [Table 9.1](#). Fig. 9-5a is an isometric plot of surface flatness, where the vertical lines indicates the relative height of the surface plate. For table orientation, the tag is always on the top-side. Labeled on the bottom are the description of the item, the serial number, the measurement date and the operator. The table size, flatness and closure errors are also shown. The flatness is defined as the separation between the base plane and a parallel plane through the highest point. The closure error, E7 is a measurement error which is the difference in height at the center of the table between the measurement C1 and the average. The closure error E8 is similar to E7, but between C2 and the average. Typically, both the closure error E7 and E8 should be less than half of the flatness value.

For a more qualitative presentation, a numerical plot of surface flatness is shown in [Fig. 9.5b](#). The numbers indicate the vertical heights at that location. The unit of the height number is shown on the bottom of the plot. For example, the number 136 near the center is 136 times the unit in 0.000001 in., equal to 0.000136 in. That is, the center is 0.000136 in. higher than the lowest point. Please note that there are always 20 numbers in a row and 19 numbers in a column independent of the table size or the number of steps in the measurement. You need to properly scale the actual distance between the location of two numbers in a row and two numbers in a column.

The measurement data is shown in [Table 9.1b](#). The top half is the direct LDDM™ readings and the bottom half is the adjusted straightness on each line of measurement. D1 and D2 are the two diagonal lines; P1, P2, P3 and P4 are

the 4 peripheral lines; C1 and C2 are the two center lines. The method used to generate the surface flatness is based on the Moody technique.

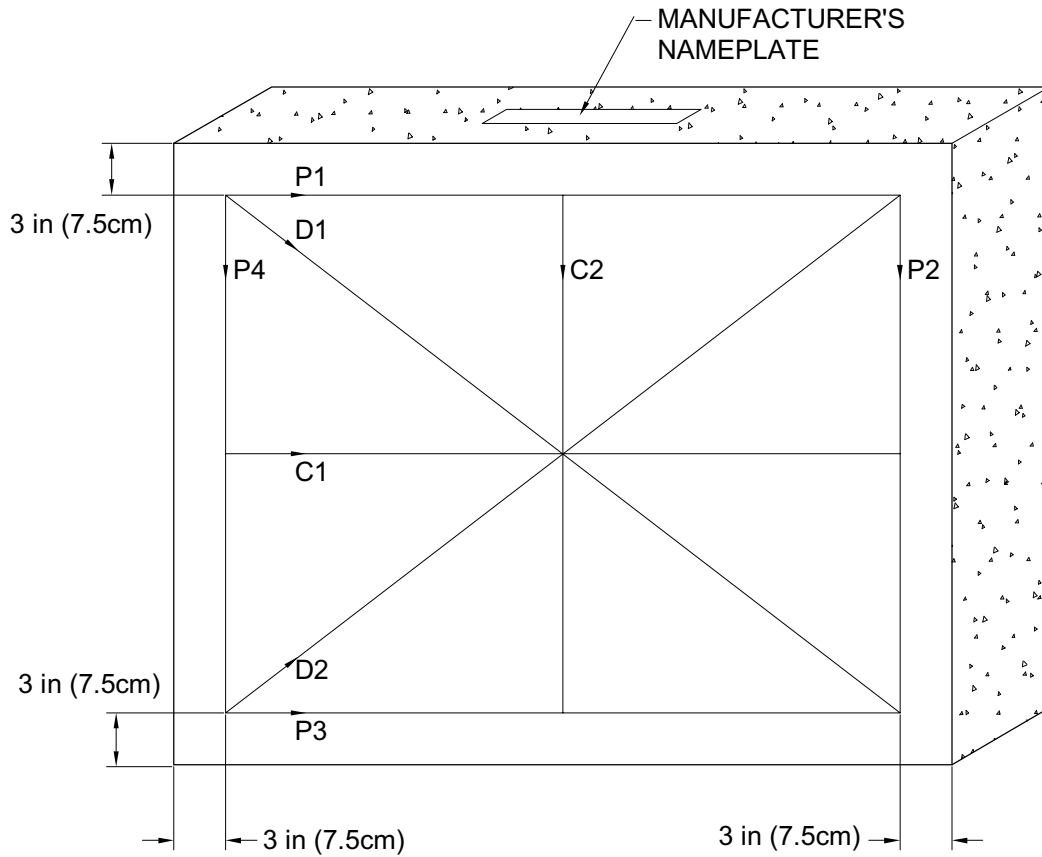


FIG. 9-3 GRID MAP OF SURFACE PLATE

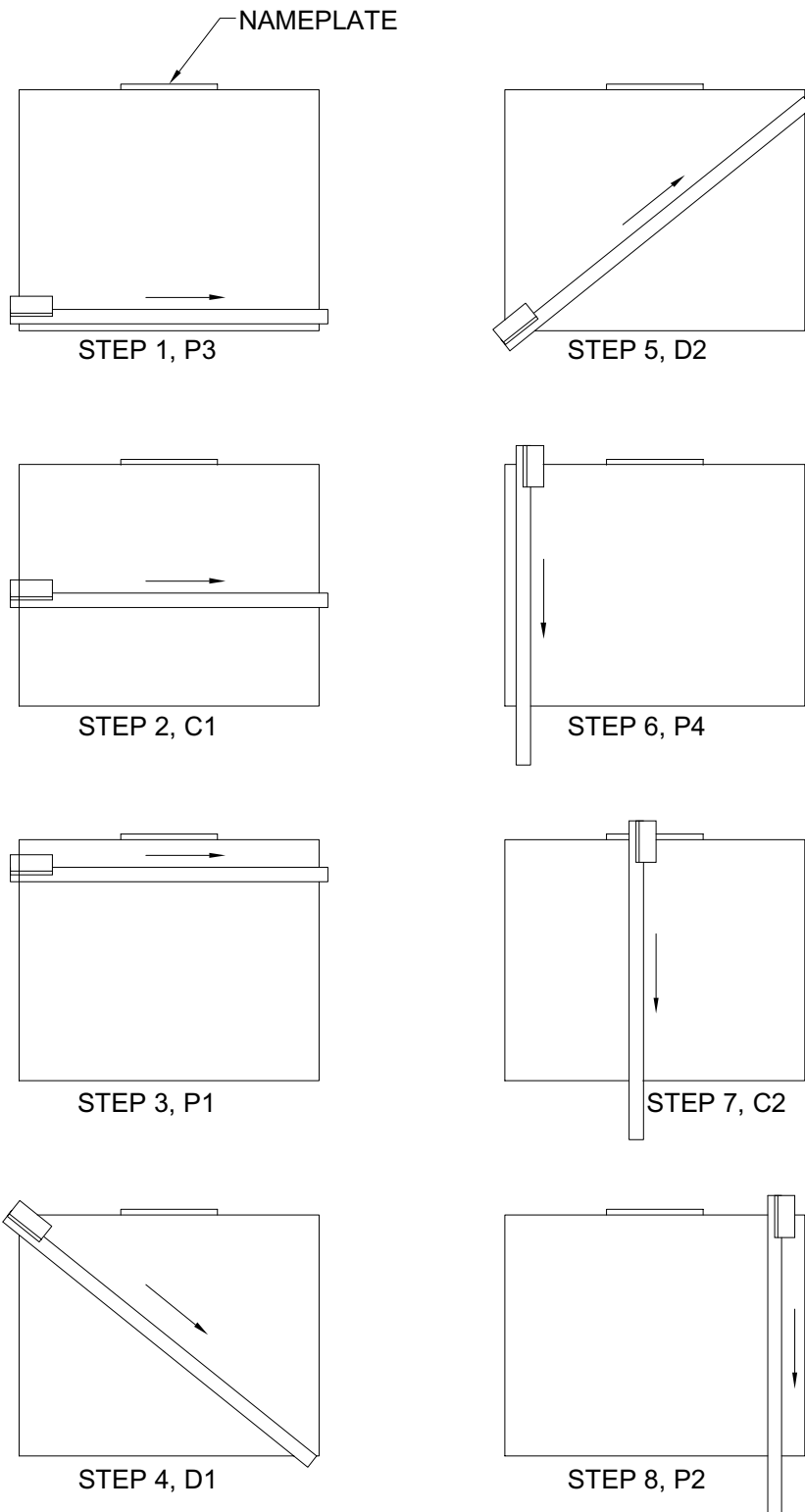


FIG. 9-4 SUGGESTED ROUTINE FOR MEASUREMENT

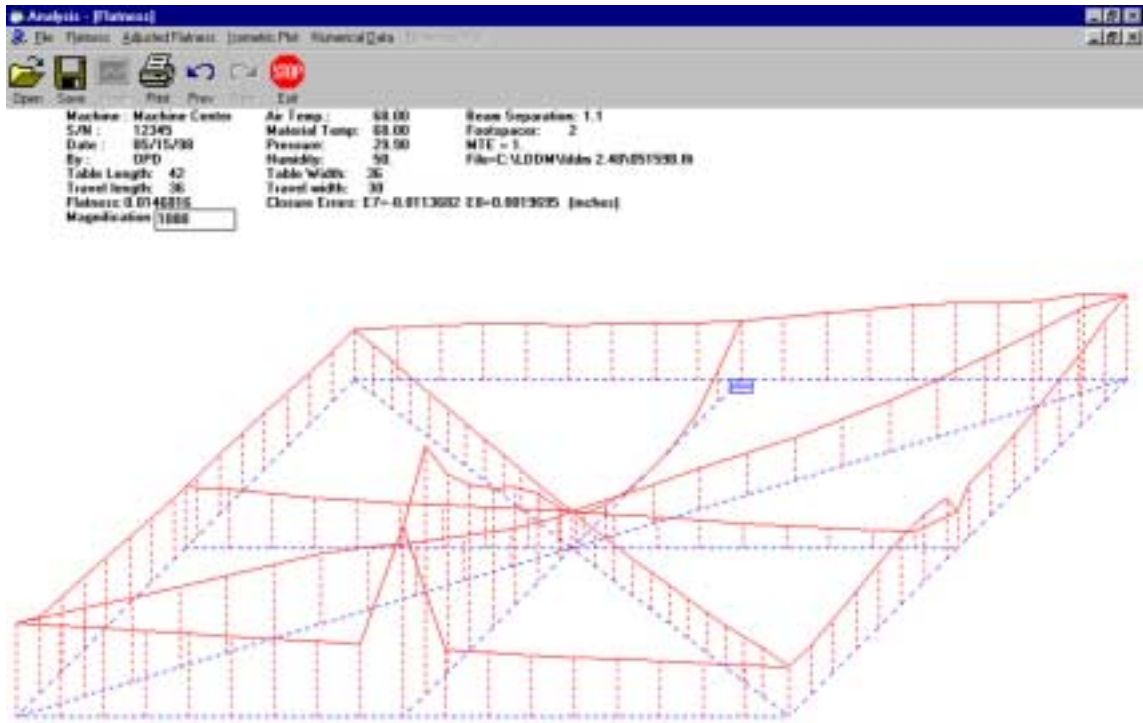


FIG. 9-5a ISOMETRIC PLOT OF SURFACE FLATNESS

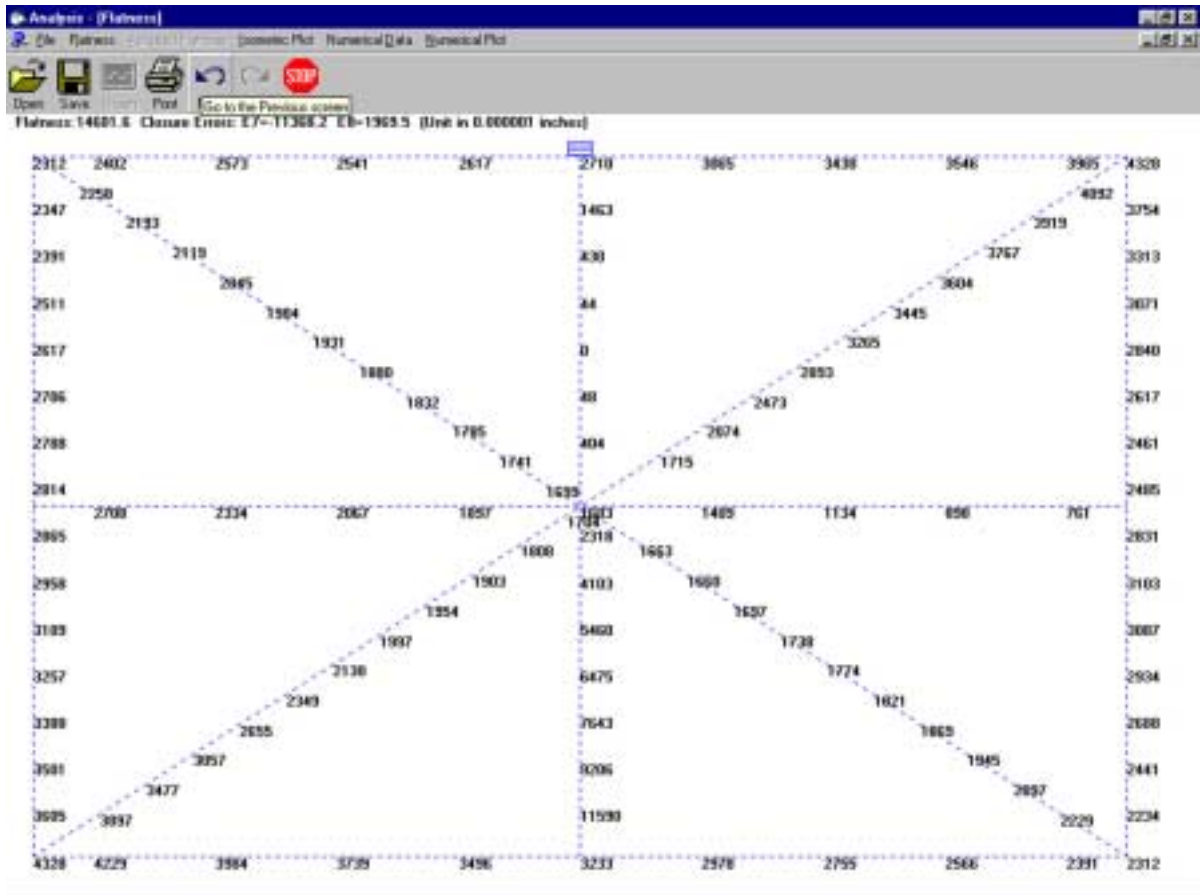


FIG. 9-5b NUMERICAL PLOT OF SURFACE FLATNESS

Machine: Machine Center
S/N: 12345
Date: 05/15/98
By: DPD
Table Length: 42
Travel length: 36

Air Temp.: 68.00
Material Temp.: 68.00
Pressure: 29.50
Humidity: 50.
Table Width: 36
Travel width: 30

Beam Separation: 1.1
Footspacer: 2
MTE = 1.
File=C:\LDDM\kdda 2.48\051598.B

Position In	P4	P3	P2	P1	C1	C2	D1	D2
0.	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
2.	-0.0000190	0.0000240	-0.0001460	-0.0000060	0.0000750	-0.0002360	0.0000120	-0.0000110
4.	-0.0000940	0.0000940	-0.0002190	0.0000210	0.0000130	-0.0007110	0.0000100	-0.0000010
6.	0.0000000	0.0000240	-0.0001590	0.0000050	0.0000020	-0.0000130	0.0000120	-0.0000300
8.	-0.0000950	0.0000000	-0.0002270	0.0000420	-0.0000130	-0.0000120	-0.0000040	-0.0001000
10.	0.0000140	0.0000160	-0.0002320	0.0000110	-0.0000350	-0.0000950	0.0000030	-0.0001240
12.	-0.0000040	0.0000100	-0.0004260	0.0000500	-0.0000190	-0.0011290	-0.0000060	-0.0002040
14.	-0.0000130	0.0000270	-0.0005000	0.0000400	-0.0000140	-0.0016410	0.0000000	-0.0002220
16.	-0.0000510	0.0000000	-0.0003440	-0.0000510	-0.0000050	-0.0016340	-0.0000000	-0.0001950
18.	-0.0000760	0.0000100	-0.0002700	-0.0000400	0.0000040	-0.0011710	0.0000030	-0.0001740
20.	-0.0000400	0.0000200	-0.0001930	-0.0000620	0.0000100	-0.0013170	-0.0000100	-0.0001000
22.	-0.0000570	0.0000000	-0.0001600	-0.0000500	0.0000020	-0.0013400	-0.0000240	-0.0002050
24.	-0.0000200	0.0000000	-0.0001920	-0.0000420	0.0000000	-0.0017510	-0.0000210	-0.0003630
26.	-0.0000400	0.0000000	-0.0002110	0.0000140	-0.0000010	-0.0022430	-0.0000340	-0.0005060
28.	-0.0007000	-0.0000100	-0.0005000	0.0000040	-0.0000270	-0.0024420	-0.0000660	-0.0004000
30.		-0.0000070		-0.0001000	-0.0000300		-0.0000390	-0.0005300
32.		0.0000000		0.0001400	0.0000400		-0.0000600	-0.0003520
34.		-0.0000220		-0.0001520	-0.0000240		-0.0000500	-0.0003200
36.							-0.0000030	-0.0003290
38.							-0.0000790	-0.0003230
40.							-0.0001400	-0.0003100
42.							-0.0000960	-0.0003400
44.							-0.0000670	-0.0003050
46.								

TABLE 9-1a FLATNESS MEASUREMENT DATA

Machine: Machine Center
S/N: 12345
Date: 05/15/98
By: DPD
Table Length: 42
Travel length: 36
Flatness: 0.0146016

Air Temp.: 68.00
Material Temp.: 68.00
Pressure: 29.50
Humidity: 50.
Table Width: 36
Travel width: 30

Beam Separation: 1.1
Footspacer: 2
MTE = 1.
File=C:\LDDM\kdda 2.48\051598.B

Close Error: E7=-0.0113682 E8=-0.0019055

Position In	P4	P3	P2	P1	C1	C2	D1	D2
0.	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
2.	-0.0000590	0.0000132	-0.0004395	-0.0000222	-0.0000118	-0.0020400	-0.0000539	-0.0002359
4.	-0.0001899	0.0000047	-0.0007463	-0.0000309	-0.0000736	-0.0030655	-0.0001106	-0.0004090
6.	-0.0002044	-0.0000076	-0.0008540	-0.0000749	-0.0001473	-0.0050445	-0.0001925	-0.0005612
8.	-0.0002325	-0.0000190	-0.0009499	-0.0001034	-0.0001720	-0.0050009	-0.0002663	-0.0007223
10.	-0.0002779	-0.0000263	-0.0010305	-0.0001531	-0.0001746	-0.0066255	-0.0003275	-0.0008827
12.	-0.0003306	-0.0000297	-0.0010607	-0.00014015	-0.0001427	-0.0070627	-0.0003004	-0.0010621
14.	-0.0004387	-0.0000474	-0.0009021	-0.0001792	-0.0001054	-0.0072110	-0.0004315	-0.0014344
16.	-0.0005223	-0.0000790	-0.0004216	-0.0001905	-0.0000072	-0.0067336	-0.0004799	-0.0018040
18.	-0.0005631	-0.0000864	-0.0000196	-0.0006100	-0.0000009	-0.0057410	-0.0005205	-0.0022533
20.	-0.0005467	-0.0000095	0.0001031	-0.0005495	-0.0000009	-0.0051773	-0.0005703	-0.0026120
22.	-0.0005330	-0.0001100	0.0000045	-0.0004709	-0.0001155	-0.0045955	-0.0006124	-0.0026905
24.	-0.0005366	-0.0001303	-0.0000209	-0.0003994	-0.0001302	-0.0045000	-0.0006353	-0.0026234
26.	-0.0005583	-0.0001171	-0.0001292	-0.0003300	-0.0001510	-0.0030100	-0.0006403	-0.0025201
28.	-0.0005083	-0.0001038	-0.0002123	-0.0003347	-0.0001627	-0.0022191	-0.0006521	-0.0024250
30.	0.0000000	-0.0000015	0.0000000	-0.0004460	-0.0001491	0.0000000	-0.0006151	-0.0023736
32.		-0.0000520		-0.0004530	-0.0001036		-0.0005734	-0.0023303
34.		-0.0000332		-0.0002905	-0.0000464		-0.0005373	-0.0021970
36.		0.0000000		0.0000000	0.0000000		-0.0004911	-0.0019703
38.							-0.0004423	-0.0016731
40.							-0.0003670	-0.0012700
42.							-0.0002145	-0.0000911
44.							-0.0000030	-0.0004306
46.							0.0000000	0.0000000

TABLE 9-1b ADJUSTED FLATNESS MEASUREMENT DATA

10.0 Squareness, Parallelism and Straightness Measurement

10.1 Introduction

In determining machine geometry, a laser beam is used to produce an ultra precision equivalent to the straight-edge. An optical square is used to bend the laser beam precisely at a 90° angle, and a quad-detector is used to determine the centroid of the laser beam.

A straightness measurement is the measurement of perpendicular motion along a travel path as shown in Fig. 10-1.

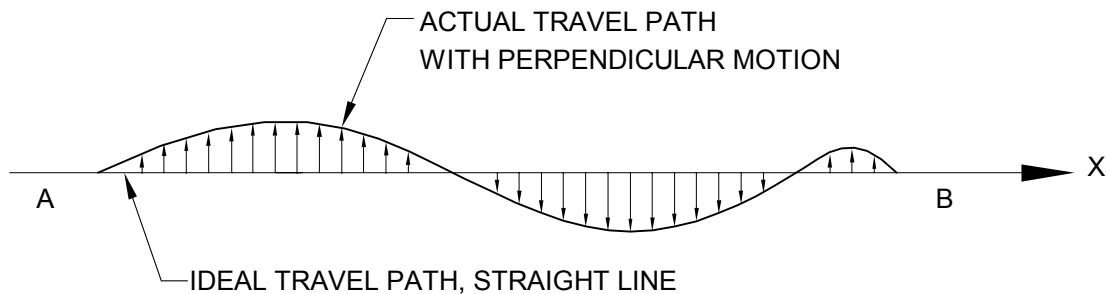


FIG. 10-1 DEFINITION OF STRAIGHTNESS

The ideal travel path is a straight line. Any deviation from the straight line in the horizontal direction is called horizontal straightness. In the vertical direction it is called vertical straightness.

Attach a target with a cross in the center to the travel mechanism and align the cross to the center of the laser beam, as shown in Fig. 10-2. Assume the laser beam travels from A to B and follows the ideal path. The center of the cross should follow the actual travel path. By measuring how far the cross is deviated from the center of the laser beam along the travel path, we can determine the straightness.

For more accurate measurement, the centroid of the laser beam can be measured by using a quad-detector which is a large area photodetector cut into four quadrants, as shown in Fig. 10-3.

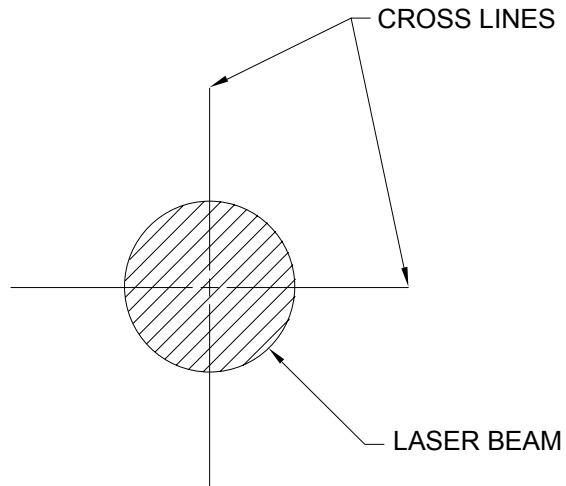


FIG. 10-2 LASER BEAM AND CROSS-LINE TARGET

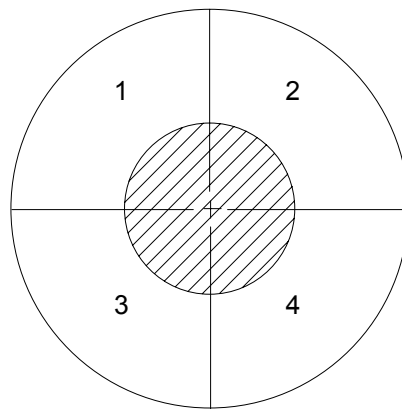


FIG. 10-3 QUAD-DETECTOR AND LASER BEAM

If a laser beam shines at the center of the quad-detector, the output from the four detectors, 1, 2, 3 and 4 should be the same. However, when the quad-detector is moved toward the left, detectors 1 and 2 should have higher outputs than detectors 3 and 4. Similarly, when the quad-detector is moved up, detectors 2 and 3 should have higher outputs than detectors 4 and 1. Hence, the straightness or the vertical deviation y and the horizontal deviation x can be expressed as:

$$Y = \frac{(I_1 + I_2) - (I_3 + I_4)}{I_1 + I_2 + I_3 + I_4}$$

$$X = \frac{(I_1 + I_4) - (I_2 + I_3)}{I_1 + I_2 + I_3 + I_4}$$

where I_1 , I_2 , I_3 , and I_4 are the outputs of detectors 1, 2, 3 and 4 respectively, and S_x and S_y are scale factors for x deviation and y deviation respectively. Assuming a Gaussian laser beam of diameter d , the minimum detectable deviation Δ can be calculated as:

$$\Delta = \frac{d}{4} \cdot \frac{\sqrt{\pi}}{\left(\frac{S}{N}\right)}$$

where d is the laser beam diameter, Δ is the minimum detectable deviation and S/N is the signal to noise ratio of the detectors. For example, for a laser beam diameter of 0.25 in. and $S/N = 1000$, the minimum detectable deviation is:

$$\Delta = 0.0001 \text{ in.}$$

Higher resolution can be obtained by averaging over a longer period of time, decreasing d or increasing the S/N .

When the laser beam is bent through a precise 90° angle by an optical square, it can be used to measure squareness and parallelism. The optical square is a penta-prism, which bends the incoming laser beam to 90° . As shown in Fig. 10-4, because the two reflecting surfaces are at a fixed angle, the output laser beam is always $90^\circ \pm$ tolerance from the incident laser beam, independent of the incident angle. Typical accuracy for an optical square is 2-5 arcsec. Higher accuracy of less than 1 arcsec is available. Using the incident beam direction as the axis of rotation, rotating the optical square will generate a plane perpendicular to the incident laser beam. Care must be taken to minimize any skew when using optical square for parallelism measurement.

A HeNe laser produces an intense beam of red light which is a straight line of the greatest accuracy in a vacuum. In atmosphere, the straightness of a laser beam may be changed by temperature gradients or air currents. Accuracy is determined by the straightness of the laser beam which is controlled by the temperature gradient or the air current across the laser beam. For a typical indoor condition, the stability of the laser beam is about 0.0001 in. per 12 inches.

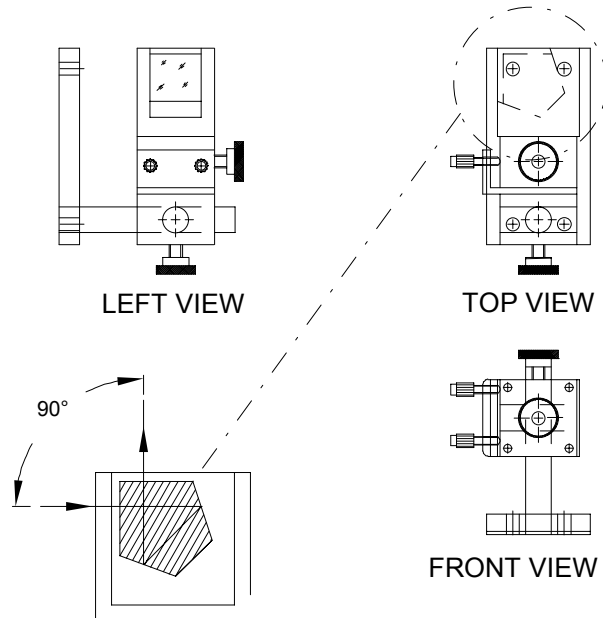


FIG. 10-4 SCHEMATIC OF A PENTA-PRISM

10.2 Hardware Required

The basic hardware and software required for linear calibration are the following:

a. Dual Aperture Laser Head	L-101
b. Processor Module with RS-232 Interface	P-111
d. Ø1" Retroreflector	R-106
e. Quad-Detector	LD-42
f. Optical Square	LD-16
g. 90° Beam Bender (Ø1")	LD-15
h. Magnetic Base	LD-03
i. Adapter Platform	LD-14
j. 12 ft. cable set	LD-21
k. Notebook Computer	LTC

10.3 Operation Specifications

<u>Accuracy:</u>	Overall accuracy is the sum of optical reference accuracy plus the Quad-detector accuracy. The laser beam is a straight line in a vacuum. However, in atmosphere, there are temperature gradients, air currents, and turbulence. A typical accuracy of the laser beam straightness is 0.0001 in/ft in an air conditioned room. The quad-detector accuracy is $\pm 3\%$ of displayed value for deviation less than 0.01 inch and is $\pm 5\%$ for deviation less than 0.04 inch.
<u>Resolution:</u>	0.0001 inch and 0.00001 inch selectable (0.001 mm and 0.0001 mm selectable)
<u>Straightness Deviation Range:</u>	± 0.04 inch
<u>Maximum Distance:</u>	Up to 16 ft.
<u>Temperature Range:</u>	60°F to 90°F or (15.5°C to 32°C)

10.4 Reference Material

- [Appendix D](#). Description of microprocessor control and firmware.
- [Appendix K](#). Straightness Measurement Techniques.

10.5 Installation and Alignment

10.5.1 Important Considerations

1. Check to see that all cables are firmly connected before connecting power cable and switching the power switch to on.
2. Always mount the laser head on a stationary part and the quad-detector on a moving part. Never use a tripod to mount the laser head. The tripod may cause large error in measurement and/or erroneous data.
3. When installing the laser head, be certain that the laser beam coming out from the 90° beam bender will travel in the direction of the straightness measurement.

4. Vibration and loose connections must be minimized by proper mounting. Make sure that all supports and cables are completely stationary. A spindle, for example, must be secured by a brake so it won't rotate.

CAUTION! Never turn on the spindle of the CNC while either the laser or retroreflector are mounted there. This could cause injury to the operator and/or damage to the equipment.

10.5.2 Installation

Attach the 90° beam bender to the front of the laser head by (2) ¼-20 3/8" long screws. Four mounting positions are possible. For pointing in the left or right direction, use only one screw as shown in Fig. 7-2. Be sure both the exit beam and return laser beam are covered by the steering rectangular mirror inside the 90° beam bender. To mount the laser head to the spindle, you may use the spindle mount adapter Fig. 7-3 or the magnetic holder Fig. 7-4. To mount the quad-detector on the bed by screws or a magnetic holder, be sure all screws are tight and the surface of the magnetic holder is free of grease. Connect the cable from the quad-detector to the processor module. Make sure the cable is firmly secured to the bed.

10.5.3 Description

1. Decide which axis of travel you want to measure, which part is moving and which part is stationary for this axis of motion.
2. Mount the laser head on the stationary part, the quad-detector on the moving part. Move the movable part of the machine to the 'starting' point or the 'end' point, then mount the quad-detector as close to the laser head as possible.
3. Adjust the laser head or the 90° beam bender so that the output beam is parallel to the direction of travel.
4. Align the laser beam through A and B as per Fig. 10-1. Attach the quad-detector to the travel mechanism, and align it to the center of the laser beam at A or B. The straightness can be measured by recording x and y along the line of travel. For a typical calibration of a machine tool or a slide, the laser beam is adjusted to be parallel to the motion of the machine slide, table or spindle. The quad-detector target, riding at the tool point, is moved along the line of motion and the display module, continuously displaying the vertical and horizontal shift of the slide.

5. A squareness measurement consists of two perpendicular straightness measurements made from the same laser beam. Perpendicularity is achieved by using an optical square, as shown in [Fig. 10-5](#). Squareness is calculated by adding or subtracting the slopes for each straightness measurement to a right angle provided by the optical square.

6. A parallelism measurement consists of two parallel straightness measurements made from the same laser beam. Parallelism is achieved by using an optical square at two different locations as shown in [Fig. 10-6](#). Parallelism is calculated by comparing the slopes of the two straightness measurements.

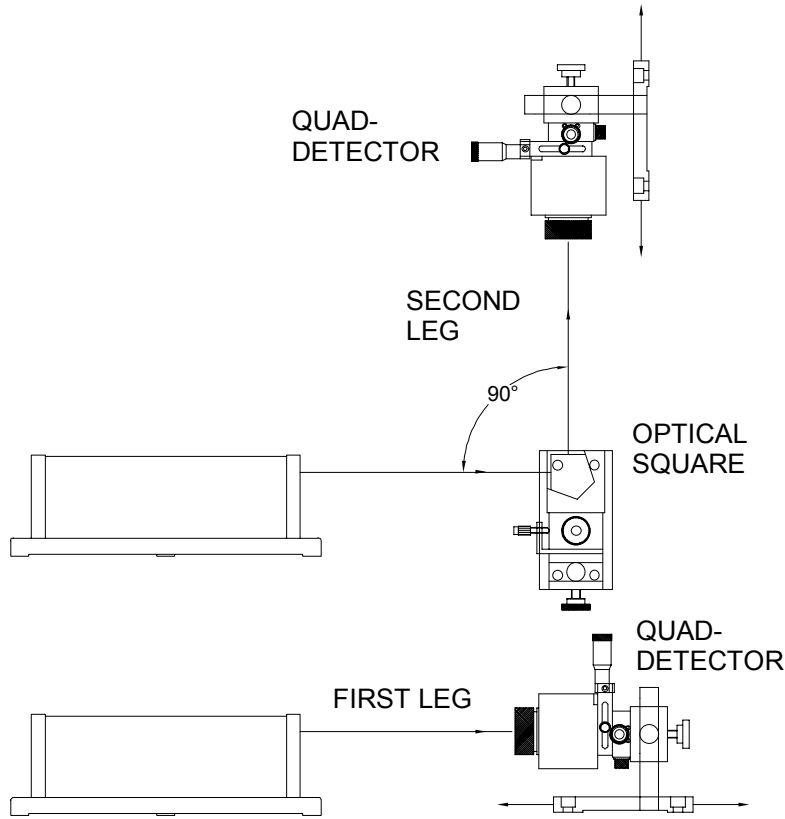


FIG. 10-5 SQUARENESS MEASUREMENT SETUP

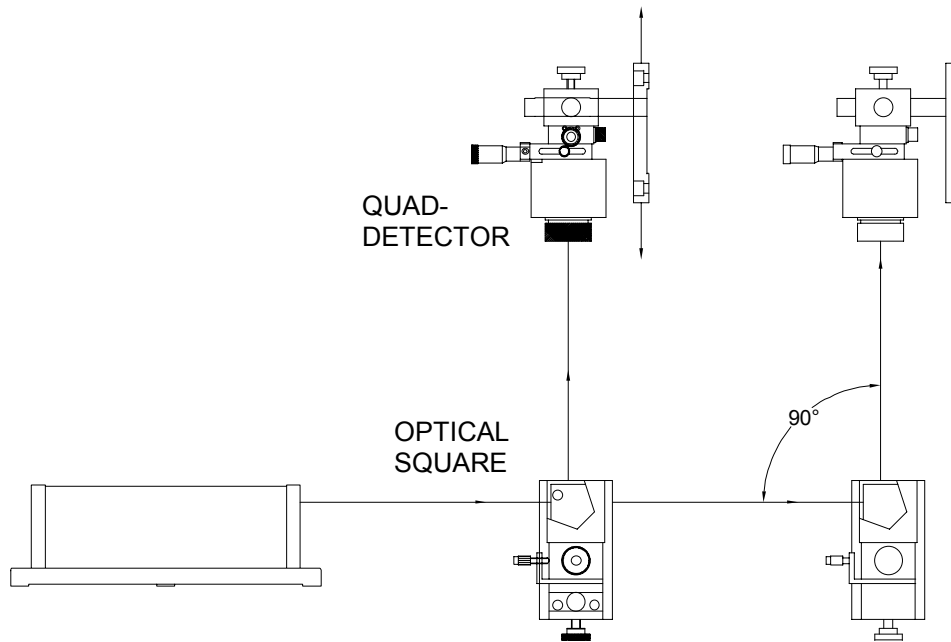


FIG. 10-6 PARALLELISM MEASUREMENT SETUP

10.5.4 Alignment Procedure

Mount the laser head and quad-detector for the initial leg. Move to the point of closest approach. The distance between the laser head and the quad-detector should be as short as possible at this point, but allow sufficient clearance to prevent inadvertent contact between them.

Use the X-Y stage on the quad-detector of machine motion to center the laser beam approximately in the quad-detector window. Press X and Y RESET buttons on the display module to show the quad-detector Horizontal and Vertical straightness readings in inches. (See appendix C for a description of display module modes.) If these buttons have not been pressed since the unit was powered up, the proper display should be produced by holding down the X RESET while pressing the Y RESET once. If the quad-detector is not properly connected to the processor, the readings will not appear until the connection is made. Once in the quad-detector display mode, pushing the Y RESET button will cycle through quad-detector display options. Pressing Y RESET three times will show the quad-detector straightness outputs in inches with 4, 3, and 5 digits shown after the decimal point upon each push. Pushing the Y RESET again will display four readings representing current outputs from the four quad-detector sections. Pushing Y RESET now will toggle the straightness outputs to millimeters with 4, 3, and 5 digits shown after the decimal point upon each push. Pushing Y RESET will display the four current outputs again, followed by a repeat of all the modes just described.

As an alternative to the procedure just described, the software can be used to set the display to show the quad-detector straightness outputs in inches. This can be done by following the software instructions for a measurement under the squareness program.

With the displays showing Horizontal and Vertical straightness readings in inches, use the X-Y stage or machine motions to adjust both channels to be close to zero, within ± 0.001 inch. Verify that when the quad-detector center moves below the laser beam center, the Y display shows positive deviation, and that when the quad-detector center moves to the right of the laser beam center, (facing the quad-detector from the laser head), the X display shows positive deviation. The quad-detector should have arrows printed on its face corresponding to the motion directions just indicated. If your quad-detector does not have these arrows printed on it, you should mark the directions for +X and +Y motion for reference use when answering questions posed by the software.

Now move to the point of furthest distance between the laser head and quad-detector. Without changing the X-Y stage or machine motion in axes other than the primary axis being moved, adjust the laser beam angle (using the

adjustment screws on the 90° beam bender) to produce near zero readings on both the X and Y display windows.

Go back to the point of closes approach. If the reading magnitude of either the X or Y display is greater than 0.001, readjust the X-Y stage or use machine motion to bring both channels to near zero readings. Again, go to the furthest point and readjust the beam angle to again zero both channels. Repeat this procedure until both channels read less than 0.001 inch at both the closest approach and furthest point.

You are now ready to take straightness data, or data for the first leg of the squareness or parallelism measurement. See section 10.6 below.

10.5.5 Alignment Procedure for Optical Square

For subsequent legs of squareness or parallelism measurements, first position the optical square with the glass end piece facing the laser head, and the glass side piece facing the direction of the second or other leg, as show in Fig. 10-5 and 10-6. Be sure that the small adjustment screws are in position to rotate the optical square around the axis of the incoming laser beam, so that the outgoing beam can be adjusted across the center of the quad-detector as it is positioned in the second or other leg. The optical square may have these adjustment action is the same regardless of their position.

Temporarily move the quad-detector out of the way or block the path between the optical square and the quad-detector, to eliminate reflections from the quad-detector face from interfering with the alignment procedure to be described. This procedure is necessary for the use of optical squares which do not have a non-reflective coating in good condition, to prevent angle dependent discrepancies from affecting squareness and parallelism measurements.

The optical square must be mounted in a fashion so that it can be rotated over several degrees in the plane defined by the incoming and outgoing laser beams. In certain mounting positions, an adapter which rotates the mounting post 90° is needed for achieving this adjustment capability. The base may be mounted directly to the machine bed or to a magnetic holder, and the adapter may be rotated around the first post and the optical square around the second post to achieve the alignment capability required.

Set up the optical square so that the incoming laser beam strikes the approximate center of the glass end piece, with the end piece approximately perpendicular to the beam. Tilt the optical square back and forth slightly and look for the front surface reflection on the face of the laser head. Assuming that a 90° adjustable mirror is mounted on the laser head, you should be able to see the reflected spot shining on the laser head face through this mirror. Verify that the reflected spot you see is from the front surface of the optical square by

observing the correlation of the spot movement with the slight tilting motions of the optical square. Adjust the optical square angles so that the reflected spot exactly lines up with the laser beam output aperture.

Now adjust the optical square a few degrees in each direction, in the plane containing both the incoming and outgoing beams. As the optical square is rotated, notice that the reflection from the optical square, which appears as a single spot very near the beam output aperture, diverges into two spots as the adjustment angle increases away from the aperture. One is the front surface reflection, and the second spot is the reflection from the exit face of the optical square.

Find the angular adjustment point where the two beams are just separated. If the optical square is far from the laser head, the point at which the two spots become completely separated may be off the laser head face. In this case, you may need to hold a business card or other piece of paper near the laser head to view the spots as the optical square is rotated. Either way, find the adjusted angle at which the two spots just become separated.

Please note, this rotation must always be made in the plane containing both the incoming and outgoing beams.

At this point, the rotational adjustment controlled by the two small screws on the optical square needs to be made. This is done by first moving the machine to the point of closest approach between the optical square and the quad-detector. As before, this distance should be as short as possible without making contact between the machine and quad-detector. If the beam path between the optical square and the quad-detector had been blocked as suggested earlier to prevent interference from the beams reflected from the quad-detector, remove the blocking device so that the beam can illuminate the quad-detector.

At this closest approach point, adjust the X-Y stage or machine motion to achieve readings close to zero on both the X and Y displays. Now move the machine to the point of furthest separation between the optical square and quad-detector.

At this furthest separation point, carefully adjust the two small screws (first slightly loosen the locking screw which locks this motion) to bring the beam back to the approximate center of the quad-detector. You will notice that adjusting the small screws directly controls one of the display windows, while having only a small effect on the other channel. If it is not clear which channel is being controlled by the small screw adjustment mechanism, they can be adjusted over a wide enough angle to change the readings on the controlled axis as the way from one extreme to the other. Once you determine which display window is controlled by the small screw adjustment, use the screws to bright that display reading close to zero. The other display channel cannot be brought exactly to

zero by the small screw adjustment, because it represents the squareness or parallelism being measured.

Move back to the closest approach point and re-zero both displays using the X-Y stage or machine motions without adjusting the two small screws on the optical square. Then move back to the furthest separation point and repeat the adjustments of the previous paragraph. This procedure may need to be repeated several times until the reading magnitude on the channel controlled by the small screws remains under 0.001 inch at both the closest and furthest point.

10.5.6 Straightness Measurement

After completing the alignment, you are ready to take data for straightness or for the first leg of squareness or parallelism.

Follow the directions of the software to set up the increment size and number of points per run, and answer the questions of laser beam axis and direction, laser head or quad-detector moving, direction of motion, and starting position.

Next, select one of four choices to assign machine axis directions to the two quad-detector channels, X and Y. This selection is to be made by noting the arrow labels on the face of the quad-detector and selecting the positive machine axis directions which correspond to the X and Y arrow labels. Before the choice menu appears, the software has already been given the information on which is the movement axis and the direction of motion. It prepares four options for the non-movement axes where the straightness data is to be taken, assuming a right handed coordinate system, so that one of the four choices should fit any combination of mounting configurations. Choose the one where the quad-detector arrows correspond with positive machine axis directions. If your system is left-handed, there may not be a choice with exact correspondence. In that case, choose a configuration where only one axis has a reversed sign, note the choice made, and make a sign correction afterward if necessary.

For straightness, the measurement is now complete, and the data can be plotted or printed as required. Follow instructions of the software.

For squareness or parallelism, see section [10.5.4](#) for alignment of the optical square.

10.5.7 Squareness Measurement, Second or Subsequent Leg

After the alignment procedure of sections 10.5.4 has been completed, take the actual measurement data as directed by the software. Answer the questions posed by the software according to the direction of the arrows on the quad-detector as described above. After taking the first and second leg data, the software will automatically calculate the overall squareness or parallelism and report it, as described in the following paragraphs.

For a 3-axis machine, there are 3 orthogonal planes, namely XY, YZ, and XZ planes, as shown in Fig. 10-2. The squareness is measured within those planes, in the quadrant between the axis pairs defined to be the positive going directions from the origin. A deviation from perfect squareness is specified by a small angle which is positive if the angle between axes is greater than 90° , or negative if the angle is less than 90° . This angle is defined between the positive going (from the coordinate system origin) axes. The software computes this angle in radians, and reports it as an integral number of μrad and in arc seconds.

Notice that if the squareness deviation angle is positive, (angle between the axes $> 90^\circ$), then the angle between the same axes in the quadrant where both axes go negative from the origin is also greater than 90° . But in the two quadrants where one axis goes negative while the other goes positive, the squareness deviation will be of opposite sign, and in the situation just described the angle would be less than 90° . This concept is important because measurements may be made in any of the 4 quadrants where the sign of the squareness deviation is opposite from the "first" quadrant where both axes are positive going.

The software is setup to ask the operator a number of questions which will resolve the issue of the deviation polarity. The operator is asked to specify the axis and direction where the laser beam is pointing, whether the quad-detector or the laser head is the moving part and the questions are answered properly, the software will calculate the squareness deviation for the proper quadrant.

10.6 Software Description

See [Section 7.6](#) or the software manual.

10.7 Accuracy and Error Sources

Potential straightness measurement errors are unlike those for linear or angular measurement. The basic error sources are: 1, straightness of the laser beam; 2, linearity and skewness of the quad-detector; 3, accuracy of the optical square; and 4, thermal expansion of the machine. The laser beam is a straight line in vacuum. However, in air, the speed of light or index of refraction is a

function of air temperature and atmospheric pressure. A temperature gradient will bend the laser beam, and air turbulence will randomly steer the beam. Both of these are caused by temperature differences in the air. To remove these differences, you should remove their sources (e.g. open doors, lamps, exhaust fans, motors, etc), and mix the air thoroughly along the measurement path, using a large fan. The linearity and skewness of the quad-detector is part of the detector accuracy described in the specifications (Section 10.3). The accuracy of the standard optical square is 5 arcsec. A more precise optical square is also available. The thermal expansion of the machine or optics is very difficult to estimate. These effects can be minimized by letting the machine and optics reach thermal equilibrium before taking a measurement. Other error sources are machine vibrations and electronic noise pickup. These can be minimized by adequate fixturing, proper grounding and shielding.

10.8 Taking a Measurement

10.8.1 Straightness Measurement

1. Decide which axis you are going to measure, from which 'starting' point to which 'end' point, and the increment per stop.
2. A typical set up to measure the horizontal and vertical straightness of X-axis and a vertical machine center is shown in [Fig. 10-7](#). Similar measurements for Y-axis and Z-axis are shown in [Fig. 10-8](#) and [10-9](#). Make sure all cables are firmly attached to the bed so that the movement of the bed will not disturb the laser head or the quad-detector. The above setup is preferred when both straightness and squareness need to be measured.
3. The spindle mount as shown in [Fig. 10-10](#) is 'more convenient' when only X-axis and Y-axis straightness need to be measured.
4. Setup the LDDM™ by following the instructions in [Section 10.5](#). After aligning the quad-detector, you may manually record the data or use a portable computer to record the data.

5. Move the quad-detector close to the laser head to get 0 on the X and Y displays. Enter the reading.

Move the quad-detector along the Axis of interest by about one inch and enter the X and Y value.

Similarly, move the quad-detector all along the length of the object; enter the values of X and Y displays at convenient points.

By comparing the values you can determine the straightness of the travel.

6. If you are using a portable computer, boot the computer and load the appropriate software by following the instructions in the software manual.
7. All the software is menu-driven; follow the instructions on the monitor.
8. Move the machine to the 'starting' point and press "c" to record the data.

Move to the next stop and press "c" to record the data.

9. Continue step 8 until the 'end' point.
10. Both vertical and horizontal straightness may be plotted on a monitor or by a printer. (See the software manual).

10.8.2 Squareness Measurement

1. For a 3-axis machine, there are (3) orthogonal planes, namely XY, YZ and XZ planes, as shown in [Fig. 6-2](#). The squareness is measured within those planes.
2. A typical setup for the measurement of squareness is the XZ plane, as shown in [Fig. 10-11](#). Squareness in other planes is shown in [Fig. 10-12](#) and [10-13](#).
3. Make two readings along the X-axis and calculate the angle.
4. Mount the optical square and make two readings along the Z-axis and calculate the angle.
5. The out of squareness is the sum of these two angles, $\theta_1 + \theta_2$.
6. For more accurate measurement, make sure both X and Y readings are less than 0.01 inch.

7. Squareness in XY and YZ planes is measured in a similar way (see Figs. 10-12 and 10-13).

10.8.3 Parallelism Measurement

1. Use an optical square to generate parallel reference lines as shown in Fig. 10-6.
2. The measurement is limited to the parallelism within the plane. Skewness cannot be determined by this measurement.
3. Align the laser beam to be parallel to Y_1 . Move the optical square and measure the deviations at two points along Y_2 . The angle between Y_1 and Y_2 is $(\Delta X_1 - \Delta X_2)/D$, where ΔX_1 and ΔX_2 are deviations at locations 1 and 2 respectively, and D is the separation between location 1 and location 2.

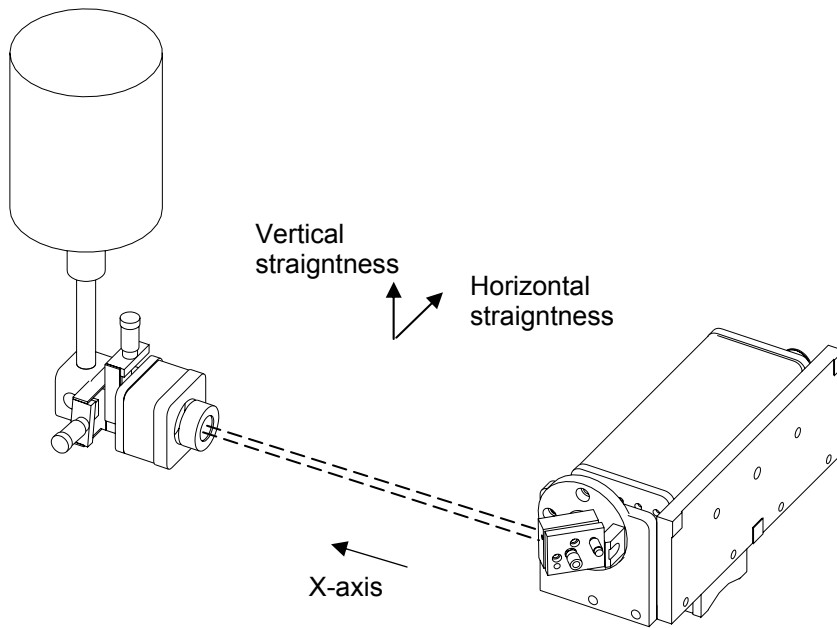


FIG. 10-7 HORIZONTAL AND VERTICAL STRAIGHTNESS OF X-AXIS

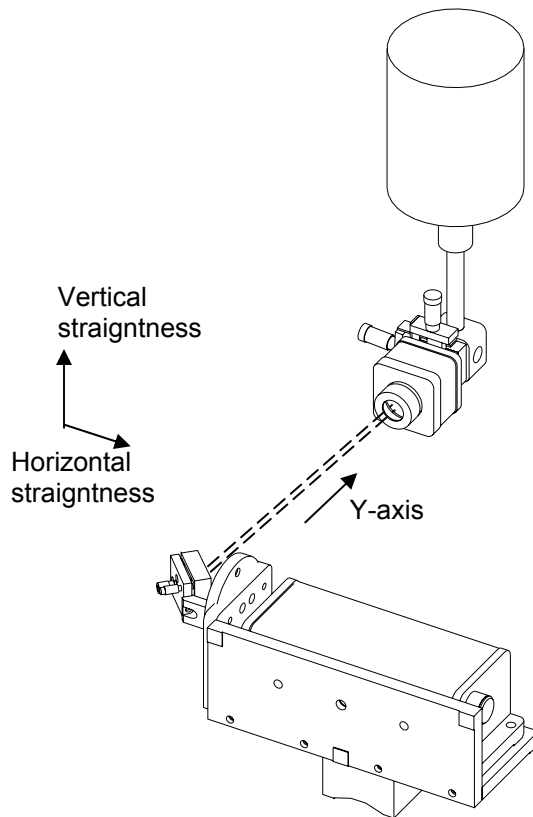


FIG. 10-8 HORIZONTAL AND VERTICAL STRAIGHTNESS OF Y-AXIS

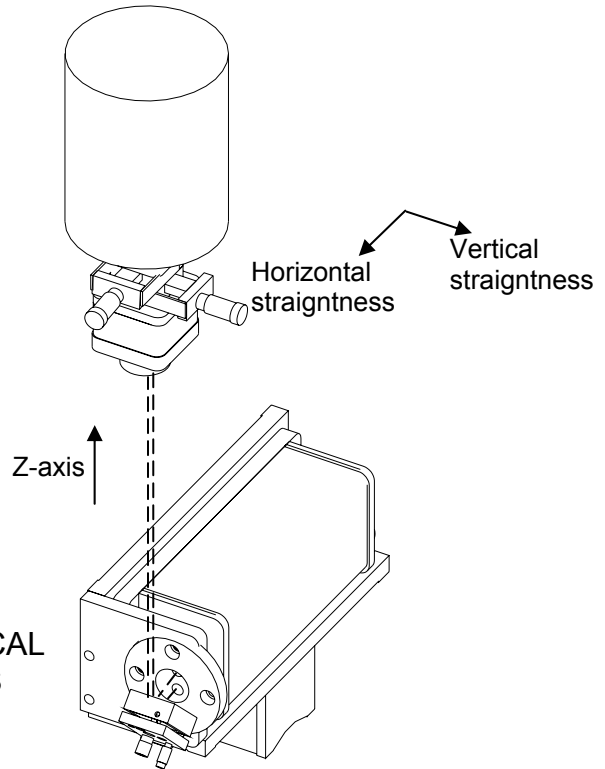


FIG. 10-9 HORIZONTAL AND VERTICAL STRAIGHTNESS OF Z-AXIS

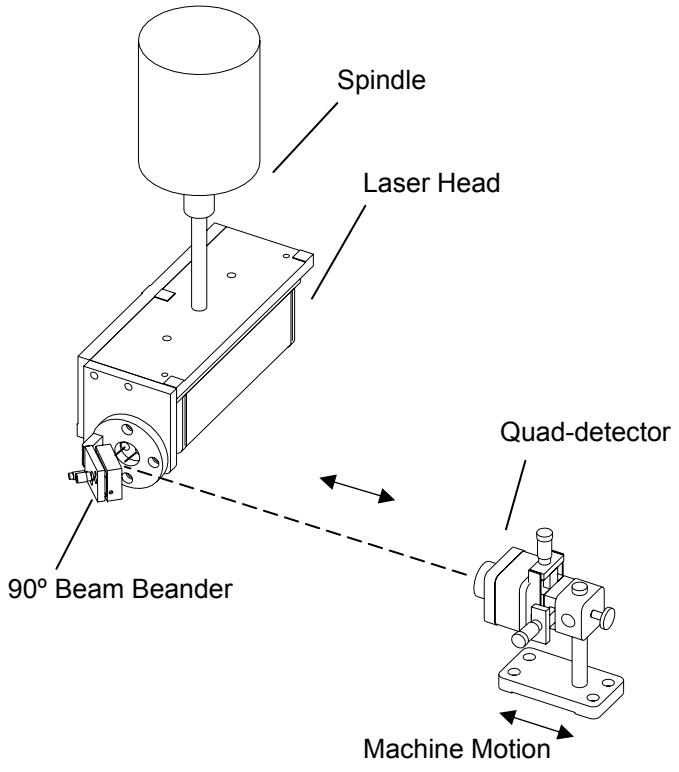


FIG. 10-10 SPINDLE MOUNT

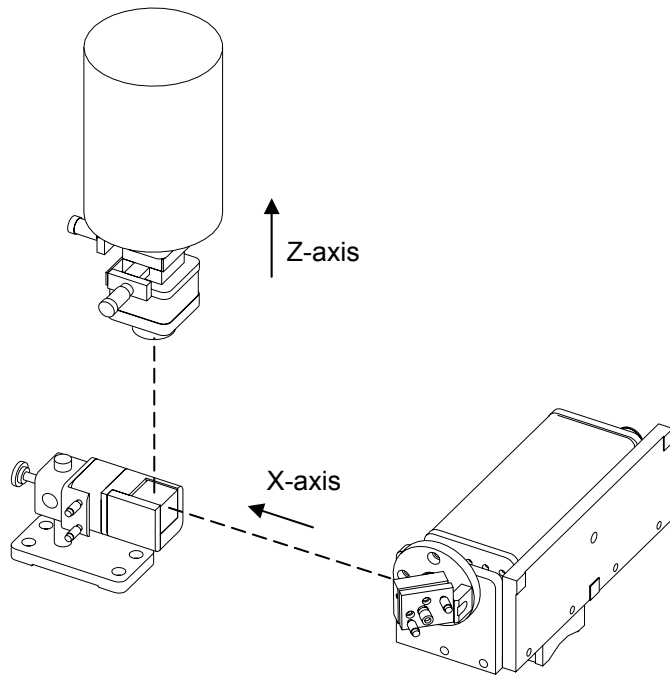


FIG. 10-11 SQUARENESS IN X-Z PLANE

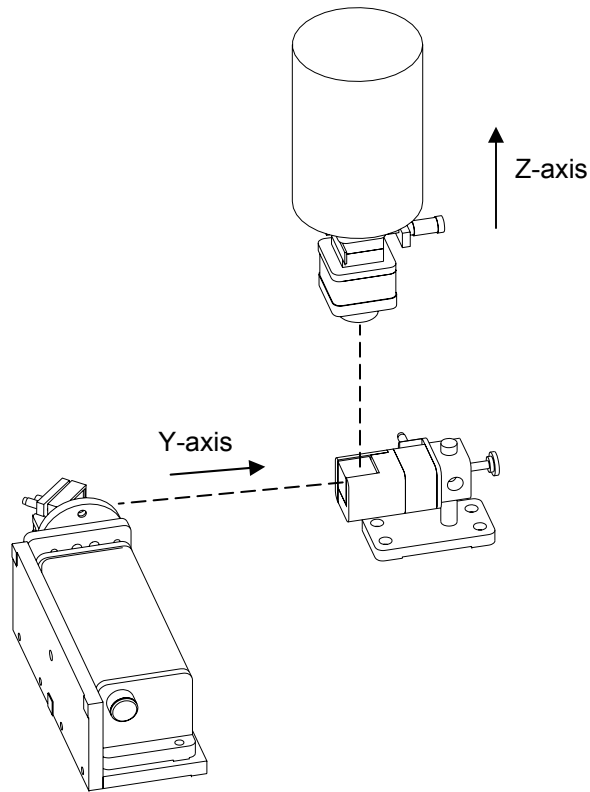


FIG. 10-12 SQUARENESS IN Y-Z PLANE

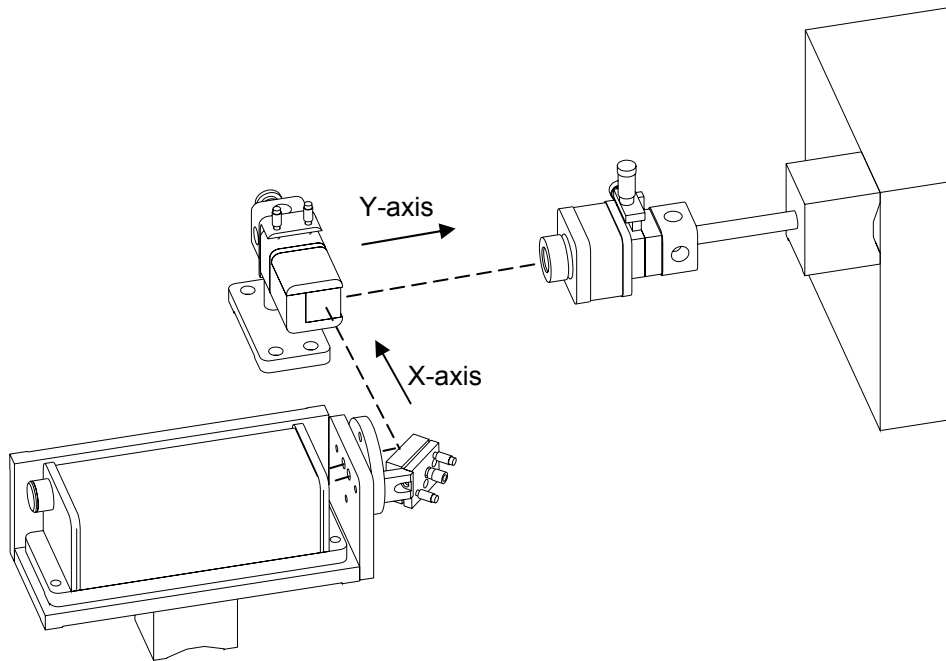


FIG. 10-13 SQUARENESS IN X-Y PLANE

11.0 Velocity, Acceleration, & Vibration Measurement

11.1 Introduction

The vibration sensor package is a versatile, non-contact laser precision sensor for displacement, velocity and acceleration measurement. It is designed to capture transient phenomena such as vibration or acceleration. It performs as an oscilloscope for mechanical vibrations. Due to its high sensitivity, high data rate and high signal to noise ratio, acceleration can be obtained by differentiating the displacement data twice without introducing excessive high frequency noise.

With the user friendly software and a PC/AT computer, the system can collect and analyze vibration data at a sampling rate up to 800,000 data points per second. Software for plotting displacement, velocity, acceleration, power spectra density, shock response spectra, etc. is also available. The vibration sensor package is an important tool for the study and understanding of dynamic properties, such as the vibration and resonance of a mechanical structure, the settling time of a precision stage, the vibration spectrum of a spindle and the resonance frequency and damping of an optical table.

11.2 Hardware Required

The basic hardware and software requirements for vibration measurement are the following:

Hardware:	Single-aperture laser head	L-102
	Ø1/2" retroreflector with mount	R-103
	Processor module with IBM PC port and extended resolution	P-101-HR1
	Display	D-101
	Cable set	LD-21
	IBM PC interface card, 400 kHz	IPC1-400
	Option:	IBM PC compatible computer
Accessories:	Carrying case	L-20
	90° beam bender	LD-37
Software:	catch/view software	S-106S
	analysis (differentiation and FFT)	S-107

11.3 Operating Specifications

<u>Accuracy:</u>	For displacement measurement the accuracy is \pm ppm (see section 7.3 for environmental effects). For velocity and acceleration measurement the accuracy is determined by the clock which is used to control the sampling rate. Typical accuracy is 0.1% for velocity and 0.2% for acceleration.
<u>Sensitivity:</u>	Displacement: 2.5 nm (0.1 μ in) Velocity: 0.1 μ m/sec Acceleration: 0.1 μ m/sec ²
<u>Maximum range:</u>	Displacement: up to 2.5 m Velocity: up to 2.5 m/sec Acceleration: up to 100,000 g
<u>Sampling Rate:</u>	6.25 kHz to 800 kHz (see Fig. 11-1 , Range Nomograph)
<u>Data size:</u>	64 K x 2 bytes per record
<u>Trigger mode:</u>	post or pre-trigger
<u>Power:</u>	100 VAC, 60 Hz
<u>Operating environment:</u>	Temp: 60° to 90°F Altitude: 0 to 10,000 ft. Humidity: 0-95% (non-condensing)

11.4 Reference Material

[Appendix F](#), IBM PC Interface Card
[Appendix D](#), Description of Interfaces

11.5 Installation and Alignment

11.5.1 Important considerations

1. Ensure that all cables are firmly connected before connecting power cable and switching the power switch on.
2. Vibration and loose connections must be minimized by proper mounting.
3. Select the appropriate optical configuration for different frequency response and measurement requirements.

11.5.2 Installation

For vibration measurement, the resonance frequency of the retroreflector must be higher than the frequency to be measured. The resonance frequency of a simple mass, m , and a spring constant, k , is proportional to the square root of k/m . Hence for higher frequency response, you need to use a smaller retroreflector (smaller mass) and stiffer mounting (larger k). There are three types of optical configurations for different frequency responses and applications.

LDDM Vibration Sensor

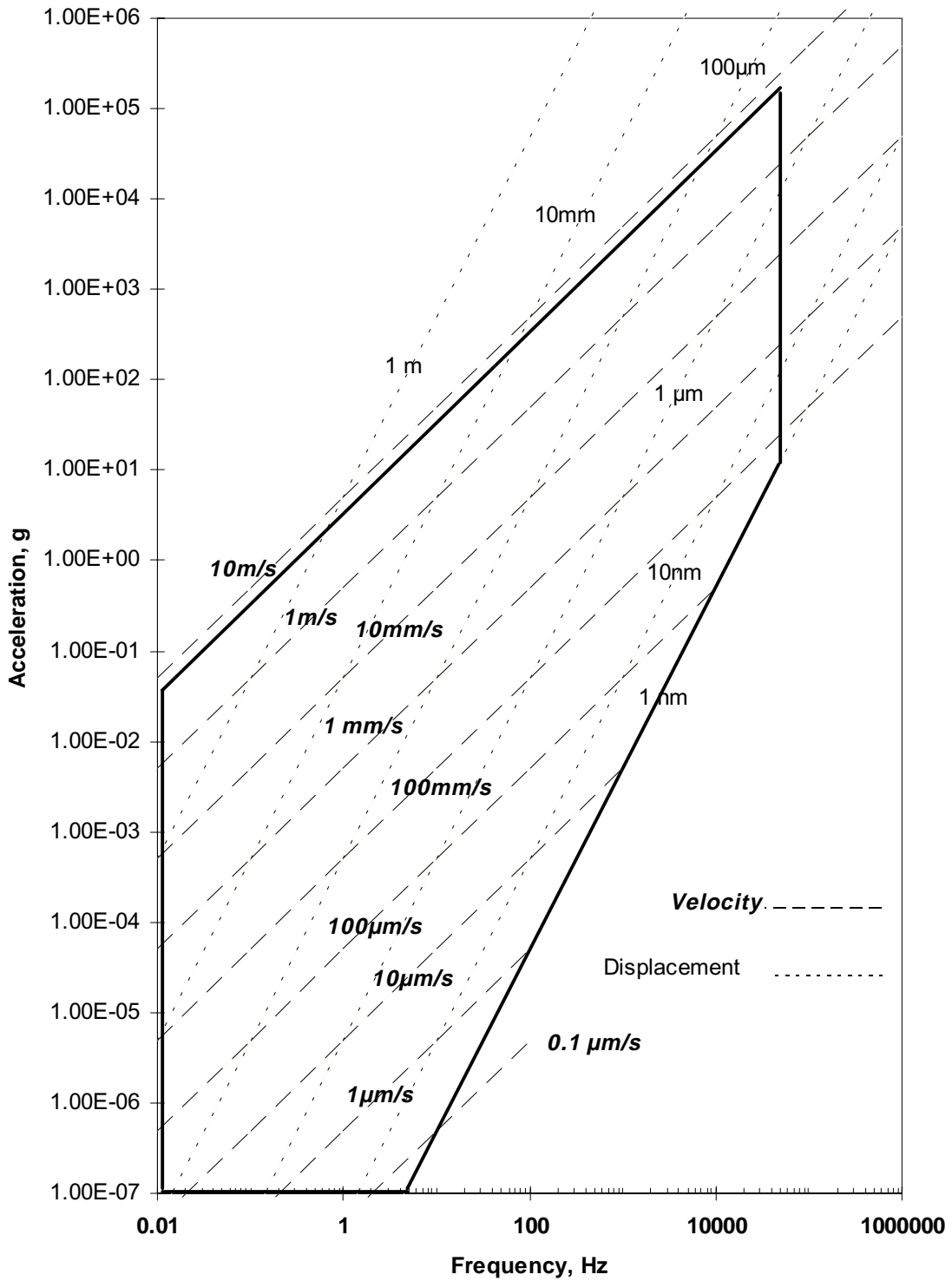


Fig. 11-1 Range Nomograph

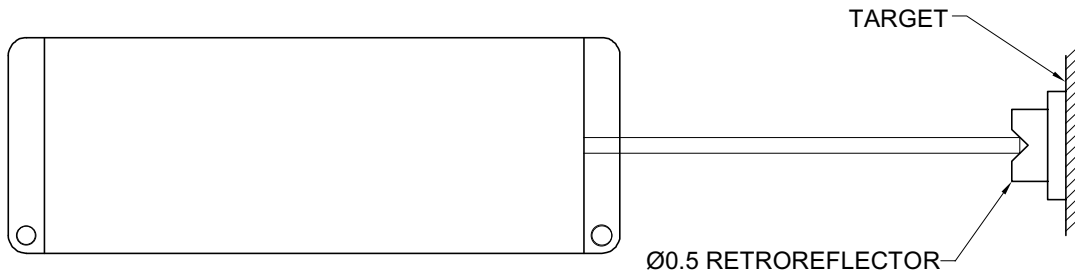


FIG. 11-2 SINGLE-APERTURE LASER
AND 0.5" RETROREFLECTOR

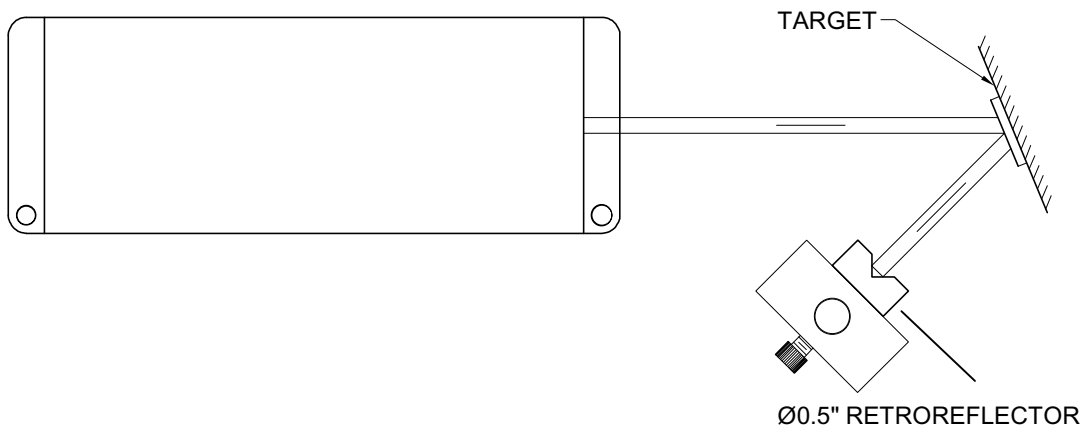


FIG. 11-3 DOUBLE-PASS OPTICAL
ARRANGEMENT

1. For low frequency response, up to 100 Hz.
 - A. You may use a single-aperture laser head and a $\text{Ø}1/2$ " retroreflector tightly secured to the target as shown in Fig. 11-2.
 - B. You may increase the frequency response to more than 10 kHz by using a $\text{Ø}1/8$ " retroreflector and proper mounting. Typical applications are mechanical vibrations and settling time of slides or beds.
2. For median frequency response, up to 100 kHz, you may use a single-aperture laser head and a small ($\text{Ø}1/4$ ") flat mirror as a target. However, the alignment is very critical (within 30 arcsec). For easy alignment, you may use a double-pass arrangement as shown in Fig. 11-3. Here the alignment is very easy (within 1°). The limitation is that the maximum displacement range is a few mm (for very small angle, this may extend to a few cm). The advantages are easy alignment and twice the displacement sensitivity. Typical applications are parashock and high-frequency shakers, mechanical vibrations, spindles, structures, optical tables, etc.
3. For very high frequency response or small target, you may use a single-aperture laser head and a lens to focus the laser beam to a focal point at the target as shown in Fig. 11-4. Here the focal length is about a few inches and the focal spot is less than one thousandth of an inch. The target can be any metallic diffusive or speculative reflector. Typical applications are extremely high frequency and non-contact vibration measurement, such as the magnetic head of a disk drive, ultrasonic wire bonder, etc.
4. For a target with large rotational and lateral motion, it is possible to use the double-pass optical arrangement as shown in Fig. 11-5. Here the target is a large retroreflector which can be rotated and laterally moved without loss of alignment. Also, the displacement measured is not sensitive to the rotational or lateral motion.

11.5.3 Description

1. Select the appropriate optical configuration, sampling rate and trigger mode.

2. For 800,000 data/sec sampling rate, the recording time is only 80 msec. It is important to synchronize the trigger with the event or use the displacement trigger.
3. A rule of thumb for good data analysis is that you need at least 10 data points per cycle and at least 10 cycles per record.
4. Check the range nomograph (Fig. 11-1) and make sure the measurement is within the range.

11.5.4 Alignment Procedure

For long travel, see alignment procedure in sec 7.5.4. For a double-pass arrangement (Fig. 11-3), first cement the small flat-mirror to the target, then aim the laser beam at the flat mirror. Make sure the reflected beam is near the laser head. Set the retroreflector at the beam center such that the returned beam enters the aperture on the laser head. Check the intensity reading and make sure it is above threshold (larger than 4 bars) over the whole travel of the target. For the non-contact arrangement, the total range of travel is only a few microns, and the alignment is critical. First, secure the focal lens (typically 1.5 to 3 inches focal length) in front of the single-aperture, then measure the focal length by moving a piece of paper in front of the laser beam. At the focal point, the focal spot is the smallest or brightest. Mount the laser beam with the lens in front of the target and move the laser head back and forth such that the target is exactly at the focal point. Select a spot with more glint or more light reflected to the laser head. Check the intensity reading and make sure it is above threshold.

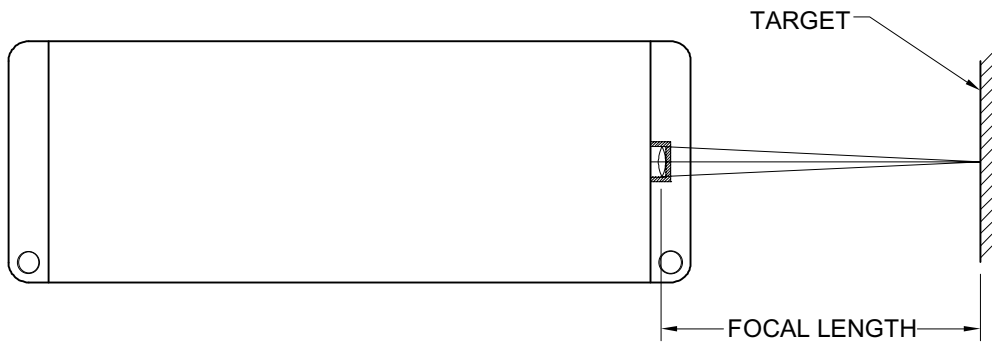


FIG. 11-4 NON-CONTACT MEASUREMENT WITH FOCAL LENS

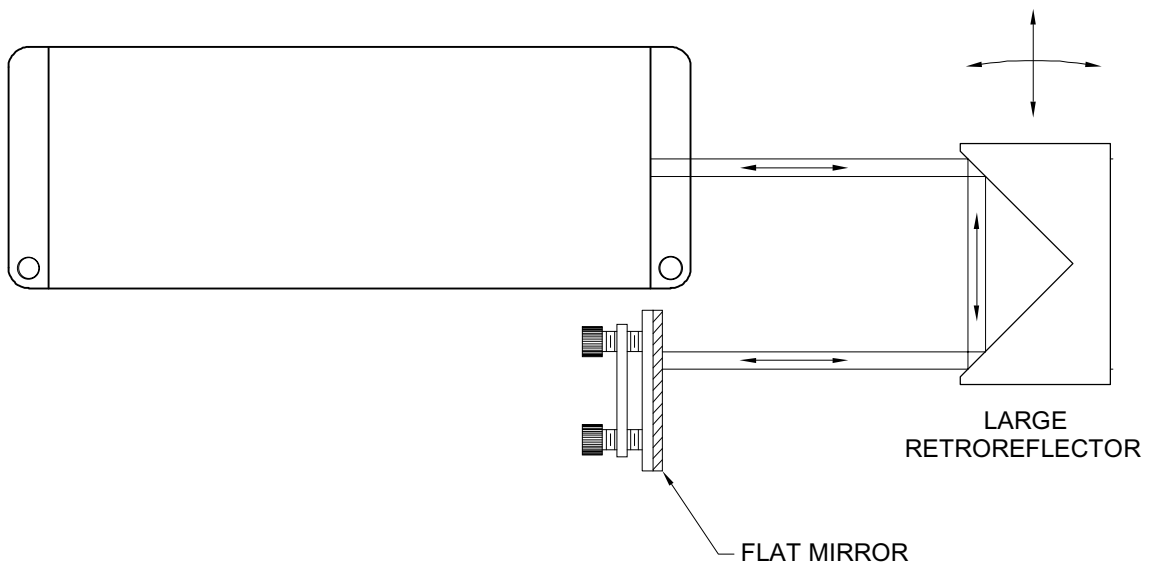


FIG. 11-5 OPTICAL ARRANGEMENT WITH LARGE TOLERANCE FOR ROTATION AND LATERAL MOVEMENT OF RETROREFLECTOR

11.6 Software Description

The basic software programs are "CATCH" and "VIEW". Depending on the interface card, up to 3 channels of data can be collected simultaneously. The sampling rate is selectable from 6,250 data/sec to 800,000 data/sec. The data is stored in binary form. Each data is 2 bytes and each record is 64,000 data points or 128,000 bytes. After the data is collected, a "VIEW" program can be used to view the data as a graph. There are two cursors for time and two cursors for amplitude. You may zoom in or zoom out to see details or global features. To analyze the data, an analysis program could be used to obtain velocity and acceleration by differentiation. The power spectra density, fast Fourier transform and shock response spectra, can be calculated. Data can also be filtered (Band Pass Filter) and plotted.

11.7 Accuracy and Error Sources

The major error source is the transfer function of the retroreflector. Make sure that the resonance frequency of the retroreflector is much higher than the frequency of interest. The accuracy for displacement measurement is very high, a few ppm. The errors for velocity and acceleration measurement are clock error, numerical differentiation error and cosine error.

11.8 Taking a Measurement

The LDDM™ vibration sensor can be applied for a wide range of applications. For example, it may be used for 1, the calibration of transducers, linear variable differential transformers (LVDT), accelerometers and proximity sensors; 2, the measurement of dynamic properties such as settling time, resonance frequency and damping of linear slides, XY-stages, spindles and carriages; 3, monitoring the performance of disk drive servo-track writers, printed circuit board drilling machines, and wire bonders; and 4, studying impact dynamics, collision and damping, impulse response and modal analysis. The following sections are examples to illustrate the above applications.

11.8.1 Vibration of a Linear Slide

To minimize the effect of ground vibration, both the precision slide under test and the LDDM™ vibration sensor are mounted on a vibration isolated table. A half-inch retroreflector is mounted on the moving stage and the laser head is mounted on the table near the stage. The stage is driven by a step motor at 0.5 in/sec speed and 0.5 in/sec² acceleration. Each increment is 50 μin (1.25 μm). The vibration sensor is set at 80,000 data/sec. A typical result is shown in Fig. 11-6. Here the over-shoot, oscillations, and damping are clearly visible. The power spectra density, obtained by differentiating the displacement data twice and then using the Fast Fourier Transform,

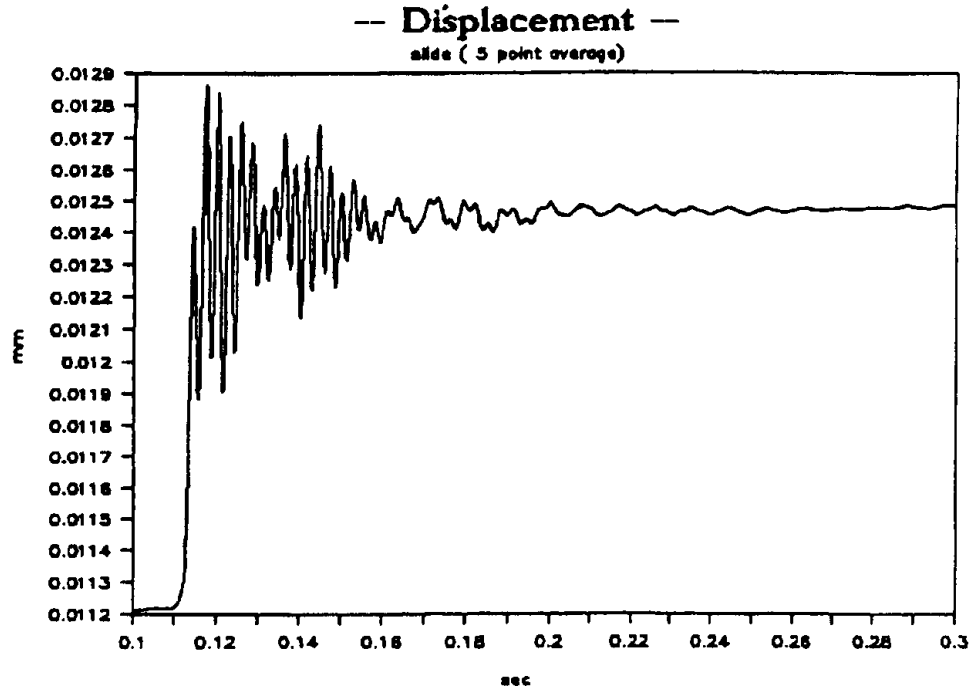


FIG. 11-6 TYPICAL DISPLACEMENT vs. TIME CAPTURED BY THE VIBRATION SENSOR

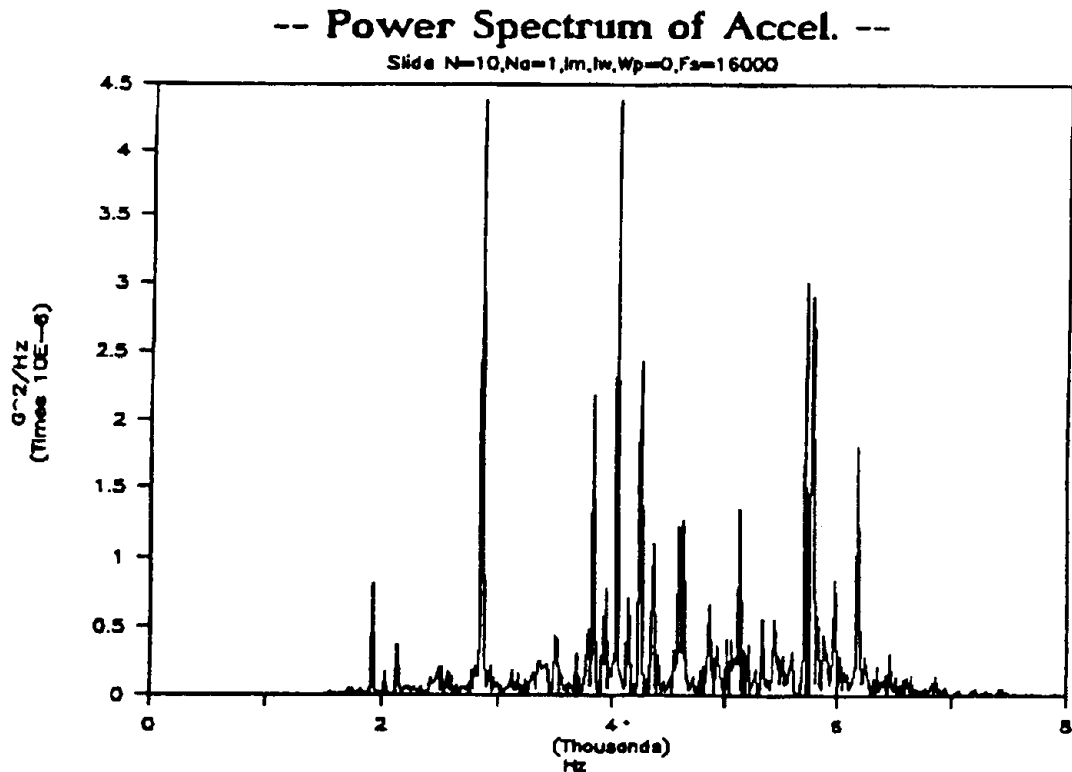


FIG. 11-7 POWER SPECTRAL DENSITY OF ACCELERATION OBTAINED BY DIFFERENTIATING DISPLACEMENT DATA TWICE

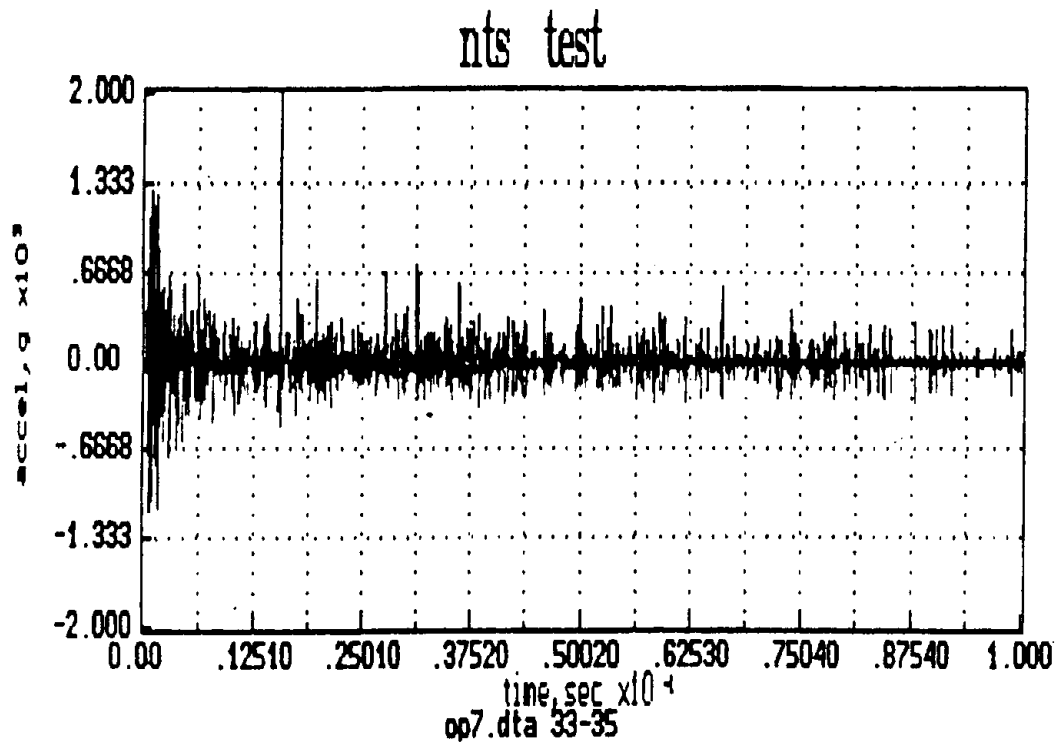


FIG. 11-8 ACCELERATION HISTORY DURING PYROTECHNIC SHOCK

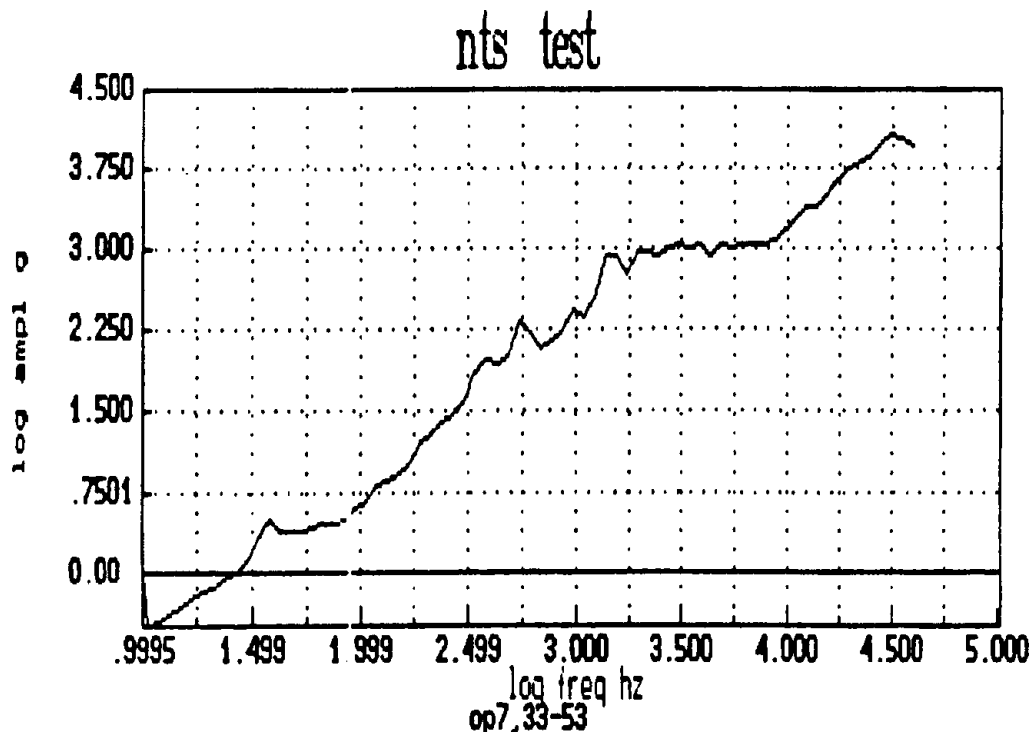


FIG. 11-9 ACCELERATION SHOCK RESPONSE SPECTRA OF PYROTECHNIC SHOCK

FFT, is shown in Fig. 11-7. The measured settling time is 50 msec and the oscillation frequency peaked at 460 Hz.

11.8.2 Vibration of a Pyrotechnic Shock

The vibration of a pyrotechnic plate under explosive loading is measured by an LDDM™ vibration sensor. Several accelerometers and a retroreflector are mounted together on the plate. The laser head, processor module and computer are set on a table about 6 ft from the plate. A typical acceleration history recorded by the LDDM™ vibration sensor is shown in Fig. 11-8, and the corresponding shock response spectra is shown in Fig. 11-9. Please note that very high peak accelerations and high frequency responses have been obtained.

11.8.3 Vibration of an Ultrasonic Wire Bonder

To measure the vibration of an ultrasonic wire bonder, the configuration shown in Fig. 11-4 is used. The focal length of the lens is 50 mm. The resonance frequency of the transducer is 60 kHz. The laser beam can be focused on the transducer horn or the capillary. A typical measured displacement is shown in Fig. 11-10. The displacement can be measured to a resolution of a few μm .

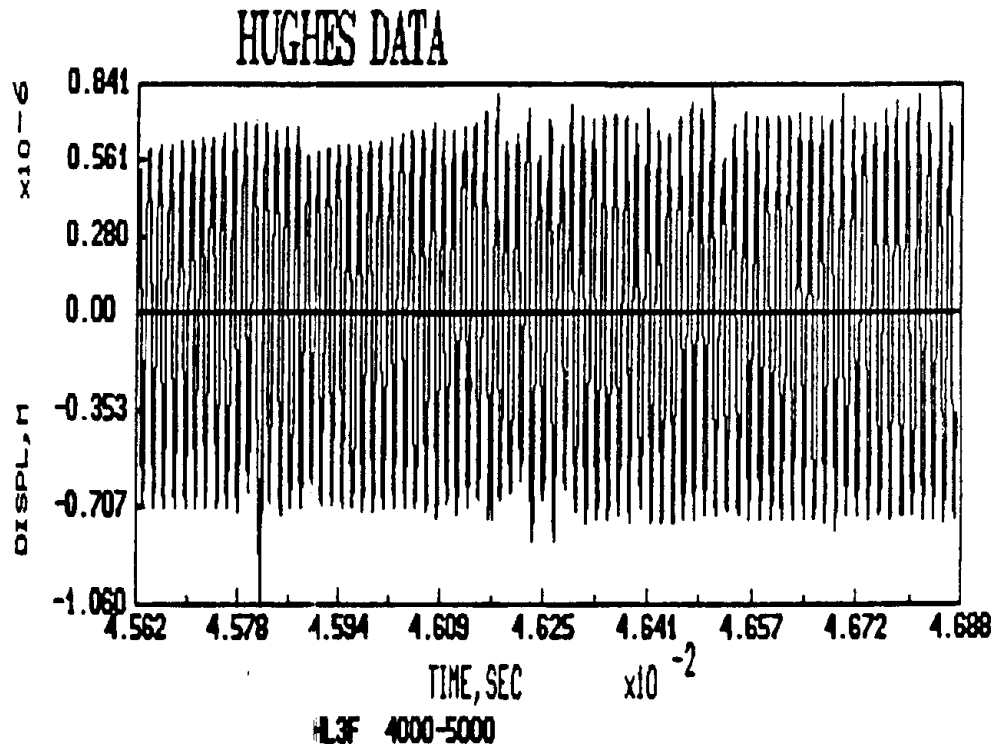


FIG. 11-10 60 kHz OSCILLATION OF ULTRASONIC TRANSDUCER HORN

11.8.4 Velocity and Acceleration of a Collision

The velocity and acceleration during a collision of a mass and a wall at a relative speed of 5 miles per hour can be measured by a LDDM™ vibration sensor. A retroreflector is mounted on a carriage of a vertical rail. A rubber stopper is then set on the bottom of the rail. The laser head is mounted on the top of the rail and aligned with the retroreflector. The carriage with a retroreflector is lifted to a height of 40 cm and released. The peak velocity may reach 3 meters/sec before hitting the rubber stopper. A typical displacement (before and after collision) is shown in Fig. 11-11a. The sampling rate is 100,000 data/sec. Differentiating the displacement data once obtains velocity and twice obtains acceleration. The results are shown in Figs. 11-11b and 11-11c. Here the first small deceleration is due to the foam rubber and the large deceleration and the rebound is due to the hard rubber. The variation in acceleration during the free-fall is due to the friction and oscillation of the carriage.

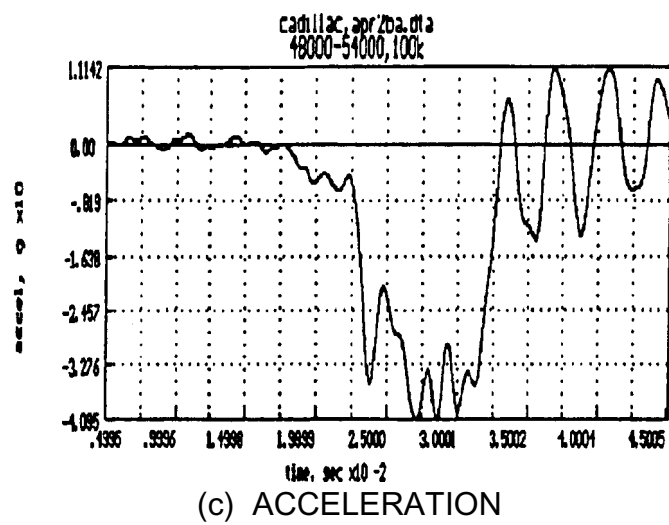
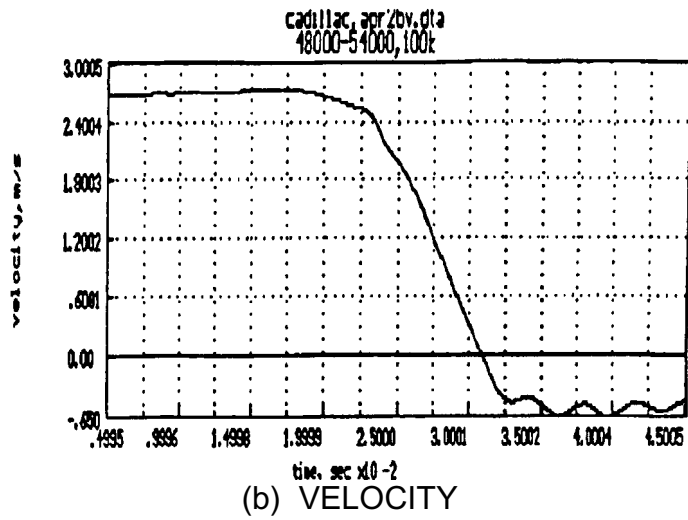
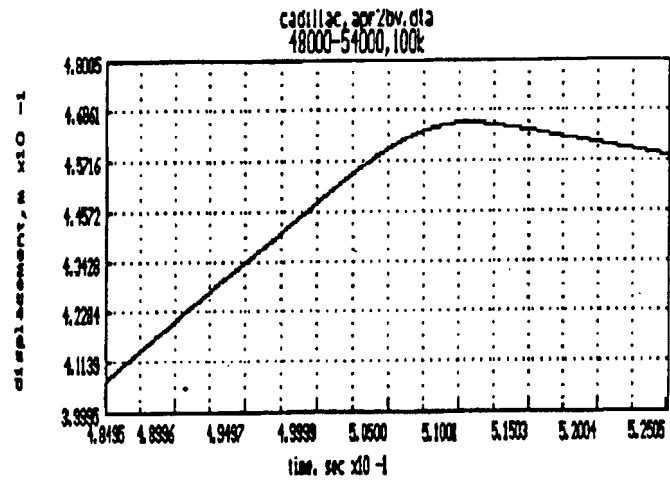


FIG. 11-11 DATA HISTORY DURING A COLLISION

11.9 Various Vibration Measurement Techniques

The LDDM™ is based on the principles of radar, the Doppler effect and optical heterodyning. The measured phase is directly proportional to the displacement. The velocity and acceleration can be obtained by differentiating the displacement data once and twice respectively. However, as compared to laser Doppler velocimetry (LDV), which measures the averaged frequency shift of the target motion, the measured average frequency shift from many scatter centers on the target is directly proportional to the velocity. The acceleration can be obtained by differentiating the velocity once and the displacement can be obtained by integrating the velocity once. The advantage of LDV is that no retroreflector is needed. The disadvantage is that the signal-to-noise ratio is rather low and long average time is necessary. Also, because of the Doppler ambiguity, there is a minimum frequency shift even if the velocity is zero. Hence it is more suitable for the monitoring of low-frequency vibration. A comparison of the LDDM™ vibration sensor, interferometer and LDV vibrometer is shown in Table 11-1.

The major features of the LDDM™ vibration sensor are:

1. High sensitivity and high frequency response,
2. Non-contact, no wire attached and minimum interference.
3. Large dynamic range, over 6 deca.
4. No calibration constant, no non-linear amplifier, no RC time constant and no ringing frequency.
5. Compact, portable and easy to set up.

Table 11-1 Comparison of the LDDM, Interferometer, and LDV

	LDDM™ Vibration Sensor	Interferometer	LDV Vibrometer
Laser Stability	10E-7	10E-7	10E-6
Resolution	1.2 nm	9.6 nm	1 μm/sec (minimum vel.)
Max. Speed	3000 mm/sec	10 mm/sec	100 m/sec
Data Rate	800K data/sec	4K data/sec	1K data/sec
Frequency Response	80 kHz	400 Hz	100 Hz
Signal-to-noise	High	High	Low
Ratio Alignment & Setup	Easy	Difficult	Difficult
Reflector type	Flat Mirror Ø¼" retroreflector	Flat Mirror Ø½" retroreflector	Flat Surface
Remarks	Compact/Low Cost	Large Size/High Cost	Need long avg. time to improve S/N
Doppler Effect	Measures phase or displacement	Counts fringe or displacement	Measures freq. or velocity
Shaft Vibration	Measures the changing distance to the target surface (including changing geometry)		Measures the shaft oscillation only

12.0 Calibration of Rotary Tables and 5-Axis Machines

12.1 Rotary Table Calibration

The dual-beam LDDM™ system can measure both linear displacement and the rotational angle of a dual-retroreflector up to $\pm 10^\circ$. With a small turntable, the angular measurement range can be extended to 360° . Hence it can be used to calibrate rotary tables or stages.

Because of the large alignment tolerance of the LDDM™ system and the simultaneous measurement of 2 channels, the angular measurement is not effected by the runout, wobble, parallelism, and co-axial alignment of the rotary tables. The set up and alignment are not critical. The accuracy of the measurement is determined by the LDDM™ system.

Briefly, a dual-retroreflector is placed on top of a small turntable supplied by Optodyne, which is in turn mounted on the test device, a rotary table or stage. The test device is programmed (or manually) to move in incremental steps of any angle. At the end of each step, press the space-bar of the notebook computer to record the data, rotate the small turntable in the opposite direction to near initial position, and press "R" of the notebook computer key to record the residual value. Hence the rotational angle of the test device and the rotational angle (in the opposite direction) of the small turntable are all recorded. The software will calculate the difference (error) data from both the forward and reverse angular measurements and linear measurements and will provide full data storage, analysis and plots.

Please note that, the above method is different from the conventional comparative method. That is, the test device is compared to the known inaccuracies in a master rotary calibrator which is very expensive.

12.2 Hardware Required

Dual beam laser head	L-104
Processor module with R-232 Interface	P-210
Dual retroreflector	R-103
Small turntable	LD-52
Adjustable mount	LD-46A
Rotary table calibration accessories	LD-54
12 ft cable set	LD-21
Carrying case	LD-20
Rotary table calibration program	S-102RS
Notebook PC Computer	LTC

12.3 Operating Specification

Accuracy: Angular displacement measurements are accurate within $\pm 0.2\%$ of displayed value ± 0.2 arcsec.

Resolution: Angular displacement 0.2 arcsec

Maximum Range: $\pm 10^\circ$
 360° with a rotary table

12.4 Reference Material

[Appendix C](#). Description of Microprocessor Control
[Section 8](#). Pitch, Yaw and Straightness Measurement

12.5 Installation and Alignment

12.5.1 Important Considerations

1. Make sure all cables are firmly connected before connecting power cable and switching the power switch on.
2. Vibration and loose connections must be minimized by proper mounting. Make sure that all supports and cables are completely stationary.
3. The output laser beam and the retroreflector must be aligned properly so that the beam intensity is above the minimum requirement (4 or 5 bars) along the entire measurement range.
4. The centers of rotation of the test device and the small turntable should coincide to within 0.002 in (0.05 mm).
5. The dual-retroreflector should be seated at the center of the small turntable and parallel to the surface.
6. Initially, the laser beam should be perpendicular to the retroreflector to within 30 arc minutes.
7. Align the laser beams to be parallel to the surface of the rotary table.

12.5.2 Installation

Attach the adapter plate (LD-14DB) to the adjustable mount (LD-54) and mount the dual-beam laser head to the adapter as shown in Fig. 8-2. For vertical rotary table, mount the laser head as shown in Fig. 8-1. Mount the dual-retroreflector on the small turntable (LD-52), as shown in Fig. 12-1, and place the small turntable on top of the test device as shown in Fig. 12-2. The stand off distance between the laser head and the retroreflector should be as close as possible from a few inches to 10 inches. For less accurate measurements, longer stand-off distances of up to 100 inches will be acceptable. Screw the return-rod on the turntable and set the stopping post near the return-rod. Position the stopping post such that when the return-rod touches the stopping post, the retroreflector is perpendicular to the laser beam. For a motorized turntable, the return rod and the reference post are not needed as shown in Fig. 12-2.

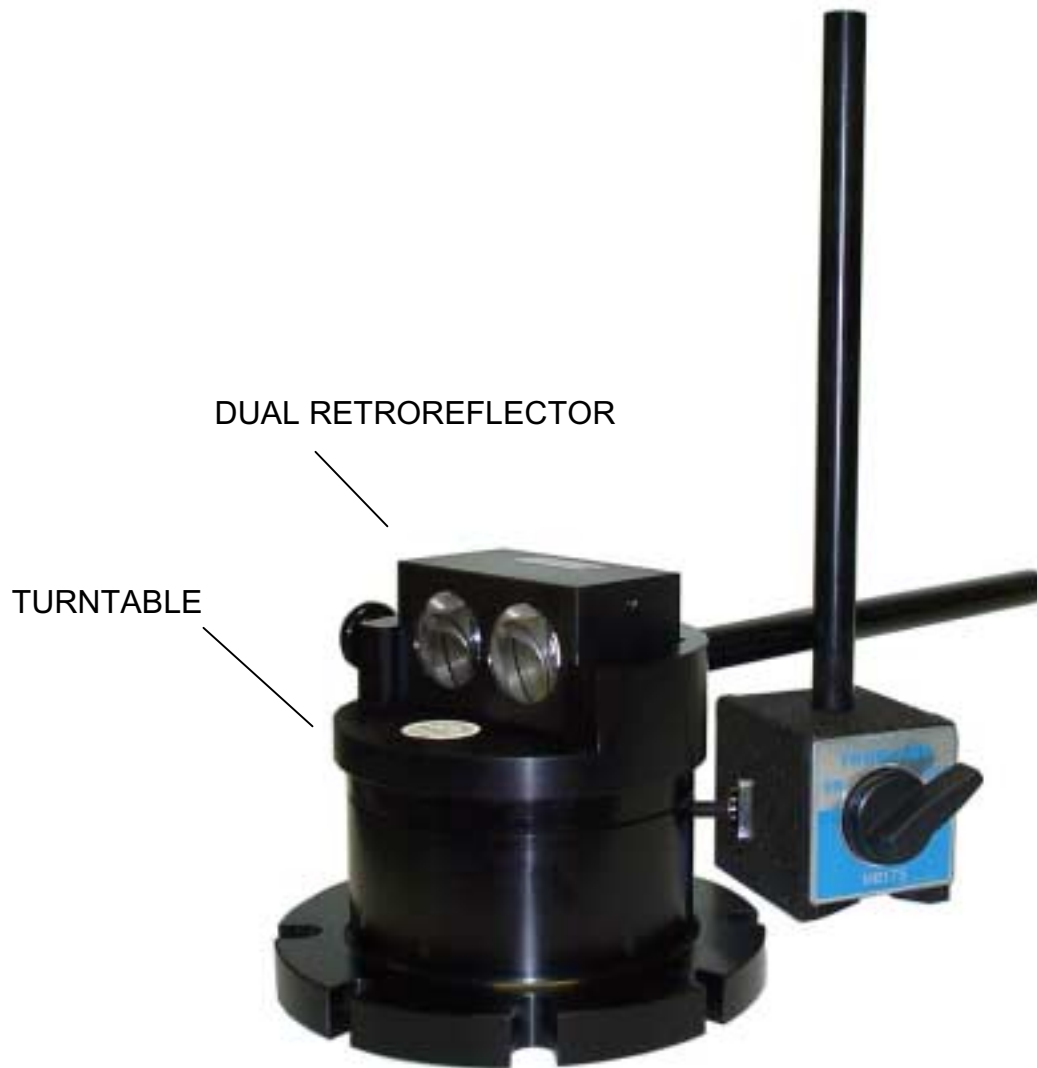


FIG. 12-1 SMALL TURNTABLE WITH
DUAL RETROREFLECTOR

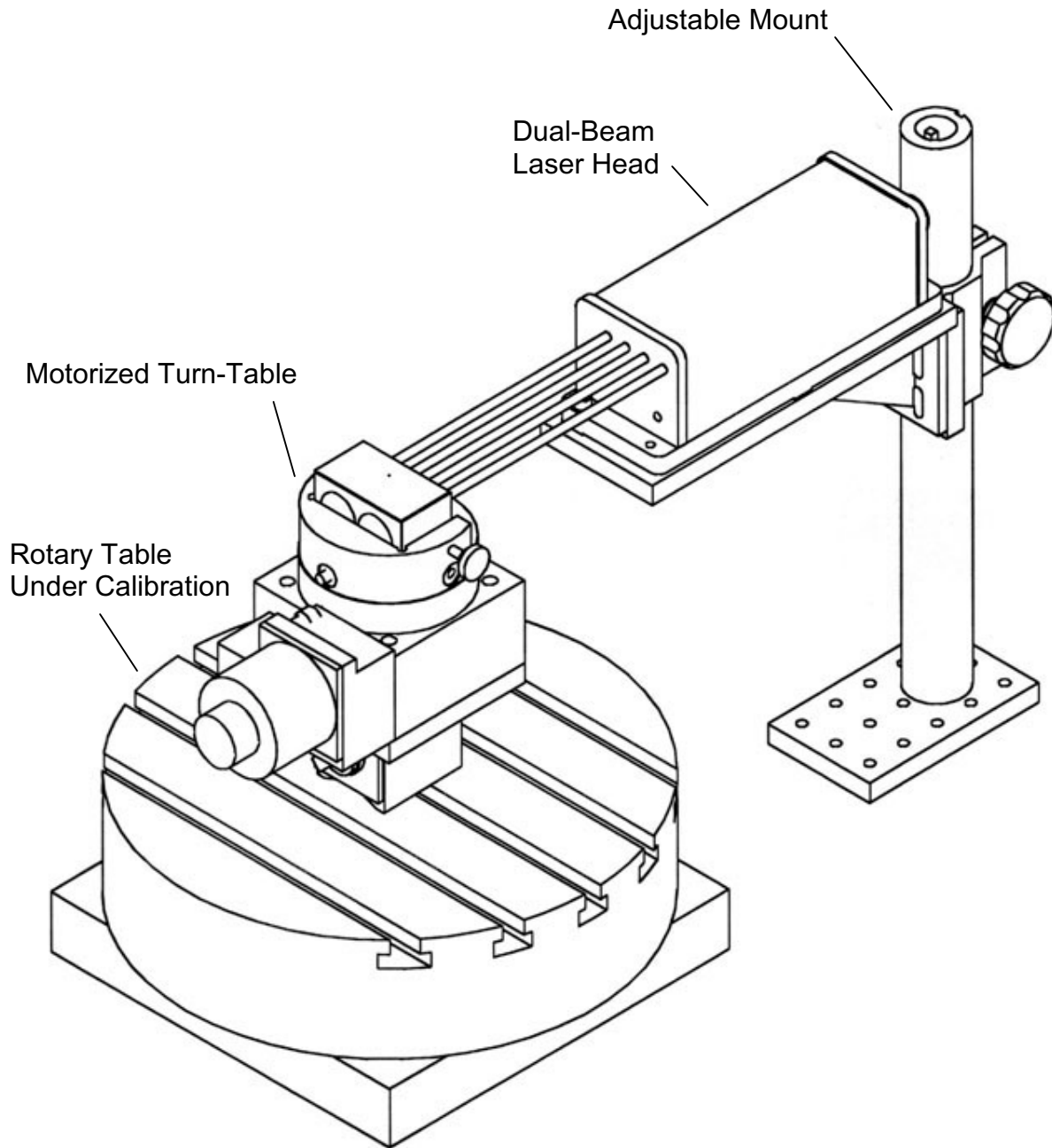


FIG. 12-2 SCHEMATIC OF THE BASIC SETUP WITH A MOTORIZED TURNTABLE

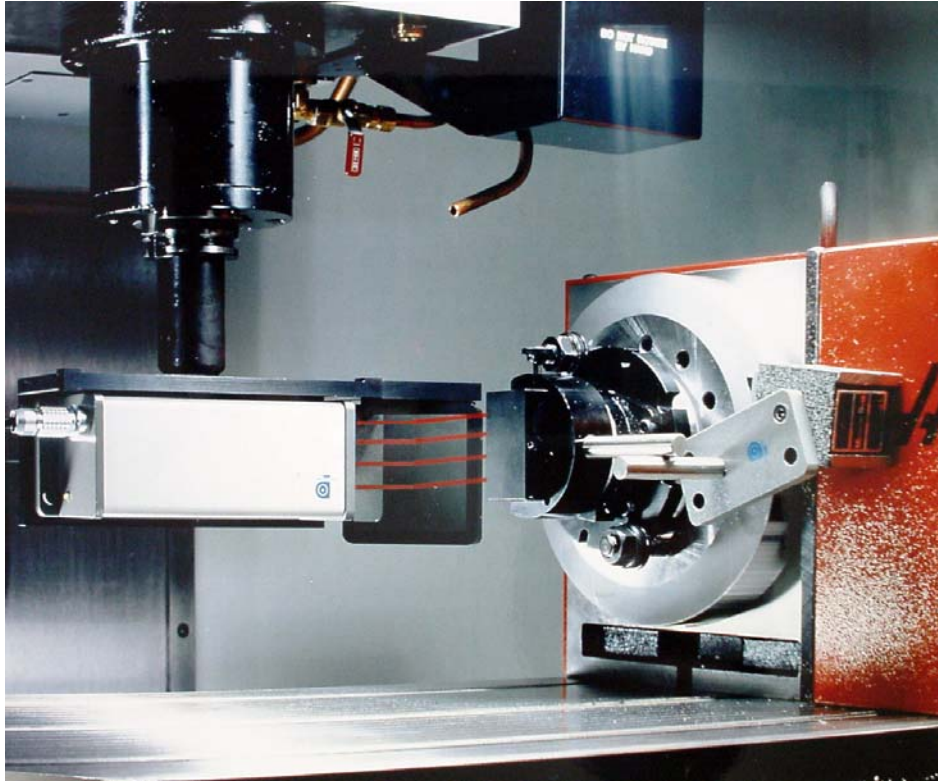


FIG. 12-3 PHOTOGRAPH OF ROTARY TABLE ON MACHINE

12.5.3 Description

If you are not familiar with the LDDM™ angular measurement, see [section 8.5.3](#) and [8.5.4](#) for the basic laser set up and alignment. Follow the alignment procedure below to align the laser to the dual-retroreflector, which is mounted on the small turntable on top of the test device.

12.5.4 Alignment Procedure

A. Using a manual turntable

1. Mount the laser head on the adjustable mount, making sure the laser beams are parallel to the surface of the test device and the rotation is at the center between the two laser beams. This can be checked by using a piece of paper at the center of the test device and two crosses marked at the location of the two laser beams. Rotate the test device 180°. If the two crosses are centered at the two laser beam again, the laser is aligned. Otherwise, move the laser beam and try again.
2. Place the small turntable on top of the test device. Center the small turntable with the center of the test device. Make sure the centers of rotation of the two rotary tables coincide to within 0.002 inches (0.05 mm). This can be checked by the same method as in step 1, but rotate the small

- turntable 180° instead of the test device. Rotate the test device 90° and repeat the test again (see Step 6 for more precise alignment).
3. Place the dual-retroreflector at the center of the small turntable and tighten the clamping screw.
 4. Move the laser head up and down by the adjustment screw such that the laser beams reached the center of the retroreflectors and the reflected beams entered the receiving aperture. Then tighten the locking screw.
 5. To do a final check of the alignment, press the X and Y buttons of the display simultaneously several times, until the display shows linear displacement in X and angular displacement in Y. Press the X and Y button separately to reset X-display and Y-display. Leave the return-rod pressed against the stopping post and rotate the test device slowly over 360°. Make sure at all angular positions, more than 2/3 of the laser beam remains in the receiving aperture and the flashing "A" on the display doesn't appear. Otherwise better alignment is needed by repeating steps 1 to 4. If you do not have a display, use the computer and the demo program.
 6. For more accurate measurements, the center of rotation of the dual-retroreflector, the center of rotation of the small turntable and the center of rotation of the test device should be coincident. To check this, first set the retroreflectors perpendicular to the laser beams. This is done by reflecting the first surface reflected laser beams back to the exit apertures of the laser head. The first surface reflected beams are images reflected from the face of the retroreflectors and will appear as faint red spots on the laser head face. Second, turn on the notebook computer, connect the RS-232 cable and load the rotary table program. Third, reset the notebook computer display to zero, then rotate the small turntable CW until the bottom display reads 0.200000 inches (about 11°). Reset the display zero again. Rotate the small turntable CCW until the bottom display reads 0.400000 inches. Two times the top reading minus the bottom reading should be less than 0.000800 inches or 0.2% of the bottom reading. The small turntable is factory aligned. If the reading is more than 0.2% upon repeated checks, the center of rotation of the dual-retroreflector can be shifted laterally with a paper shim. Similarly, follow the same procedure but while rotating the test device for checking the center of rotation. The bottom reading should be less than 0.000800 inches (<0.2% of the bottom reading). Otherwise, move the small turntable left or right to center it. Rotate the test device 90° and repeat the above procedure.
 7. For more accurate measurements, the residual readings should be less than 0.000400 at all positions. To check this, push the return rod against

the stopping post and rotate the small turntable 360°. The bottom readings should be less than 0.00400 throughout one complete revolution.

8. For quick measurements, set the measurement increment to 20° and set the return-rod pressed against the stopping post at -10°, measured from the position where the dual-retroreflector is perpendicular to the laser beam.
9. For a more accurate measurement, the initial position of the dual-retroreflector should be perpendicular to the laser beam. To check this, at the initial position, reset the LDDM™ readings. Move CW 5° and then CCW 10° (5° past zero). The sum of these two readings (CW is negative -, CCW is positive +) should be less than 0.000400. Otherwise rotate the turntable a small amount and check again. Set the stopping post at the zero position.
10. Set the rotary table at the zero position and with backlash removed. Set the turntable at the initial position, return-rod pressed against the stopping post. Reset the display and follow the instructions on the monitor or the software manual in the menu to take data.

B. Using a motorized turntable

1. Mount the laser head on the adjustable mount, making sure the laser beams are parallel to the surface of the test device and the center of rotation is between the two laser beams. Set the rotary table to 0 position or the starting position.
2. Place the small motorized turntable on top of the test device. Rotate the small motorized turntable such that the surface of the two retroreflector is perpendicular to the laser beam direction. Laterally move the small motorized turntable such that both laser beams entered the receiving apertures (the two outside apertures).
3. Rotate the rotary table cw 90 degrees and rotate the small motorized turntable ccw 90 degrees. Move the small motorized turntable laterally such that both laser beams entered the receiving apertures.
4. Rotate the rotary table cw 90 degrees and rotate the small motorized turntable ccw 90 degrees. Rotate the laser head, such that the return beams are 50% closer to the receiving apertures. Move the small motorized turntable laterally such that both laser beams entered the receiving apertures.
5. Repeat steps 3 and 4 until both laser beams always enter the receiving apertures. After 360 degrees, untangle the cables, before the second 360 degrees, or reverse the direction to untangle the cables.

6. Set the rotary table at 0 degree or starting position. Rotate the turntable such that the retroreflectors are perpendicular to the laser beam.
7. The motorized turntable has 10 preset programs as the followings.

Program Number	Function
0	Start button move ccw Stop button move cw
1	Move 10 degrees cw
2	Move 10 degrees ccw
3	Move 10 degrees cw, stop 5 seconds, 36 times then move 10 degrees ccw, stop 5 seconds, 36 times.
4	Move 10 degrees cw, stop 5 seconds, and continue until stop button is pressed.
5	Move 10 degrees ccw, stop 5 seconds, and continue until stop button is pressed.
6	Move 90 degrees, cw
7	Move 90 degrees, ccw
8	Move 10 degrees cw, stop 6 seconds, continue 36 times. Then move 10 degrees ccw stop 6 seconds, continue 36 times. Repeat the above 3 times.
9	Same as 8, except start ccw direction

Note: The time required to rotate 10 degrees is set to 1 second.

8. The rotary table needs the following programs
 - 1) Return to 0 position
 - 2) Rotate 90 degrees cw
 - 3) Rotate 90 degrees ccw
 - 4) Rotate 10 degrees cw, stop 6 seconds, and continue 36 times. Then rotate 10 degrees ccw, stop 6 seconds and continue 36 times. Repeat the above 3 times.

- 5) Same as 4, except start ccw direction.
- 6) The speed of rotation is 10 degree/sec. For example, at a distance of R inches from the center of rotation, the feed rate should be G93 F [feed rate in/minute] A10. Where feed rate = $10.2 * R$.
- 7) The time for each 10 degrees increment is 7 sec. For 360 degrees, it is $36 * 7 = 252$ sec
= 4 minutes 12 seconds

The total time for 3 round trips is 25 minutes 12 seconds.

12.6 Software Description

See [Section 7.6](#) or the software manual

12.7 Accuracy and Error Sources

For angular measurements, the angle is derived by the difference in displacement of the two retroreflectors. Hence the speed of light compensation is not necessary. For rotary table calibration, because of the complete closure property, that is 360° is equal to 0° , it can be self calibrated and may achieve higher accuracy.

As shown in Section 8 or 9, the dual-beam LDDM™ system measures both the linear displacement of one retroreflector and the difference of linear displacements of the two retroreflectors. For the application here, only the later measurement will be used. The rotational angle θ can be expressed as:

$$\sin \theta = \Delta/d \quad (1)$$

or,

$$\theta = \arcsin (\Delta/d) \quad (2)$$

Where Δ is the difference of displacements of the two retroreflectors, and d is the separation of the two retroreflectors. It is noted that this measurement is not effected by non-rotational movement, such as lateral or longitudinal displacements. Hence, the measurement is not sensitive to runout, wobble, parallelism and non-coaxial alignment of the small turntable or the test device.

For high accuracy measurements, the major error sources are the following:

1. The distance between the two retroreflectors may change. If this distance changes during a measurement, the measurement results will include the error. This distance will change if the temperature of the dual retroreflector's housing changes during a measurement.
2. For an angle larger than 1° , the large angle correction must be made, i.e. corrected angle = \arcsin (displaced angle).
3. Excessive roll motion of the dual retroreflector may create error.
4. The temperature gradient or air turbulence in the room will diffract the laser beam. To minimize this effect, make sure the stand off distance is as short as possible and avoid direct air current or near heating or cooling sources.

5. Non-perpendicular error is due to the initial set up, when the laser beam is not perpendicular to the dual-retroreflector. The non-perpendicular error, ε_p can be expressed as:

$$\begin{aligned}\varepsilon_p &= \sin(\theta_{max} + \varepsilon) - \sin \theta_{max} - \sin \varepsilon \\ &= \frac{1}{2}[\varepsilon(\theta_{max})^2 + (\varepsilon^2)\theta_{max}]\end{aligned}\quad (3)$$

Where ε is the angle deviation from perpendicular and θ_{max} is the maximum rotational angle. For example assume $\varepsilon = 30$ arcminutes, $\theta_{max} = 3^\circ$, the non-perpendicular error $\varepsilon_p = 2.5$ arcsec. With better alignment, the non-perpendicular angle may be reduced and the accuracy improved.

6. Cosine error is due to the laser beam not being parallel to the surface of the table. The cosine error, ε_c can be expressed as:

$$\begin{aligned}\varepsilon_c &= 1 - \cos \Psi \\ &= \frac{\Psi^2}{2}\end{aligned}\quad (4)$$

Where Ψ is the angle between the laser beam plane and the surface of the rotary table. Usually, this error is negligible.

7. Retroreflector rotational error is due to the rotation of the retroreflector. As shown in Hewlett Packard Application Notes 325-11 the rotational error ε_R can be expressed as:

$$\begin{aligned}\varepsilon_R &= \frac{nD}{R} \left[\frac{1}{\cos(\sin^{-1}(\frac{\sin \theta}{n}))} - 1 \right] \\ &\quad + \left[\frac{D}{n} \tan \theta - D \tan[\sin^{-1}(\frac{\sin \theta}{n})] \right] \frac{\sin \theta}{R} \\ &\quad - \frac{D}{nR} \left[\frac{1}{\cos \theta} - 1 \right]\end{aligned}\quad (5)$$

Where n is the index of refraction of the retroreflector, D is the distance from surface to the apex, R is the radius of rotation and θ is the rotational angle. For example assume 1 inch glass retroreflector, and 1 inch separation between the two retroreflectors the rotational error $\varepsilon_R = 0.3$ arcsec for a rotational angle of 3° .

8. The inversion error Δ/R is due to the calculation of arcsin (Δ/R). Using the Taylor's expansion formula, we can express the angle θ as:

$$\theta = \frac{\Delta}{R} + \frac{1}{6} \left(\frac{\Delta}{R} \right)^3 - \frac{1}{120} \left(\frac{\Delta}{R} \right)^5 + \dots \quad (6)$$

The inversion error is a known error and can be corrected by software.

12.8 Taking a measurement

A. Using a manual turntable

1. Set up the LDDM™ and align properly.
2. Set up the Notebook computer and load the appropriate software by following the instructions in [Section 7.6](#) or the software manual.
3. The software is menu-driven, just follow the instructions on the monitor. Select automatic data collection (for manual rotary table, use manual data collection).
4. Move the machine to the starting point.
5. Reset the LDDM™ reading to zero.
6. Move the machine to the first stop, the data will be collected automatically.
7. Move the return-rod and stop at the stopping post, the Notebook will record the residual value automatically.
8. Repeat steps 6 and 7 until the measurement has been completed.

B. Using a motorized turntable

1. Set up the LDDM™ and align properly.
2. Set up the Notebook computer and load the appropriate software by following the instructions in [Section 7.6](#) or the software manual.

3. The software is menu-driven, just follow the instructions on the monitor. Select automatic data collection in the setup screen. Select number of steps per 360 degree (For example, 10 degrees increment, select 36 steps), number of runs and auto reverse. Select movement direction, counter clockwise or clockwise. Make sure to program the rotary table to move at the same angular speed and dwell time as the motorized turntable.
4. Move the machine to the starting point.
5. Reset the LDDM™ reading to zero.
6. Press the start button to move the machine to the first stop, the data will be recorded automatically.
7. Press the start button of the motorized turntable, 3 seconds after the machine start button, to move the motorized turntable in the opposite direction with the same angle and stop. The residual reading will be recorded automatically.
8. Both the machine and the motorized turntable continue to move until 360 degrees is reached.

12.9 Description of a measurement

After a measurement is done, the data can be analyzed by the same software. The output of a typical measurement on a rotary table is shown in Fig. 12.4 and the data is shown in Table 12.1. The data here was taken in 10° increments for 360° . Fig. 12.4 shows the deviations in arcsec over 360° . Table 12.1 shows the data. The first column is the run number. The second column is the number of points (each point is 10°). The third column is the target position in degrees. The fourth column is the angular deviation in arcsec, and the fifth column is the angular deviation in degrees.

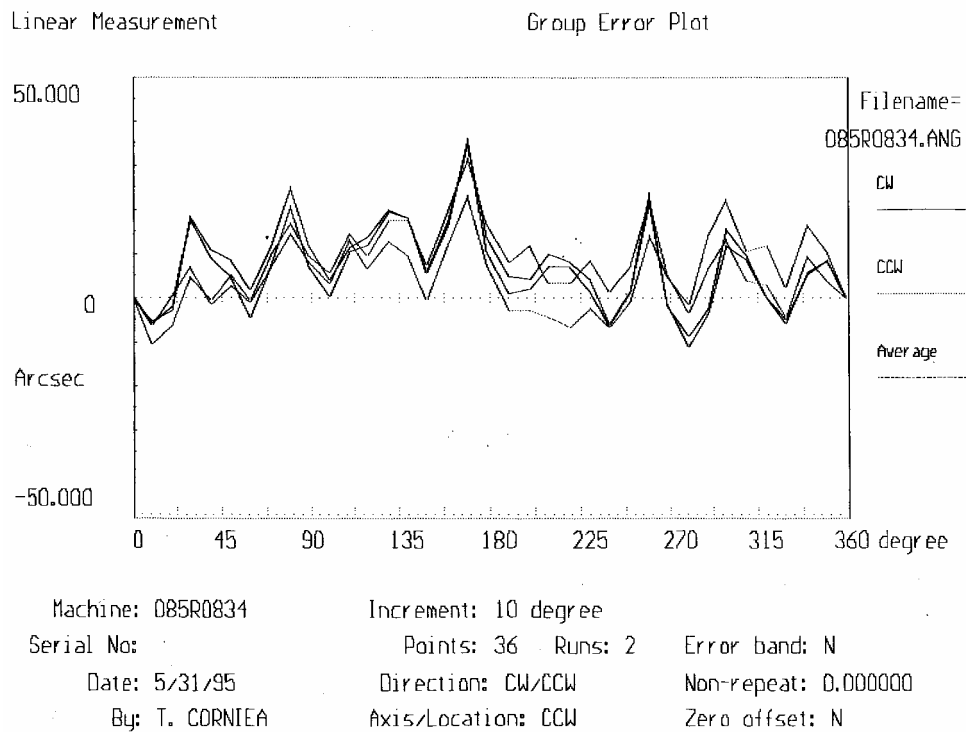


FIG. 12-4 TYPICAL ROTARY CALIBRATION ERROR PLOT

** Linear Measurement ** Group data

Positioning error table Filename:085R0834.ANG
 Machine : 085R0834 Material Temp.: 74.80
 S/N : Air Temp.: 78.14
 Date: 5/31/95 Pressure : 29.12
 By: T. CORNIEA Humidity : 32.00

 * The measurement has 2 runs data
 * 36 Points each direction
 * MTE = 1.000000
 * 360.000000 Mm Total travel

Run No	Point No	Position Degree	Arcsec Deviation	Degree Deviation
1	0	0	0.565	0.000157
1	1	10	-6.129	-0.001703
1	2	20	-2.272	-0.000631
1	3	30	18.345	0.005096
1	4	40	11.090	0.003081
1	5	50	8.729	0.002425
1	6	60	2.036	0.000566
1	7	70	11.918	0.003311
1	8	80	25.190	0.006997
1	9	90	11.718	0.003255
1	10	100	4.084	0.001134
1	11	110	11.519	0.003200
1	12	120	13.680	0.003800
1	13	130	19.796	0.005499
1	14	140	18.187	0.005052
1	15	150	6.411	0.001781
1	16	160	17.612	0.004892
1	17	170	36.346	0.010096
1	18	180	13.832	0.003842
1	19	190	4.882	0.001356
1	20	200	4.404	0.001223
1	21	210	9.956	0.002766
1	22	220	7.972	0.002214
1	23	230	4.104	0.001140
1	24	240	-6.168	-0.001713
1	25	250	1.267	0.000352
1	26	260	21.886	0.006079
1	27	270	-2.135	-0.000593
1	28	280	-11.652	-0.003237
1	29	290	-3.841	-0.001067

2	27	270	4.965	0.001379
2	26	260	14.432	0.004009
2	25	250	-1.529	-0.000425
2	24	240	-6.943	-0.001929
2	23	230	-2.750	-0.000764
2	22	220	-7.033	-0.001954
2	21	210	-4.911	-0.001364
2	20	200	-3.165	-0.000879
2	19	190	-3.491	-0.000970
2	18	180	7.671	0.002131
2	17	170	23.539	0.006539
2	16	160	12.287	0.003413
2	15	150	-0.847	-0.000235
2	14	140	9.750	0.002708
2	13	130	12.624	0.003507
2	12	120	6.458	0.001794
2	11	110	13.287	0.003691
2	10	100	3.542	0.000984
2	9	90	8.111	0.002253
2	8	80	14.754	0.004098
2	7	70	7.269	0.002019
2	6	60	-1.535	-0.000426
2	5	50	3.034	0.000843
2	4	40	-1.813	-0.000504
2	3	30	7.275	0.002021
2	2	20	0.354	0.000098
2	1	10	-6.752	-0.001876
2	0	0	0.264	0.000073

Maximum =	-0.000000	Minimum =	-0.000000	
Mean =	-0.000000			

TABLE 12-1 TYPICAL ROTARY CALIBRATION DATA TABLE

12.10 Calibrate the Rotary A- and B-axis of a 5-axis Machine.

The accessory, a L-shaped bracket, shown below is used to set the small rotary-table with the dual-retroreflector to the center of rotations. Mount the dual-beam laser head on the bed and point the laser beam up to the dual-retroreflector. Follow the same procedure as the calibration of a rotary table, with the new rotary calibration software rotational angles less than 360 degrees can be measured.

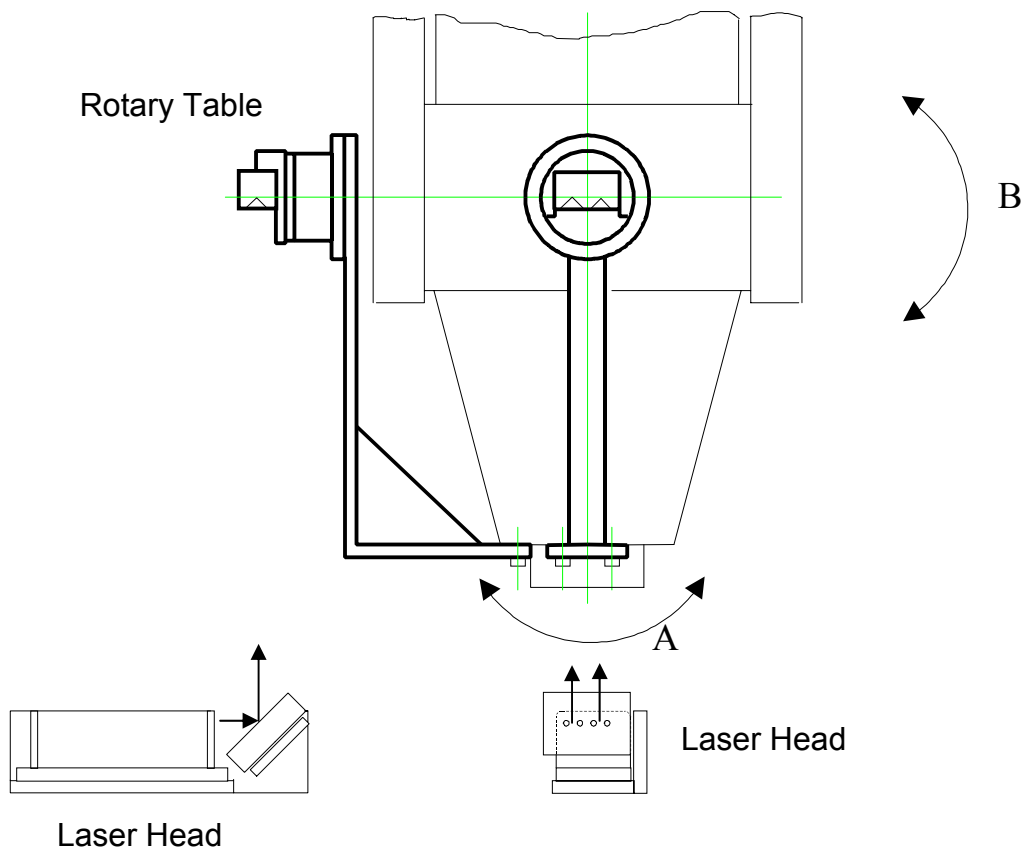


Fig. 12-5 Calibration of 5-axis Machine

Alignment procedure

1. The L-bracket is made of steel. Use a magnetic holder to mount the small rotary table to the L-bracket. Move the rotary table such that the center of rotation of the small rotary table and the rotary axis are on the same axis.
2. Using a centering pin with a magnetic holder to locate the center of rotation by rotating the rotational axis. Once the center of rotation is located, move the spindle away and mount the rotary table on the L-bracket. Move the spindle close to the rotary table and move the rotary table such that the center of rotation (marked on the top of the rotary table) is the same as the center of rotation of the machine axis. Using another magnetic holder as marker, we can make very small movement of the rotary table.
3. The L-bracket is mounted on the stationary part of the spindle. Usually, there are 8 to 12 screws on the stationary part of the spindle. Use 2 of the screws to mount the L-bracket. Mount the dual-beam laser head on the bed by a magnetic holder, and use a large flat mirror to point the laser beam up. The alignment is relatively easy, since the spindle is free to move in all 3 axes.
4. Since the spindle sizes and hole patterns are different for different machines, the L-bracket has to be specially made for this particular machine. For some machine, the length of the L-bracket is long, a steel I-beam has to be used to increase the stiffness.
5. If the rotary axis can move +/- 90 degrees, a flat-mirror can be used to calibrate the beam separation. Otherwise, the beam separation has to be calibrated on a rotary table.
6. For some machine, a long stopping rod is needed for the returning rotation of the retroreflectors.
7. After the system is aligned, follow the same procedure as the calibration of a rotary table for data collection and analysis.

13.0 Circular Test (Laser/Ballbar)

13.1 Introduction

The circular test accessories (LB-500) are designed for circular test with an MCV-2002 laser system. An optical adapter is used to convert the dual-beam laser system to a single aperture laser system. Hence, a flat-mirror can be used as a target. Pointing the laser beam in the X-direction and mounting the flat-mirror target on the spindle, the X-coordinate of the spindle motion can be measured even with a large Y-direction movement. By repeating the measurement in the Y-direction, the Y-coordinate of the spindle motion can be measured. The data on X-coordinate and the data on Y-coordinate can be combined to generate the measured circular spindle path. Hence the MCV-2002 can be used as both a laser for positioning measurements and a ballbar for circular tests. As compared with a telescopic ballbar, the major features of the circular test using the MCV-2002 are the following.

1. The measurement is non-contact, no cables to worry about, no friction or bearings.
2. The circular path radius can be varied continuously from 0.01 inches to 6 inches.
3. The data rate is up to 1000 data/sec.
4. The measuring speed is up to 4m/sec.
5. Large alignment tolerance is achieved by using an optical adapter.
6. Linear accuracy is traceable to N.I.S.T.
7. The tangential velocity and acceleration can be measured and displayed.
8. A compact notebook computer can be used with user friendly Windows™ software for data collection and analysis.

13.2 Hardware Required

The basic hardware and software required for the circular test are listed below:

a. Dual Beam Laser Head	L-104
b. Processor Module with RS-232 Interface	P-111 or P-210
c. 6" Flat-mirror w/steering	LD-71
d. Metrology/Analysis Program with Circular Path	W-500/w-500lb
e. Optical Adapter	LD-69DB
f. Magnetic Base	LD-03
g. Adapter Platform	LD-14DB
h. 12 ft Cable Set	LD-21L
i. PC Card and Cable	IPC5-1000
j. Notebook PC	Not supplied

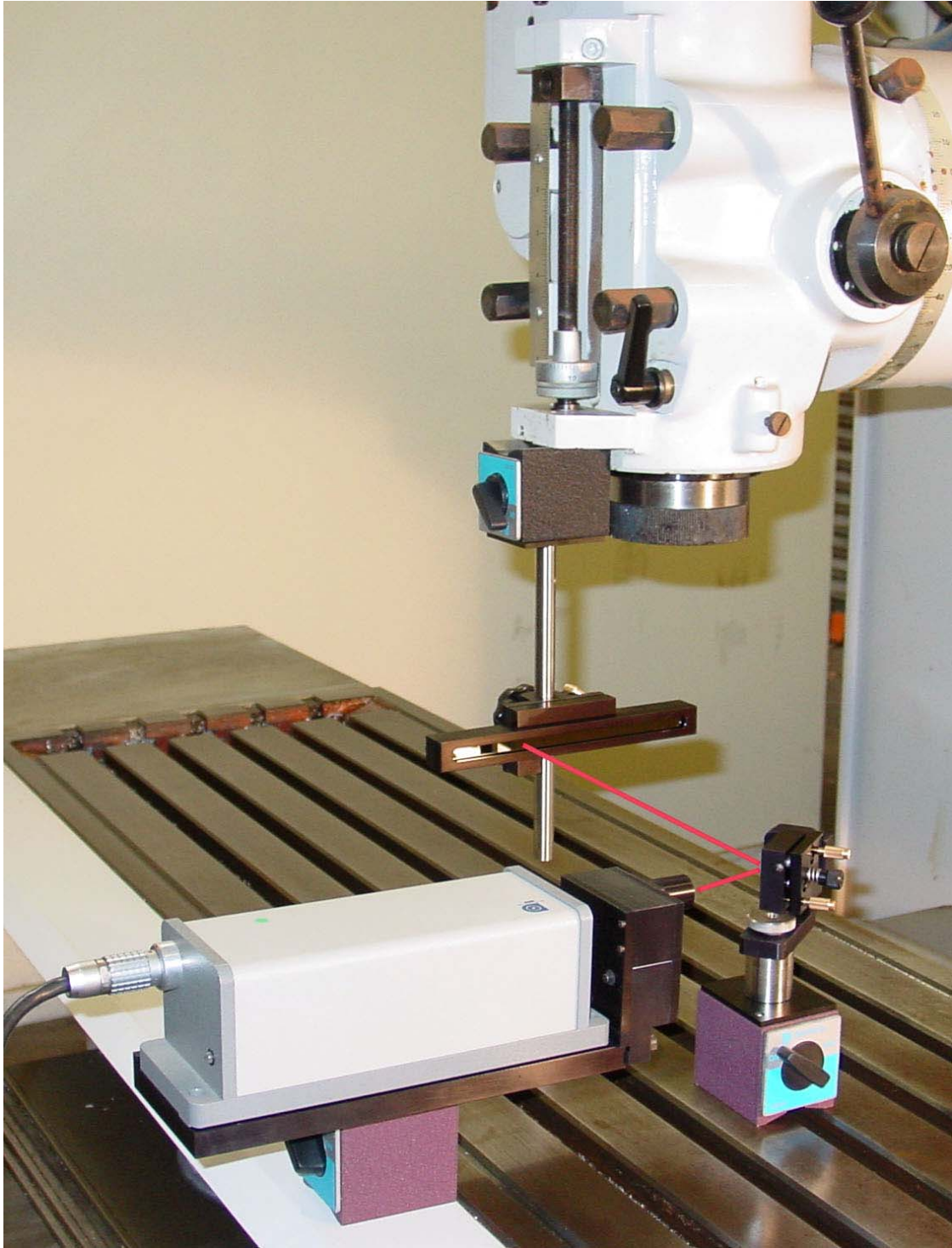


FIG. 13-1 LASER/BALLBAR CIRCULAR TEST SETUP

13.3 Operating Specifications

Accuracy: The laser stability at an atmospheric pressure of 29.9 in Hg and an air temperature of 68°F is 0.1 ppm. At other pressures and temperatures, the measurement accuracy depends upon the velocity of light compensation and the material thermal expansion correction. With manual compensation and correction, the accuracy depends upon the accuracy of the measured air temperature, air pressure, and the material temperature. With automatic temperature and pressure compensation, an accuracy of ± 1 ppm could be achieved. For more detailed discussion on accuracy see Appendices H and J.

Resolution: Standard resolution is 1 μ in (0.01 μ m).

Maximum Velocity: 144 inch/sec (3600 mm/sec)

Measurement Range: Up to 50 ft (15 m)

Temperature Range: 60°F to 90°F or (15.5°C to 32°C)

13.4 Reference Material

Appendix H, ATC and Calibration

Appendix J, Accuracy

Charles Wang and Bob Griffin, "A non-contact laser technique for circular contouring accuracy measurement", Review of Scientific Instruments, Vol 72, No.2, pp1594-1596 (Feb. 2001)

13.5 Installation and Alignment

13.5.1 Important Considerations

1. Check that all cables are firmly connected before connecting the power cable and switching the power switch to the on position.
2. Always mount the laser head on a stationary part and the flat-mirror on a moving part. Never use a tripod to mount the laser head. The tripod may introduce an error. For example, on most CNC machine tools, the spindle is moving in the Z-direction and the bed is moving in X- and Y-direction. Hence, when measuring the X- and Y-direction, mount the laser head on the spindle (or near the spindle by a magnetic holder) and the flat-mirror on the bed. Then to measure the Z-direction, mount the laser head on the bed and the flat-mirror on the spindle. However, for most CMM machines, the bed is fixed and the spindle is moving in X-, Y-, and Z- directions. Therefore, always mount the laser head on the bed and mount the flat-mirror on the spindle or the moving carriage.

CAUTION! Never turn on the spindle of the CNC while either the laser or flat-mirror are mounted there. This could cause injury to the operator and/or damage to the equipment.

3. When installing the laser head, make sure that the laser beam coming out will travel in the direction of the measurement, and is perpendicular to the flat-mirror.
4. Vibration and loose connections must be minimized by proper mounting. Make sure that all supports and cables are completely stationary. A spindle, for example, must be secured by a brake so it will not rotate.
5. The output laser beam and the flat-mirror must be aligned properly such that the beam intensity is above the minimum requirement along the entire circular path.

13.5.2 Installation

13.5.2.1 Set up LDDM Program

See Section 7.5.2.1.

13.5.2.2 Starting LDDM Program

See Section 7.5.2.2.

13.5.2.3 Install PCMCIA Card

Set the PC Notebook near the Processor module. Insert the interface PCMCIA Card (IPC5-1000) to the PC Notebook. Each card is for a single channel and up to 2 PCMCIA Cards or 2 channels for two laser systems. Make sure all the hardware is installed and aligned properly. Make sure the PCMCIA Card is plug-in firmly with good contact and proper communication established. For some PC, the PCMCIA Card has to be inserted before boot.

13.5.2.3 Setup Laser head and Flat-mirror target

Install the Laser head onto the Optical adapter LD-69DB with a magnetic holder and the flat-mirror on the spindle directly or with a magnetic holder, as shown in Fig.13-4. For some machine, the bed is moving, then mount the laser head on the spindle and the flat-mirror on the bed. For XY-plan measurement, pointing the laser beam in the X-direction (or Y-direction) and the flat-mirror perpendicular to the laser beam. Move the laser head or the flat-mirror such that the laser beam is always reflected by the flat-mirror over the whole circular path. The standard flat-mirror is 6" long. It will cover a circular path of 6" diameter. For large diameter, a longer flat-mirror is available.

Finally, adjust the two screws on the mounting of the flat-mirror (Fig.13-4) such that the return laser beam enters the aperture of the optical adapter. The green light on the data collection screen should be on. Move the spindle along the circular path and make sure the green light is always on. Otherwise, fine adjust the flat-mirror again.

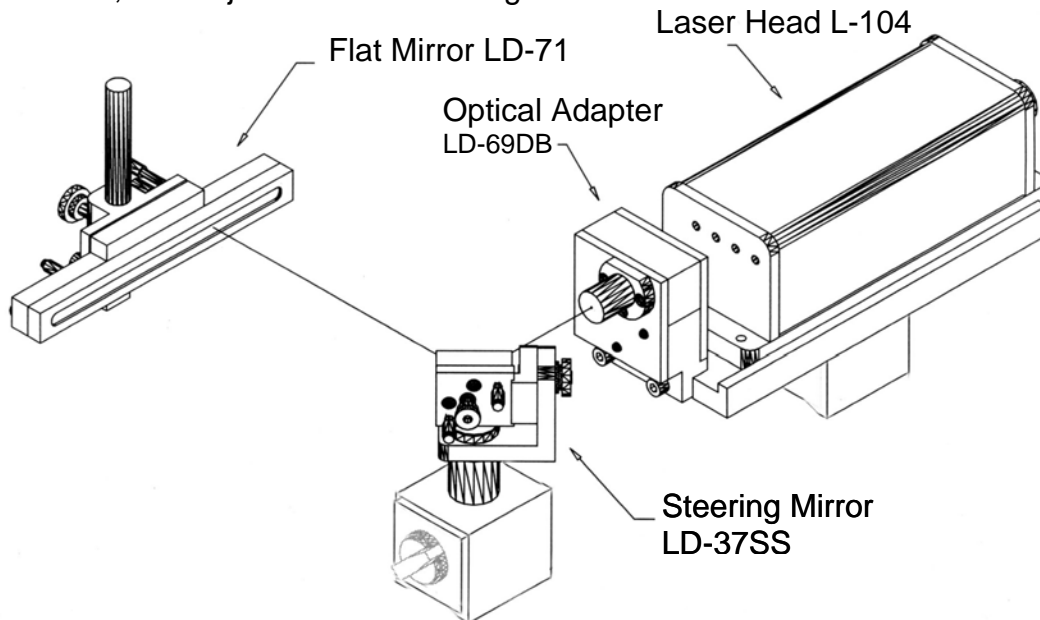


FIG. 13-2 SET UP OF LASER BALL BAR TEST

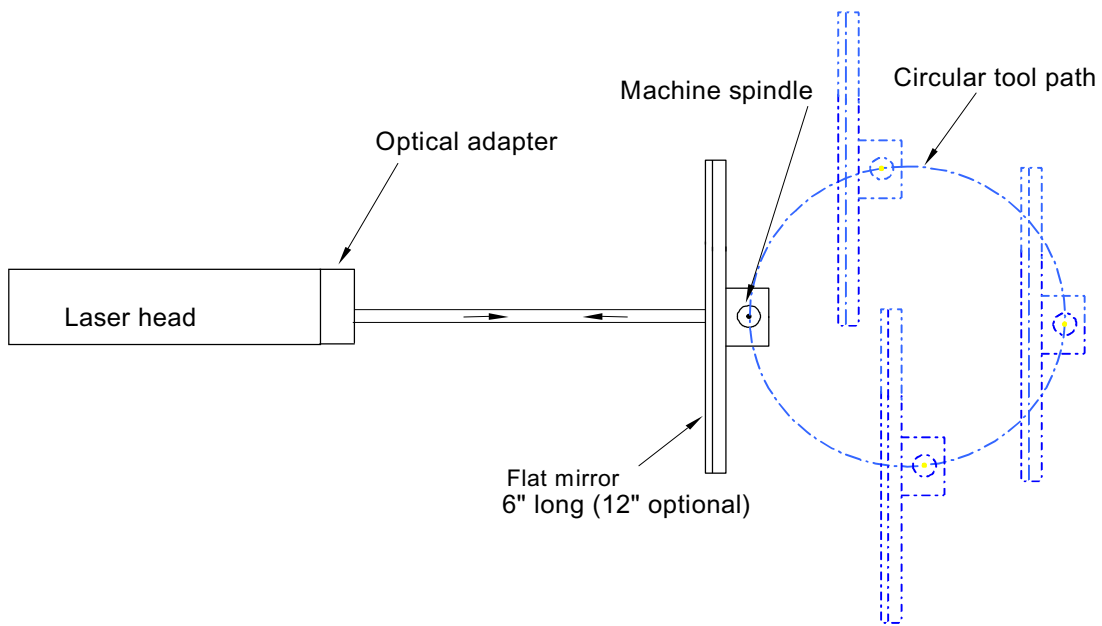


FIG. 13-3 SCHEMATIC OF LASER CIRCULAR TEST

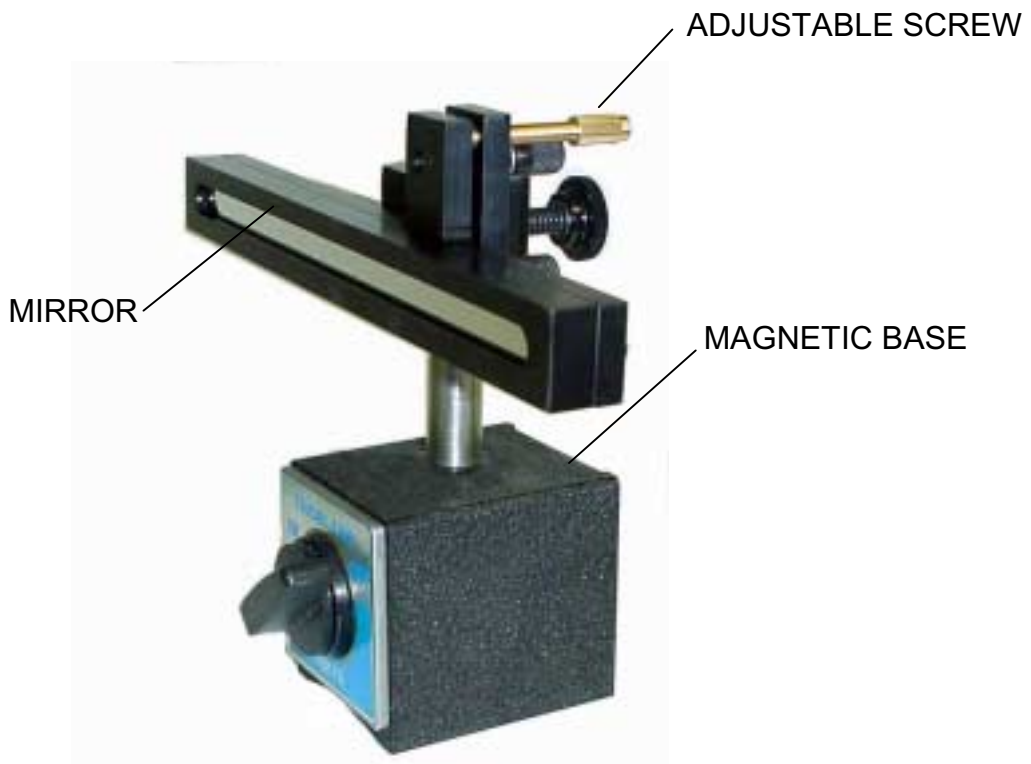


FIG. 13-4 FLAT-MIRROR TARGET WITH TWO ADJUSTABLE SCREWS

13.5.3 Description of Circular Path, Feed Rate, and Radius

Program the machine spindle to move a circular path of radius R and feed rate F for at least 3 complete revolutions in CCW and then in CW. A typical G-code for 1 revolution at radius $R = 2''$ and feed rate $F = 40$ in/minute is shown below.

```
G01 X0 F40. Y2.;  
G02 X0 Y-2. R2.;  
G02 X0 Y2. R2.
```

Repeat for more revolutions and change G02 to G03 for clockwise rotation.

Select the feed rate defined by the standards, namely 10% and 80% of the maximum machine feed rate. Then calculate the data rate to be within the following formula.

$$100 \leq 360 * \frac{S}{F} R \leq 1000$$

Where S is the data rate [data/sec], F is the feed rate [in/min] or [mm/min] and R [in] or [mm] is the radius of the circular path.

For machine dynamic accuracy measurement, it is important to perform the circular test at high feed rate and small radius. Please note that the circular test here is non-contact. Hence the radius can be varied continuously down to near zero and the data rate can be up to 1000 data/sec.

13.6 Software Description

13.6.1 General Description

For general description, windows, installation and starting LDDM program, see section 7.6.

13.6.2 2D Time Base Data Collection

The 2D time base collects data through a special PCMCIA card. The maximum data rate is 1000 data/sec. Click on the "2D time base" button in the main menu to get the data collection screen as shown in Fig.13-5. For two PCMCIA cards, the available address are: 350,110, 220,100 and 300.

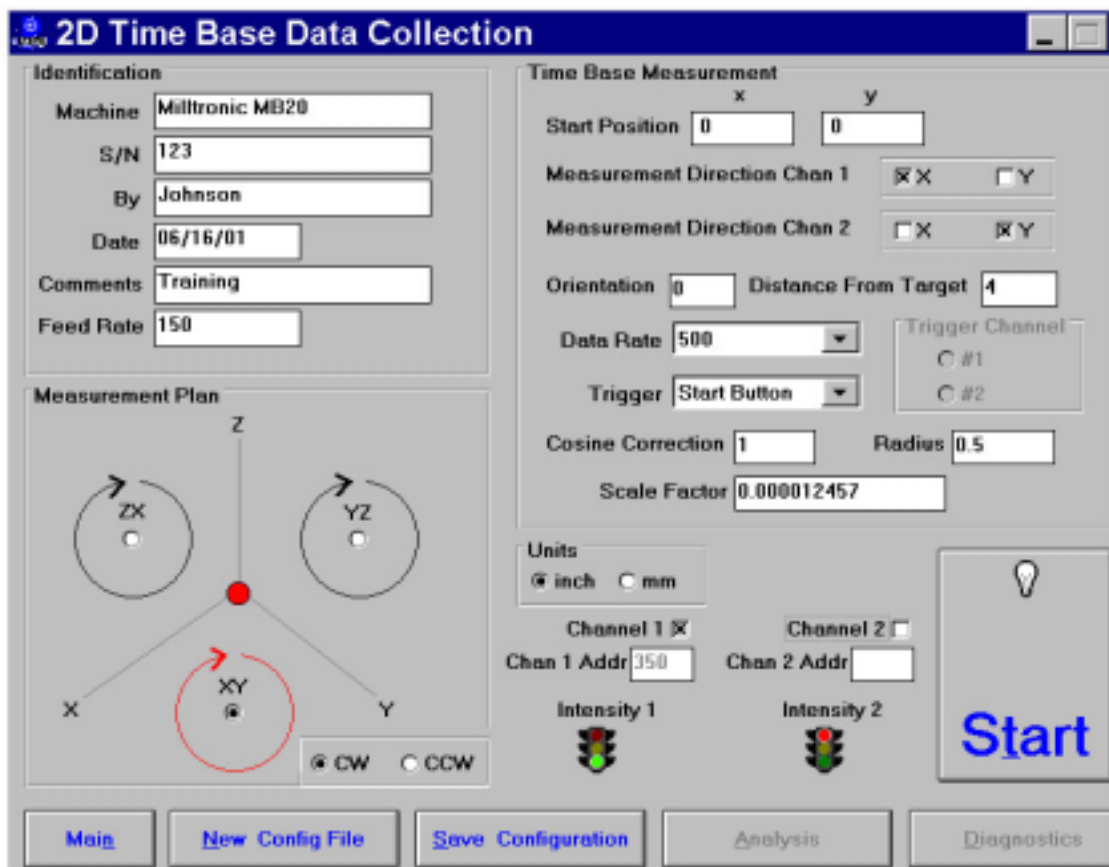


FIG. 13-5 2D TIME BASE DATA COLLECTION SCREEN

Choices on the data collection screen are as follows:

Identification: Input the machine type, serial number, operator, date, your comments or remarks and feed rate in/min or mm/min.

Measurement plan: Select the plan of measurement, xy, yz, or zx, and direction of the circular path, either cw or ccw.

Time base measurement: Enter start position, measurement direction, and distance from the target. The orientation is the angle between the measurement direction and the first-axis direction. The data rate is determined by the selected feed rate and radius (see section 13.5.3). Trigger mode is “start button” only. The displacement or velocity trigger will be added later. Cosine correction is 1 for normal operation. It is $2\cos(\text{angle})$ for double pass and the angle is the angle between outgoing and return beams. The radius is the radius of the programmed circular path. The scale factor is 0.000024914 in or 0.000632816 mm. Click “in” for inch unit and “mm” for metric unit. Click both channels for 2 channel data collection.

Intensity: The green light indicates the laser is aligned properly and the red light indicates the alignment is off. Block the laser beam to check whether the PCMCIA Card is installed properly.

Start/stop: Click “start” to start the data collection and “stop” to stop the data collection. After stop, enter the filename to save the data collected. The extension .2dr will be added automatically.

13.6.3 Data Analysis

To analyze data, go to the main menu first then click on the “analysis”. Click on “file” to open a file with extension .2dr. The file usually is very large, please wait a while for the file to be ready. After the .2dr data shown on the screen, click on “data selection” and “displacement 1”. The displacement values will be calculated and displayed as shown in Fig 13-6.

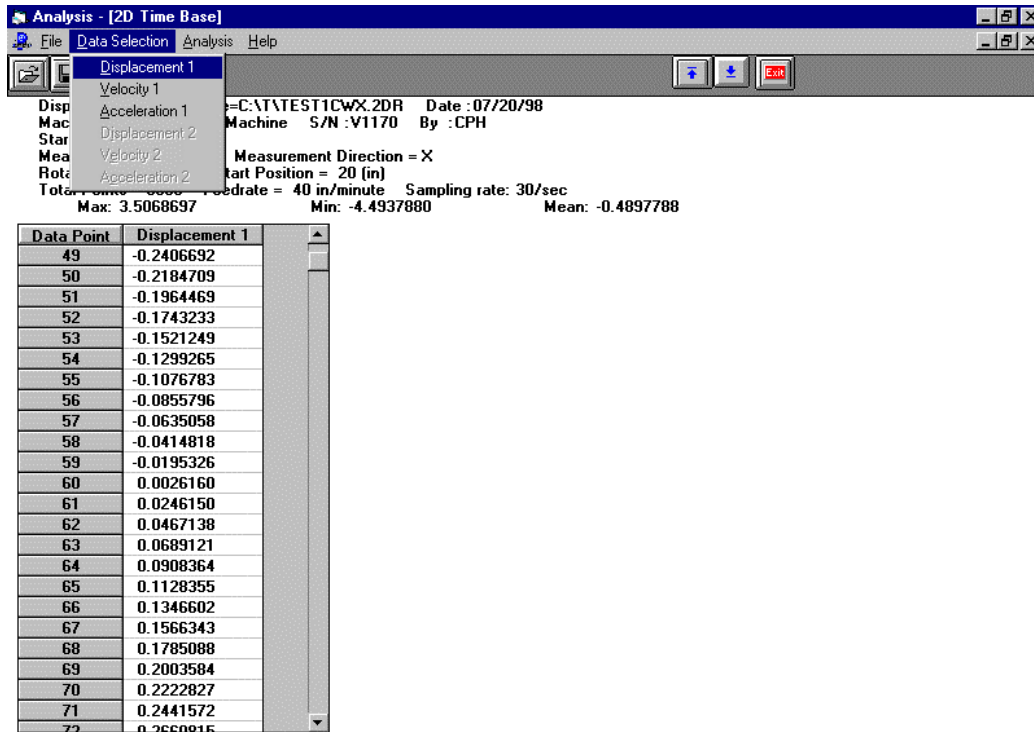


FIG.13-6 THE ANALYSIS SCREEN WITH DISPLACEMENT DATA

After the displacement values are displayed, click on the “graph” to plot the displacement. A typical plot of the displacement is shown in Fig 13-7.

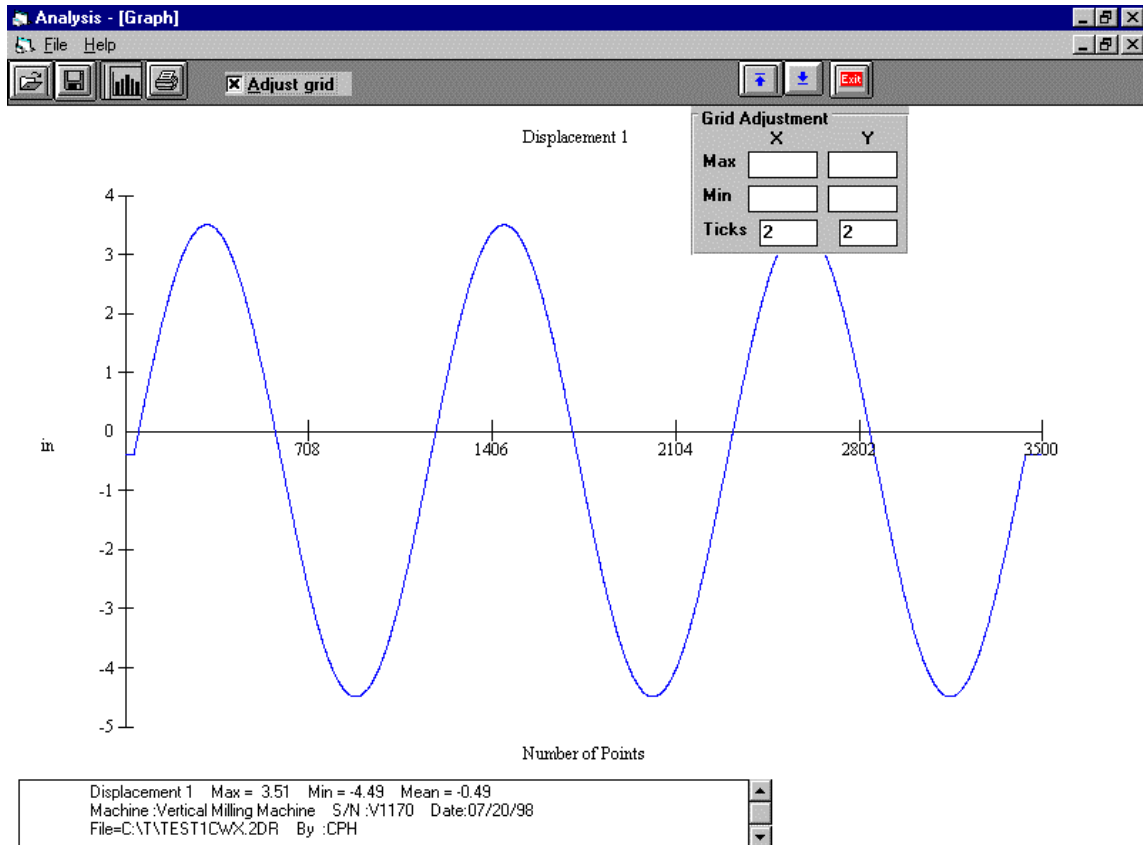


FIG. 13-7 A TYPICAL PLOT ON DISPLACEMENT DATA

To generate a data file for polar plot, click on "file" and "save". A popup screen asking the starting point and ending point of the data file. The starting point should be before the first maximum and the ending point should be at least 2 and $\frac{1}{4}$ cycles after the first maximum. If not enough data, only one cycle will be processed, and a popup screen will indicate so. Enter a filename to save the data file. The extension .2dd will be added automatically. A popup screen will show the actual starting point, number of points per cycle, ending point, and the data file is for one or two cycles. After click on "Yes", another screen will popup for the change of number of points per cycle. You may enter an integer either larger or smaller than the default value. Please make sure that all 4 2dd files have the same number of points per cycle. We believe, 360 points per cycle is adequate. Of course, more points provide more resolution, but it also need more storage space and larger processing time. The default value is the existing number of points per cycle. If there is no change, press "enter" or click on "ok", then another screen popup to change the shift. You may enter any shift value between -10 to $+10$. The default shift is zero.

For some machine, the feed rate can not be controlled exactly, hence the number of points per cycle varies. It is more desirable to keep the number of points per cycle the same for all 4 files. Please note that to generate a complete circular path, 2 data files, one in the x-direction and the other in the

y-direction (for xy-plan) are needed. The number of points in these two data files should be the same. If one data file is 2 cycles and the other is 1 cycle, only one cycle of the data will be processed.

13.6.4 Circular Path

To generate a circular path, first to process all raw data files (.2dr) to generate the data files (.2dd).

Click on “analysis”, “circular”, “polar plot” and “ISO 230”, a screen will popup. The file cannot be entered by type the filename. Click on the right-hand-side to enter the files. The first line is cw, x-direction, the second line is cw, y-direction, the third line is ccw, x-direction and the forth line is ccw, y-direction. For a complete circular path, 2 data files in the same cw or ccw rotation are needed. For both cw and ccw circular path, enter all 4 files. For most machine, click on “ok”. “sync” is for machines without velocity control. Please wait for the data files to be displayed on the screen. Click on “graph” to plot the circular path in polar plot as shown in Fig. 13-8.

Before the polar plot, a screen will popup and ask for the values of S1, S2, S3, S4, Rcw, Rccw, sc and scc. These shifts and rotations are used when the measurement directions are not perpendicular to each other or the measurement directions are not along any axis direction.

For the measurement of servo mismatch or squareness errors, it is desirable to measure in the directions 45 degree from the axis. Hence, in the polar plot enter Rcw and Rccw equal to 45 degree or – 45 degree.

Positive S shifts in the ccw direction and negative S shifts in the cw direction. S is the number of points to be shifted. It is zero or an integer. S1, S2, S3, and S4 are the shifts in cwx, cwy, ccwx and ccwy respectively. Positive R rotates in the ccw direction and negative R rotates in the cw direction. The maximum angle of rotation is +/- 180 degree. Rcw and Rccw are rotational angles for cw measurements and ccw measurements respectively. Sc and scc are shifts between cw and ccw rotations respectively.

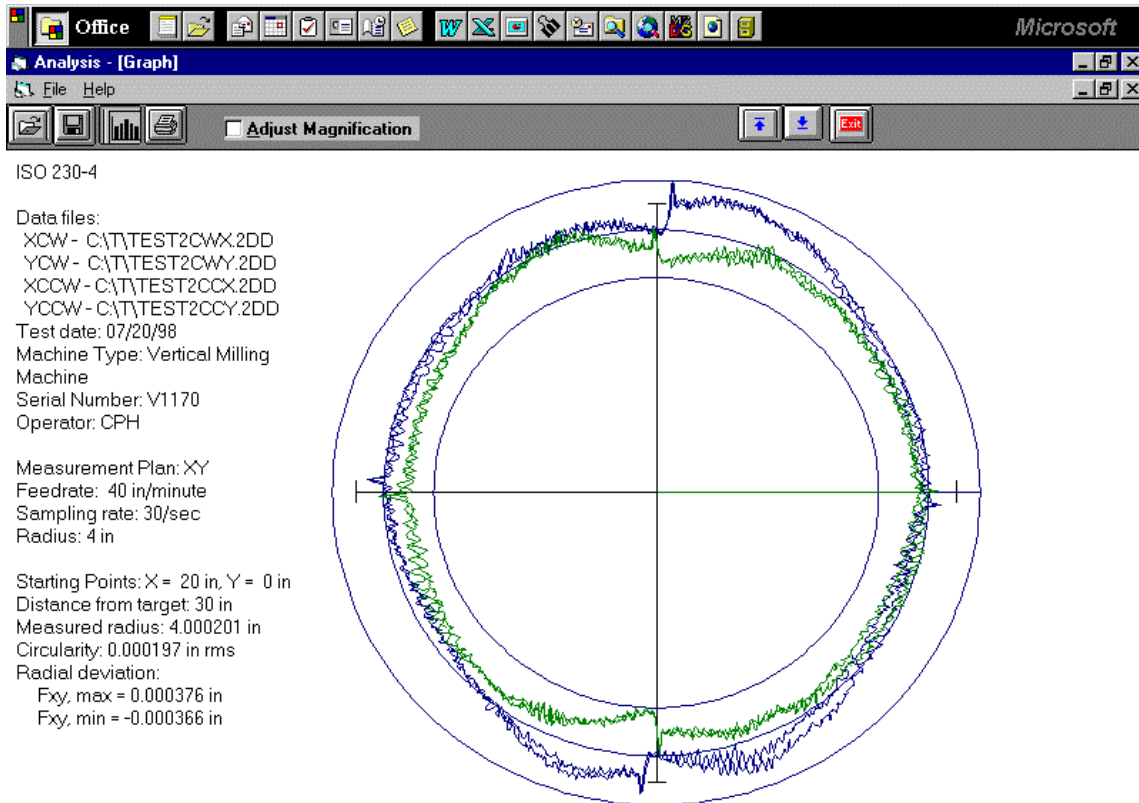


FIG. 13-8 A TYPICAL POLAR PLOT OF THE CIRCULAR PATH

There are 3 circles on the plot. The radius of the middle circle is the measured radius. The radius of the largest circle is the measured radius plus the $F_{xy,max}$ and the radius of the smallest circle is the measured radius minus the $F_{xy,min}$. Or the distance between the largest circle and smallest circle is equal to $F_{xy,max} - F_{xy,min}$. Click on the “adjust magnification” to change the magnification of the plot. The circularity is the rms value of the deviations from the measured radius.

To view more details such as vibration frequency, backlash values, reverse spikes, etc., click on “analysis”, “circular”, “polar plot”, “linear plot”, and “one of the 4 files”, then click on the “graph” button. A popup screen will let you input the starting point and the ending point of the plot. A typical linear plot is shown in Fig 13-9.

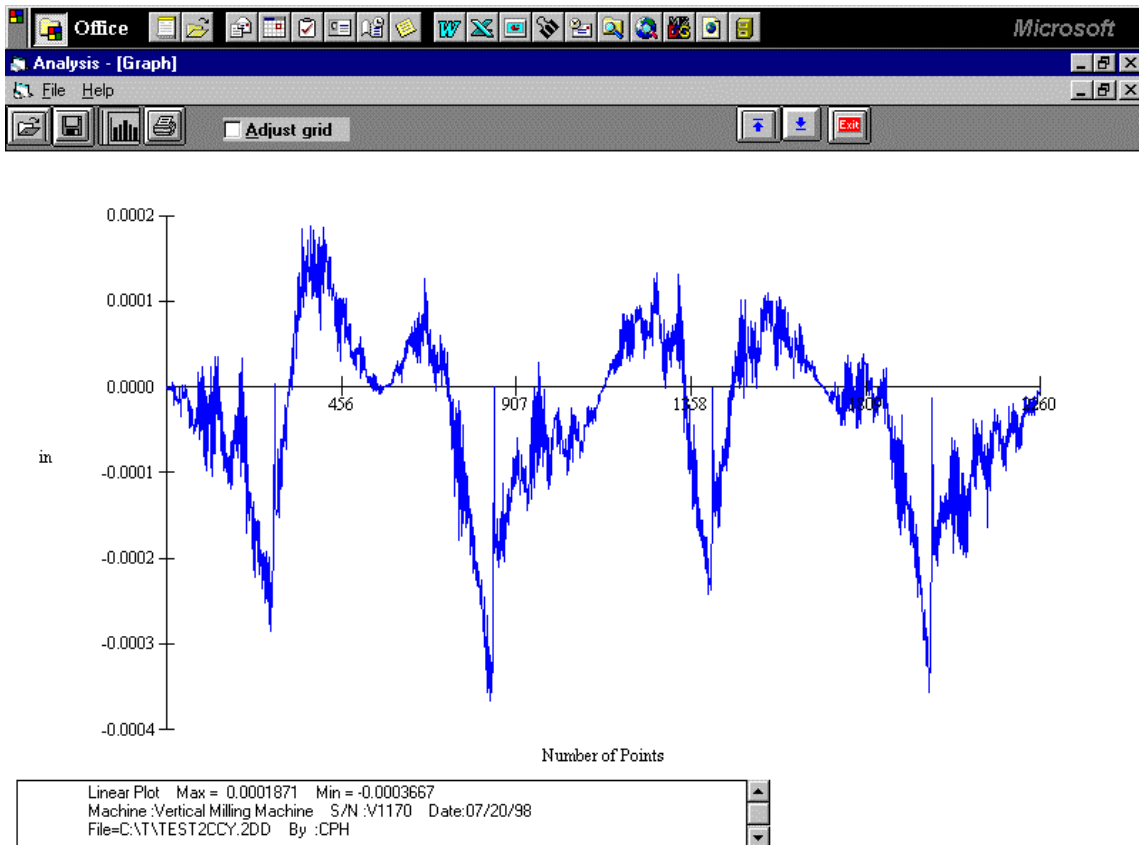


FIG. 13-9 A TYPICAL LINEAR PLOT OF THE CIRCULAR PATH

You may view more details in a region by enter the starting point and the ending point near the region of interests. You may also adjust the grid to change the vertical scale.

13.6.5 Output Data File for “Polarcheck” or “Polaranalyser” Software

To use a commercial analysis or diagnostic software, such as Polarcheck* or Polaranalyser, a compatible data file can be generated. In the previous section, before click on “graph” to plot the circular path in polar plot as shown in Fig.13-7, click on the “file”, then “save”, a screen will popup. Enter a filename and a file will be generated with extension .rtb.

This data file is similar to a telescoping ball-bar data file. The first 24 line header is machine information and parameters. Run count is how many 360 degree cycles. Max Targets is the number of points in 1 run or a 360-degree cycle. Direction -1 is cw and +1 is ccw. The best R is the actual measured radius. Since there is no center offset, hence the best X and Y

are all zero. The first column is the point number and the second column is the deviation in the radial direction. EOF is end of file.

A typical polar plot similar to Fig.13-8, but using the .rtb data file and the Polarcheck software, is shown in Fig.13-10.

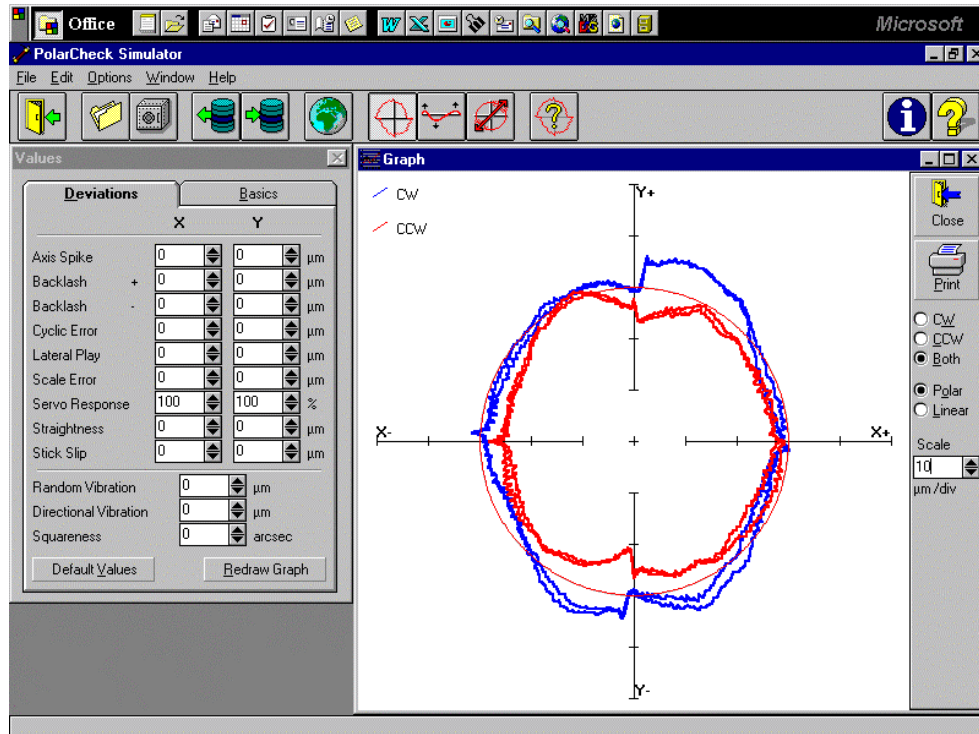


Fig. 13-10 A TYPICAL POLAR PLOT USING POLARCHECK

- For more information, check the Polarcheck Analyser Web Site: <http://kiila.me.tut.fi/projects/dbbbros.htm> or e-mail jouni.holsa@qplus.fi

13.6.6 “rtb” button to generate output file directly

To generate an output file directly from 2dr files, click on the “rtb” button. A screen will popup and allow you to enter 4 2dr files. You may click on “ok” or “sync”. For most machines, click on “ok”. “sync” is for machines without velocity control. Enter the filename to save the output data file. To verify the output data, click on “graph” to view the polar plot. In case of error, use the procedure in the previous section.

13.6.7 Velocity, acceleration and other measurements

As shown in section 13.6.3, the displacement values can be displayed or plotted. Click on the “velocity 1”, the velocity values are calculated and displayed. Click on the “graph” to plot the velocity profile.

Similarly, the acceleration values can be calculated by click on the “Acceleration 1” button. To remove a spike or spikes, click on the “R-spike” button, and specify the starting point and the ending point, the spike or spikes between the starting and ending point, will be removed and the displacement values recalculated. Please note that, remove the spikes may distort the circular path.

The 2D time base data collection can collect data up to 1000 Hz. It can also be used for many other applications, such as small increment displacement test, etc.

13.6.8 Feedforward and Velocity Feedback

For some controllers without the feedforward function or the feedforward function is not turned on, there is a notch on the velocity profile as shown in Fig. 13-11. These velocity notches may cause non-uniform cutting and effect the surface finish of the part.

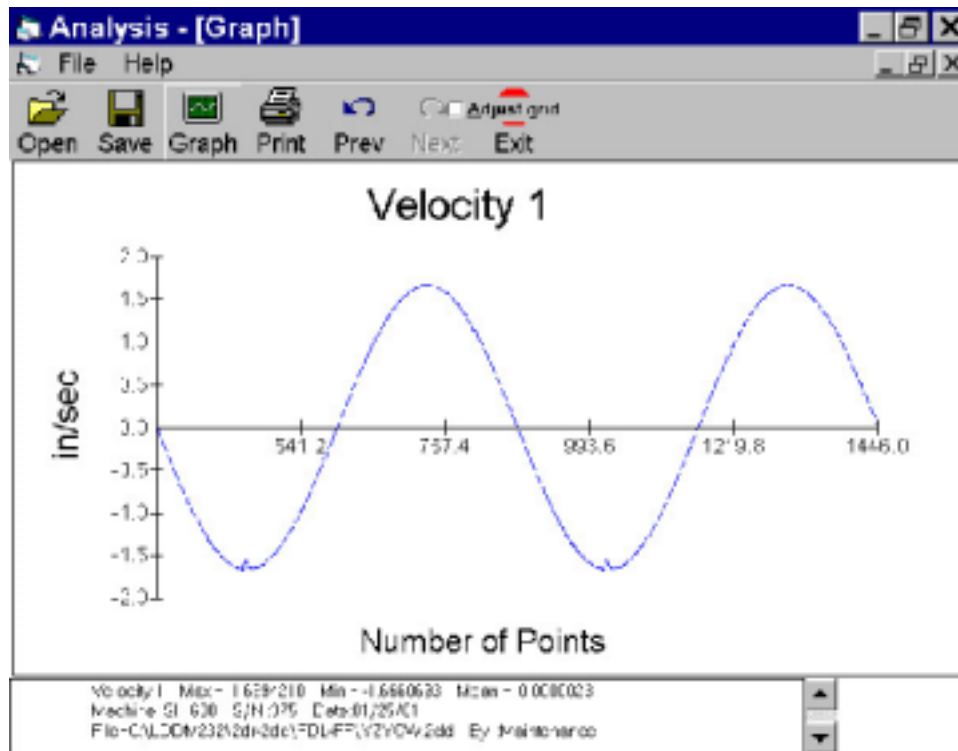


Fig. 13-11 A Plot of Velocity Profile without Feedforward. There are Notches near the Maximum Velocity in the Negative Direction.

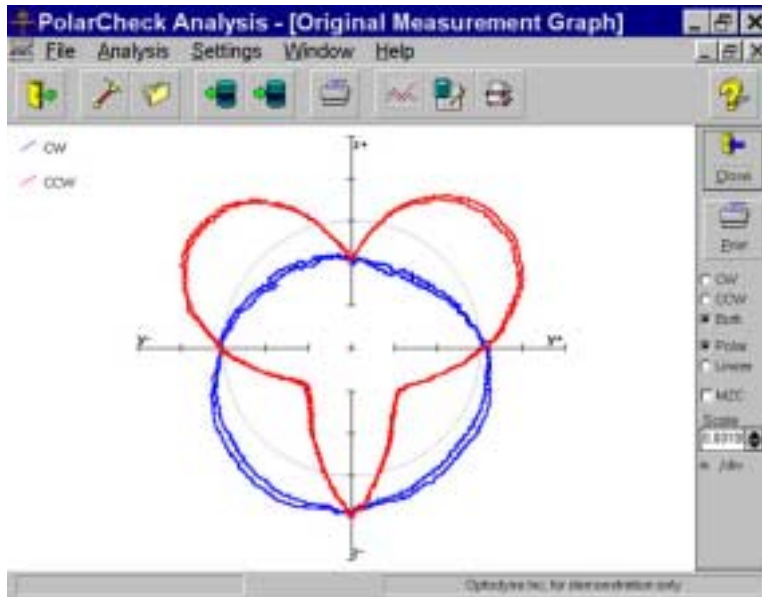


Fig. 13-12 A Polar Plot of the Circular Contouring Error without Feedforward

The large non-roundness shown in Fig. 13-12 is caused by the velocity notches. Once the feedforward function is turned-on, the velocity notches in Fig. 13-11 are removed and the polar plot shown in Fig. 13-13. The non-roundness is reduced considerably.

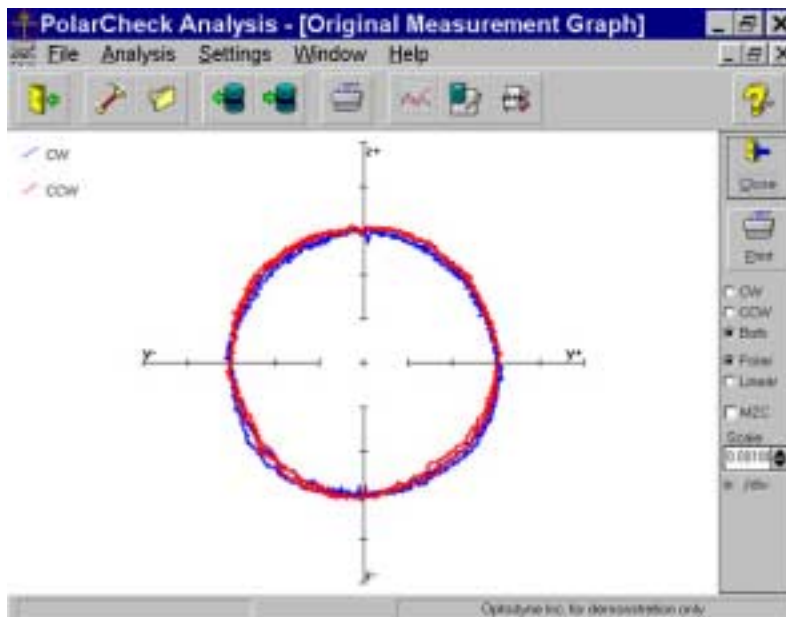


Fig. 13-13 A Polar Plot of the Circular Contouring Error with Feedforward

For some controllers, there is no velocity control, the velocity profile looks like triangular shape (see Fig. 13-14) instead of the sinusoidal shape. The polar plot, (see Fig. 13-15) shown large loop and the non-roundness is excessive large. This is because in the data processing,

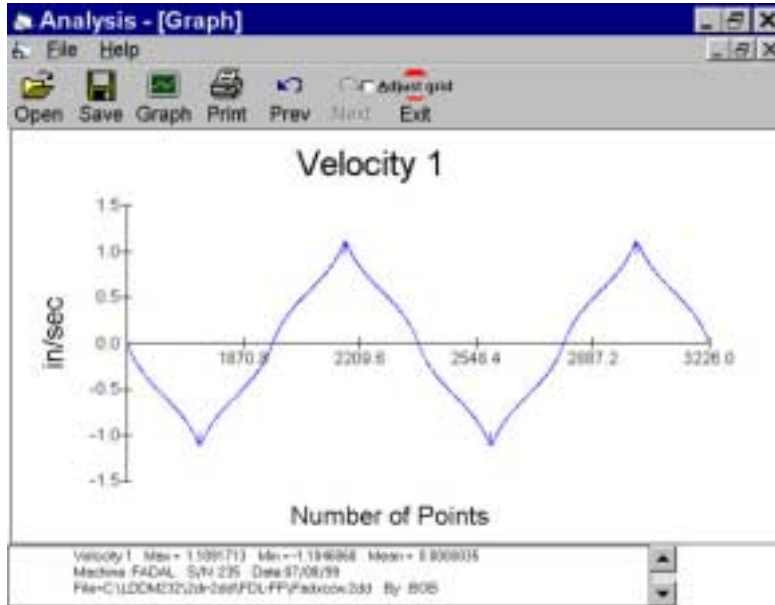


Fig. 13-14 A Plot of Velocity Profile without Velocity Feedback

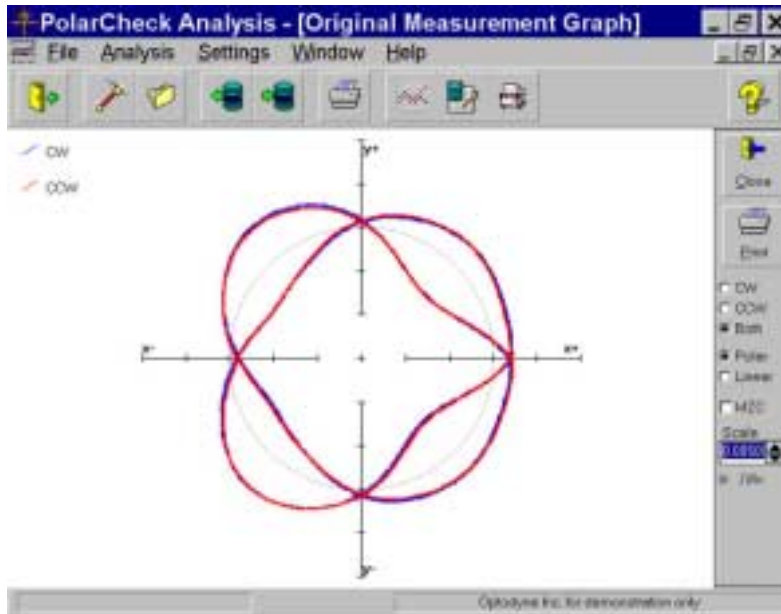


Fig. 13-15 A Polar Plot of the Circular Contouring Error without the Synchronized Data Processing

it is assumed that the velocity is uniform or sinusoidal. To fix this problem, a “sync” button is added in the “select Axis Data files” screen. The non-roundness is reduced as shown in Fig. 13-16.

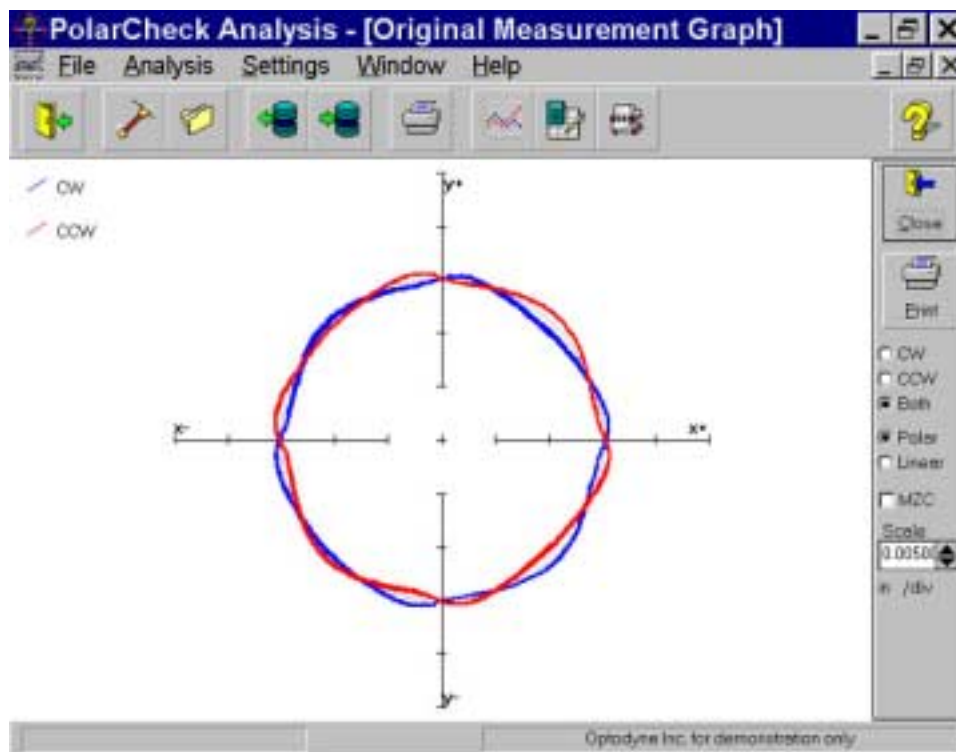


Fig. 13-16 A Polar Plot of the Circular Contouring Error with the Synchronized Data Processing

13.7 Accuracy and Error Sources

13.7.2 The general accuracy and error sources are discussed in section 7.7 and appendix J.

13.7.3 The circular path measurement here is a 2 dimensional measurement. That is both the x-coordinate and the y-coordinate of the circular path are measured. As compare with the telescopic ballbar measurement, only the deviations in the radius direction are measured. The angular position is calculated by the feed rate and the data rate. Hence the constant feed rate and the constant data rate are very important. Also, the telescopic ballbar needs constantly calibration to maintain accuracy.

The laser measurement is non-contact and no cable is on the way. Hence there is no mechanical errors such as friction, contact and forces between the ball and the socket, weight of the linkage, and the pulling of the cable.

13.7.4 Alignment errors

The cosine error is due to the laser beam not parallel to the plan of rotation. Since the cosine error is a constant, it will not effect the circular measurement except the measured radius. The cosine error can be corrected if the cosine angle is known. When the laser beam is not exactly parallel to the axis of movement, the measured angular position will be shifted by the same amount. Usually the accuracy of the angular position is not critical.

13.8 Taking a Measurement

13.8.2 Set up

- 1, Connect all cables and turns on the power.
- 2, Make sure all of the hardware is installed and aligned properly.
- 3, The PCMCIA card should be plugged into the notebook pc, and make sure the proper driver is selected and communication established.
- 4, Load the MCV-500 program and click on the “2d time base”.
- 5, Make sure the PCMCIA card is properly connected and functioning and the green light is on when aligned.
- 6, Determine the feed rate, the data rate, the plan of measurement and axis of measurement.

13.8.3 Alignment

- 1, Mount the laser head on the bed (or spindle) and pointing the laser beam in the x-direction (within a few degrees).
- 2, Mount the flat-mirror target on the spindle (or bed) and position the flat-mirror to cover the entire circular path. Align the flat-mirror by using the fine screws on the back. Make sure the return beam enters the laser aperture and the green light on the notebook PC is on over the entire circular path.

13.8.4 Data collection

1. Click on the LDDM Logo to start.
2. Click on the “2D Time Base” in the main menu to get the data collection screen.
3. Enter machine identification and feed rate. Select a measurement plan, rotation sense (CW or CCW).
4. Enter the start position, the measurement direction, orientation, and distance from target. The orientation is O for on axis direction. For measurement between two axes, enter the angle in degree from the first axis. Enter data from 1 to 1000 data/sec. Select the feed rate F[in/minute], the radius R[in] and the data rate S[data/sec] within the following range

$$100 < 360 * \frac{S}{F} R < 1000$$

For example,

$$R=2 \text{ in, } F=40 \text{ in/min, then } \frac{100}{18} < S \leq \frac{1000}{18} \text{ or select the data rate}$$

between 4 to 60.

5. Trigger—start button only
Cosine Correction—Single pass = 1
Double pass = $2\cos\theta$

Where θ is the angle between the outgoing and return beam.

Radius of circular path—should be less than $\frac{1}{2}$ the length of the flat-mirror.

Scale factor = 0.000024914 in.

Channel number – automatically selected by your PC or manual selection.

Intensity – green means okay
Red means out of alignment

Start – press start to start collecting data and press end to stop.

Maximum data file is 16000 data points.

Start the spindle motion first, then press start.
Collect at least 3 cycles of data.

6. Save data, enter the file name and an extension .2DR will be added automatically.

13.8.5 Data Analysis

1. To analyze data, go to the main menu first, then click on “Analysis”. Click on “File” to open a file with extension .2DR.
2. The file usually is very large. Please wait a few seconds for the file to be ready. The .2DR data will show on the screen. Click on “Data Selection” and “Displacement 1”, the displacement values will be calculated and displayed.
3. Click on “Graphics” to plot the displacement data. Enter starting point and ending point for the plot. A Sine curve should be plotted on the screen.
4. For a circular test, select 2 and $\frac{1}{4}$ cycle data points, starting before a first maximum and ending at $\frac{1}{4}$ cycle or more after the third maximum. (For 1 cycle, select the ending point $\frac{1}{4}$ cycle after the second maximum).
Return to the table and click on “File” and “Save”. Enter the starting point and the ending point.
5. A “Save Displacement Data” screen will pop up. Enter the filename and “OK”. The data will be saved in the file with extension .2DD.
6. A “Displacement Cycle Determination” screen will pop up. Confirm the starting point, the ending point and total number of points in 2 or 1 cycle.

7. Click on “Analysis”, “Circular”, “Polar Plot” and “ISO230”.
A “Select Axis Data Files” screen will pop up. Enter the files by clicking on the right-hand buttons.
8. The selected files will be displayed. Click on “Graphic” to plot the Circular path. Click on “Adjust Magnification” to change the magnification factor.
9. The left-hand-side is the description of the test. The measured radius is the actual radius. The circularity is the rms deviation from a best fitted circle. The Fxy.max and Fxy.min is the maximum deviation larger than the unit circle and the maximum deviation smaller than the unit circle, respectively.
10. To get a linear plot, click on the “Analysis”, “Circular”. “Linear Plot” and select the file to be plotted. Click on “Graphics” to plot. Enter the starting point and ending point.
11. To plot velocity, click on “Data Selection” and “Velocity”. Click on “Graphics” and enter the starting point and ending point, the velocity vs point number will be plotted.
12. To plot acceleration, click on “Data Selection” and “Acceleration”, click on “Graphics” and enter.

13.9 Diagnostics

13.9.2 General Description

The linear measurements are important for the compensation of the linear positioning error. The circular measurements are important for the turning of servo-controller to achieve the dynamic motion accuracy resulting from two or more axes coordinating properly. As the machine is traversing with multiple axes along a circular trajectory each axis goes through sinusoidal acceleration, velocity and position changes. The measured circular path data will show any deviations the machine makes from a perfect circle. The error sources are backlash, reversal spike, servo mismatch, squareness error, machine vibration, cyclic error, stick-slip, etc.

13.9.3 Common errors

1. Backlash step:
A step along one axis indicates lost motion from backlash or play. An outward step may be caused by play in the drive system or over compensated. An inward step may indicate hysteresis in the encoder.
2. Axis reversal spike:
A pair of short spikes, starting on either axis, indicates an axis not reversing properly. This may be caused by sticking, or slow response time in the CNC's backlash compensation, or not enough lost motion compensation.
3. Servo mismatch:
An oval shape tilted by 45 degrees and shifts back and forth by 90 degrees, depending on the direction of travel. This indicates mismatched servo gains in the CNC, or sometimes called servo follow error.
4. Squareness error:
An oval shape tilted by 45 degrees as in the servo mismatch. However, the tilt is always in the same direction for either CW or CCW rotation.
5. Machine vibration, cyclic error and stick-slip:
Oscillation that does not vary in frequency indicates machine vibration. If it varies in frequency, indicates cyclic error, due to flaws in the axis leadscrew. Noise like oscillation results when friction causes the axis to stick-slip.

13.9.4 Definitions in ISO 230-4 standard

1. Circular hysteresis:
“H” is the maximum radial difference between two actual paths, where one path is carried out by a CW contouring motion and the other are by an CCW contouring motion.

2. Circular deviation:
“G” is the maximum radial separation of two concentric circles enveloping the actual path (minimum zone circles) and which may be evaluated as the maximum radial range around the least square circle.

3. Radial deviation:
“F” is the deviation between the actual path and the nominal path, where the center of the nominal path is obtained either,
 - a) from the centering of the measuring instruments on the machine tool or
 - b) from the least square centering analysis for a full circle only.

APPENDIX A. LIST OF COMPONENTS

FEATURES AND BENEFITS OF OPTODYNE LDDM™ COMPONENTS		
Component Code/Description	Features	Benefits
L-101 Dual-aperture Laser Head	Dual aperture collimated laser beam Separate aperture for both output and return beams	Compact Light weight Long range, up to 60 m Easy alignment and large lateral tolerance
L-102 Single aperture Laser Head	Single aperture Collimated laser beam Output and return share the same aperture	Compact Light weight Small retroreflector May use flat mirror as target Double-path arrangement possible
L-104 Dual-beam laser head	Dual beam Two collimated laser beams Two Detectors	Compact Light weight Detect both linear and angular displacement Equivalent to two interferometers in one system
P-111 Standard Processor Module	One signal channel RS-232 port ATC amplifier Universal power supply	Fast data processing, 72 ips 9600 Baud RS-232 serial port for notebook computer or serial printer. Amplifiers for ATC or QD. Input power may vary from 100V to 230V, 50 to 60 Hz. Other input interfaces available.

FEATURES AND BENEFITS OF OPTODYNE LDDM™ COMPONENTS		
Component Code/Description	Features	Benefits
P-210 Dual-channel Processor Module	Two signal channels RS-232 port ATC amplifier Universal power supply	Measures linear and angular displacement simultaneously. Extended resolution 1µin or 0.01 µm (display; 0.05 µin or 0.001 µm.
D-101 Display Module	2 rows of 10 digit large LED display 2 reset buttons	May view displacement at a long distance may reset or change displacement mode by pressing push-buttons.
R-106 Ø1in retroreflector	Ø1in retroreflector	Return a parallel laser beam to the laser head.
R-102 Ø½ in retroreflector	Ø½ in retroreflector	Small, compact retroreflector High resonance frequency for vibration measurement.
Flat Mirror	Mirror for vibration measurement	Low-cost, disposable mirror for high frequency vibration measurement.
Two inch focal lens	Two inch focal lens for vibration measurement	Non-contact measurement. Small focal spot. High resonance frequency.
LD-ATC ATC Sensors	Measure air pressure, air temperature, and material temperature	Automatically compensate for speed of light changes. Measures the material temperature for the correction of thermal expansion.
QD Quad-detector	Determines the centroid of the laser beam	Locate the centroid of the laser beam for squareness and straightness measurement.
LD-16 Optical Square	Generate a reference beam exactly 90° from the entrance beam	Generate a 90° reference for squareness measurement.

IPC-400 Computer Interface Card	Handle up/down pulses, analog phase signal and error signal from the processor module	Fast and direct interface with computer. Store 64,000 data points per axis and up to 3 axes Data rate up to 800,000 data/sec.
Software	DOS or Windows Menu-driven Store previously entered parameters as default View & plot from screen	User friendly with instructions on the bottom margin of the monitor, help file in Windows. Eliminates need to re-enter parameters for repeated measurement, reducing measurement time and error. Eliminates need for plotter.
IPC5-1000 PCMCIA Interface card	Up/down pulses, digital phase signal and error signal from the processor module	Fast & direct interface with notebook PC. Date rate up to 1000 Hz

FEATURES AND BENEFITS OF OPTODYNE LDDM™ COMPONENTS		
Component Code/Description	Features	Benefits
S-102R Metrology Program	<p>Manual data collection</p> <p>Automatic data collection</p> <p>Data analysis and plot</p>	<p>Enter actual stopped positions for manually-operated machine. Eliminates time-consuming fine adjustments of target position. Compensate for changes in air pressure, air temperature, and material temperature. Automatic data collection without having to press a button at each step.</p> <p>Data stored on floppy disk can be recalled for later use, or to generate a compensation file for the machine controller.</p>
S-103R Flatness and Angle Program	<p>Manual data collection</p> <p>Automatic data collection</p> <p>Pitch, yaw or straightness data collection and analysis</p> <p>Surface flatness data analysis</p>	<p>With 2-channel processor module, data can be collected automatically without stopping. Use Moody's method to generate surface flatness table, isometric surface plate plot and numeric plot for surface flatness. Angular displacement can be plotted in μradian, arcsec or straightness in μin.</p>
S-106 Catch/View Program	<p>Catch and transport data from SRAM to disk memory</p> <p>View data on the monitor with zoom-in and zoom-out features</p>	<p>Capture data with pre- or post-trigger. Trigger with push-button, keyboard, or displacement. Quick view data on the monitor.</p>

S-107 Analysis Program	Convert binary data file to ASCII data file Differentiate displacement to obtain velocity Differentiate velocity to obtain acceleration Use FFT to obtain PSD Use FFT to do band-pass filter Calculate SRS	Calculate velocity and acceleration. Obtain settling time, resonance frequency, and damping. Process data to obtain PSD, SRS, etc.
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APPENDIX B. LDDM™ SYSTEM CONFIGURATION

APPENDIX C. DESCRIPTION OF MICROPROCESSOR AND FIRMWARE

The C3 board is a single board computer based on the HD64180 microprocessor, which uses an enhanced Z80 instruction set. It uses a Crystal Frequency of 12.288 MHz and runs at a clock speed of 6.144 MHz. Memory management, an interrupt controller, a programmable timer, and an asynchronous communications interface are all provided on the chip.

Two types of program memory are used. The main system firmware is stored in a read-only memory. The application program, which can be configured to suit the user, is stored in a non-volatile electrically erasable read-only memory; it can be re-programmed in the field via the built-in RS-232C port, using an IBM-PC compatible computer.

The C3 board has three basic functions: (1) data acquisition, (2) display and I/O control, and (3) serial communications (RS-232C). Data acquisition capabilities include two up/down counter channels for displacement information, two high speed analog channels for high resolution displacement information, and eight analog channels for temperature, pressure, and laser signal strength. Four of the analog channels can be used for quad cell inputs instead of temperature and pressure, and two are reserved for future use.

The firmware interprets the acquired data to provide quad cell position, two channel displacement, bar-graph signal strength indicators, ambient temperature, atmospheric pressure, and two material temperatures. If a temperature/pressure probe is connected, the displacement is corrected for variations in air temperature and pressure. The presence of a temperature/pressure probe is automatically detected; if the probe is not present, correction is based on standard conditions of 760 mm Hg and 20°C. Values are sent to the display in inch or metric units, and user inputs from the display unit are monitored allowing a choice of displayed information. If an IBM-PC compatible computer or an ASCII terminal is connected to the serial port, both display and user input functions can be controlled from the keyboard, from PC application programs or from the display keyboard, from PC application programs or from the display unit. The data which is sent to the display is also sent to the PC or terminal CRT screen; both displays are updated 10 times per second.

Summary of Display Modes

Hold X and Press Y to change modes (see Fig. 2-5).
Press Y to rotate down the columns as shown below:

Mode 1 X-Intensity	Mode 2 Quad Cell	Mode 3 2 channel (inch)	Mode 4 2 channel (mm)	Mode 5 X-Y extra
Wavelength	0.0000	X- Displacement	X- Displacement	X-Wavelength
Intensity	0.0000	Y- Displacement	Y- Displacement	Y-Wavelength
X- Displacement	0.000	<i>Reset X or Y</i>	<i>Reset X or Y</i>	X-Intensity
Intensity	0.000			Y-Intensity
X- Displacement	0.00000			M-T1 M-T2
P _{AIR} T _{AIR}	0.00000			P _{AIR} T _{AIR}
X- Displacement	ADC			
M-T1	ADC			
M-T2	ADC			
<i>mm/in toggle</i>	<i>mm/in toggle</i>			

Downloading Firmware to the LDDM™ Processor Box

The Optodyne software XXM.BAT and XM.EXE can be used to load firmware into the LDDM™ Processor unit's non-volatile memory from a personal computer. The XXM.BAT program sets the communications parameters for the COM1 serial port. The DOS external program MODE.COM must be available on the disk or in the DOS path.

1. Connect the serial port of the computer to the serial port of the LDDM™ (use a standard modem cable).
2. Turn on the computer and boot DOS, then turn on the LDDM™.
3. Put the disk with XXM.BAT and XM.EXE into drive A.
4. Type A: then press ENTER.
5. Type XXM then press ENTER.
6. Data will be scrolling down the screen. If not, press "C".
7. Hold down the SHIFT key and press "6".
8. Press the PAGE DOWN key (file name prompt appears). Type the name of the firmware file you want to download then press ENTER.
9. When the data stops scrolling on the screen, type g0 (the letter, "g" and the number, zero) then press ENTER.
10. To load a different file, begin at step 7.
11. To end this program, hold down the CONTROL key and press the END key.

APPENDIX D. DESCRIPTION OF INTERFACES

The LDDM™ Processor Unit can be configured to give the following outputs:

- Up/Down Count pulses
- Analog Phase
- A Quad B Quadrature square wave
- Laser error signal
- BCD

Up/Down Count

The Up/Down pulses are high going TTL level pulses with a minimum pulse width of 30 ns, and a maximum pulse rate of 10 MHz. The inactive pulse output is held low while the other is active. The output buffer can source 15 ma (output high current) and sink 24 ma (output low current). In some configurations an RSV-422 buffer provides single ended outputs with 50 ma source and sink.

Analog Phase

The Analog Phase signal is voltage which is used to interpolate values between position pulses. With movement in the up direction, this voltage changes from 1.7 to 4.2 volts between two up pulses; with movement in the down direction, the voltage changes from 3.1 to 0.6 volts between down pulses. The voltage ranges are different because the pulse output has hysteresis when the direction changes. The leading edges of the up/down pulses are coincident with the respective extremes of the analog voltage ranges.

Digital Phase

Same as analog phase except the output is 8-bit digital signal.

A Quad B

The quadrature square wave signals are at TTL levels. In the normal configuration an RS-422 buffer provides 50 ma differential outputs. In some configurations the output is from a single ended output buffer, which can source 15 ma (output high current) and sink 24 ma (output low current).

Error Signal

The Error Signal is a TTL level digital output which is LOW to indicate that the laser signal level is too low, and HIGH to indicate that the laser signal level is sufficient. During an error condition, the position pulse outputs are disabled.

BCD

The BCD output is a bi-directional clocked serial port. The output data is in a special format for the LDDM™ BCD display unit. The port also accepts input data from the push buttons on the LDDM™ display unit.

APPENDIX E. RS-232C INTERFACE

The LDDM™ C3 board provides an RS-232C serial port for interface with a computer or terminal. The serial port is implemented with a (FEMALE) D-sub 9 pin connector (DB9). The LDDM™ is Data Communication Equipment (DCE), and it uses a standard modem cable. The connections are 2=RX, 3=TX, 5=GND. The LDDM™ requires no other RS-232 connections, but it may be necessary to make other connections at the terminal such as jumping pins 20 (DTR), 5 (CTS), 6 (DSR), and 8 (DCD) together. The Data Terminal Equipment (DTE) may require DTR, CTS, and DCD to be asserted before it will operate; the DTE usually asserts DTR at power on, so the jumpers enable to satisfy its own requirements.

After the power is turned on, the LDDM™ sends data continuously to the serial port at 19200 baud, with no parity, eight data bits, and one stop bit (19200, N, 8, 1). Only seven bit ASCII data is sent, so the eighth bit can be ignored. The data is the same as the LDDM™ display except that a carriage return and line feed are sent at the end of each line. The choice of data can be controlled along with the LDDM™ display unit through keyboard commands detailed below.

RS-232 Keyboard Commands

A..... Mode 1, Sub-mode 2	Displacement/Pressure, Temperature
D Change main mode	
Y..... Change sub-mode	(similar to pushing Y button in any mode)
L..... Mode 1, Sub-mode 1	Wavelength/Intensity
M..... Mode 1, Sub-mode 3	Displacement/Temperature, Temperature
Q Mode 2, Sub-mode 1	Quad Cell/4 Place
F..... Mode 2, Sub-mode 3	Four ADC (weighted average)
E..... Mode 3, Sub-mode 1	X & Y inch displacement
I Mode 5, Sub-mode 1	X & Y wavelength in inches
R Displacement Reset	(X-channel)
T..... Displacement Reset	(Y-channel)
S..... Stops serial output	Each "S" returns one line of data
C Continuous serial output	(Resume after "S" or "W")
Z..... Millimeter mode	(Not effective in modes 2 & 3)
K..... Inch	(Not effective in modes 2 & 3)
W..... Stop display and send identification	

APPENDIX F. DESCRIPTION OF PC INTERFACE BOARDS, CATCH BOARD AND PCMCIA INTERFACE

General Purpose Board

The IBM Interface Board is a ¼ length plug-in board for IBM PC and compatible computers. The board accepts UP and DOWN pulses along with an analog phase signal that is used to interpolate positions between up or down pulses. There is also an EXTSW (External switch) input for external trigger control. The up and down pulses are counted in a 22 bit up/down counter. On command from the PC or from an external switch, the count is latched and the analog signal is sampled and digitized; the computer then uses this information to calculate position. When ERROR is a logic low, the laser signal is not valid.

Jumpers on the board provide a means to choose internal or external latching and to choose which interrupt the PC uses to detect when digitizing of the phase signal is complete. This interrupt is optional since the same information is included in the counter register. The EXTSW signal is pulled high on the board. It should be pulled low by the external switch for the quiescent state, and released high to trigger position latching.

There is an 8 position DIP switch on the board for selecting the bus address:

	1	2	3	4	5	6	7	8
210H to 213H	ON	ON	OFF	ON	ON	ON	ON	OFF
214H to 217H	OFF	ON	OFF	ON	ON	ON	ON	OFF
218H to 21BH	ON	OFF	OFF	ON	ON	ON	ON	OFF
21CH to 21FH	OFF	OFF	OFF	ON	ON	ON	ON	OFF

External connections to the board are made via a female DB9 connector. Pin assignments are as follows:

1	Analog Ground
2, 3, 4	Digital Ground
5	EXTSW (External Switch)
6	Analog Signal (Phase)
7	ERROR
8	DOWN
9	UP

Three Channel Catch Board

The Three Channel Board (3C) is a full length IBM PC plug-in board. It can be configured for one to three channels. The board accepts UP and DOWN pulses along with an analog phase signal and an ERROR signal from the LDDM™. The analog phase signal is used to interpolate positions between up or down pulses. The data is stored in on-board memory at rates from 6.25 kHz to 800 kHz. After the storage rate clock is turned on, the point at which data stops being stored is determined by one of three types of trigger; keyboard, external button switch, or a displacement from 1 to 3000 μ in indicated by the input signal. When the board is triggered, it stops recording data after a previously chosen delay. The delay can be nothing, half of the recorded data, or all of the recorded data. The data can be taken before the trigger, half before and half after the trigger, or after the trigger. The data is then read by the PC and used to calculate position information.

There is an 8 position DIP switch on the board for selecting the bus address:

	1	2	3	4	5	6	7	8
210H to 213H	ON	ON	OFF	ON	ON	ON	ON	OFF
214H to 217H	OFF	ON	OFF	ON	ON	ON	ON	OFF
218H to 21BH	ON	OFF	OFF	ON	ON	ON	ON	OFF
21CH to 21FH	OFF	OFF	OFF	ON	ON	ON	ON	OFF

External connections on the board are made via a female DB25 connector. The following are the pin assignments:

Channel 1		Channel 2		Channel 3	
1	Analog	5	Analog	9	Analog
	Ground		Ground		Ground
14	Analog	18	Analog	22	Analog
	Signal		Signal		Signal
2	ERROR	6	ERROR	10	ERROR
3, 4, 17	Digital	7, 8, 21	Digital	11, 12, 25	Digital
	Ground		Ground		Ground
15	UP	19	UP	23	UP
16	DOWN	20	DOWN	24	DOWN

Minimum Sampling Rate

For high resolution catch board, the data input is 6-bit up/down pulse, 10-bit ADC. The resolution is 0.6 nm.

Minimum sampling rate is:

$$= \frac{V_{\max}}{6\text{-bit} \cdot 12.5\mu\text{in} \cdot \frac{1}{2}} = \frac{V_{\max}}{400} \times 10^6 \text{ data/sec}$$

Assume sine waves:

$$\begin{aligned}x(t) &= x_0 \sin 2\pi ft \\v(t) &= 2\pi f x_0 \cos 2\pi ft \\v_{\max} &= 2\pi f x_0\end{aligned}$$

Minimum sampling rate:

$$= \frac{2\pi f x_0}{400} \times 10^6$$

For example, $f = 1 \text{ Hz}$
 $x_0 = 1.4 \text{ in.}$

The minimum sampling rate is:

$$\begin{aligned}&= \frac{2\pi \cdot f \cdot 1.4 \times 10^6}{400} \\&= 21 \text{ kHz}\end{aligned}$$

For a high speed laser head, the minimum sampling rate is half the standard one, ie. 10.5 kHz.

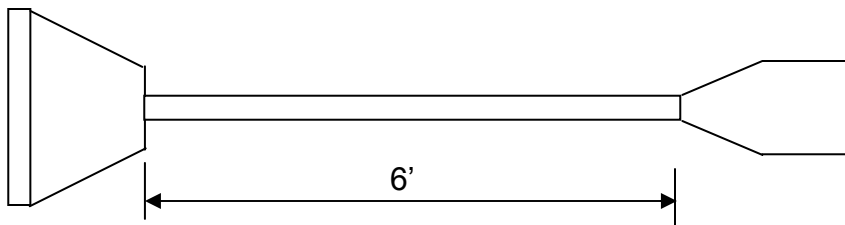
For the standard catch board, the data input is 8-bit up/down pulse and 8-bit ADC. The minimum sampling rate is 4 times lower.

PCMCIA Interface

The PCMCIA interface is a PCMCIA card for the notebook PC. The card accepts UP and DOWN pulses along with a 8-bit digital phase signal that is used to interpolate positions between up or down pulses. The up and down pulses are counted in a 16 bit up/down counters. The up counts, down counts, and digital phase signal are recorded at a sampling rate of 1 Hz to 1000 Hz (higher data rates are available in DOS operating system). When ERROR is a logic low, the reading is not valid. The available bus addresses are: 350, 110, 220, 100 and 300. The 350 is the default address.

The pin assignments are the followings.

	Microminiature PCMCIA Connector Pin #	15 DB Connector (Male)
ADC	1 – 8	1 - 8
ERROR	17	9
RD	21	10
UP CNT	28	12
DN CNT	31	11
GND	33	13



APPENDIX G. LIST OF SOFTWARE

There are four types of software which is a function of units and communication method used. the letters at the end of the part number indicates the type. For example, "R" indicates the software is for English units (switchable by a DIP switch) and communicates through an RS-232 port; "RC" indicates the software is for either English or metric units (switchable by a computer command) and communicates through an RS-232 port; "G", "S", or no letter indicates the software is for either English or metric units and communicates through a special IBM PC interface card (p/n IPC-1 or p/n IPC-400).

p/n	Program Name	Description
W-102	Linear Calibration Program	For linear displacement measurement and calibration
W-103	Straightness/ Surface Flatness	For linear, angular, straightness and Flatness measurement
W-104	Squareness Program	For aquareness and atraightness measurement
W-105	Rotary Table Calibration Program	For calibration and compensate rotary table
W-106	Straightness Display Program	For the alignment of long guide ways
W-125	Winpipe comp. File Program	For automatic download comp. files
W-500	Linear Program for MCV-500	For linear displacement measurement
W-500LB	Circular contour Program	For non-contact circular contour measurement
W-500PC	Polarcheck Diagnostics Program	For diagnostic of circular contour
W-500SD	Sequential Diagonal Program	For the volumetric calibration and compensation
W-500BS	Circular Contour & Sequential Diagonal Program	For both circular contour & volumetric Measurement
S-106G (DOS)	Catch/View Program	Catch vibration data at 800kHz data Rate and to view data on the monitor
S-107 (DOS)	Analysis Program FORTRAN data Analysis	Process the vibration data at generate Velocity, acceleration by differentiation, to Generate power spectrum density and band pass filtering by FFT and to Generate shock response spectrum
W-Comp	Volumetric Comp. and Linear Comp.	Generate volumetric comp. And linear comp. Files for various controllers

APPENDIX H. AUTOMATIC TEMPERATURE COMPENSATION (ATC)

Accurate measurement is dependent upon the measuring system's ability to adjust to environmental changes and upon the user's/operator's ability to set-up and operate the system properly.

Environmental changes affect the wavelength of the laser beam and the material's physical properties. The wavelength of the laser beam is the standard for distance measurements and is proportional to the velocity of light in air.

The velocity of light in air changes due to varying air temperature, pressure and relative humidity.

As a rule of thumb, a 1°K increase in temperature corresponds to an increase in laser beam wavelength of 1 ppm. A 1°K increase in temperature is equivalent to a 3.3 mbar decrease in pressure, or 25% decrease in relative humidity.

THUS, FOR ACCURATE MEASUREMENTS, AIR TEMPERATURE, PRESSURE AND RELATIVE HUMIDITY SHOULD BE MEASURED AND THEIR EFFECTS COMPENSATED.

Most materials undergo expansion or contraction due to change in temperature. If a part is measured at two different temperatures, two different values will result. Sometimes this difference can be as great as 100 ppm and can be the most significant source of error in distance measurements.

Ideally and distance measurement made with the LDDM™ should be done in a temperature controlled room held at the standard temperature of 68°F (20°C). Then all parts will be at their "true" size as defined by the International Committee on Weights and Measures.

Since a temperature controlled room is not always available, there should be a compensation factor (Material Thermal Expansion Coefficient) to compensate for the amount of change due to temperature variations. At the time of the measurement, the temperature of the material must be known. Material temperature and the material's coefficient of expansion will allow you to determine the amount of change due to fluctuations in temperature. The material thermal expansion coefficient depends on the type of material. A list of materials and their thermal expansion coefficient is provided in the software.

THUS, FOR ACCURATE MEASUREMENTS, MATERIAL TEMPERATURE SHOULD BE MEASURED SO THAT THE EFFECT OF EXPANSION/ CONTRACTION CAN BE COMPENSATED.

Setup and measurement error is due to misalignment of the machine travel along the laser measurement axis (cosine error). For an accuracy of 1 ppm, the misalignment angle should be less than 1 mrad. There is also error due to uncompensated measurement path length (dead path error).

In order to accurately correct the effects of environmental changes and material temperature on the laser reading, the Automatic Temperature Compensation Factor and Material Thermal Expansion Coefficient should be keyed in. This can be done manually if you can measure the temperatures and feed in the data with the help of the table given in the software. To compensate automatically, you have the option of attaching the ATC (for notebook PC's) or the ATCC (for IBM's/compatible's). The ATC and the ATCC will automatically compensate for the environmental changes.

The ATC package comes with an ATC board, air sensor and material temperature sensor. In order to compensate for the temperature change, you must place the sensors where they can monitor the conditions influencing the laser. The air sensor (black box, which continuously monitors the atmospheric conditions) should be kept as close as possible to the actual measurement path, so that it can monitor the conditions the laser beam is experiencing. The material temperature sensor should be placed on the part of the machine closest to its displacement measurement system. Do not place the air sensor on top of the processor box during a measurement. The processor box heats up due to its power supply, and placing the air sensor on top of the processor could alter the air reading.

Important: Note that when you are using Optodyne's ATC package, you do not have to key-in air temperature; it will be compensated for automatically. But, for the Material Thermal Expansion Coefficient, you have to key-in the TYPE of MATERIAL of which you are measuring the displacement. Two tables of Thermal Expansion Coefficients are provided in the software.

ATC Specifications:

Temperature:

Range: 60-90°F (15-32°C)
Accuracy: 0.18°F (0.1°C)

Pressure:

Range: 25-32 in Hg (635-813 mm Hg)
Accuracy: 0.05 in Hg (1.3 mm Hg)

Cable:

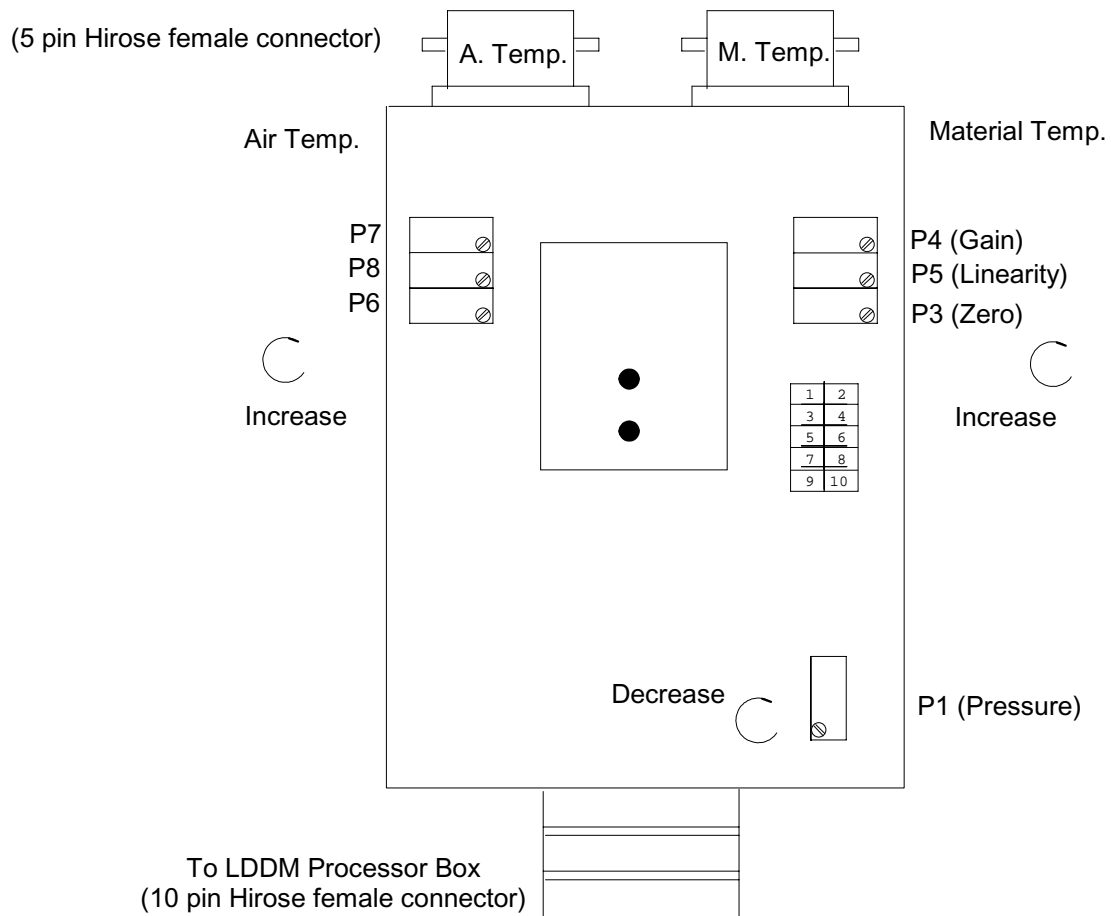
4 ft., standard (1.25m)
12, 36 ft available (3.5, 11 m)

Material
Temperature:

One material temperature sensor is standard.
Additional material temperature sensors up to
4 is optional.

Temperature/Pressure Probe Calibration Procedure

1. Connect the temperature/pressure probe to the processor box, turn on power.
2. Place both the ambient air temperature & the material temperature probes in a thermally stable place together with a standard thermometer. Wait 10 minutes or more for the temperature to stabilize.
3. Observe atmospheric pressure from a standard barometer, and adjust the potentiometer P1 on the sensor box. Turn counterclockwise to increase the pressure reading.
4. Observe the temperature from the standard thermometer. Adjust P6 (for air temperature adjustment), P3 (for material temperature). Turn clockwise to increase the temperature readings.
5. Wait 15 minutes, then recheck the pressure and temperature readings. Repeat the adjustments from step 3 if necessary.



APPENDIX I. STABILITY OF LASERS

The amplitude and frequency fluctuations of an internal mirror HeNe laser are attributed to variations in the laser tube length due to thermal expansion. The standard LDDM™ laser heads are stabilized by controlling the tube temperature to a constant value. Usually, it takes about 15 minutes to reach within 1% of the final tube temperature and another 10 to 15 minutes to reach within 0.1% of the final tube temperature. To keep the laser tube at a constant temperature, the power generated by the laser head is about 14W at 75°F (21W at 60°F and 7W at 90°F).

It is well known that the physical principles of laser action preclude any HeNe laser from producing light of a wavelength which differs from the accepted value by more than ± 1 ppm. Hence, for all technical purposes, a HeNe laser which produces a beam realizes the international and US standard of length to accuracy sufficient to the needs. It is stated by the National Bureau of Standards, NBS that "It is our opinion that such devices are a priori traceable and that no calibration by NBS is required." See Section J for the system repeatability, accuracy and traceability.

For higher laser frequency stability, the LDDM™ precision laser head is stabilized to 0.002 ppm by locking the laser output to the gain curve. Thermal expansion and contraction cause the resonant frequency of the cavity to drift through the gain profile and produce peak-to-bottom changes in the laser output. Typical amplitude fluctuations are $\pm 10\%$.

The laser frequency is stabilized by employing a linear portion of the laser output power as the feedback signal to control the laser cavity length. When the laser frequency is locked, it is operated at two axial modes with linear polarization. The mode separation is 1085 MHz and the horizontal polarized axial mode is always less than 20% of the vertically polarized axial mode.

The short term (less than a few minutes) frequency stability is ± 0.001 ppm and the long term (more than a few hours) frequency stability is ± 0.004 ppm. Furthermore, there is no permanent magnetic field inside the laser head and the frequency stability is not affected by any magnetic field near the laser head. The reflected light back to the laser resonator will not affect the frequency stability.

APPENDIX J. MEASUREMENT ACCURACY

The repeatability is defined as the maximum deviation between measurements under the same conditions and with the same instrument. The repeatability of the LDDM™ can be checked by repeatedly moving the target between two fixed stops. The 3σ distribution of the readings at each stop is a good indication of how repeatable the instrument is.

The accuracy is defined as the maximum deviation of a measurement from a known standard or true value. Hence, accuracy is the repeatability plus calibration. Since the wavelength of all HeNe lasers is certified by NIST to be accurate to within ± 1.5 ppm (See NBS technical note 1248), no calibration is necessary for accuracy less than ± 1.5 ppm once the repeatability of the instrument is established.

For certain applications, an NIST traceable number is required. An Optodyne LDDM™ system (s/n 9010000401) was calibrated by NIST on July 17, 1991, Test # 821/248196-91. A report was issued stating that the laser wavelength stability is ± 0.004 ppm, while the system accuracy is less than 0.2 ppm without automatic temperature and pressure compensation, and is less than 0.8 ppm with automatic temperature and pressure compensation. For those who have the need, Optodyne, can provide a certificate that the LDDM™ system has been calibrated against the LDDM™ system (s/n 9010000401) and a copy of the test data.

The instrument accuracy is only part of the measurement accuracy. The measurement accuracy is determined by the vector sum (root sum of the square of the individual components) of the error components in the system's error budgets. There are three types of error sources, namely, measurement instrument, environmental changes and installation. Some of the errors are proportional to the measurement length and some of the errors are fixed quantities.

Typical instrument errors are laser wavelength variation, electronic error and optical non-linearity. Typical error due to environmental changes are atmospheric compensation error, material thermal expansion compensation error and optics thermal drift error. Typical error caused by improper installation are dead-path error, Abbé error and cosine error. The following is a more detailed description of these error sources.

1. Laser Wavelength

A laser system's accuracy is based on the laser's wavelength accuracy. For a standard LDDM™, the laser's wavelength is 1 ppm. For the precision laser head the stability is 0.002 ppm and the wavelength accuracy certified by NIST is better than 0.1 ppm.

2. Electronic Error

The electronic error is a fixed error and is equal to the least resolution of the system. For a standard LDDM™, the resolution is 1 μin (0.01 μm).

3. Optical Non-linearity

This error is referred to as optics non-linearity and occurs solely as a result of the optical leakage of one polarization into the other polarization. For LDDM™, the laser beam is not polarized, hence there is no optical non-linearity error.

4. Atmospheric Compensation Error

The magnitude of this error depends on the accuracy of the air temperature and pressure sensor and how the atmospheric conditions change during the measurement. The index of refraction, n , of air is related to λ_V and λ_A by:

$$n = \frac{\lambda_V}{\lambda_A}$$

where λ_V and λ_A are wavelength in vacuum and air, respectively. Change in air density, which is a function of air temperature, pressure, humidity, and composition, affect the index of refraction. Assuming a standard and homogeneous air composition, 1 ppm error results from any one of the following conditions:

- a 1°C change in air temperature
- a 2.5 mm Hg change in air pressure
- an 80% change in relative humidity.

5. Material Thermal Expansion

Since the machine's dimensions are a function of temperature, a correction for expansion or contraction may be required. This correction relates the distance measurement back to a standard temperature of 20°C (68°F). To achieve this correction, the temperature expansion coefficient must be known. This correction or compensation term is known as Material Thermal Expansion Compensation (MTE) and is defined as:

$$MTE = 1 - \alpha\Delta t$$

where

α = thermal expansion coefficient
 $\Delta t = T - 68^\circ\text{F}$

The magnitude of this error is a function of the object's temperature and the temperature sensor's measurement accuracy.

6. Optics Thermal Drift

Changes in temperature of the retroreflector during the measurement can cause a change in optical path length which appears as an apparent distance change. A typical thermal drift is about $0.2 \mu\text{m}/^\circ\text{C}$. To eliminate this optical thermal drift, you may use a mirror-type retroreflector.

7. Dead-path Error

Dead-path Error is caused by an uncompensated length, D , of the laser beam between the laser head and the retroreflector, with the positioning stage at the zero position. In most applications, the dead-path errors can be minimized by reducing the dead-path distance, D . The dead-path error can be added to the atmospheric compensation error by adding D to the measurement length, L . That is, the effective length is $D + L$.

8. Abbé Error

The Abbé Error occurs when the measuring point of interest is displaced from the actual measuring scale location, and when angular error exists in the positioning system. The Abbé error is equal to the offset distance, s , times the tangent of the offset angle, ϕ .

9. Cosine Error

Misalignment of the laser beam to the mechanical axis of motion results in an error between the measured distance and the actual distance traveled. This is called Cosine Error. The cosine error is:

$$\text{Cosine Error} = 1 - \cos\theta$$

where

θ is the misalignment angle.

For small θ , the cosine error is approximately equal to $\theta^2/2$. For example, when $\theta = 1 \text{ mrad}$ (3 arcmin), the cosine error is 0.5 ppm.

For example, with the following variables:

controlled environment	$T = \pm 0.5^{\circ}\text{C}$
total machine travel	$L = 50 \text{ in.}$
dead-path	$D = 3 \text{ in.}$
misalignment angle	$\theta = 1 \text{ mrad}$
machine guideway pitch angle	$\phi = 25 \mu\text{rad}$
Abbé offset	$s = 1 \text{ in.}$
material thermal expansion coefficient	$\alpha = 6.5 \text{ ppm}$
laser wavelength error	$1 \mu\text{in}$

The following errors would result:

The atmospheric compensation error:	$1 \text{ ppm} \times 50 \text{ in} \times 0.5^{\circ}\text{C} = 25 \mu\text{in.}$
The material thermal expansion:	$6.5 \text{ ppm} \times 50 \text{ in} \times 0.5^{\circ}\text{C} = 162.5 \mu\text{in.}$
The dead-path error:	$1 \text{ ppm} \times 3 \text{ in} \times 0.5^{\circ}\text{C} = 1.5 \mu\text{in.}$
The Abbé error:	$1 \text{ in} \times 25 \mu\text{rad} = 25 \mu\text{in.}$
The cosine error:	$(1 \text{ mrad})^2 / 2 \times 50 \text{ in} = 25 \mu\text{rad.}$

The total error, E would then be:

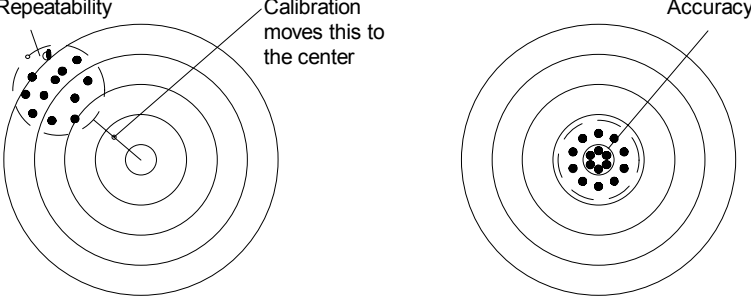
$$E = \sqrt{50^2 + 1^2 + 25^2 + 162.5^2 + 1.5^2 + 25^2 + 25^2}$$

$$\cong 175 \mu\text{in.}$$

To achieve optimum measurement accuracy it is recommended that:

1. Whenever possible make the measurement in a tightly controlled environment and use appropriate compensation method to correct for atmospheric and material effects.
2. Position the laser head such that both the dead-path and Abbé offset are minimized.

APPENDIX K. OPTODYNE, INC. GLOSSARY

TERM	DEFINITION
Abbé Error	Abbé error occurs when a displacement measurement is taken at a location which is offset from the displacement to be measured, and the slide ways which provide the displacement exhibit angular motion.
Acceleration	The rate of change of velocity with respect to time. Maximum acceleration for the LDDM™ is 1000 cm/s ² or 40 in/s ² .
Accuracy	<p>Accuracy is repeatability plus calibration.</p> 
Alignment	Because the LDDM™ uses the principle of laser radar, no critical alignment is necessary when using a retroreflector as a target.
Angstrom	Metric unit for length, equal to 10 ⁻¹⁰ m or 0.1 nm, or 0.0001 μm.
Angular Measurement	Accomplished using two LDDM™'s separated by a fixed distance or by using a dual beam LDDM™.
Aperture	The dual aperture laser head requires the use of a corner cube reflector. A single aperture laser head should be used for a corner-cube or flat mirror reflector with a diameter less than Ø½". When using a flat mirror as a reflector, the return beam must be aligned to within 30 arcsec.
Arcsecond	Unit for angle: 3600 arcsec is 1 degree.

Automatic Compensation	LDDM™ systems may be configured to compensate for both speed of light and material thermal expansion. An environmental sensor card with three sensors--air temperature, atmospheric pressure, material temperature--is plugged into an IBM PC or the processor module. Optodyne software provides the automatic compensation.
Average	Readings shown on the LDDM™ display are averaged over one quarter of a second.
Axes	The basic LDDM™ is designed for use in a single axis. A special processor may be used with two laser heads for 2-axis measurement.
Calibration	LDDM™ uses laser frequency and the speed of light for displacement measurement. Here periodic calibration is not necessary. However for the electronics or the ATC in the system, calibration every 6 months or one year is recommended.
Computer	An interface card and software are available for IBM PC compatible computers. An RS-232 bus and software are available for use with a notebook computer or printer.
Cosine Error	Error due to misalignment. If the misalignment angle between the trajectory of the stage and the trajectory of the light beam is θ , then the cosine error is approximately θ^2 .
Data Rate	The maximum data rate is 3 MHz for the IBM PC interface card, and 9600 baud for the RS-232 bus.
Doppler Effect	When a target is moving at a velocity, v , the observed frequency shift, Δf is directly proportional to v . Discovered by Christian Doppler, 1842. $\Delta f = f_0 \cdot \frac{v}{c}$ <p>where f_0 is the original frequency and c is the speed of light.</p>

Dual Beam	A dual beam laser head is used for angular measurement. Two output beams are reflected back by two separate corner-cube reflectors. The output of this laser head is the difference between these two path length changes. If the two corner-cubes are mounted together, the output is not sensitive to the linear motion of the target, but rather to the angular motion.
Error, instrument	Instrument error may be due to laser frequency stability, electronic noise, and accuracy of alignment and optics. These errors in total are less than 10^{-6} for the standard LDDM™.
Error, environmental	Environmental error may be caused by temperature and pressure, non-uniformity and variations, mechanical vibrations and stresses, and thermal stresses. Care must be taken to minimize environmental error when the measurement accuracy is $> 10^{-5}$.
Flatness	A dual-beam laser head may be used to measure the flatness of a surface plate.
Fringe Counter	A fringe counter uses the detector intensity variation and a zero-crossing circuit to count the number of fringes moving across the detector. In a Michaelson interferometer, a fringe counter is used to count the moving interferometer fringes to determine displacement. With a fringe counter, the resulting measurement will always be <u>interpolated</u> .
Gage Block	An LDDM™ system is available to retrofit a supermicrometer for gage block measurement or calibration. The resolution is 3 μ in. It features automatic data collection, statistical averaging, and computer data processing.
Hysteresis	Hysteresis is the failure of a property that has been changed by an external agent to return to its original value when the cause of the change is removed. The LDDM™ achieves high resolution and high slew rates simultaneously. The built-in hysteresis eliminates problems associated with mechanical vibrations, jitter, and fast reversal.

Interferometer	An optical, acoustical, or radio-frequency instrument that uses interference phenomena between a reference wave and an experimental wave, or between two parts of an experimental wave, to determine wave lengths, wave velocities, distances, and directions. In 1881, Michaelson used an interferometer to investigate the theory concerning the existence of "ether". The use of interferometers for length measurement gained significance with the invention of the laser.
Interfaces	Available interfaces are TTL up and down pulses; A Quad B square waves, IBM PC interface card and software, IEEE 488 or HP-1B bus from IBM PC, RS-232C, others upon request.
Laser Doppler Displacement Meter (LDDM™)	Based on principles of laser radar, Doppler effect, electro-optics, and optical heterodyne techniques for precise, fine displacement measurement. Basic physics for LDDM™ and interferometer are the same, both are subject to environmental variations. However, the data processing technique is completely different.
Laser	Acronym for "Light Amplification by Stimulated Emission Radiation." A laser converts incident electromagnetic radiation of mixed frequencies to one or more discrete frequencies of highly amplified coherent visible radiation.
Laser Head	The LDDM™ laser head measures 2.5" x 3" x 8" and is quite compact.
Latching	Using an IBM PC interface card, both internal and external latching are available. Typical latching delay is less than 50 ns.
Light source, LDDM™	LDDM™ uses a temperature stabilized HeNe laser.
Micron	One millionth of a meter (micrometer, μm)
Microinch	One millionth of an inch (microin., μin)
Microradian	One millionth of a radian (microrad, μrad)

Noise	There are three types of noise: electronic, mechanical, and thermal. Noise should be properly minimized to achieve high accuracy measurements. LDDM™ is designed to minimize noise. It is well-shielded and the input line is filtered with an RF filter. The basic limitation is the shot-noise of the detector. The laser head's compact and integrated structure effectively minimizes the influence of acoustical noise and mechanical vibrations. The interior of the laser head is maintained at a constant temperature. This minimizes the influence of external temperature fluctuations such as structural distortions, OPD changes, etc.
Optodyne	"Opto" means "optics" and "dyne" means "dynamics." Optodyne manufactures precision laser measurement and diagnostic instruments.
Position Transducer	For accurate linear displacement or position measurement, there are linear encoders (including glass, magnetic, and holographic scales), laser interferometers, and the LDDM™. The laser interferometer is an order of magnitude more accurate than the best linear encoder, but the cost is equally greater. The LDDM™ provides interferometer accuracy with a price comparable to that of a good linear encoder.
Power	Power input for the LDDM™ is 110/220 VAC and 60/50 Hz or 15 VDC, and 5 VDC.
Phase Detector	A phase detector is the major component of the LDDM™. The LDDM™ uses a phase-detector and a counter to measure the total phase shift due to position variations. The displacement, X is directly proportional to the phase, φ, namely:
	$X = \frac{c}{2 \cdot f_0} \cdot \left(N + \frac{\phi}{2 \cdot \pi} \right)$
	where N is the number of half-wavelengths.
ppm	Parts per million. Accuracy of 1 ppm may be expressed as 1 μin per inch, or 1 μm per meter.

pitch	Rotational movement about a side-to-side horizontal axis.
Range, standard	Standard range for the LDDM™ is 100 feet or 30 meters.
Range, extended	Extended range for the LDDM™ is 200 feet or 60 meters.
Reflector	There are several reflectors: Flat mirror--very sensitive to angle. Typical tolerance is less than 30 arcsec. Corner cube--insensitive to angle. Cat-eye--Insensitive to angle. Range is rather small. Phase conjugate--Insensitive to angle and disturbance. Extremely expensive.
Resolution	For the standard LDDM™, resolution (minimum readable readings are 1 μin, or 0.01 μm).
Resolution	LDDM™ offers extended resolution of 0.05 μin or 0.001 μm.
Safety	The LDDM™ uses a 0.5 mw-Class II laser. Caution! Avoid staring directly into the beam. There is high voltage in both the laser head module and in the processor module. Be sure that all cables are firmly connected to both modules before turning on the laser power switch.
Signal-to-noise ratio (s/n)	In normal operation, the s/n is 60 dB for shot noise, so it will perform even when the return beam is attenuated by 90%.
Slew Rate	The LDDM™'s maximum slew rate or maximum velocity is 72 ips or 50 m/min. Higher slew rates up to 144 ips are available.
Software	Software is available for IBM PC-compatibles and notebook computers. Software includes Demo, Metrology, Analysis, Gage Block Calibration, Rail, etc. Special custom software is also available upon request. The software is available in DOS or Windows versions.

SPC	Statistical Process Control--software available.
Speed of Light	The speed of light is defined as a length standard. It equals 299,792,458 m/s.
Spindle	An adapter plate is available to mount the LDDM™ laser head on a spindle. A beam bender may be attached to the laser head to bend the laser beam 90°. For calibration of CNC machine tools, it is more convenient to mount the laser head on the spindle using a 90° beam bender. The retroreflector with a magnetic holder as a base may be mounted at any convenient location on the bed. Setup and alignment of the beam is typically accomplished in a few minutes.
Stability	The laser is stabilized at better than 0.5×10^{-6} .
Standard Deviation	The software on the statistical package will calculate averaged value: $\bar{X} = \frac{1}{N} \cdot \left(\sum_{i=1}^N X_i \right)$ and the standard deviation: $\sigma = \sqrt{\frac{1}{N-1} \cdot \sum_{i=1}^N (X_i - \bar{X})^2}$
Straightness	Straightness may be measured with a dual-beam laser head or a quadratic detector target. Typical sensitivity is 0.000001" for the dual-beam laser head and 0.00001" for the quad-detector depending on the dynamic range and the distance of the target.
Supermicrometer	The LDDM™ retrofit kit upgrades Supermicrometer A or B to 3 μm accuracy. The system, which includes an IBM compatible PC, does not require a dedicated PC for the supermic measurements. Thus, the computer can be used to run DOS or Windows software as well.

Tripod	Most interferometric devices use a tripod to mount the laser head. The remote interferometer and retroreflector are mounted on the moving stage for linear displacement measurement. This requires that three items be aligned. Furthermore, any vibration or movement of the tripod can introduce error. The LDDM™ does not require a tripod, and only two units need to be aligned.
Units	English and metric units are available.
Velocity	Maximum velocity (maximum slew rate) is 72 ips or 100m/min. Higher maximum velocities up to 144 ips are available.
Warm-up	Typical warm-up time for the laser to lock frequency is 15 to 30 minutes. An indicator light will turn on when the laser frequency is locked.
Yaw Angle	Rotation about a vertical axis.
3σ (3-Sigma)	3 x standard deviation from the calculated value.

APPENDIX L. REPRINTS OF ARTICLES

APPENDIX M. LDDM™ BROCHURES

APPENDIX N. Trouble Shooting Procedure

I) Laser Head

- A) *No laser beam:* Check AC Power 90 to 230 VAC, Switch and Fuse.
Check DC Power, 15VDC (measure from the LEMO Connector).
Check Cable between laser head and processor model.
Bad laser tube.
- B) *Weak laser beam:* Check DC voltage level, and lose connector or contact.
Check and clean Optics.
Bad laser tube.

II) ATC Sensors

- A) *No reading:* Bad sensor or connection.
Check resistance, it should be about 120 Ω (for MCV-500 between RTD1 and RTD2, For MCV-2002, between TA, Tm1, Tm2 and Pressure to ground)
- B) *Erratic readings:* Bad sensor or bad grounding. Firmware may be damaged. Bad. Reload the firm\ware.
Bad IC.
- C) *Wrong readings:* Need calibration (MCV-2002 only, see attached instruction sheet).

III) RS232 Port

- A) *No communication:* Wrong comm. Port setting or bad cable.
No output, check RXD (Pin2), it should be $\pm 10V$.
- B) *Wrong information:* Firmware damaged, reload the firmware.
Bad IC.

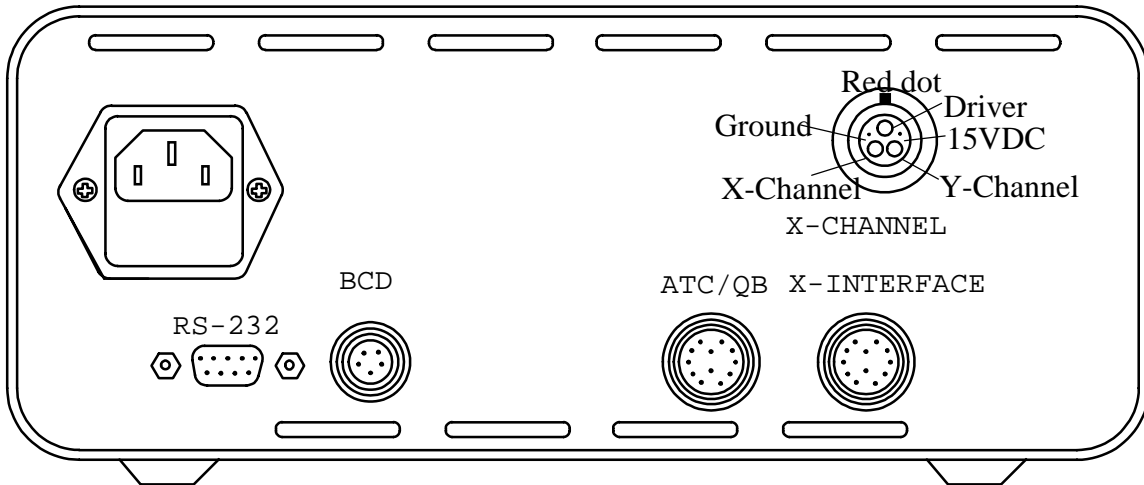
IV) Quad-detector

- A) *No reading:* Bad detectors, use chip voltage to check voltage, it should be about 2.3V (measure from male

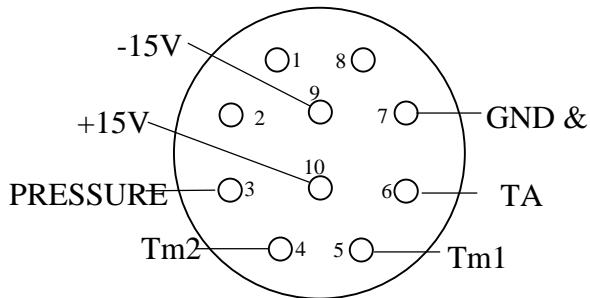
cable connector end, Pin3, Pin4, Pin5, Pin6 to Pin7 ground).

B) *Erratic reading:*

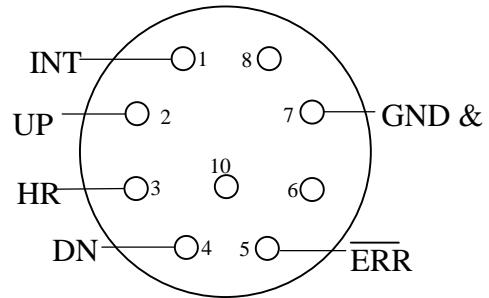
One of the detector may be bad.
 Replace the Quad-detector by the ATC.
 If reading also erratic, reload firmware or
 replace IC. If reading okay, repair the quad-
 detector.



ATC/QD



X-INTERFACE



PIN ASSIGNMENT

APPENDIX O. DESCRIPTION OF ANALOG OUTPUT

Digital to Analog Converter (DAC) Functional Specification

Circuit Description

The LDDMTM provides two types of displacement signals. Up/down pulses and analog phase voltage. The up/down pulses are 24.914154 μin per pulse, and the analog phase signal changes 2.5 V between pulses. The analog phase signal (100 mV/ μin) is available as an output option.

The DAC combines these signals into an analog output voltage. The up/down pulses are applied to an up/down counter whose output controls the upper 6 bits of an 8-bit digital to analog converter. The reference voltage for the DAC is 12 V so the output is 7.5 mV/ μin . The DAC output and the scaled analog phase signal are then added to produce Analog Output #1.

The up/down pulses are also applied to a 12-bit DAC with a reference voltage of 12 V. This reference voltage provides an analog output of 117.2 mV/1000 μin with an output accuracy of ± 1 LSB which is Analog Output #2.

Specifications

Analog Output #1

output	7.5 mV/ μin
range	0 to 12 V (1600 μin)
maximum frequency	250 kHz
output current	10 ma

Analog Output #2

output	117.2 mV/1000 μin
range	0 to 12 V (0.102 in)
maximum frequency	1 MHz
output current	10 ma

APPENDIX T. Instruction of the Motorized Turntable

The motorized turntable is controlled by the keypad terminal. The top line displays the angular position of the turntable in degrees. The bottom line displays the soft keys F1, F2 and F3 functions. For more detailed setup, start, trouble shooting, other functions, diagnostic display and programming, please see the SmartStep controller User's Manual.

To start, connect the keypad and motor to the SmartStep controller. Connect the AC power to the top of the SmartStep controller. As show in the figure below. There are 3 cables, Motor Cable with 7-pin female terminal block and DB-9 female connector and Keypad Cable with 5-pin female connector and 5-pin male connector. The third cable, Smart PC Cable with DB-25 male connector and DB-9 male connector is used for trigger mode only. The Motor Cable connects the SmartStep controller (7-pin terminal block, marked motor. Do not use the 2 other terminal blocks marked Limit and Encoder) and the Motor (DB-9 male, **the DB-9 female is not used**). The Keypad cable connects the Keypad (5-pin female connector) and the SmartStep controller (5-pin male connector, marked Keypad). For trigger mode, program 31 to 34, the Smart PC cable connects the SmartStep controller (DB-25 female connector, marked Discrete I/O port) and the LDDM processor (DB-9 female connector, marked RS-232). For all other programs, 1 to 15, make sure the SmartPC cable is disconnected.



Turntable Connection

To run jog mode, press “run” and the display shows Program (above F1), Jog (above F2) and Test (above F3). Press F2 and the display shown <Lo> (above F1) and High (above F2). Select <Lo> for low speed and High for high speed. After the selection, press → to rotate clock wise and ← to rotate counter clock wise. Press “ESC” to end the jog mode.

To run a program, press “run”, press F1, press 1 (or any other program number listed below), and “enter”. For program #1, press → to rotate clock wise 10 degrees and ← to rotate counter clock wise 10 degrees. Press “ESC” to end the program.

List of programs in motorized turntable

1. Move 10 degrees CW or CCW, press → for CW and ← for CCW.
2. Move 5 degrees CW or CCW, press → for CW and ← for CCW.
3. Move 90 degrees CW or CCW, press → for CW and ← for CCW.
4. Move 45 degrees CW or CCW, press → for CW and ← for CCW.
5. Move 180 degrees CW or CCW, press → for CW and ← for CCW.
6. Move 10 degrees CW, stop for 5 sec, and continue until ESC button is pressed.
7. Move 10 degrees CCW, stop for 5 sec, and continue until ESC button is pressed.
8. Move 10 degrees CW, stop for 5sec, and continue 36 times. Then repeat in CCW, stop for 5 sec, and continue 36 times.
9. Move 10 degrees CCW, stop for 5sec, and continue 36 times. Then repeat in CW, stops for 5 sec, and continue 36 times.
10. Move 10 degrees CW, stop for 6sec, and continue 36 times. Then repeat in CCW, stop for 6 sec, and continue 36 times. Repeat 3 times.
11. Move 10 degrees CCW, stop for 6sec, and continue 36 times. Then repeat in CW, stops for 6 sec, and continue 36 times. Repeat 3 times.
12. Move 5 degrees CW, stop for 5 sec, and continue until ESC button is pressed.
13. Move 5 degrees CCW, stop for 5 sec, and continue until ESC button is pressed.
14. Move 5 degrees CW, stop for 5sec, and continue 72 times. Then repeat in CCW, stop for 5 sec, and continue 72 times.
15. Move 5 degrees CCW, stop for 5sec, and continue 72 times. Then repeat in CW, stops for 5 sec, and continue 72 times.
31. Trigger mode, 10 degrees CW
32. Trigger mode, 10 degrees CCW
33. Trigger mode, 5 degrees CW
34. Trigger mode, 5 degrees CCW

Rotary axis calibration trouble shooting procedure

1, LDDM device not detected (USB interface)

Make sure the LDDM processor is turned on and the USB cable is connected. Go to the control panel and device manager. Click on Human Interface Devices, there should be 6 lines of HID-compliant device and 6 lines of USB Human Interface Devices. If any line is missing or has a yellow exclamation mark, replace the USB cable or use an USB cable with booster.

2, LDDM software works okay, but the motorized turntable not work properly

First check the **hardware**: Make sure the motorized turntable, motor controller and the display panel are all connected. Use the display panel to select jog mode and press → or ← to more the turntable clock wise and counter clockwise. If not work, check the controller, motor and mode. If worked okay, Use the display panel to select a trigger

mode, #31 or #32. Disconnecting the cable from LDDM processor to the controller, the turntable should continue rotate 10 degrees, stop, 10 degrees again, stop, and continue. Connect the cable to the LDDM processor and the turntable should stop rotating. If not worked, problem may be due to wrong mode or bad cable. If worked okay, check software.

Check **software**: make sure the laser is properly aligned and the motorized turntable properly setup. Click on LDDM icon to start the LDDM program. Click on the “Rotary calibration” to start rotary data collection screen. Click on the Auto button, enter the number of steps and run number. Click on start to start data collection. The initial position, 0 should be recorded on the first line. Move the rotary axis to 10 degrees and the 10 degrees position should be recorded on the second line. Then a trigger signal should be sent to the controller to move the turntable back to 0 degree. If not, the trigger signal may be missing or interfered by noises. Move the USB cable or replace the USB cable by an USB cable with booster. If still not work, use print screen to record the data collection screen. Send both the print screen and the LDDMtrac file (in C:) to Optodyne for trouble shooting.

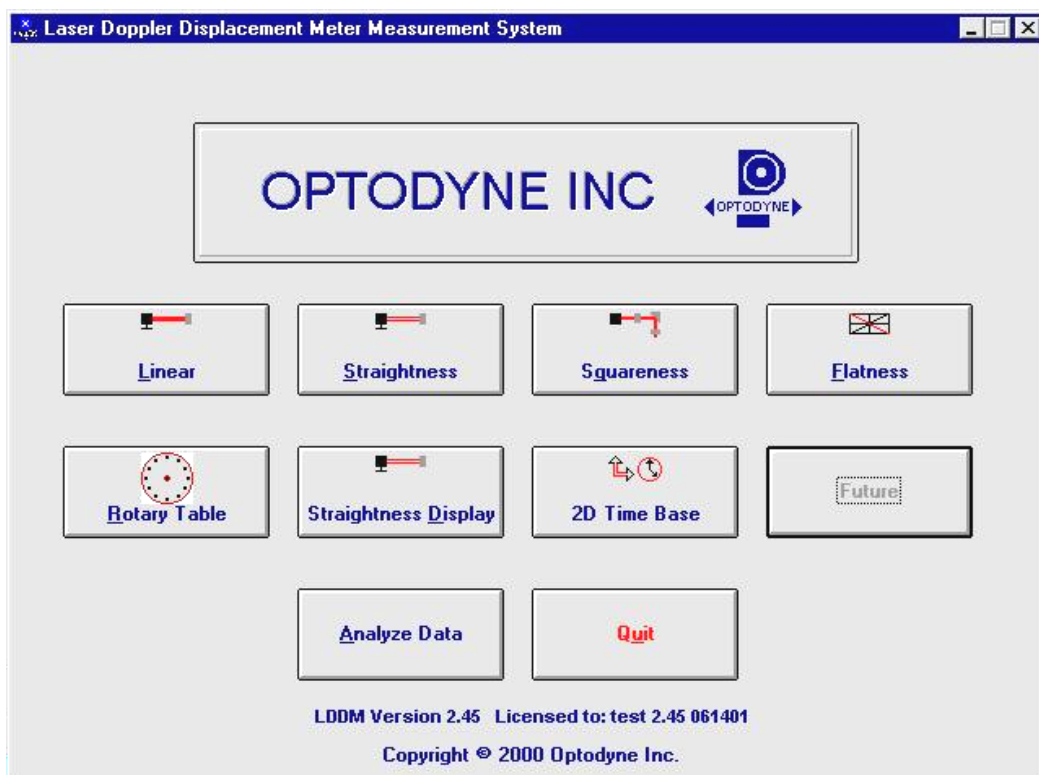
3, LDDM device not found (RS-232 interface)

RS-232 direct interface: disconnect the RS-232 cable from the PC and reboot the PC. After reboot, turn the LDDM processor off and on to reset, then connect the RS-232 cable to the PC and start the LDDM program. If still cannot find the LDDM device, go to device manager to check the com port. The RS-232 should be in one of the com port. If not, check the hard ware.

RS-232/USB converter interface: just connect the USB converter to the PC and check the Device Manager, and Com Port. The USB should be in one of the Com Port. If not, check the USB driver and make sure it is the correct one and proper installed. If problem is still there, disable the external mouse or some other devices and connect the USB converter again. If problem is still there, use a different USB converter. If the USB is in one of the Com Port, connect the LDDM processor RS-232 cable to the USB converter and start the program. If problem is still there, check the LDDM program and the LDDM.ini file, make sure the program is installed properly and the LDDM.ini file is set correctly (make sure the bud rate matches with the LDDM processor) or re-install the program from the original CD-ROM disk.

LASER DOPPLER DISPLACEMENT METER

LDDM FOR WINDOWS Version 3.0 SOFTWARE MANUAL



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1.0 Welcome

Thank you for purchasing the LDDM for Windows software package for your Laser Doppler Displacement Meter. We hope that you find this software package extremely helpful in your usage of the Machine Calibration package that you have purchased.

Easy to install and operate, LDDM for Windows allows for the usage of the LDDM to this fullest ability to reduce your downtime and ultimately save you money. Along with the user-friendly graphical interfaces, and the software's fully automatic data collection ability, we believe that you will find that the LDDM is the easiest to use laser calibration system on the market, without sacrificing laser accuracy.

1.1 This Manual and LDDM for Windows

In this manual, you will find descriptions about each choice and action on every screen in the software. You will also find instructions on how to take a measurement run for each type of measurement.

1.2 Bolded characters

In this manual, you will find **bolded** characters. When prompted, these bolded characters should be typed where specified.

1.3 Using the Mouse

In the **LDDM for Windows** package, only the left mouse button is used. In the program, a single click on the left button is usually sufficient to carry out an action, with a few exceptions. When prompted to click on a button, please move the mouse marker to that particular button, and simply click the left mouse button on it.

1.4 Text Boxes:

Instead of clicking on buttons, there are some boxes in the software where you must type in text. Move the mouse to the open box and look for the mouse marker symbol to change into a vertical line which looks similar to an I. There are then two ways to enter text. You may click the left mouse button at the beginning or end of the text, use the **Backspace** key to delete the previous text, and then enter your new text. You may also "Block" the text to be deleted by first moving the I (mouse text marker) to the beginning of the text, holding down the left mouse button, and then moving the mouse to the end of the text. You may then replace the whole text you have "blocked" by typing in your new text.

2.0 Installation

2.1 Set up LDDM Program

To setup LDDM program from Windows 95/98 and Windows Millennium

1. For optimum performance exit all other applications before setting up LDDM program.
2. Insert LDDM CD into CD-Rom driver and wait for the folder to appear from My computer Icon. Double click on setup.exe to install the software.
3. Follow the instructions on your screen to continue through the setup progress.
4. After the setup is installed successfully, an LDDM icon will show in the screen. The LDDM program is ready to run.

2.2 Starting LDDM Program

To start LDDM from windows, run Windows and double clicking on the LDDM icon. The main menu of LDDM program will appear on your screen (see Fig. 3-1). Click on Linear for linear measurement. The measurement program will appear on your screen (see Fig. 4-1).

2.3 LDDM software instruction

There are 2 types interface between the Notebook PC and the LDDM processor module, one is serial interface through the com port and the other is USB human interface. All the software is stored in a CD-ROM. Click on "Setup" to install the software to your Notebook PC.

Serial interface through Com Port

- 1, Using RS-232 port on your Notebook PC

Boot the Notebook PC first with the RS-232 cable disconnected. Turn on the LDDM processor, connect the RS-232 cable, and start the LDDM program. If the LDDM program couldn't find the interface, check the "device manager", and "Com Port" to make sure the Com Port is available. Also, make sure all the cables are connected properly and reset the Processor by turn-off the power and turn-on again. Many times, the problem is caused by a bad (poor contact) RS-232 cable or poor connection.

- 2, Using USB port with RS-232/USB converter

Make sure the driver for the RS-232/USB converter is installed. Connect the RS-232/USB converter to the Notebook PC, turn-on the LDDM processor, connect the RS-232/USB converter to the RS-232 port and start the LDDM program. If the LDDM program couldn't find the interface, check the "device manager", and "Com Port" to make sure other device, such as external mouse, is not using the same com

port. Sometimes, the external mouse has to be disabled. Also, make sure all the cables are connected properly and reset the Processor by turn-off the power and turn-on again. Many times, the problem is caused by a bad (poor contact) RS-232 or USB cable or poor connection.

Direct USB human interface

Make sure the laser head and ATC sensors are connected to the processor. Connect the USB cable between the Notebook PC and the LDDM processor. Start the LDDM program. For Windows Vista, use “Run as administrator”. If the LDDM hardware is not connected and you want to do analysis, there is a popup screen stating: “Report missing USB device, Yes or No”. Click on No, the main menu will be displayed and click “analysis” to perform data analysis. If all the LDDM hardware is connected, the main menu will be displayed, otherwise a popup screen stating: “Linear USB data device not connected. Continue? Yes/No”. Click Yes to continue and No to exit.

For some Notebook PC with too many USB ports, the voltage becomes marginal or too low, an external USB hub with power should be used. Go to “device manager” and click on “Human Interface Devices”. There should be 6 lines of HID-compliant device and 6 lines of USB Human Interface Device. If any of these are missing or with a yellow exclamation mark on the corner, external USB hub with power should be used.

3.0 Main Menu

There are six working choices to be made on the Main Menu (Fig.3-1). They are to choose which kind of measurement you would like to take. Linear measurement can be done with any LDDM system. Straightness can only be used with a dual beam laser head. Squareness can only be used with a quad detector. The angular and flatness sections can only be used with a dual beam laser head. Choose analyze data to look at previously created data files. All types may be viewed with this choice.

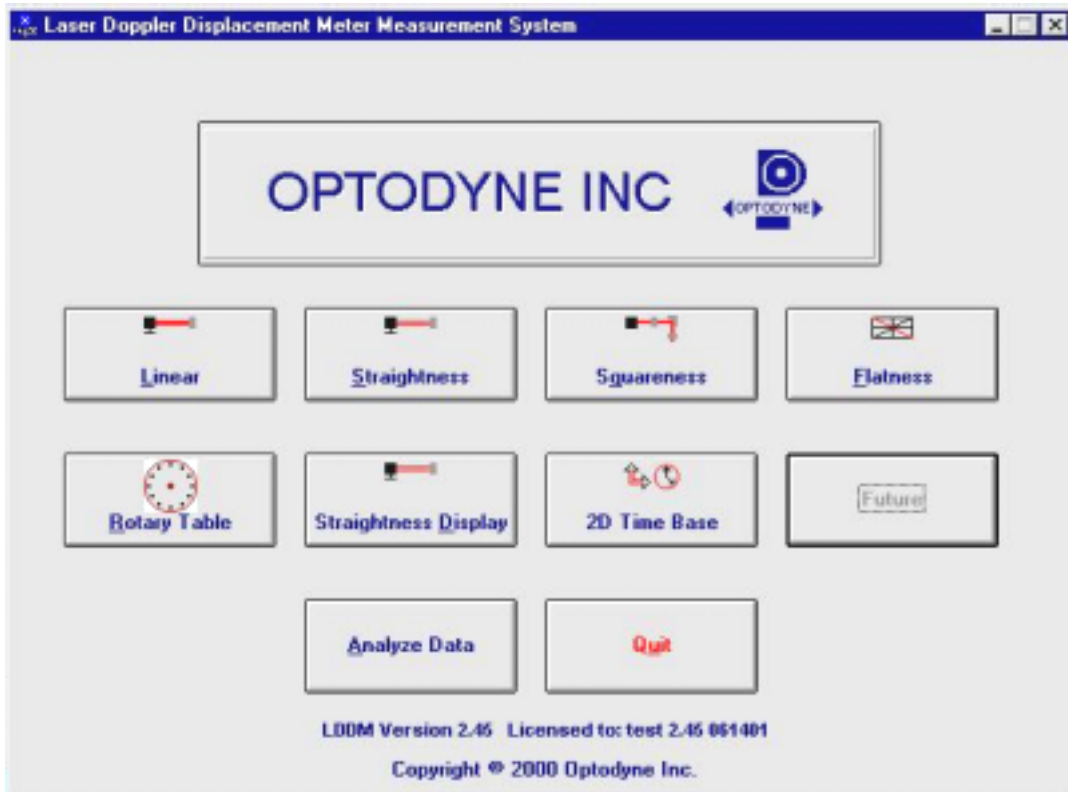


Fig. 3-1 Main Menu

Click on **Linear** if you would like to take a linear measurement.

Click on **Straightness** if you would like to take linear and straightness/angular measurements.

Click on **Squareness** if you would like to take a squareness measurement.

Click on **Flatness** if you would like to take a flatness measurement.

Click on **Rotary Table** if you would like to take a rotary measurement.

Click on **Straightness Display** if you would like to display straightness.

Click on **2D Time Base** if you would like to take circular contour measurement.

Click on **Analyze Data** if you would like to view/analyze a previous data measurement.

Click on **Quit** if you would like to exit the program.

4.0 Linear Measurements

After clicking the **Linear Measurement Box** on the Main Menu, you will be greeted by the Linear Measurement Data Screen (Fig. 4-1). If the LDDM is not connected to communication port, a message box will appear telling you that the LDDM interface not found. Please check your connections and the LDDM reading on the display should appear.

4.1 Linear Measurement Main Display

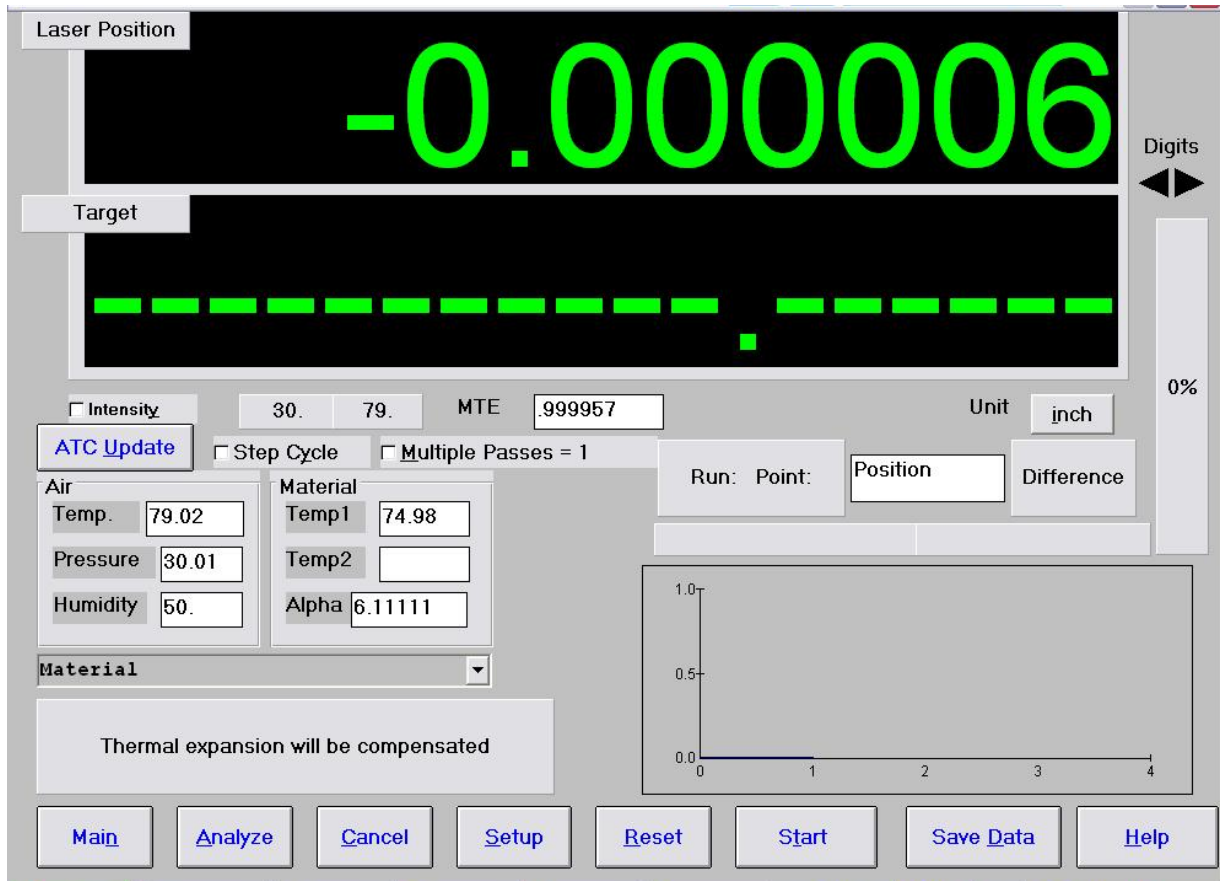


Fig. 4-1 Linear Measurement Main display

Choices on the Main Display are as follows:

Intensity: Align your system visually, then check your alignment by clicking on this box. A blue bar will appear in-between the Laser Position window and the Target window. This blue bar will range from between 0 and 100%. Please make sure that the intensity is at least 40% over your whole run. Press the intensity box again to return the system to its original state.

The two boxes next to the Intensity box show the Pressure and Temperature that the Processor Box is reading. If you have an ATC probe, these numbers will be continually changing. If you do not have an ATC probe, the values will be 68 degrees and 29.9 inHg. When the Intensity Box is clicked on, these values will disappear.

ATC Update: The ATC update updates the air pressure, air temperature and material temperature readings from the processor box. The MTE value will be calculated from these updated values and Alpha material coefficient. A X mark will appear when the ATC value has been updated correctly for the next measurement.

Step Cycle Measurement Style: Normal data collectings are linear cycle. However, for long machine or other situation, it is desirable to collect data by quasi-pilgrim step cycle. Click this box, the data collection will be changed to quasi-pilgrim step cycle (see ISO 230-2).

MTE: The MTE value can be manually changed in this box.

Unit: This box, when clicked on, will allow the user to change between the inch and metric systems.

Digits: Clicking the left arrow will decrease the amount of digits shown (data will still be taken to 6 digits). Clicking the right arrow will increase the amount of digits shown (max 6). To decrease the amount of digits shown, click the right arrow once, and then the left arrow.

Air/Material Environmental, Alpha Boxes: Values may be entered in the Air Temperature and Pressure boxes for those people who do not have an ATC probe. Humidity should be entered for all users of the LDDM system. The Material Temperatures are averaged together to get the MTE coefficient value. The material alpha can also be manually changed if the material list does not include the material of the machine being calibrated.

Run: Point, Position, Difference: The values in these boxes are during a measurement. They show the Run number that you are taking (up to 7), the point number, the target position, and the difference between the LDDM reading and the target position.

The percentage bar shows how much of the current measurement is done.

For automatic measurements, a stoplight will appear. The green light indicates that the program is ready for the system to go to the next data point. The yellow light indicates that the retroreflector has dropped below the velocity threshold and is waiting for the set delay to complete. The red light indicates that the system is taking the data point.

Material Box: The material list and their corresponding alpha values are listed here. Click the mouse on the down arrow and a list of materials are shown. Please choose from the material list or enter your own value to the alpha box above.

The dialog box is just underneath the material box. This box tells you messages and describes the actions you are taking.

Buttons at the bottom of the screen:

Main: exits the linear measurement package and loads the main menu.

Analyze: exits the linear measurement package and enters the analyze data package. A box will appear asking if the current module should be unloaded. Please type **Yes** unless you are taking a flatness measurement.

Cancel: By pressing this button, you can cancel the last data point taken during a run, or you can cancel the whole measurement.

Setup: Opens the setup window, where measurement specifications may be edited or viewed.

Reset: Using this key allows for the reset of the LDDM. This key will also change the mode of the processor box to the current measurement type, i.e. if the processor is manually switched to a dual-beam mode while the program is in the linear measurement mode, the reset will return the processor to the linear measurement mode.

Start Measurement: This button starts the measurement defined in the setup window.

Save Data: This button will allow for the data storage of the last measurement taken.

The Laser Position window shows the current position of the retroreflector. This value always shows a value compensated for air temperature, pressure and relative humidity, but may or may not be compensated for MTE (if MTE compensated box is clicked on or off).

The Target window will show a value during a measurement. This value is the next point where data collection will take place.

4.2 Linear Measurement Setup Screen (Fig. 4-2)

To input information: Please move the mouse pointer over the box on which you wish to change the information. The mouse pointer will turn in to a vertical bar. Two things may be done:

- 1) Block the text. Hold the mouse button down and move over the text completely. The text being blocked will become inverted in color (white on black). Type in the information to be entered. The original text will be replaced by the new information.
- 2) Click the mouse button while the vertical bar is over the box. Use the arrow keys and the delete key to erase the previous information. Then input the new information.

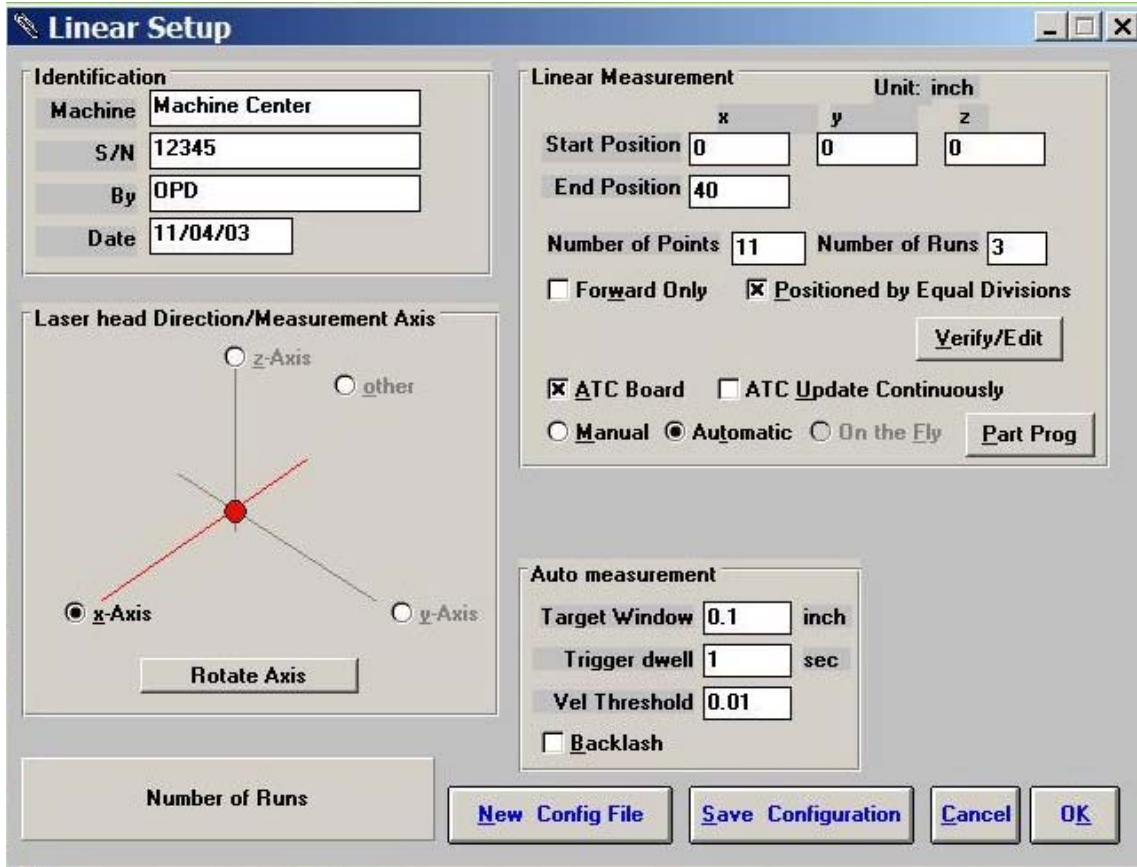


Fig. 4-2 Linear Measurement Setup Screen

Identification Box:

The identification of the machine, i.e. the machine type, serial number, the person doing the calibration, and the date, is entered here and is saved in the data file. The date is automatically entered using the computer system date.

Laser head direction/Measurement Axis Box:

You may choose either the x-axis, y-axis, or z-axis for on-axis measurements, or if you have the diagonal measurement kit, you may choose other for a volumetric measurement. Click on the circle closest to the type of measurement you would like to take. Click on Rotate Axis to rotate the axes orientation to match with the machine coordinate.

Linear Measurement:

Start Position: Enter the coordinate of the machine position that you are going to be starting at (for that given axis). Also enter the Start Position of the laser beam location. These information are used for pitch and yaw angular error calculation.

End Position: Enter the final coordinate of the machine position that you will be ending at (for that given axis).

Number of Points: Counting the zero point as the first point, please enter the number of points for the run up to 9999 points.

Number of Runs: Choose the number of runs for this measurement, 1 through 7.

Verify/Edit: Click on this button to see the data acquisition setup. Make sure that your increments are correct. If there are increments to be changed to an irregular interval, you may edit the box.

Forward Only: Click the box to an X mark if the measurement is to be forward only. Leave the box blank if it is to be a bi-directional measurement.

ATC Board: If you have an ATC board, please click the mouse here and make an X mark. If you do not have an ATC board, please make sure that there is no X mark there. To manually set the speed of light correction, click the ATC board on and off, then enter the barometric pressure in mmHg and the air temperature in °C. The barometric pressure and air temperature values will be reset to 760 and 20 automatically once leave the program to avoid possible double correction.

ATC update continuously: If you have the ATC board option marked with an X, you can choose ATC Continuous Update to monitor your material temperature for changes during the measurement. This is only necessary for larger machines, or measurements that take many hours to complete (otherwise the material temperature change should be negligible for most machines). This option will cause the MTE value in the Analysis program to be 1.000000.

Please choose the type of measurement you wish to take:

Manual: The Start Measurement button will turn into a "TAKE" button after the measurement begins. At every collection point, this button will have to be pushed.

Automatic: The software will collect data every time the retroreflector comes within a "Target Window", drops under a certain velocity and sits still for a designated dwell time.

Parts Program: A G-code parts program will be generated to move the machine for the measurement.

On-the-Fly: The software will automatically take data as soon as it is sensed that the retroreflector is within the "Target Window" of the target position. There is no On-The-Fly capability for Linear Measurement.

Auto Measurement Box:

Target Window (automatic and on-the-fly): For automatic and on-the-fly measurements, being within this value of the target position allows the software to take data. For on-the-fly measurements, the maximum speed is 10 times the target window.

Trigger dwell (automatic only): For automatic measurements, the settling time of the machine (typically 3-5 seconds) is entered here. Choose a value of at least 2 seconds less than the programmed machine dwell time.

Vel Threshold (automatic only): This is the threshold that the retroreflector must drop underneath so that a data point can be taken.

Backlash (automatic only): If the box has an X, backlash at the end and beginning of each run (other than the first point) will be taken. The distance necessary to remove the backlash and allow the software to re-trigger is twice the target window.

New Config File: You may load a previous configuration file if you have one for this particular machine.

Save Configuration: This updates the LDDM.CFG file so that the data seen on the screen will appear each time LDDM for Windows is run.

Cancel: Cancel the above changes and revert to the previous values.

Ok: Settings are ok for this measurement. If you saved this setup as the default, it will come up first every time, otherwise the previous setup will re-appear next time the program is run.

4.3 Example of a Linear Measurement

Linear Measurement Main Display (See Fig. 4-1):

- 1) Check your units in middle right hand side. If it is not the correct type, click on the **inch/mm** icon.
- 2) Align the laser head visually according to the user's guide. Click the **intensity** button on the middle left hand side and check to see if the laser is aligned over the whole travel. After alignment, click off the **intensity**.
- 3) Click once on the **setup** icon on the bottom row of Icons.

Linear Measurement Setup Screen (See Fig. 4-2):

- 4) Setup your system information on the upper right hand side of the machine. Input the **identification** of the machine you are calibrating. To type the text, please move the arrow of the mouse pointer until it turns into a text cursor (an up and down line). Or please hit the tab key until one of the text boxes is highlighted. Type your machine data in.
- 5) Enter the axis of measurement (or the diagonal) by clicking the appropriate box on the bottom left graph (**X**, **Y**, **Z** or **OTHER** for diagonal)
- 6) Enter the **machine coordinates** that you wish to calibrate in the upper right corner.
- 7) Enter the **number of points**, including zero, that you wish to calibrate. E.g. For a ten inch run, with 2 inch increments, enter 6.
- 8) Enter the **number of runs** (typically 7 for NMTBA, or 5 for VDI, ISO and B5)
- 9) Press the **Verify/Edit** button to see the increments. You may manually change these increments if you would like to.
- 10) If you are manually changing the values, make sure that the **Positions Equally Divided box** is clicked off to show: **Positions As Shown Below**.
- 11) Change the # of points as necessary to achieve the correct increment that you desire (Press **Verify/Edit** to check again).
- 12) Choose **Forward Only** or **Bi-Directional** runs.
- 13) Click on the **ATC board** if you have one.
- 14) Click on **ATC Continuous Update** if you are taking a long measurement.
- 15) Choose your type of measurement:

Manual

- you may:
- 1) Hit the **enter key** at each point, or
 - 2) Click the **mouse** on Take at each point

Automatic

To take data automatically, you will have to program the machine controller to do 2 or 3 things: to move in a certain increment with a delay time in-between movements (3-5 seconds recommended), and add a backlash movement that is greater than double the target window at each end (backlash is optional).

The following information will be necessary for Automatic measurements:

Target Window: This tells the computer a distance window around the target position where the computer is allowed to take data. This value is related to the backlash needed (see below). A typical value is .001 inch or .02 mm, depending how tight your machine is. The backlash movement of the machine must be at least double this value.

Trigger Dwell: Set this value for two seconds less than the machine delay time for each point.

Velocity Threshold: This value keeps the risk of false triggering down. A good value to use is 0.01 for inches, 0.1 for metric.

Backlash: Check here if you want to account for backlash. The backlash at the beginning and end of each forward/backward run has to be at least TWICE the target window value.

16) Saving the Configuration File:

Save this configuration file by clicking the **Save Config File** Icon. Type the name of the file which you would like the setup saved to (usually the name of the machine). Press **Enter** or **OK** after typing it in.

The program will ask you if you would like to save the file, press **Yes**.

The program will then ask if you want to use this file as your default. If **Yes** is clicked, this setup will be loaded every time that the Linear Measurement Module is loaded. To load a configuration file next time, click on **New Config File**. You may either:

- 1) Click on the file name and press **OK**
- 2) Double click on the file name
- 3) Type the name of the file name, example: **LDDM.1CF** and hit enter.

17) Press **OK** to get back to the main screen.

Taking Data Points for a Linear Measurement (Fig. 4-3)

18) Press **ATC update (X)** to update the values.

19) Input the **Humidity Value**.

20) Choose your material from the list given. Press the **Down arrow key** and you will get a list, press the **down arrow key** or **PgDn key** from there to scroll down.

21) Choose the number of digits on the upper right hand side of the screen you wish the screen to display. Click the **right arrow button** to increase the amount (up to six), or click the **left arrow button** to decrease the amount.

22) Move your retroreflector to the beginning of your run. Click on **Start**.

Manual: If you are manually operating the laser/machine, press the designated key to take data as shown (after you move the machine). Also, if you would like to change the target position, you may do so in the value box located in-between the run information.

Automatic: If you are running the automatic program, you will see a stoplight appear. The red means that the conditions for a measurement have been met (inside the target window, and the velocity is lower than the given one), yellow means that the delay is being counted and the green means that the data has been collected and the program is waiting for you to move to the next point (Fig. 4-3)

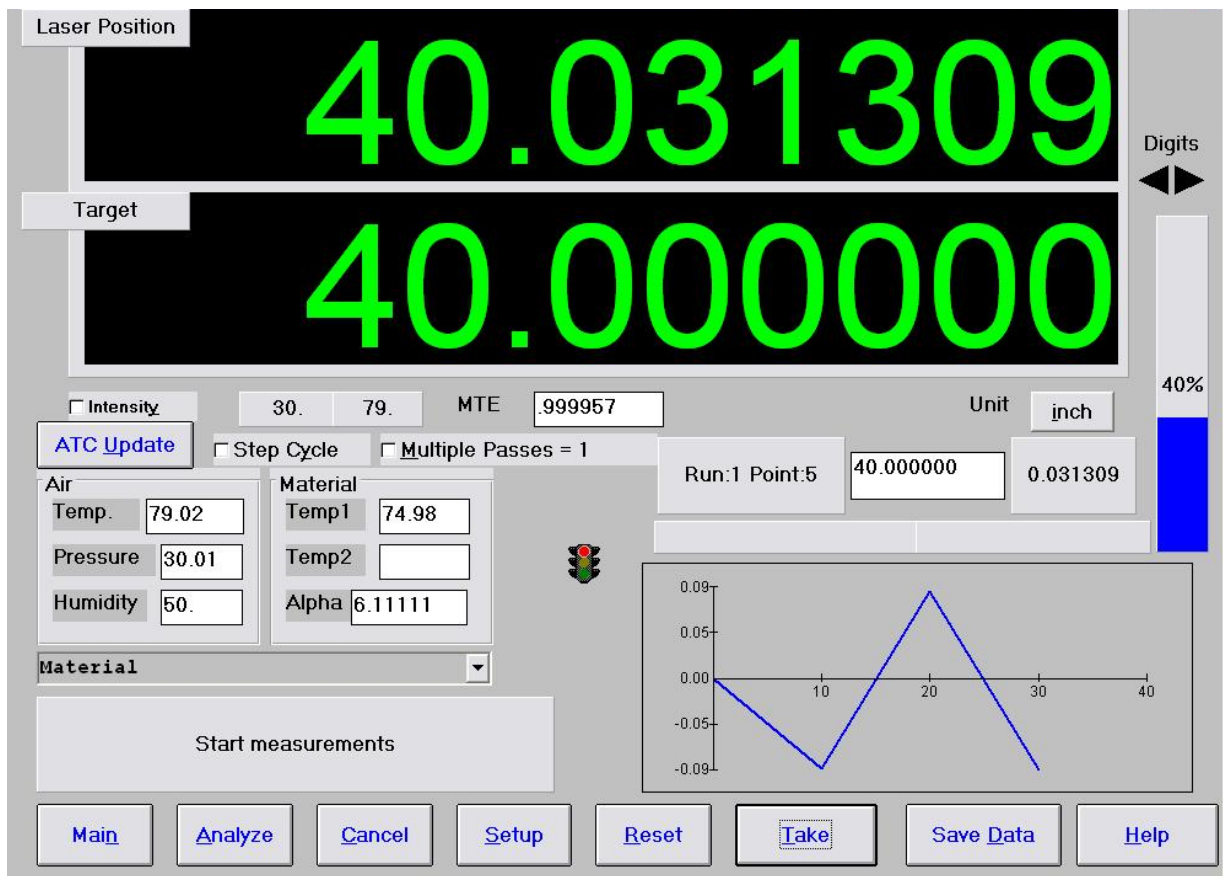


Fig. 4-3 Automatic Linear Data Collection

23) After all the data is taken, press **OK** to save the data, or **cancel** to not save the data.

24) To save data, type in the **filename** to save and hit <Enter> (the extension is automatically saved as .LIN). You may also save collected data by pressing the **save data button**, and follow the procedure above.

25) To analyze the data click on the **Analyze button**. When it prompts you, unload the module, unless you are taking a flatness measurement.

4.4 Linear Data Analysis Menu (Fig. 4-4)

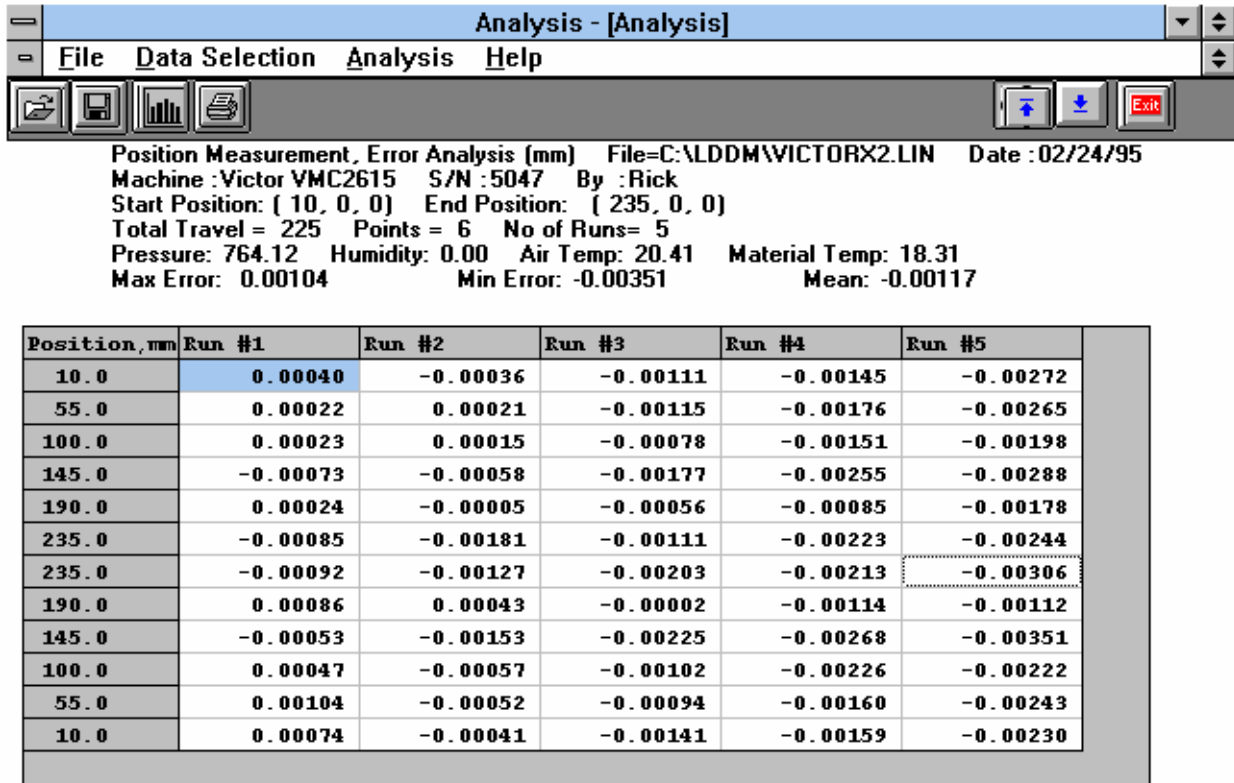


Fig. 4-4 Linear Measurement Data Analysis Table

Under the **File Menu**, you can open a **new** data file, **save** a data file, set your **printer type**, set your **printer style**, or return to the **main menu**. When loading a file, choose the files with the extension of .LIN for linear. You can only **print data** tables using the print function under this heading.

Under the **Data Selection** heading, you can only choose **Displacement** when looking at a linear (.LIN) file.

Under **Analysis**, you can choose **Error**, **NMTBA**, **NMTBA with Zero Shift**, **VDI 3441**, **ISO**, **ASME B5.54** or **ASME B5.57** for different types of data manipulation. After choosing **Error**, you will be given a choice on what you wish to see, **Runs #1-7**, and **forward** or **backward**. Click with the mouse button on which runs you wish to see. The following icons have the following function in Analysis:



Open a new data file.



Save a data file.



Graph a data file (After graphing, you may also change the scaling of the graph by checking X on adjust grid).



Print a data graph (for printing data tables, use the Print option under the “File” heading)



Moves to the previous screen.



Moves to the next screen.



Exits the program.

4.5 Generating a Compensation File

Many machine tool controllers can provide compensations for repeatable position errors on each linear axis of motion. To generate a new compensation file, first set the compensation to zero and set the LDDM™ laser measurement system to measure the position error at an increment corresponding to the compensation file requirement. Second, use the metrology software to collect position error data and to generate a position error table. Third, key in the new compensation file based on the position error table. Finally, use the LDDM™ laser measurement system again to measure the position error with the new compensation file to make sure that the position errors have been compensated. Otherwise, the machine may have large non-repeatability.

For some standard machine tool controllers, software is available to convert the measured error table to a compensation file and load the compensation file through an RS-232 port to the controller.

4.5.1 Comp files for various controllers

A button is added in the analysis program for the generation of compensation files compatible to most of the controllers, such as Fanuc and Siemens. First, open the calibration file of the axis to be compensated by click on “analysis”, “open” and enter the file name. Click on “Data Selection”, “displacement” “analysis” and “error”, the

positioning errors will be displayed on the screen. Click on “Save”, a screen will pop up as shown below.

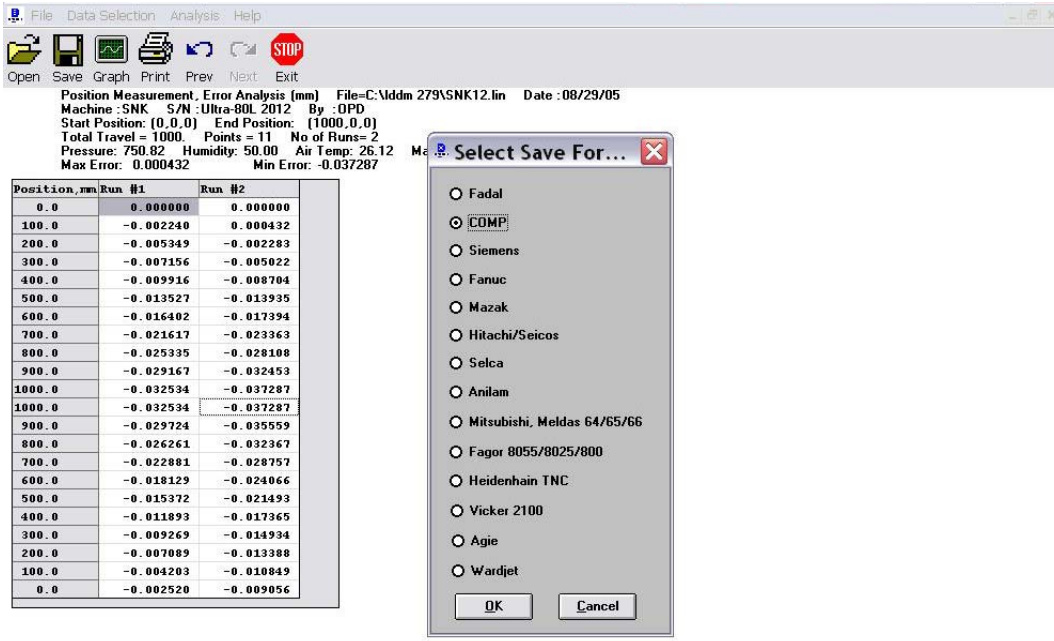


Fig. 4-5 Compensation File Selection Screen

Click on “Fadal”, “ok”, and enter a filename, a comp file with extension .svx, .svy or svz for fadal machines will be generated. Click on “comp” and “ok”, another screen will pop up as shown below.

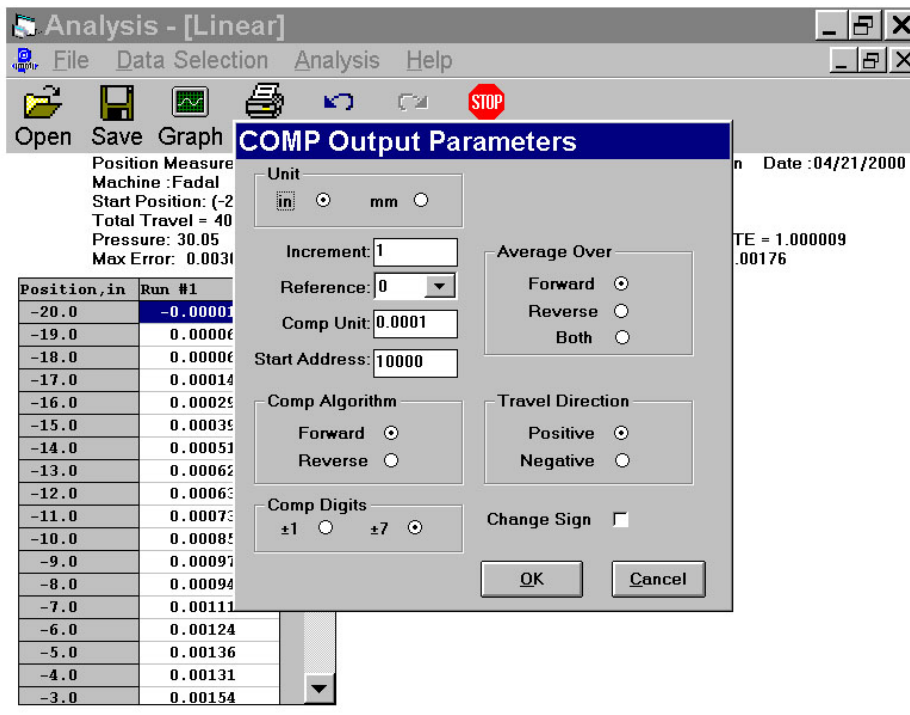


Fig. 4-6 Compensation Input Parameter Screen

Select in or mm unit for the comp file while the data file can be either in English or Metric unit. Select a increment for the comp file. The increment may or may not be the same as the data file. Select a reference point, compensation unit, start address, comp algorithm and travel direction based on the controller's requirement. For multiple-run data, select the average over forward, reverse or both. After all the parameters are selected, click "ok" and enter a filename, a comp file with extension .CPF will be generated. To view the compensation file, click on "file" and "Start Notepad", then enter the file name. A sample comp file is shown below.

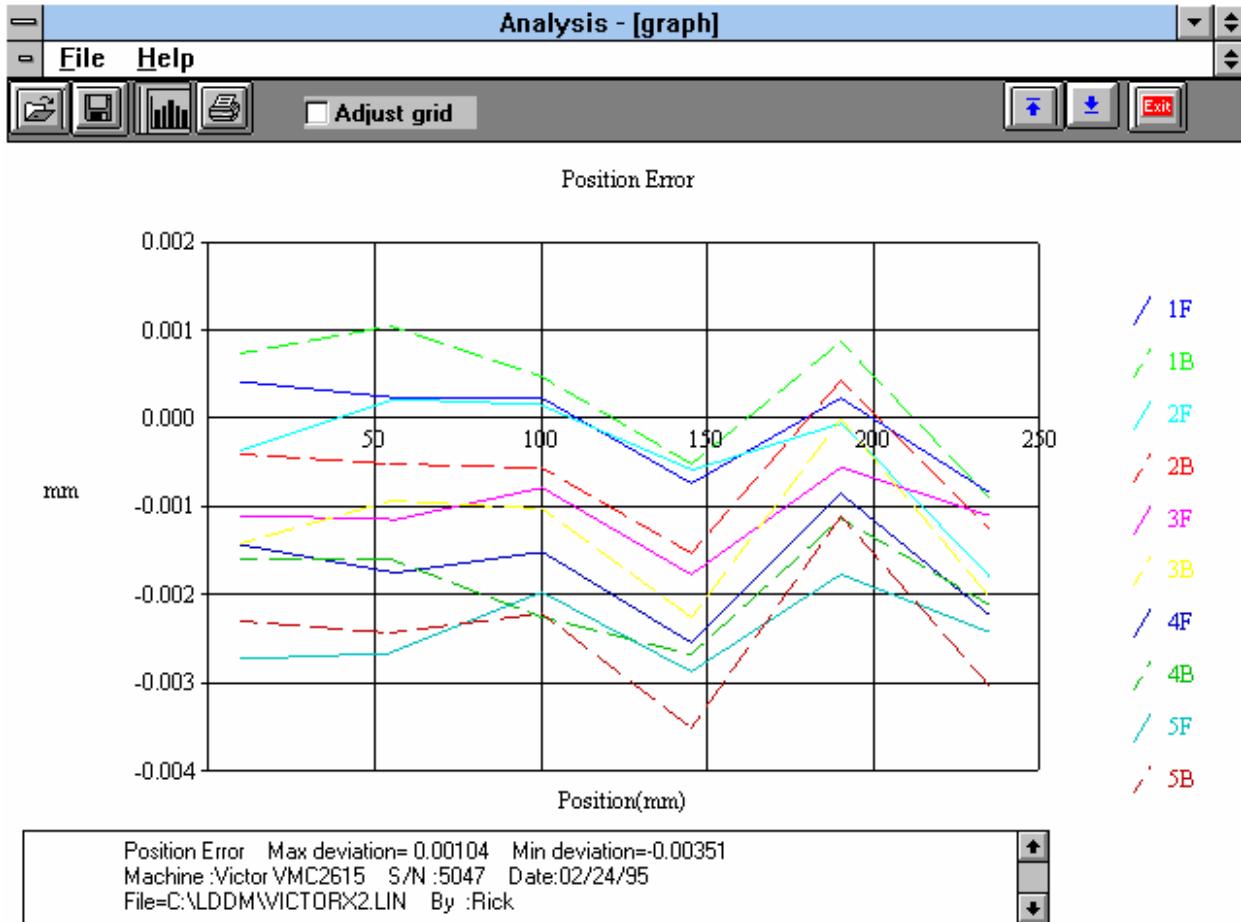


Fig. 4-7 Linear Measurement Data Plot (Individual Plots together)

5.0 Straightness/Angular Measurements

The Straightness/Angular Measurement setup is almost the same as the linear measurement, with the difference being the need to define the orientation of the laser head.

After clicking the **Straightness Measurement Box** on the Main Menu, you will be greeted by the Straightness Measurement Data Screen. If the LDDM is not connected to communication port, a message box will appear telling you that the LDDM interface not found. Please check your connections and the LDDM reading on the display should appear.

5.1 Straightness Measurement Main Display (Fig. 5-1)

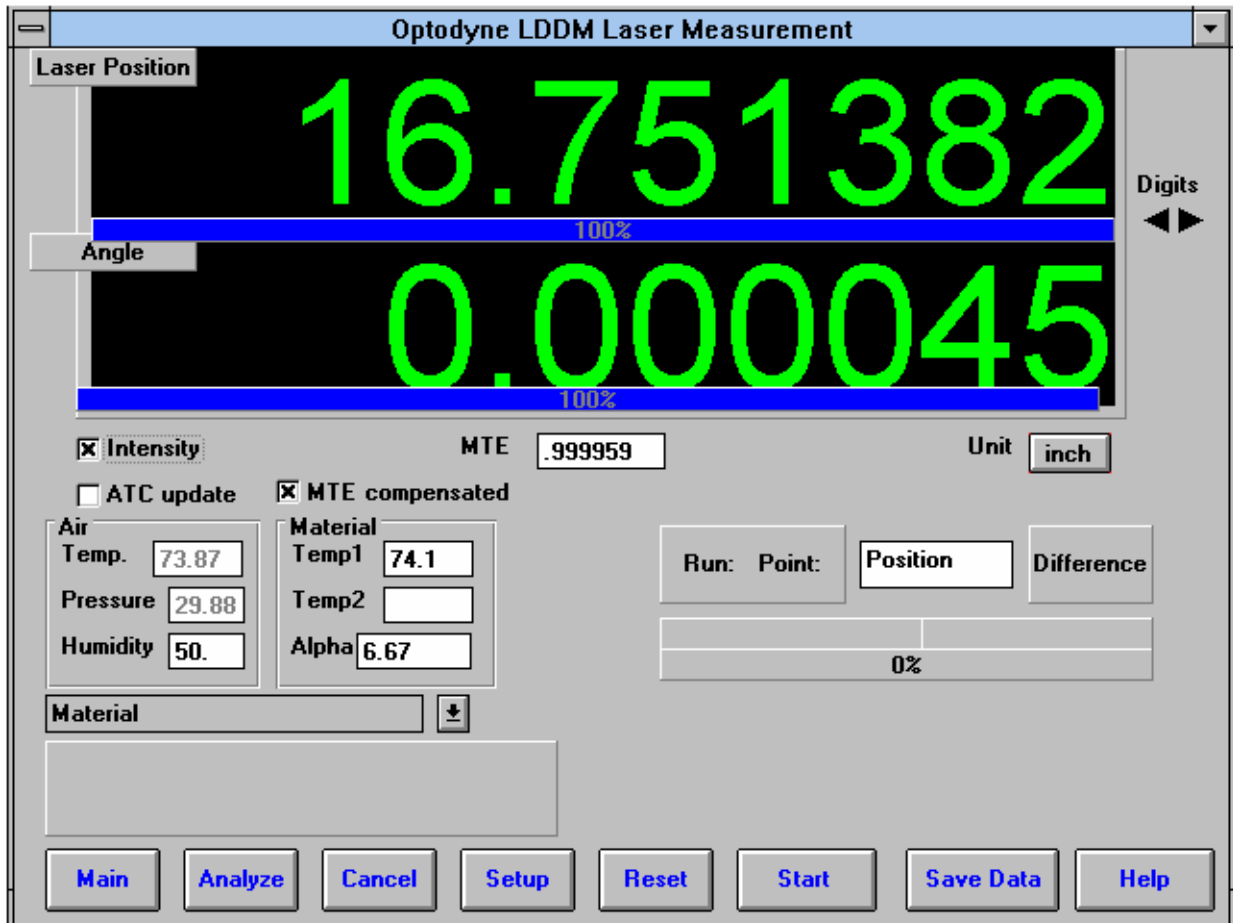


Fig. 5-1 Straightness Measurement Main Display

The display, in the straightness mode, shows the linear distance traveled on the top line, and the difference between LDDM #1 and LDDM #2 for the second line. If this second line value is divided by 1.1 (inches) or 27.94 (mm) then the value is in radians. When

you look at the outgoing laser beam aperture positions on the front of the laser head, LDDM #1 is the one closer to the center of the laser head, LDDM #1 is the one closer to the center of the laser head.

Choices on the Main Display are as follows:

Intensity: Align your system visually according to the User's Guide, then check your alignment by clicking on this box. A blue bar will appear the in-between the Laser Position window and the Target window. This blue bar will range from between 0 and 100%. Please make sure that the intensity is at least 40% over your whole run. Press the intensity box again to return the system to its original state.

The two boxes next to the Intensity box show the Pressure and Temperature that the Processor Box is reading. If you have an ATC probe, these numbers will be continually changing. If you do not have an ATC probe, the values will be 68 degrees and 29.9 inHg. When the Intensity Box is clicked on, these values will disappear.

ATC update: The ATC update updates the air pressure, air temperature and material temperature readings from the processor box. The MTE value will be calculated from these updated values and Alpha material coefficient. A X mark will appear when the ATC value has been updated correctly for the next measurement.

MTE compensated: To show compensation for Material Thermal Expansion, please click the box to show the X mark. If the X-mark does not appear on the screen, the displacement value will show only environmentally compensated values.

MTE: The MTE value can be manually changed in this box.

Unit: This box, when clicked on, will allow the user to change between the inch and metric systems.

Digits: Clicking the left arrow will decrease the amount of digits shown (data will still be taken to 6 digits). Clicking the right arrow will increase the amount of digits shown (max 6).

Air/Material Environmental, Alpha Boxes: Values may be entered in the Air Temperature and Pressure boxes for those people who do not have an ATC probe. Humidity should be entered for all users of the LDDM system. The Material Temperatures are averaged together to get the MTE coefficient value. The material alpha can also be manually changed if the material list does not include the material of the machine being calibrated.

Run: Point:, Position, Difference: The values in these boxes are during a measurement. They show the Run number that you are taking (up to 7), the point number, the target position, and the difference between the LDDM reading and the target position.

The percentage bar shows how much of the current measurement is done.

For automatic measurements, a stoplight will appear. The green light indicates that the program is ready for the system to go to the next data point. The yellow light indicates that the retroreflector has dropped below the velocity threshold and is waiting for the set delay to complete. The red light indicates that the system is taking the data point.

Material Box: The material list and their corresponding alpha values are listed here. Click the mouse on the down arrow and a list of materials are shown. Please choose from the material list or enter your own value to the alpha box above.

The dialog box is just underneath the material box. This box tells you messages and describes the actions you are taking.

Buttons at the bottom of the screen:

Main: exits the linear measurement package and loads the main menu.

Analyze: exits the linear measurement package and enters the analyze data package. A box will appear asking if the current module should be unloaded. Please type **Yes** unless you are taking a flatness measurement.

Cancel: Allows the cancellation of a measurement if it has gone out of alignment, or if something went wrong.

Setup: Opens the setup window, where measurement specifications may be edited or viewed.

Reset: Using this key allows for the reset of the LDDM. This key will also change the mode of the processor box to the current measurement type, i.e. if the processor is manually switched to a dual-beam mode while the program is in the linear measurement mode, the reset will return the processor to the linear measurement mode.

Start Measurement: This button starts the measurement defined in the setup window.

Save Data: This button will allow for the data storage of the last measurement taken.

The Laser Position window shows the current position of the retroreflector. This value always shows a value compensated for air temperature, pressure and relative humidity, but may or may not be compensated for MTE (if MTE compensated box is clicked on or off).

The Angle window shows LDDM#1-LDDM#2 at the position of the retroreflector. This value, when divided by 1.1 inches or 27.94 mm, is the angle in radians.

5.2 Straightness Measurement Setup Screen (Fig. 5-2)

To input information: Please move the mouse pointer over the box on which you wish to change the information. The mouse pointer will turn in to a vertical bar. Two things may be done:

- 1) Block the text. Hold the mouse button down and move over the text completely. The text being blocked will become inverted in color (white on black). Type in the information to be entered. The original text will be replaced by the new information.
- 2) Click the mouse button while the vertical bar is over the box. Use the arrow keys and the delete key to erase the previous information. Then input the new information.

The screenshot shows the 'Straightness Setup' window. The 'Identification' section contains fields for Machine (Machine Center), S/N (12345), By (OPD), and Date (11/04/03). The 'Laser head Direction/Measurement Axis' section features a 3D coordinate system with x, y, and z axes, and a 'Rotate Axis' button. The 'Straightness Measurement' section includes fields for Start Position (0), End Position (40), 2nd Axis Start, 2nd Axis End, Number of Points (11), and Number of Runs (1). It also has checkboxes for 'Forward Only' and 'Positioned by Equal divisions', radio buttons for 'Dual Beam' and '2 Laser Heads', and a '2nd Axis' dropdown menu. The 'Auto measurement' section has fields for Target Window (0.1 inch), Trigger dwell (1 sec), and Vel Threshold (0.01), along with a 'Backlash' checkbox. At the bottom, there are buttons for 'New Config File', 'Save Configuration', 'Cancel', and 'OK'.

Fig. 5-2 Straightness Measurement Setup Screen

Identification Box:

The identification of the machine, i.e. the machine type, serial number, the person doing the calibration, and the date, is entered here and is saved in the data file. The date is automatically entered using the computer system date.

Laser head direction/Measurement Axis Box:

- 1) Choose which axis the lasers are pointed in (X, Y or Z axis). In Fig. 5-2, it is the X-axis.

2) Double click the **X-axis**, **Y-axis** or **Z-axis** axis button until the red beams are pointing in the direction that the laser is pointed in referenced to the machine. The axis labels on the screen designate the positive direction of the machine. In Fig. 5-2, the laser is pointed in the positive x-axis. Click the Rotate Axis to rotate axes orientation to match with the machine coordinate.

3) Choose the axis of the straightness measurement. The two beams of the laser head are in the same plane of the straightness measurement. In Fig. 5-2, the two beams are aligned with the y-axis.

4) LDDM #1 (beam #1) is designated by the laser beam exiting closest to the center of the laser head. On the machine, visually place the axis that is being measured linearly between LDDM #1 and LDDM #2. If LDDM #1 is on the positive side of the straightness axis, click on the positive straightness axis. If LDDM #1 is on the negative side of the straightness axis, click on the negative straightness axis. In Fig. 5-2, LDDM #1 was found to be in the negative side of the y axis while measuring the x axis linearly.

5) If the laser head is moving, switch the sign of the dot in the straightness axis. In Fig 5-2, if the laser head was moving, the dot would be now placed on the +y axis.

These 5 steps will ensure that your straightness measurement will truly reflect what the ways of the machine are doing to the travel. If you set these steps up incorrectly, the only difference in the measurement will be that the graph should be turned over (change the sign). The actual straightness values will be unchanged.

6) If the laser head is mounted up side down or in a reversed orientation, click the box on **Reverse Orientation**. This will correct the small divergence of the two parallel beams. The value of the beam divergence is set in the LDDM.ini file. A typical beam divergence is 0.0002 m/m or $R = -0.0002$.

Straightness Measurement Box:

Start/End Position: Please enter the starting and ending coordinates from the machine here for the axis to be measured.

Number of Points: Counting the zero point as the first point, please enter the number of points for the run.

Number of Runs: Choose the number of runs for this measurement, 1 through 7.

Verify/Edit: Click on this button to see the data acquisition setup. Make sure that your increments are correct. If there are increments to be changed to an irregular interval, you may edit the box.

Forward Only: Click the box to an X mark if the measurement is to be forward only. Leave the box blank if it is to be a bi-directional measurement.

Dual Beam or 2 Lasers: For dual-beam laser head, click on **Dual Beam**, the laser beam separation will shown 1.1 in or 27.94 mm. For 2 laser heads pointing in the same direction, click on **2 Laser Heads** and the **2nd axis** same as the 1st axis. Then enter the **Laser head separation** in inch or mm (For standard box, the separation is 2.51” or 63.754 mm). For 2 laser heads pointing in two different directions perpendicular to each other, click on **2 laser heads** and the **2nd axis** different from the 1st axis. Then enter the **2nd axis start position** and **2nd axis end position**. For this case, the data collection is based on the 1st axis and the 2nd axis reading will be collected at the same time as the 1st axis. For automatic data collection, it is important that the 2nd axis is stopped before (or within the dwell time) the 1st axis is stopped. To analyze the data, open the .str file then click on the displacement 1 and save. Enter a new file name. The 1st axis displacement data will be saved in a .Lin file. Similarly, click on the displacement 2 to generate a .Lin file for the 2nd axis.

ATC Board: If you have an ATC board, please click the mouse here and make an X mark. If you do not have an ATC board, please make sure that there is no X mark there. To manually set the speed of light correction, click the ATC board on and off, then enter the barometric pressure in mmHg and the air temperature in °C. The barometric pressure and air temperature values will be reset to 760 and 20 automatically once leave the program to avoid possible double correction

Please choose the type of measurement you wish to take:

Manual: The Start Measurement button will turn into a "TAKE" button after the measurement begins. At every collection point, this button will have to be pushed.

Automatic: The software will collect data every time the retroreflector comes within a "Target Window", drops under a certain velocity and sits still for a designated dwell time.

On-the-Fly: The software will automatically take data as soon as it is sensed that the retroreflector is within the "Target Window" of the target position.

Auto Measurement Box:

Target Window (automatic and on-the-fly): For automatic and on-the-fly measurements, being within this value of the target position allows the software to take data. For on-the-fly measurements, the maximum speed is 10 times the target window.

Trigger dwell (automatic only): For automatic measurements, the settling time of the machine (typically 3-5 seconds) is entered here. Choose a value of at least 2 seconds less than the programmed machine dwell time.

Vel Threshold (automatic only): This is the threshold that the retroreflector must drop underneath so that a data point can be taken.

Backlash (automatic only): If the box has an X, backlash at the end and beginning of each run (other than the first point) will be taken. The distance necessary to remove the backlash and allow the software to re-trigger is twice the target window.

New Config File: You may load a previous configuration file if you have one for this particular machine.

Save Configuration: This updates the LDDM.2CF file so that the data seen on the screen will appear each time LDDM for Windows is run.

Cancel: Cancel the above changes and revert to the previous values.

OK: Settings are ok for this measurement. If you saved this setup as the default, it will come up first every time, otherwise the previous setup will re-appear next time the program is run.

5.3 Example of a Straightness Measurement

Straightness Measurement Main Display (See Fig. 5-1):

- 1) Check your units in middle right hand side. If it is not the correct type, click on the icon.
- 2) Click the **Intensity** button on the middle left hand side. Align the laser head/retroreflector according to the user's manual, using the intensity bar reading as a guide. After alignment, click off the **Intensity**.
- 3) Click once on the **Setup** icon on the bottom row of icons.

Straightness Measurement Setup Screen (See Fig. 5-2):

- 4) Setup your system information on the upper right hand side of the machine. Input the identification of the machine you are calibrating. To type the text, please move the arrow of the mouse pointer until it turns into a text cursor (an up and down line). Or please hit the tab key until one of the text boxes is highlighted. Type your machine data in.
- 5) Enter the axis of measurement by clicking the appropriate box on the bottom left graph (**X, Y, Z** and laser head **orientation**). Also choose the axis which best describes the position of the LDDM#1 laser beam on your dual beam laser head, compared to your machine.
- 6) Enter the **machine coordinates** that you wish to calibrate in the upper right corner.
- 7) Enter the **number of points**, including zero, that you wish to calibrate. E.g. For a ten inch run, with 2 inch increments, enter 6.

8) Enter the **number of runs** (typically 7 for NMTBA, or 4 or VDI, ISO and at least 1 run for B5)

9) Press the **Verify/Edit** button to see the increments. You may manually change these increments if you would like to.

10) If you are manually changing the values, make sure that the **Positions Equally Divided** box is clicked off to show: **Positions As Shown Below**.

11) Change the # of points as necessary to achieve the correct increment that you desire (Press Verify/Edit to check again).

12) Choose **Forward Only** or **Bi-Directional** runs.

13) Click on the **ATC board** if you have one.

14) Choose your type of measurement:

Manual

- you may:
- 1) Hit the <Enter> key at each point, or
 - 2) Click the mouse on **Take** at each point

Automatic

To collect data automatically, you will have to program the machine controller to do 2 or 3 things: to move in a certain increment with a delay time in-between movements (3-5 seconds recommended), and add a backlash movement that is greater than double the target window (backlash is optional).

The following information will be necessary for Automatic measurements:

Target Window: This tells the computer a distance window around the target position where the computer is allowed to take data. This value is related to the backlash needed (see below). A typical value is .001 inch or .02 mm, depending how tight your machine is. The backlash movement of the machine must be at least double this value.

Trigger Dwell: Set this value for two seconds less than the machine delay time for each point.

Velocity Threshold: This value keeps the risk of false triggering down. A good value to use is 0.01 for inches, 0.1 for metric.

Backlash: Check here if you want to account for backlash. The backlash at the beginning and end of each forward/backward run has to be at least TWICE the target window value.

On-the-Fly: For On-the-Fly Measurements the user must enter the number of points and the start/stop coordinates. The user will then move the retroreflector under a certain maximum speed equal to 10 times the target window. The program will automatically take data as the machine moves along.

The following information is necessary for On-The-Fly Measurements:

Target Window: The Target Window is set for variable speed control. It is, of course, better if you move your retroreflector slower, but for a quick overall check of an axis, that is unnecessary.

15) Saving the Configuration file

Save this configuration file by clicking the **Save Config File** Icon. Type the name of the file which you would like the setup saved to (usually the name of the machine). Press **<Enter>** or **OK** after typing it in.

The program will ask you if you would like to save the file, press **Yes**.

The program will then ask if you want to use this file as your default. If you press **Yes**, this setup will be loaded every time that the Straightness Measurement Module is loaded.

To load a configuration file next time, click on **New Config File**. You may either:

- 1) Click on the file name and press **OK**
- 2) Double click on the file name
- 3) Type the name of the file name, example: **LDDM.2CF** and hit **<Enter>**.

16) Press **OK** to get back to the main screen.

Taking Data Points for a Linear and Straightness Measurement (Fig. 5-3):

17) Press **ATC update (X)** to update the values if you have an ATC probe hooked up to the Processor Module.

18) Edit the Humidity Value as necessary.

19) Choose your material from the list given. Press the **Down arrow** key and you will get a list, press the **Down arrow**, or **PgDn** key from there to scroll down.

20) Choose the number of digits on the upper right hand side of the screen you wish the screen to display.

21) Move your retroreflector to the beginning of your run. Click on **Start**.

Manual: If you are manually operating the laser/machine, press the designated key to take data as shown (after you move the machine). Also, if you would like to change the target position, you may do so in the value box located in-between the run information.

Automatic: If you are running the automatic program, you will see a stoplight appear. The red means that the conditions for a measurement have been met (inside the target window, and the velocity is lower than the given one), yellow means that the delay is being counted and the green means that the data has been collected and the program is waiting for you to move to the next point (Fig. 5-3)

On-The-Fly: If you are running the On-The-Fly program, you will also see the stoplight appear. The light will turn red when a data point is taken and green when it is ready to take another data point. If you move faster than the target window allows for, you will hear a continuous beeping noise. Please move the retroreflector backwards until the beeping stops, then move it forwards again.

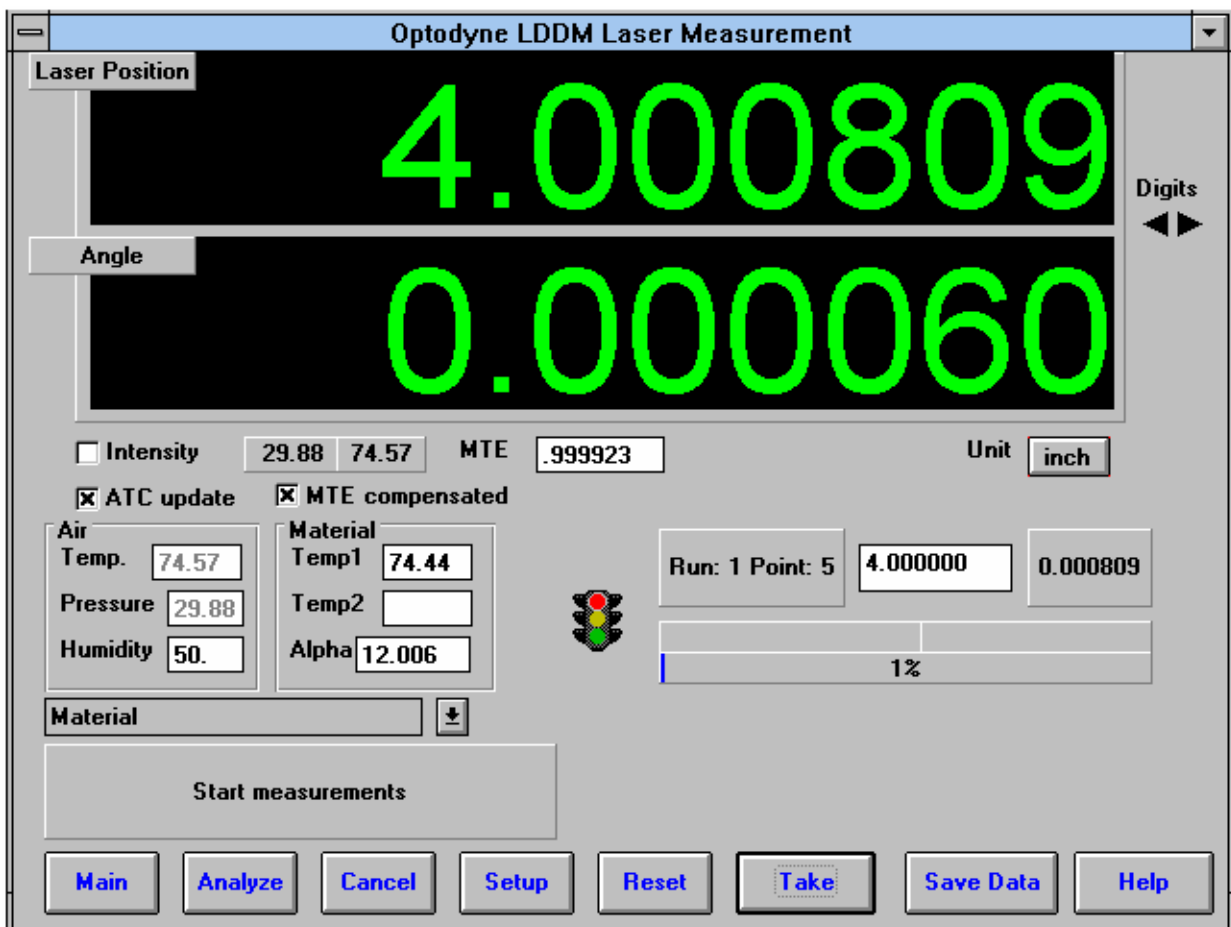


Fig. 5-3 Automatic Straightness/Linear Data Collection

- 23) After all the data is taken, press **OK** to save the data, or **Cancel** to not save the data.
- 24) To save data, type in the **filename** to save and hit **<Enter>** (the extension is automatically saved as .STR). You may also save collected data by pressing the save data button, and follow the procedure above.
- 25) To analyze the data click on the **Analyze button**. When it prompts you, unload the module, unless you are taking a flatness measurement.

5.4 Straightness Data Analysis Menu

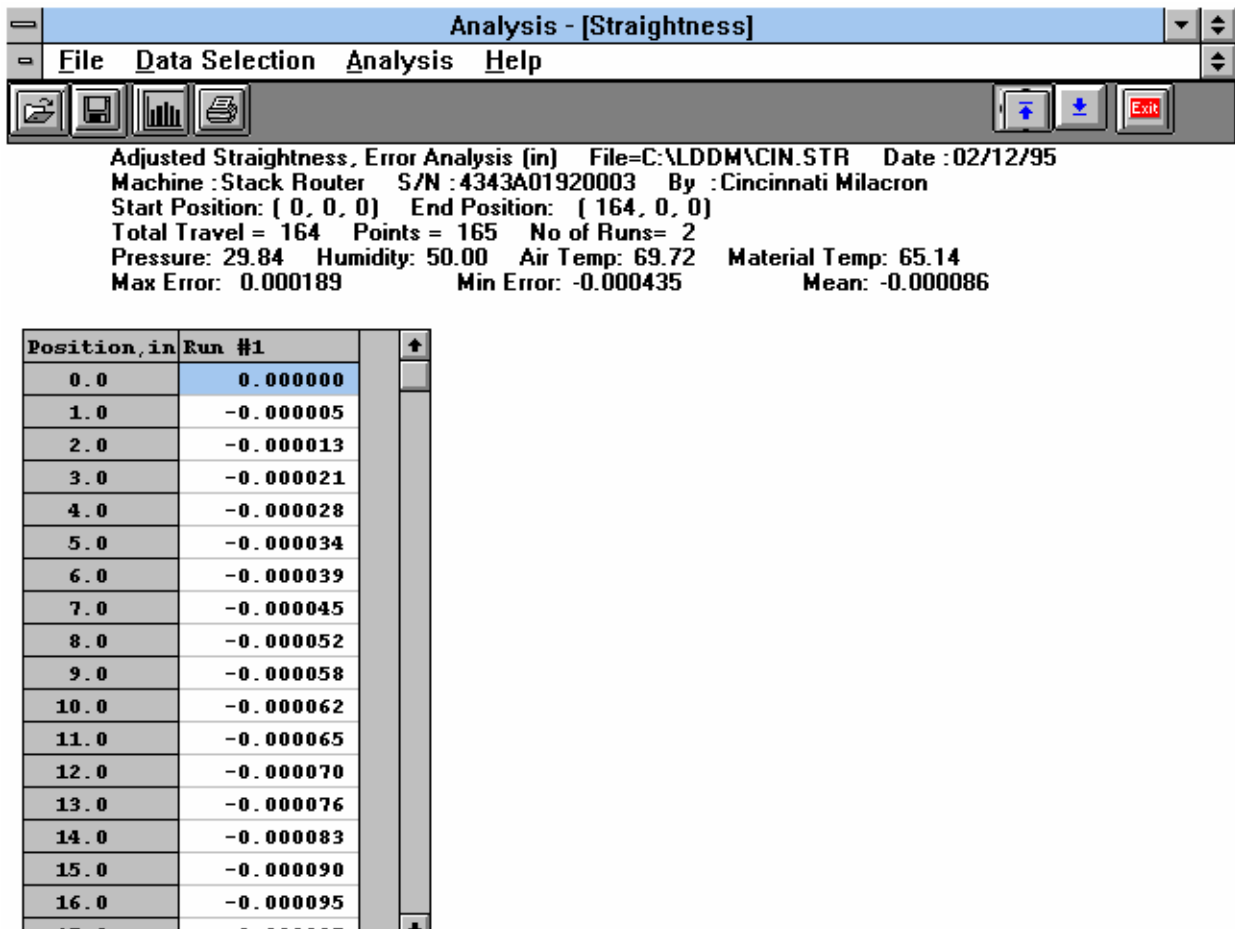


Fig. 5-4 Straightness Measurement Data Analysis Table

Under the **File Menu**, you can open a **new** data file, **save** a data file, set your **printer type**, set your **printer style**, or return to the **main menu**. When loading a file, choose the files with the extension of .STR for straightness. You can only **print data** tables using the print function under this heading.

Under the **Data Selection** heading, you may choose **displacement** data, **angle** data, **straightness** data, and **adjusted straightness** data when looking at a straightness (.STR) file.

Under **Analysis**, you can choose **Error**, **NMTBA**, **NMTBA with Zero Shift**, **VDI 3441**, **ISO ASME B5.54** or **ASME B5.57** for different types of data manipulation. After choosing **Error**, you will be given a choice on what you wish to see, **Runs #1-7**, and **forward** or **backward**. Click with the mouse button on which runs you wish to see.

The following icons have the following function in Analysis:



Open a new data file.



Save a data file.



Graph a data file (After graphing, you may also change the scaling of the graph by checking X on adjust grid).



Print a data graph (for printing data tables, use the Print option under the “File” heading)



Moves to the previous screen.



Moves to the next screen.



Exits the program.

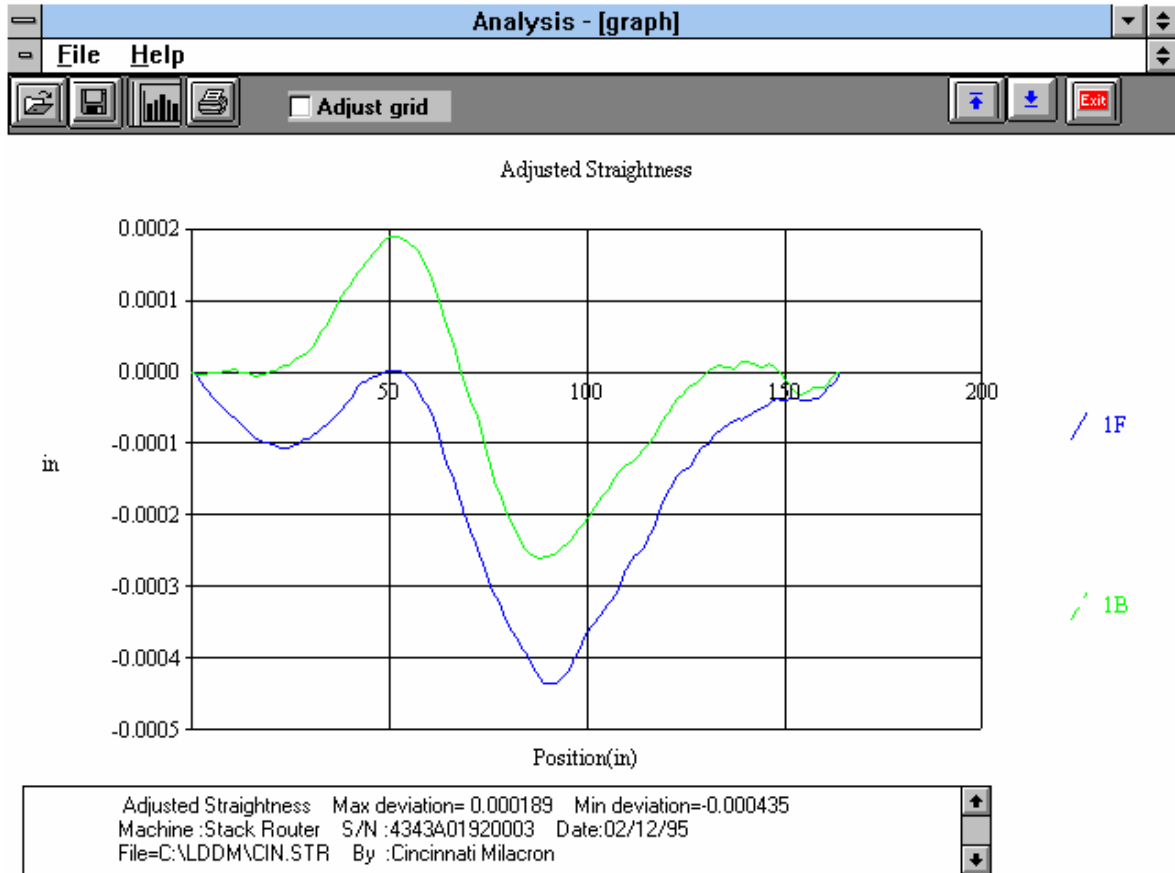


Fig. 5-5 Adjusted Straightness Measurement Data Plot

A typical straightness data plot is shown in Fig. 5-5.

5.5 Straightness Display

The straightness measurement here is very accurate and sensitive. However, for the alignment of a long guide rail. It is desirable to display the straightness for real-time adjustment of the rail. The straightness display is designed for this purpose. Click the straightness Display box in the main menu, the screen will show the straightness Display below:

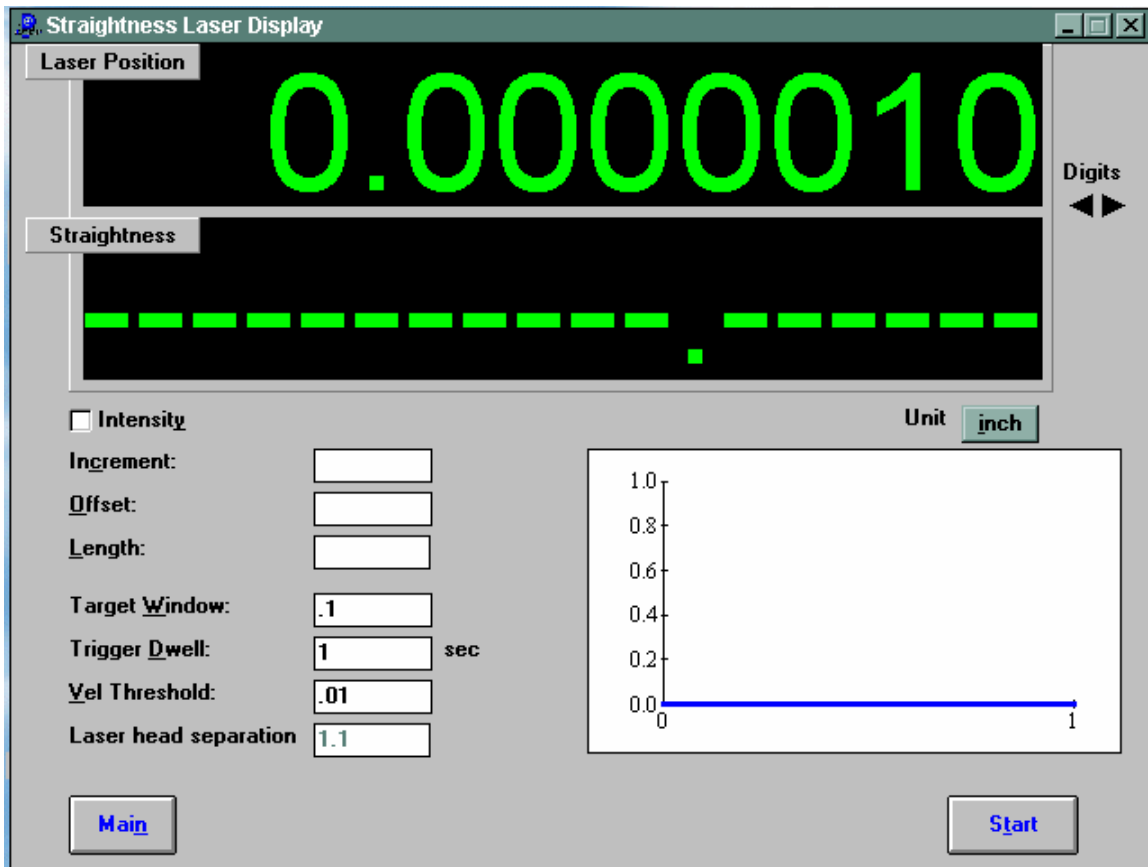


Fig. 5-6 Straightness Display Screen

The straightness displayed is calculated by integrate the measured angle times the increment and minus the off-set. Hence the straightness value displayed will be a constant between the increment.

Increment : Enter the increment value. Typical values are from 0.1 to 10 inches.

Off-set : Enter the end-point straightness value in the straightness measurement. For the first measurement, enter 0.000001. After the first measurement, enter the end-point value obtained from the display. A correct off-set value will set the end-point value to zero.

Length : This is the length of total travel Target Window. Trigger Dwell, Vel. Threshold and Laser head separation are the same as in previous sections. To start, align

the laser head and the dual-retroreflector properly and move the dual-retroreflector to the zero position then click the start box. Similar to the straightness measurement discussed before, move the dual-retroreflector to the next increment, the data will be taken automatically and display on the screen. The first line is the position and the second line is the measured straightness, as show below:

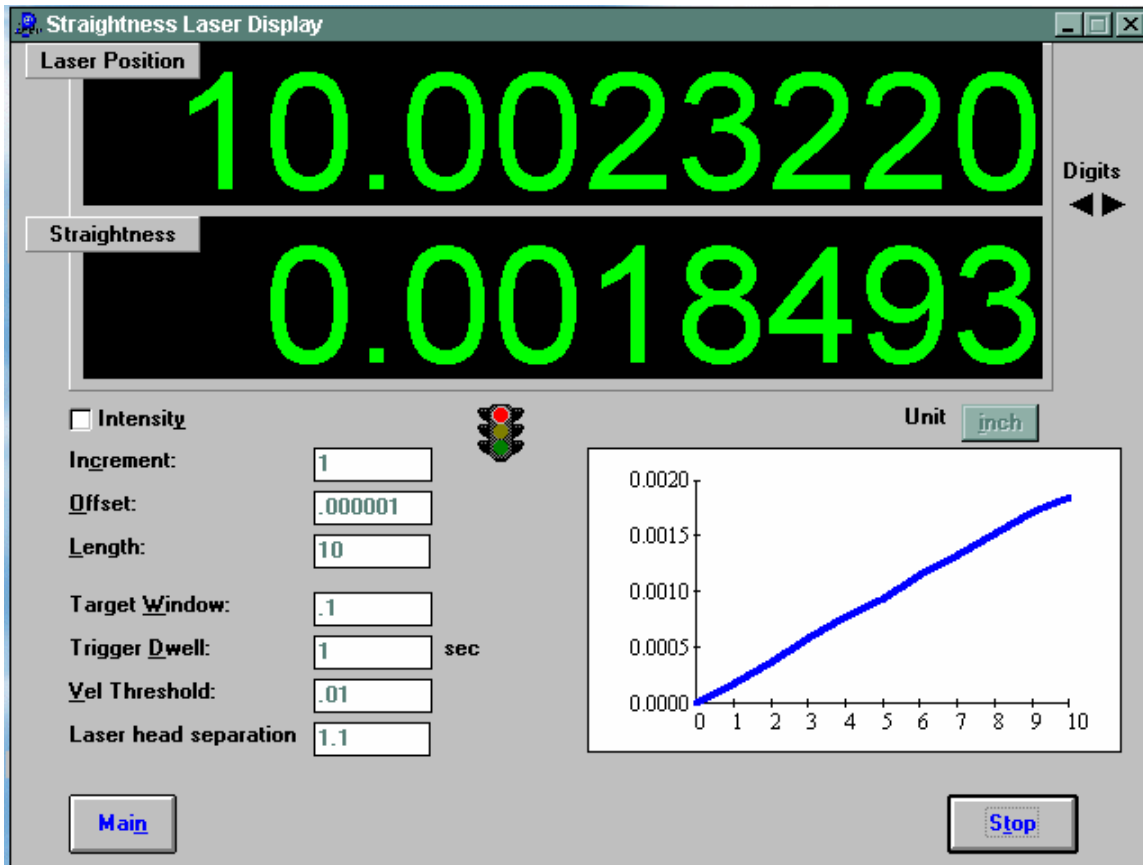


Fig. 5-7 Straightness Display Without Offset

You may move the dual-retroreflector back and forth, do a real-time adjustment on the rail, and display the straightness again.

Please note that the offset value may be changed after some real real-time adjustment on the rail. You may enter a new off-set value based on the end-point readings (add the end-point readings to the existing off-set value) .

After the rail is aligned, use the previous straightness measurement to collect straightness data and verify the straightness.

After clicking the **Flatness Measurement** Box on the Main Menu, you will be greeted by the Flatness Measurement Data Screen. If the LDDM is not in the correct port, a box with the port choice will appear asking you if the LDDM is connected to COM1 or COM2. Please enter the correct choice. If the LDDM is not connected, a dashed line will

appear in the Laser Position section of the window. Please check your connections and the LDDM reading on the display should appear.

6.0 Flatness Measurements

After clicking the **Flatness Measurement** Box on the Main Menu, you will be greeted by the Flatness Measurement Data Screen. If the LDDM is not connected to communication port, a message box will appear telling you that the LDDM interface not found. Please check your connections and the LDDM reading on the display should appear.

6.1 Flatness Measurement Main Display (Fig. 6-1)

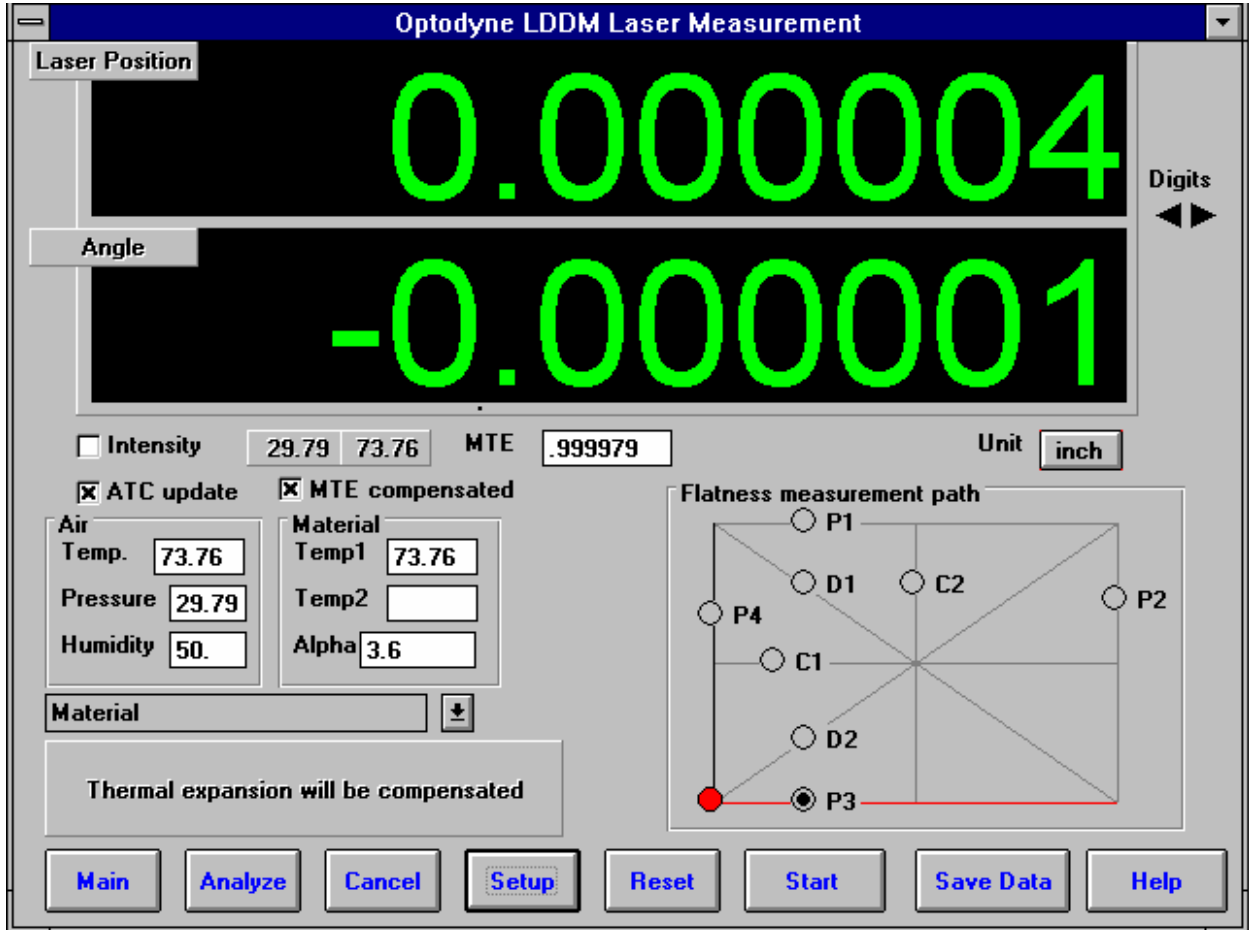


Fig. 6-1 Flatness Measurement Main Display

The display, in the straightness mode, shows the linear distance traveled on the top line, and the difference between LDDM #1 and LDDM #2 for the second line. If this second line value is divided by 1.1 (inches) or 27.94 (mm) then the value is in radians. When you look at the outgoing laser beam aperture positions on the front of the laser head, LDDM #1 is the one closer to the center of the laser head.

Choices on the Main Display are as follows:

Intensity: Align your system visually according to the User's Guide, then check your alignment by clicking on this box. A blue bar will appear in-between the Laser Position window and the Target window. This blue bar will range from between 0 and 100%. Please make sure that the intensity is at least 40% over your whole run. Press the intensity box again to return the system to its original state.

The two boxes next to the Intensity box show the Pressure and Temperature that the Processor Box is reading. If you have an ATC probe, these numbers will be continually changing. If you do not have an ATC probe, the values will be 68 degrees and 29.9 inHg. When the Intensity Box is clicked on, these values will disappear.

ATC update: The ATC update updates the air pressure, air temperature and material temperature readings from the processor box. The MTE value will be calculated from these updated values and Alpha material coefficient. A X mark will appear when the ATC value has been updated correctly for the next measurement.

MTE compensated: To show compensation for Material Thermal Expansion, please click the box to show the X mark. If the X-mark does not appear on the screen, the displacement value will show only environmentally compensated values.

MTE: The MTE value can be manually changed in this box.

Unit: This box, when clicked on, will allow the user to change between the inch and metric systems.

Digits: Clicking the **left arrow** will decrease the amount of digits shown (data will still be taken to 6 digits for inches, 5 for metric). Clicking the **right arrow** will increase the amount of digits shown (max 5 or 6).

Air/Material Environmental, Alpha Boxes: Values may be entered in the Air Temperature and Pressure boxes for those people who do not have an ATC probe. Humidity should be entered for all users of the LDDM system. The Material Temperatures are averaged together to get the MTE coefficient value. The material alpha can also be manually changed if the material list does not include the material of the machine being calibrated.

Flatness measurement path Box: This box shows which part of your flatness measurement that is being done, or is to be done next. To change directions of the measurement, please double-click the left mouse button on the circle next to the path you would like to measure. As you move the retroreflector along the path, the red dot will also move, showing the retroreflector position for this particular measurement.

For automatic measurements, a stoplight will appear. The green light indicates that the program is ready for the system to go to the next data point. The yellow light indicates that the retroreflector has dropped below the velocity threshold and is waiting for the set delay to complete. The red light indicates that the system is taking the data point.

Material Box: The material list and their corresponding alpha values are listed here. Click the mouse on the down arrow and a list of materials is shown. Please choose from the material list or enter your own value to the alpha box above.

The dialog box is just underneath the material box. This box tells you messages and describes the actions you are taking.

Buttons at the bottom of the screen:

Main: exits the linear measurement package and loads the main menu.

Analyze: exits the flatness measurement package and enters the analyze data package. For Flatness measurements, **do not** unload the module when prompted.

Cancel: Allows the cancellation of a measurement if it has gone out of alignment, or if something went wrong.

Setup: Opens the setup window, where measurement specifications may be edited or viewed.

Reset: Using this key allows for the reset of the LDDM. This key will also change the mode of the processor box to the current measurement type, i.e. if the processor is manually switched to a dual-beam mode while the program is in the linear measurement mode, the reset will return the processor to the linear measurement mode.

Start Measurement: This button starts the measurement defined in the setup window.

Save Data: This button will allow for the data storage of the last measurement taken.

The Laser Position window shows the current position of the retroreflector. This value always shows a value compensated for air temperature, pressure and relative humidity, but may or may not be compensated for MTE (if MTE compensated box is clicked on or off). The ATC or MTE compensation is NOT important for the flatness measurement.

The Angle window will show the angular value of the current position of the retroreflector. This value when divided by 1.1 inches or 27.94 mm, is the angle in radians.

6.2 Flatness Measurement Setup Screen (Fig. 6-2)

To input information: Please move the mouse pointer over the box on which you wish to change the information. The mouse pointer will turn in to a vertical bar. Two things may be done:

- 1) Block the text. Hold the mouse button down and move over the text completely. The text being blocked will become inverted in color (white on black). Type in the information to be entered. The original text will be replaced by the new information.
- 2) Click the mouse button while the vertical bar is over the box. Use the arrow keys and the delete key to erase the previous information. Then input the new information.
- 3) The P2 line of the graph always designates the "LABEL" side of the table. Please note this when setting up the measurement.

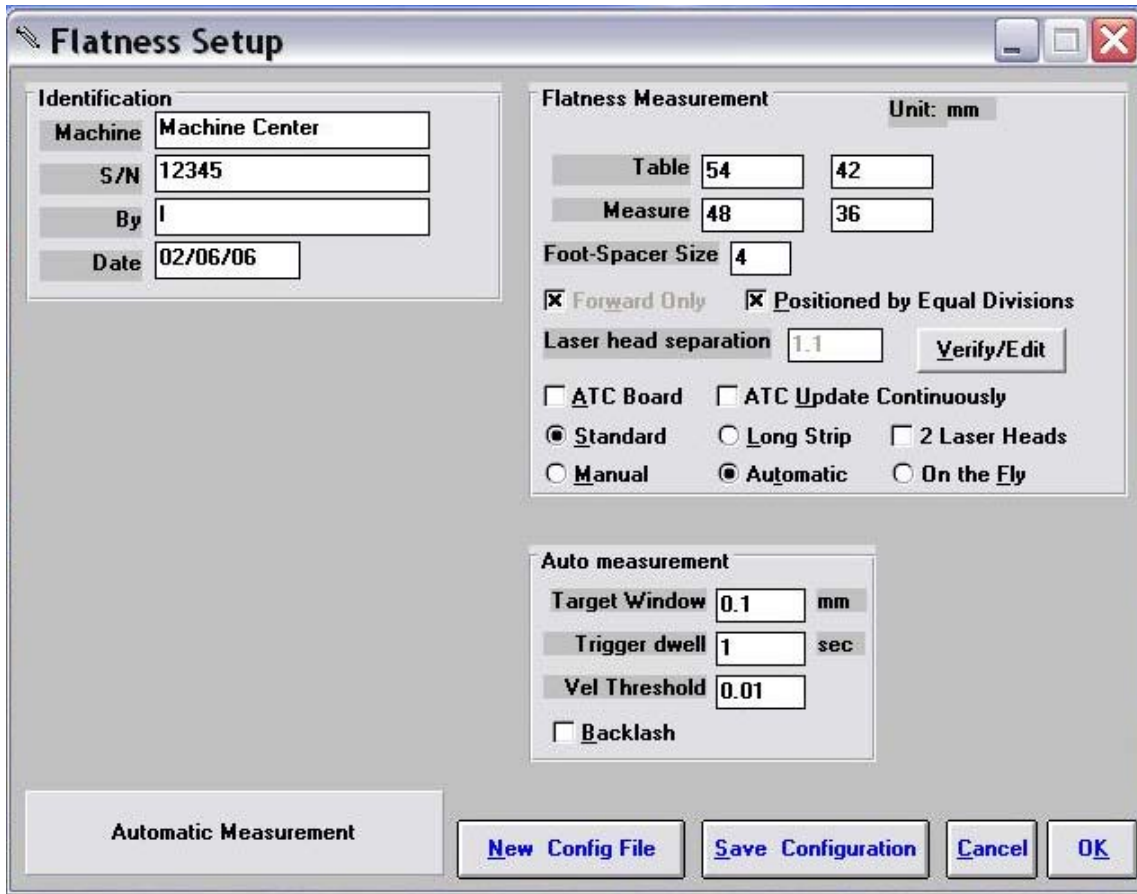


Fig. 6-2 Flatness measurement Setup Screen

Identification Box:

The identification of the machine, i.e. the machine type, serial number, the person doing the calibration, and the date, is entered here and is saved in the data file. The date is automatically entered using the computer system date.

Flatness Measurement Box:

Table, Length/Width: Enter the length and width of the table.

Measure, Length/Width: Enter the size of the surface which is to be measured.

Foot Spacer Size: Depending on which foot spacer is to be used, enter 2, 4 or 6 inches, or 50, 100, 150 mm.

Positions by Equal Divided: Make sure that this box is checked.

Verify/Edit: Click on this button to see the data acquisition setup. Make sure that your increments are correct. If there are increments to be changed to an irregular interval, you may edit the box.

Forward Only: All flatness measurements are automatically forward only.

ATC Board: Do NOT use the ATC Board when taking flatness measurements. Make sure that no X appears in the box. The ATC Board is not important to flatness data collection.

Please choose the type of measurement you wish to take:

Standard : The standard method is the Moody method or Union Jack method.

Long Strip : For a long surface plate, you may select the long strip method. Here instead of 2 diagonals and 2 centerlines, there are 5 parallel lines and only one diagonal. A total measurement of 8 segments is still the same.

2 Laser Head: for 2 laser heads (MCV-5000) click this.

Manual: The **Start Measurement** button will turn into a **Take** button after the measurement begins. At every collection point, this button will have to be pushed.

Automatic: The software will collect data every time the retroreflector comes within a "Target Window" and drops under a certain velocity. Automatic measurement is not recommended for Flatness Measurements.

On-the-Fly: The software will automatically take data as soon as it is sensed that the retroreflector is within the "Target Window" of the target position.

Auto Measurement Box:

Target Window (automatic and on-the-fly): For automatic and on-the-fly measurements, being within this value of the target position allows the software to take data. For on-the-fly measurements, the maximum speed is 10 times the target window.

Vel Threshold (automatic only): This is the threshold that the retroreflector must drop underneath so that a data point can be taken.

New Config File: You may load a previous configuration file if you have one for this particular machine.

Save Configuration: This updates the LDDM.3CF file so that the data seen on the screen will appear each time LDDM for Windows is run.

Cancel: Cancel the above changes and revert to the previous values.

OK: Settings are ok for this measurement. If you saved this setup as the default, it will come up first every time, otherwise the previous setup will re-appear next time the program is run.

6.3 Example of a Flatness Measurement

Flatness Measurement Main Display (See Fig. 6-1)

- 1) At the Main Menu, click the left mouse button on **Flatness**.
- 2) When the display screen appears, check your units, make sure that the units (inch/mm) are correct for your application.
- 3) Click the intensity box - an X and a blue bar under each measurement window will appear. Please align your system according to the User's Guide so that the blue bars are close to 100% over the complete path of measurement.
- 4) Go to the **setup** button and click the left mouse button.

Flatness Measurement Setup Screen (Fig. 6-2):

- 5) The setup screen will now appear, start with the upper left hand side of the setup window; fill in your **machine information**.
- 6) Setup your **table measurement specifications**. Input the actual table dimensions (Table), and the actual measured dimensions (Measure) for both length and width.
- 7) Choose your **foot spacer size**, 2, 4, or 6 inches.
- 8) Click on the **Verify/Edit** button to see if the diagonal travel is correct.
- 9) **Positions Equally Divided** should be clicked on at all times (due to the nature of the flatness measurement).
- 10) Make sure that the **ATC Board** option is turned **OFF**.

- 11) Choose the **type of measurement** (On-the-Fly is recommended and is the fastest).
- 12) For On-the-Fly measurements, the top speed of the retroreflector is 10x the window size you choose. If the window is 0.1 inch, the top speed of the measurement is 1 IPS.
- 13) Save your configuration by clicking on the appropriate button on the bottom of the screen. Type the name that you want to save it under and hit enter. The computer will automatically add the correct extension to the file name.
- 14) Click on **OK** to save.
- 15) If you want this setup to be the default file (the setup that appears every time you load the flatness program), click on **Yes**.
- 16) Press **OK** to return to the main screen.

Taking Data Points for an On-The-Fly Flatness Measurement (Fig. 6-3):

- 17) The measurement path (collection), by default follows the user's guide method on page 9-7.
- 18) You can change the order of measurement by clicking the left mouse button on the circle next to the run you wish to take. If you wish to change directions of your measurement path, double-click the circle of the path you want to change directions on.

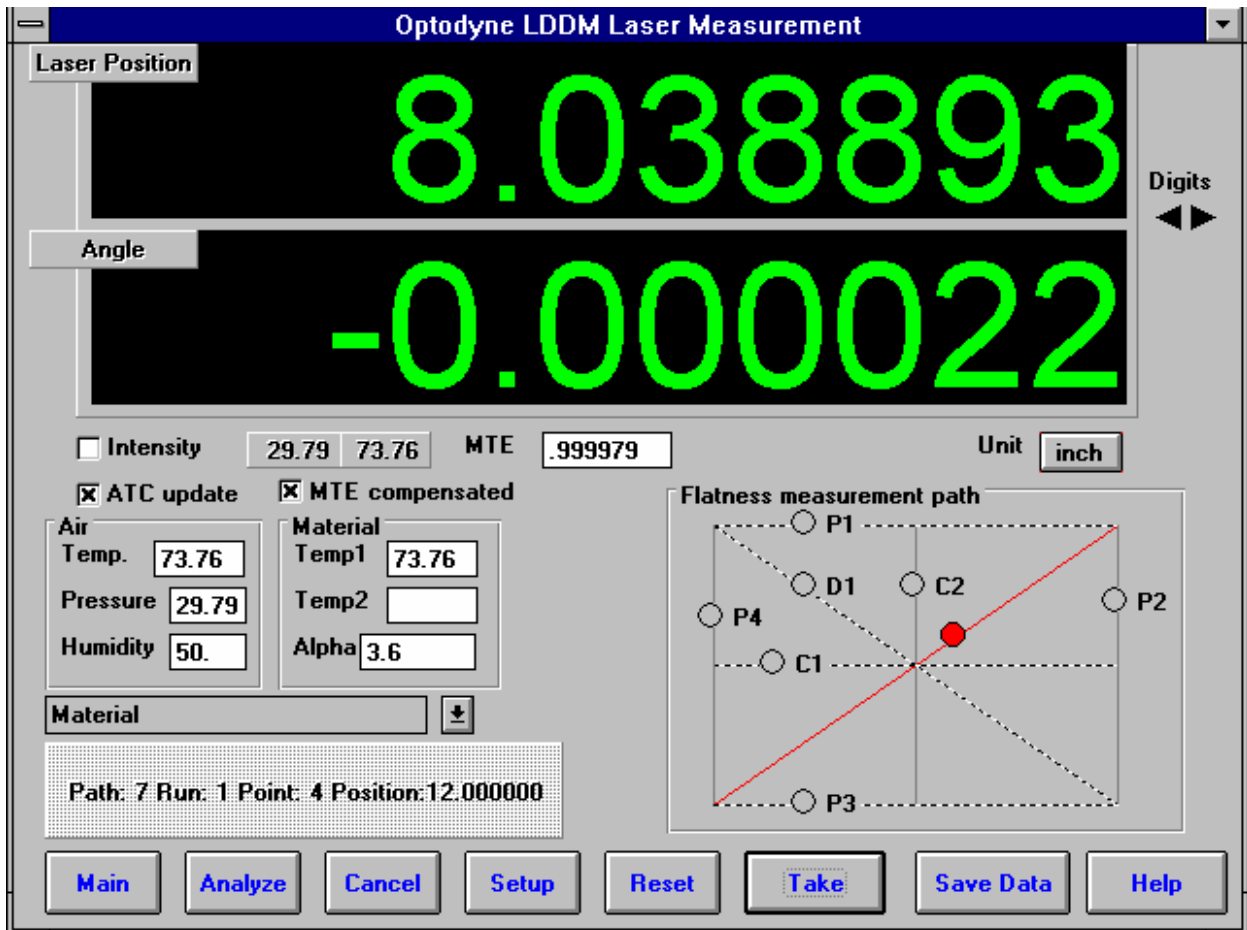


Fig. 6-3 On-The-Fly Flatness Measurement Data Collection

- 19) Press **Start** when in position and carefully pull the retroreflector across the surface.
- 21) If you move too fast or miss a point, you will hear a series of beeps, then move back until the beeps stop and continue with your measurement.
- 22) If you get the out of alignment message, find out what caused the message and fix it (be it alignment, human error, etc.). Move back to the previous position and click on the **OK** box. For automatic and on-the-Fly measurement, you will have to start that particular run over.
- 23) If you wish to redo a line, you may do so by clicking on the line you wish to redo. The resulting data will supersede the previous data.
- 24) After all of the lines have been taken, you may save the data by clicking on **OK**, when prompted, and typing in a file name. The .FLT extension will be automatically added to the filename.
- 25) You may also save the data after the run by pressing the **Save Data** key.

- 26) To analyze the data, click on the **Analyze Data** key, do not unload the module when prompted.
- 27) After viewing the table, you may want to immediately lap the surface that you are measuring. To be able to revise old data you must do the following:
- 28) Choose **Flatness** at the main menu.
- 29) Choose **Analysis** and DO NOT unload the module.
- 30) Go to **File** and **Load** the file with the data you wish to recheck.
- 31) Keep pressing the **up arrow** button (or hit the **ESC** key) until you return to the Flatness screen.
- 32) Click on **Setup** and make sure that the setup is the same. Hit **OK** after checking.
- 33) Choose the **line** which you wish to re-measure. Press **Start** and take your measurement.
- 34) After the line is taken, click on **Save Data** and save your measurement.
- 35) Go back to **Analysis** and check your data.

6.4 Flatness Data Analysis Menu (Fig. 6-4, 6-5, 6-6)

Position,in	P4	P3	P2	P1	C1	C2	D1
0.	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000
4.	-0.000006	-0.000025	-0.000059	-0.000011	-0.000057	0.000027	-0.000
8.	0.000071	-0.000015	0.000006	-0.000137	-0.000071	0.000043	-0.000
12.	0.000062	0.000051	0.000027	-0.000094	-0.000041	0.000028	-0.000
16.	0.000039	0.000076	0.000022	-0.000027	-0.000015	0.000036	-0.000
20.	0.000051	0.000076	0.000028	0.000034	-0.000011	-0.000104	-0.000
24.	0.000016	0.000029	0.000034	0.000035	-0.000036	-0.000077	-0.000
28.	-0.000001	-0.000004	0.000026	-0.000027	-0.000071	-0.000052	0.000
32.	0.000000	0.000014	0.000000	0.000000	-0.000020	0.000000	0.000
36.		-0.000004		0.000051	0.000032		0.000
40.		0.000000		0.000000	0.000000		0.000
44.							0.000
48.							0.000

Fig. 6-4 flatness Measurement Data Table

Under the **File Menu**, you can open a **new** data file, **save** a data file, set your **printer type**, set your **printer style**, or return to the **main menu**. When loading a file, choose the files with the extension of .FLT for flatness. You can only **print data** tables using the print function under this heading.

To view the Flatness table and graphs, first click on **Flatness** on the menu bar. This will convert the data shown on the table to Flatness. Then click on the **Adjusted Flatness** choice. This will convert the Flatness data into data that the Moody Method can handle. From here you may view the **Isometric (line) Plot**, or the **Numeric Plot**.

The following icons have the following function in Analysis:



Open a new data file.



Save a data file.



Graph a data file (After graphing, you may also change the scaling of the graph by checking X on adjust grid).



Print a data graph (for printing data tables, use the Print option under the “File” heading)



Moves to the previous screen.



Moves to the next screen.



Exits the program.

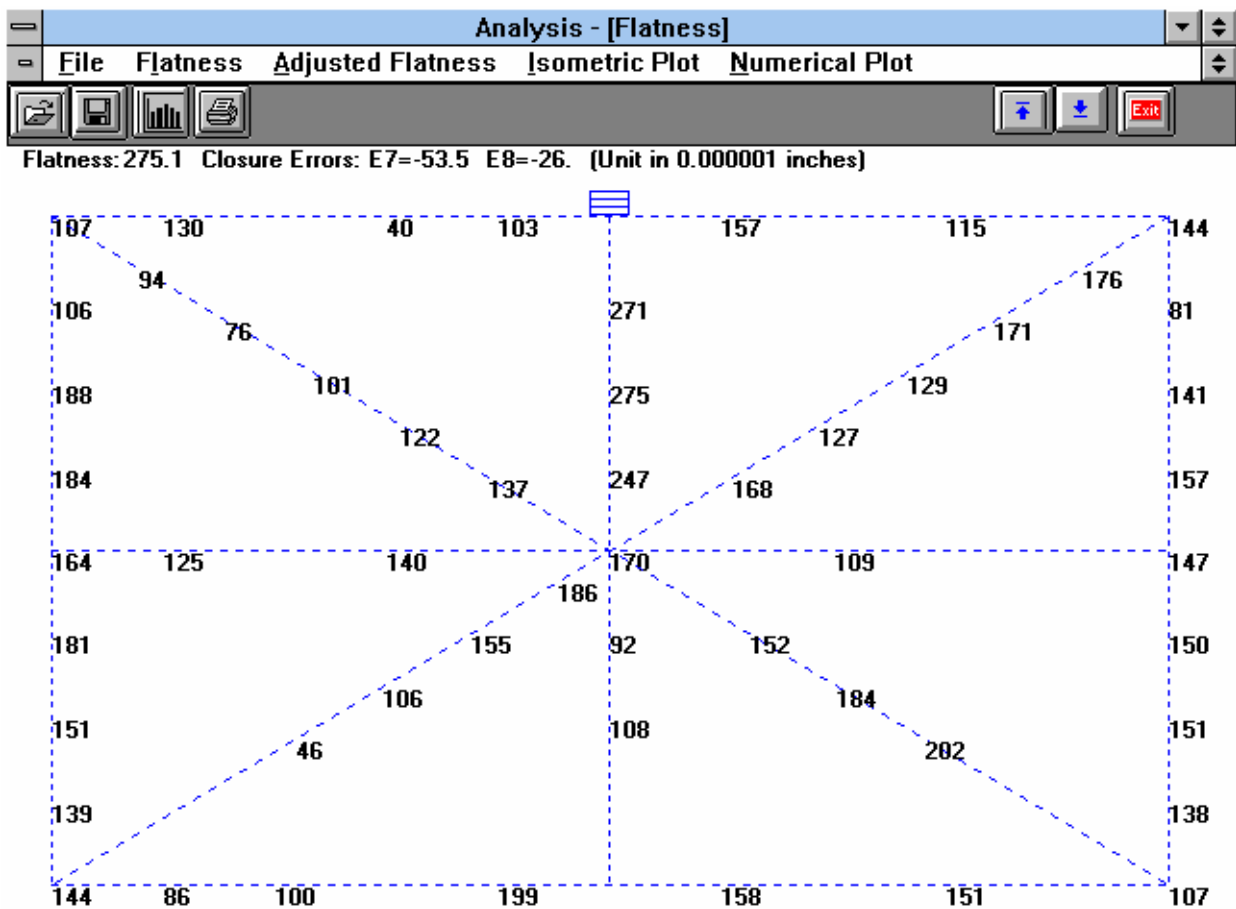


Fig. 6-5 Flatness Measurement Numerical Plot

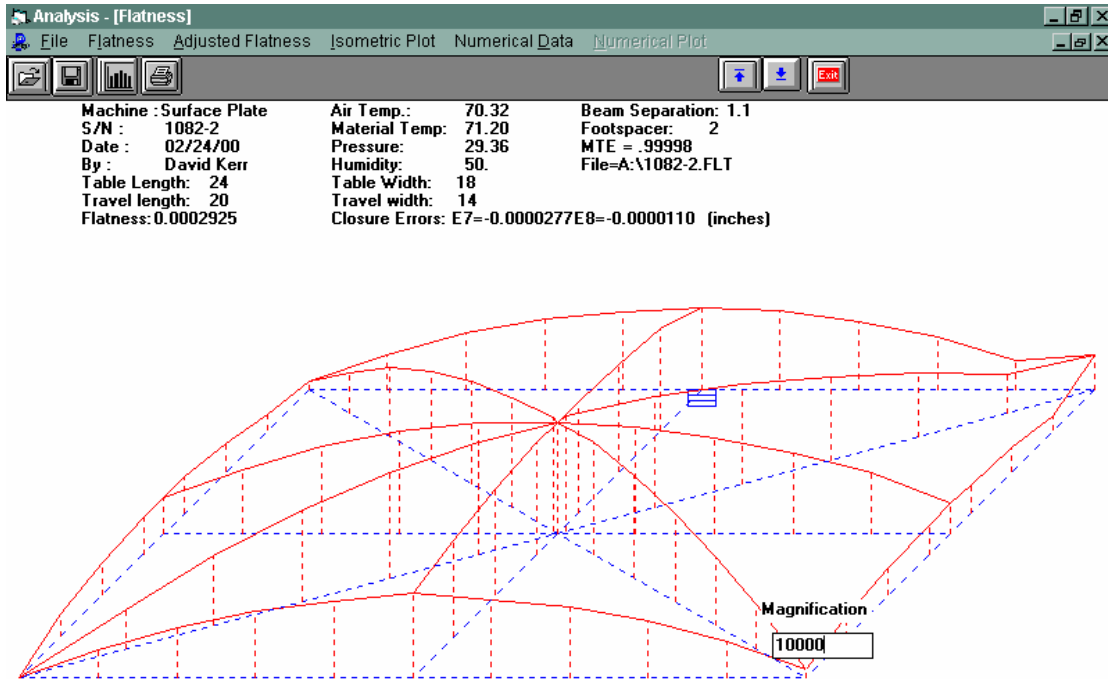


Fig. 6-6 Flatness Measurement Isometric Plot

Using the **Magnification** box in the lower right hand corner, you may increase or decrease the magnification of the graph. Enter a value and press **<Enter>**.

6.5 Revising Old Flatness Data Files

An excellent time saving feature in Flatness is the ability to revise old data files without having to reshoot a whole table. To revise an old data file, the following steps must be taken:

- 1) From the Main Menu, click on **Flatness**.
- 2) In the Flatness Main Display, click on **Analysis** but do NOT unload the program.
- 3) **Load** the file to revise (choose the flatness, .FLT, files)
- 4) Click on the **Up arrow** (or press the **ESC** key) until the Flatness Main screen reappears.
- 5) Align the laser, choose which line is to be re-shot, and click on **Start**.
- 6) After the data for that run is taken, press **Save Data** or repeat step 5 for another line.
- 7) The new data and graphs can now be viewed in **Analysis**.

7.0 Squareness Measurement

After clicking the **Squareness Measurement** Box on the Main Menu, you will be greeted by the Squareness Measurement Data Screen. If the LDDM is not connected to communication port, a message box will appear telling you that the LDDM interface not found. Please check your connections and the LDDM reading on the display should appear.

7.1 Squareness Measurement Main Display (Fig. 7-1)

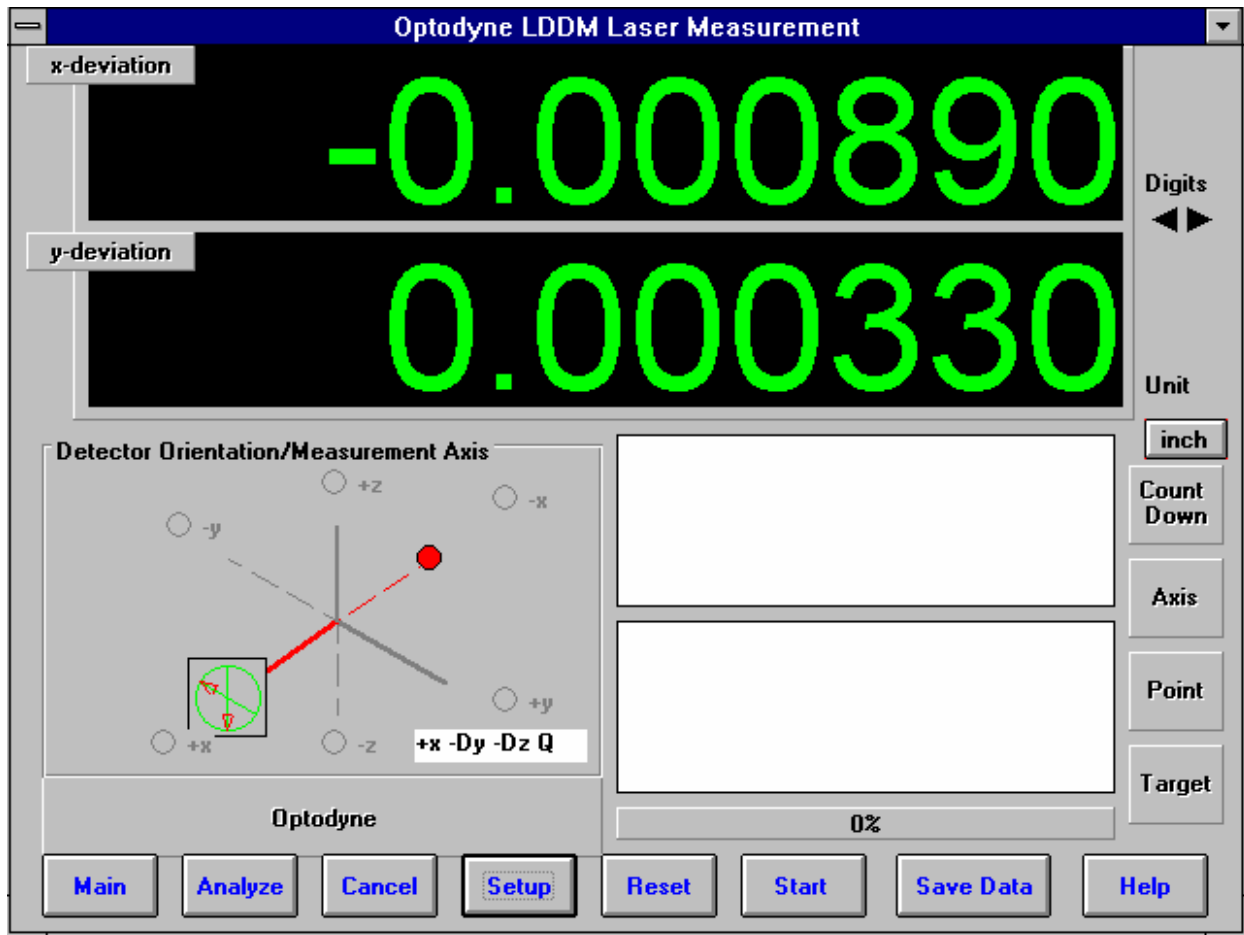


Fig. 7-1 Squareness Main display

The display, in the squareness mode, shows the deviation in inches or mm of the laser beam incident on the quad detector. The deviation in the quad detector's x and y axes are shown.

Choices on the Main Display are as follows:

Detector Orientation/Masurement Axis Box:

This box describes what axes your squareness measurement is currently taking, and if

modifications are necessary during the measurement (a setup was chosen poorly), then it can be corrected here.

The Red dot signifies the laser head/origin of the laser. The square with the two arrows designates the quad detector and its two inherent axes. The $\pm x$, $\pm y$, and $\pm z$ designate the machine axes.

The right hand side of the screen shows:

Unit: This box, when clicked on, will allow the user to change between the inch and metric systems.

Digits: Clicking the left arrow will decrease the amount of digits shown (data will still be taken to 6 digits). Clicking the right arrow will increase the amount of digits shown (max 6).

The **Countdown** box shows the number of points left to collect before an average value is calculated.

The **Axis** box shows what axis is being measured.

The **Point** box shows you what point is being measured.

The **Target** box shows the machine coordinate where the quad detector is supposed to be.

The two graphs on the right-center of the screen will show the data of the quad detector during a measurement. This will be updated after each data collection.

The measurement bar under the graphs shows what percentage of the total measurement has been completed.

The **Dialog** box is just underneath the Detector Orientation box. This box tells you messages and describes the actions you are taking.

Buttons at the bottom of the screen:

Main: exits the linear measurement package and loads the main menu.

Analyze: exits the flatness measurement package and enters the analyze data package. For Flatness measurements, **do not** unload the module when prompted.

Cancel: Allows the cancellation of the previous point or the whole measurement if something has gone wrong.

Setup: Opens the setup window, where measurement specifications may be edited or viewed.

Start Measurement: This button starts the measurement defined in the setup window.

Save Data: This button will allow for the data storage of the last measurement taken.

The Laser Position window shows the current position of the quad detector.

7.2 Squareness Measurement Setup Screen (Fig. 7-2, 7-3)

To input information: Please move the mouse pointer over the box in which you wish to change the information. The mouse pointer will turn in to a vertical bar. Two things may be done:

- 1) Block the text. Hold the mouse button down and move over the text completely. The text being blocked will become inverted in color (white on black). Type in the information to be entered. The original text will be replaced by the new information.
- 2) Click the mouse button while the vertical bar is over the box. Use the arrow keys and the delete key to erase the previous information. Then input the new information.

Identification

Machine: Machine Center
 S/N: 12345
 By: OPD
 Date: 10/30/03

Detector Orientation/Measurement Axis

+y +Dx -Dz Q -y -x
 Measurement 2
 Quad detector move
 Laser head move
 Rotate Axis +x -z +y

Linear Measurement Unit: inch

Straightness
 Squareness
 Three Squareness

Minimum Number data averaging: 10
 Error, μ Rad: 2
 90° Beam Bender: 2

Measurement	1. x-Axis	2. xy-Sqr
Direction	+x	+y
Quad Orientation	-Dy -Dz Q	+Dx -Dz Q
Start Position	0	0
End Position	10	8
No Points	6	3
Pt #1	0.0000000	0.0000000
Pt #2	2.0000000	4.0000000
Pt #3	4.0000000	8.0000000
Pt #4	6.0000000	
Pt #5	8.0000000	
Pt #6	10.0000000	

Automatic Interval: 10 Number of Runs: 3 Positions Equally Divided
 Forward Only Verify/Edit

View or Edit Positions to be measured

New Config File Save Configuration Cancel OK

Fig. 7-2 Squareness Measurement Setup Screen (Leg 1)

Identification Box:

The identification of the machine, i.e. the machine type, serial number, the person doing the calibration, and the date, is entered here and is saved in the data file. The date is automatically entered using the computer system date.

Squareness Measurement Box:

Choose which type of measurement you would like to take: Straightness, Squareness or Three Squareness.

Minimum Number Data Averaging: Choose the number of data points to be collected and averaged together.

Automatic Data Collection: Click this button for automatic data collection based on a time interval. Select a time interval from 1 to 60 seconds.

Optical Square Error: If the error of your optical square (LD-16) is known, enter it here in microradians. If your error is specified in arcseconds, multiply the value by 4.8 and enter it here. Enter 0 if you do not have your optical square calibrated.

If you have chosen **Three Squareness**, you will be asked to enter your **second optical square** value.

Detector Orientation/Measurement Axis Box:

This is critical for getting correct squareness results. The x, y, and z axes seen on the graph indicate the MACHINE axes. The box with the two arrows indicates the QUAD DETECTOR and its axes. The red dot indicates the LASER HEAD.

Rotate Axis: The default coordinate is z-axis in the vertical direction. For machine with y-axis in the vertical direction, click the “Rotate Axis” once. For machine with x-axis in the vertical direction, click the “Rotate Axis” twice.

Measurement 1: This button is to be pressed after setting up the values for the first leg of the measurement. For straightness measurements, there is only 1 leg to be measured. For squareness measurements, 2 legs are required. For three-squareness measurements, 4 legs must be measured.

Quad detector/Laser head move: For this leg, choose which is to be moving. You may NOT move or tilt the laser head after the first leg, the reference line would be lost.

Setup the graph according to the way the laser is setup on the machine. Rotate the quad detector arrows so they correspond to the axes of the machine.

Measurement box: The Direction and Quad Orientation boxes are automatically filled in when the graph axes are chosen. Enter your MACHINE Start/End coordinate, plus the number of points (including the start and end points).

Verify/Edit: Before pressing the Measurement button in the Detector Orientation box, press verify view to see if the machine coordinates selected are correct.

Number of Runs: Enter the number of runs, up to 7 runs.

Positions equally divided: If the point values in the measurement box are okay, put an X in the box here. If you would like to change the stop coordinates to what you want, do so and click the box until the X disappears.

Forward only: For bi-direction runs, unclick this button.

When you are done setting up the first leg, click the **Measurement** button and set up the next leg (if applicable) and repeat the previous steps. Please note the following change:

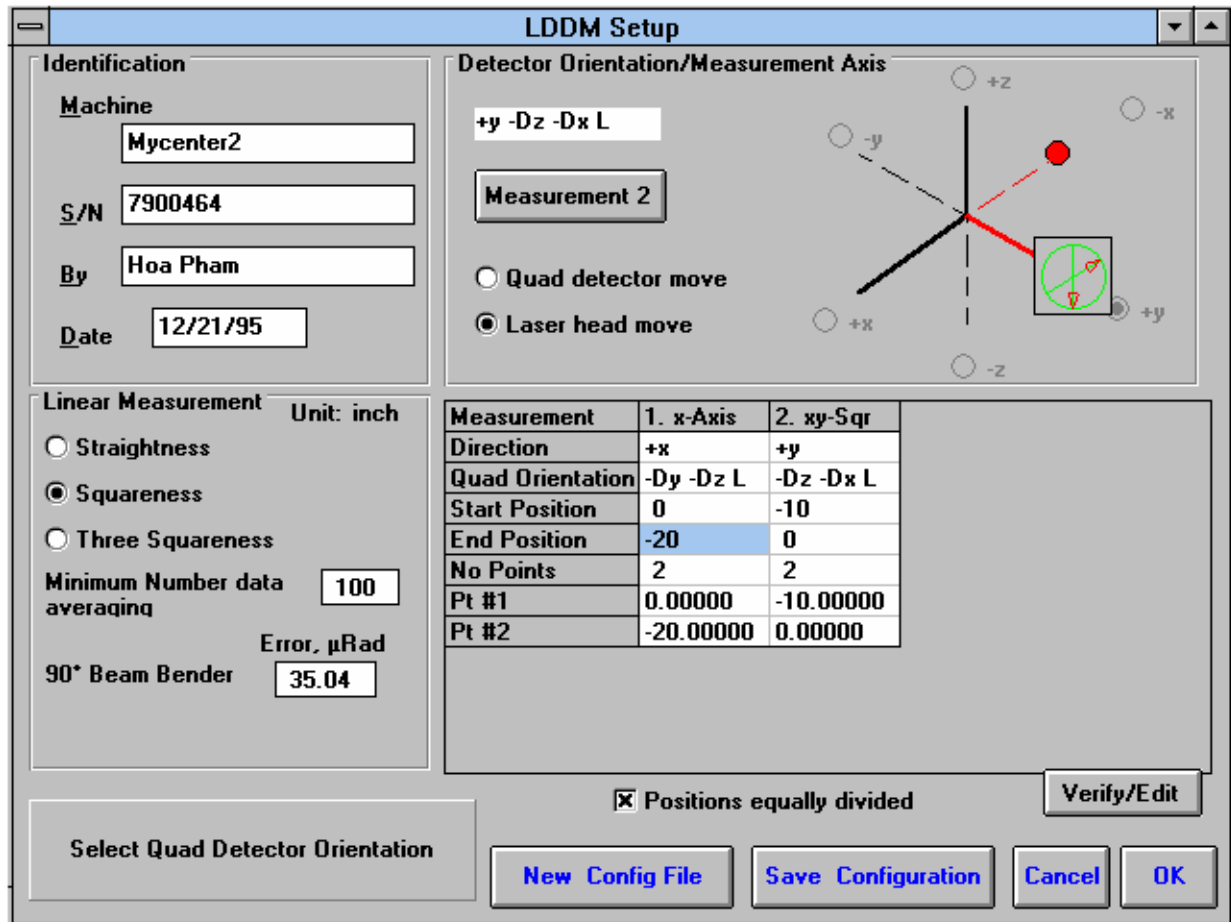


Fig. 7-3 Squareness Measurement Setup Screen (Leg 2)

For the second leg, the graph in the Detector Orientation box will bend 90 degrees. Make sure that it is set up correctly.

New Configuration: You may load a previous configuration file if you have one for this particular machine.

Save Configuration: This updates the LDDM.3CF file so that the data seen on the screen will appear each time LDDM for Windows is run.

Cancel: Cancel the above changes and revert to the previous values.

OK: Settings are ok for this measurement. If you saved this setup as the default, it will come up first every time, otherwise the previous setup will re-appear next time the program is run.

7.3 Example of a Squareness Measurement

- 1) At the main menu, click the left mouse button on **Squareness**.

Squareness Measurement Main Display (Fig. 7-1)

- 2) Check your units (**inch/mm**), change them by clicking on the button.
- 3) Go to the setup screen (Click on **Setup** at the bottom of the screen)
- 4) Enter your **machine information** and ID.
- 5) Enter the type of measurement, **Straightness**, **Squareness** (1 optical square), or **Three-Squareness** (2 optical squares).
- 6) Enter the **number of data points** you would like to average over. (10 data points/second)
The more noisy an environment, the longer you will want to average the data (around 1 minute, 600 data points at maximum)
- 7) Enter the **known errors** (in microradians, 1 microradian = 4.8 arcseconds) of the optical squares or 0 if not known.
- 8) The Setup Graph: Enter the first axis with the ball being the position of the laser head and the square being the position of the quad detector.
Note: It is important to know which direction your beam is pointing.
- 9) Determine which piece is fixed, the **quad detector** or the **laser head**.
- 10) Rotate the quad detector icon so that the arrows are pointed in the correct MACHINE axes.
To rotate, click the left mouse button on the **quad detector square** icon.
- 11) Edit the **measurement setup**, enter the start/end MACHINE coordinates and the number of points.
- 12) Press **View/Edit** to check your increments.
- 13) If you would manually like to change a point, change the values in the boxes, and click the **Positions Equally Divided** box to off.
- 14) After completing the first axis, press the **Measurement 1** button.

Squareness Measurement Setup Screen (Fig. 7-2, 7-3)

- 15) Setup your system in the second axis. Repeat steps 10-14. Repeat up to 3 times (if you have chosen 3 squareness).

16) After you are finished setting up the measurement, a setup completed message will appear. Press **Save Configuration** and enter a filename. A message will ask if you want this file to be the default file. If you answer **Yes**, this setup will become the default configuration.

17) Press **OK** to exit the setup screen. You are now ready to take measurements.

Taking DataPoint for a Squareness Measurement (Fig. 7-4)

18) Align the quad detector according to your setup and the procedure in the User's Guide. Last minute changes may be made in the bottom left hand graph of the measurements.

19) Press **Start**. Move to each point along the first axis and press the **Take** button. A countdown of data points being averaged is shown. When you are done with your first axis, the Take button will change into **Start Axis 2**.

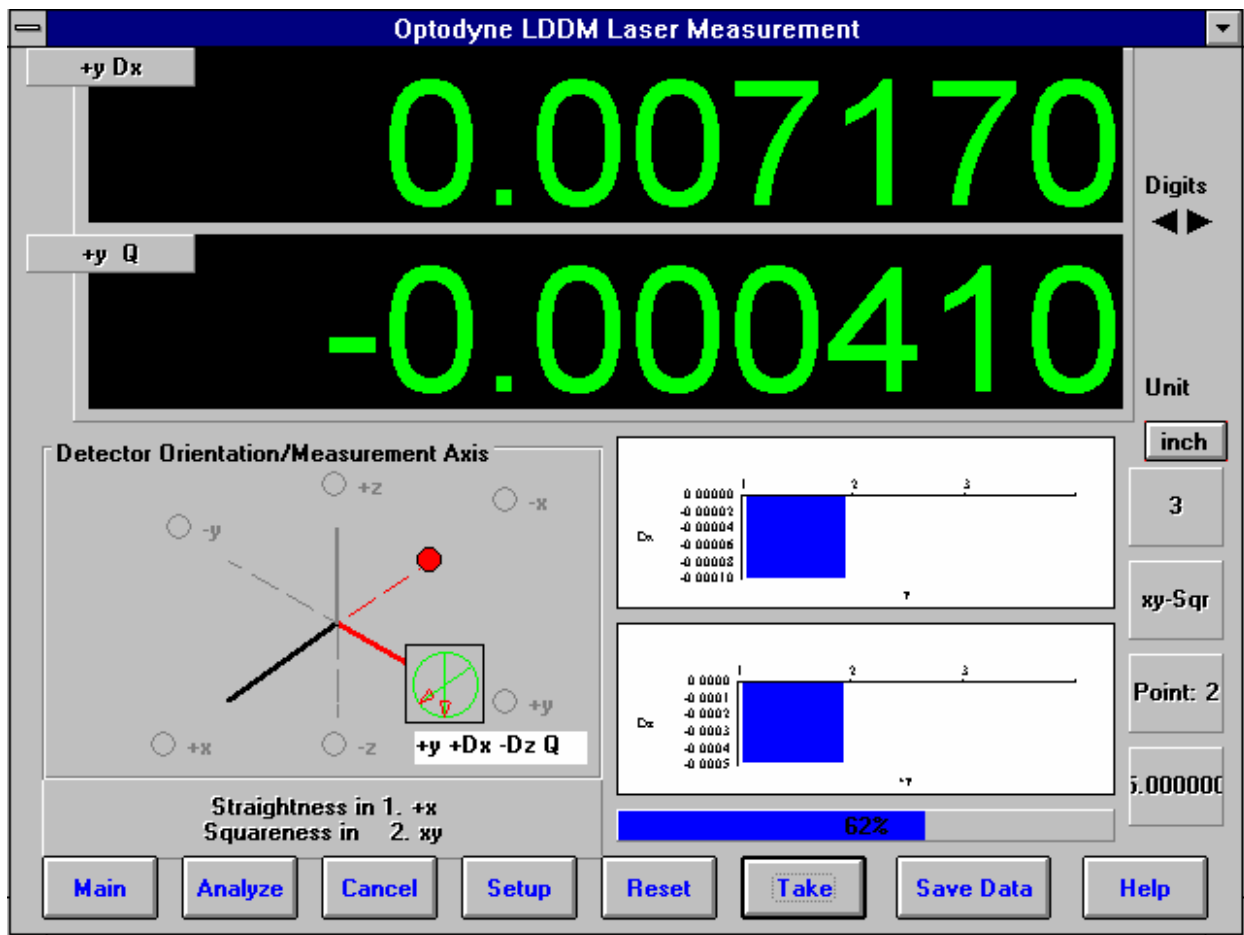


Fig. 7-4 Manual Squareness Data Collection

20) Setup your second axis and press the **Start Axis 2** button, repeat 19.

- 21) After finishing all of your data points, a save file message will appear. Press **Yes** and type in your **filename** to save your data (the extension of .SQR is automatically added).
- 22) Check your results by clicking on the **Analysis** button and opening your file for squareness.
- 23) The squareness reading you will get is + for greater than 90 degrees, - for less than 90 degrees, and will ALWAYS represent the angle in the +XYZ planes (e.g. +XY, +YZ, +ZX).

7.4 Squareness Data Analysis (Fig. 7-5, 7-6)

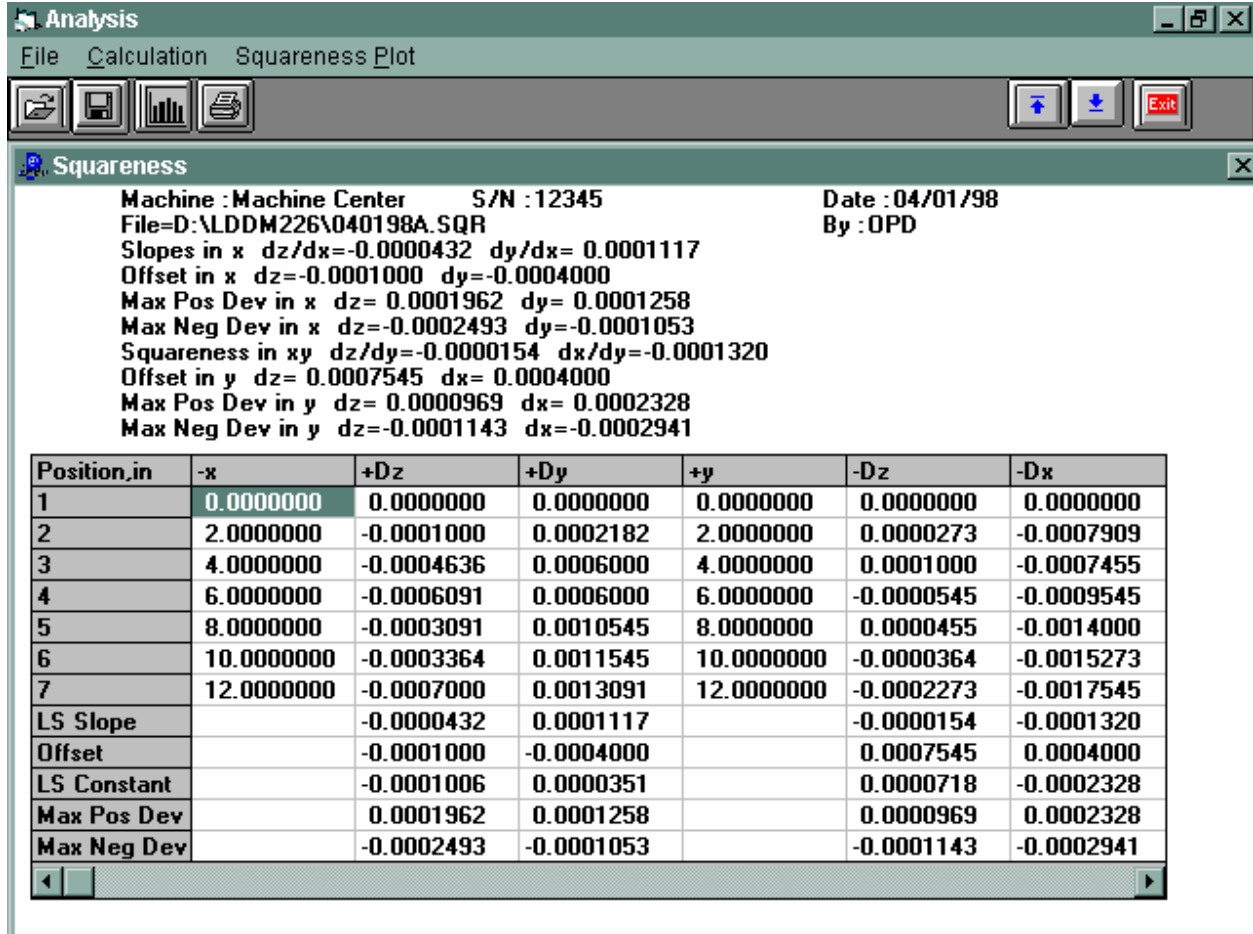


Fig. 7-5 Squareness Measurement Data Table

Under the **File Menu**, you can open a **new** data file, **save** a data file, set your **printer type**, set your **printer style**, or return to the **main menu**. When loading a file, choose the files with the extension of .SQR for squareness. You can only **print data** tables using the print function under this heading..

To view the Squareness data and graphs, first click on **Calculation** on the menu bar. This will convert the data points shown on the table to the Least Square Fit lines, their intercepts and their slopes.

These lines can be seen by clicking the **Bar Graph** choice on the second bar.

The followings are the definitions in the straightness data table, squareness data table and plots.

Off-set : this is the initial position of the quad-detector from the laser beam center.

LS slope and LS constant : this is the least square fitted straight line LS slope is the slope and

LS constant is the constant of the fitted straight line ($y = \text{LS constant}$ when $x = 0$).

Max Pos Dev and Max Neg Dev. : this is the maximum distance from the least square fitted straight line in the positive direction and negative direction, respectively. Usually, when these values are too large, you may need to measure the squareness again.

Squareness Plot: This will show the angle between the POSITIVE X, Y and Z axes of your machine (depending on which axes were measured). Note: This angle MAY or MAY NOT be the one you measured, but the angle has been calculated out to the machine's positive axes.

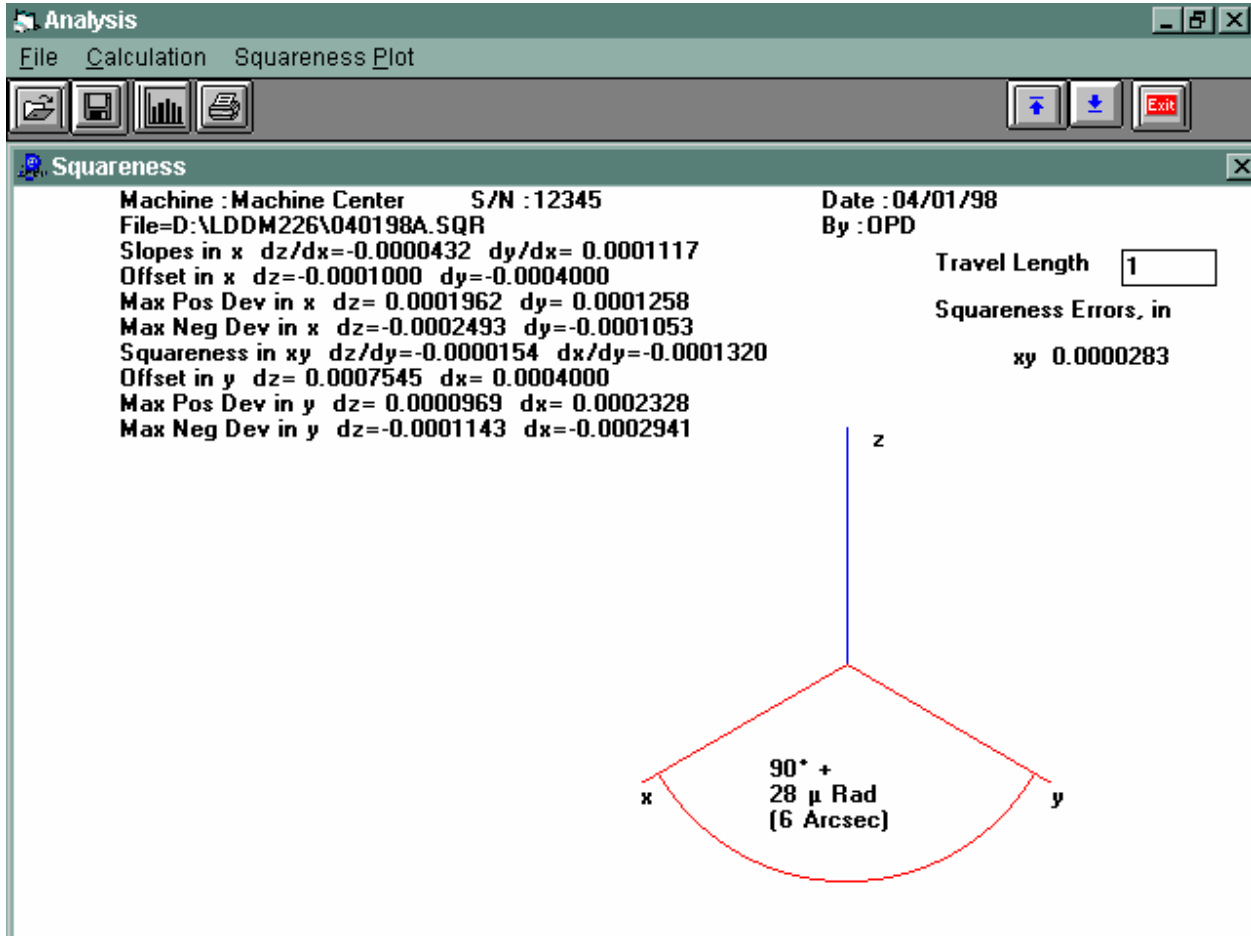


Fig. 7-6 Squareness Measurement Data Plot

7.5 Adjusted Straightness and Averaged Straightness

The squareness data consists of two straightness measurement. Click on the **Adjusted Straightness**. The table will show the adjusted straightness values. Click on the graph to display the two plots shown in Fig 7-7. Here both end points are zero.

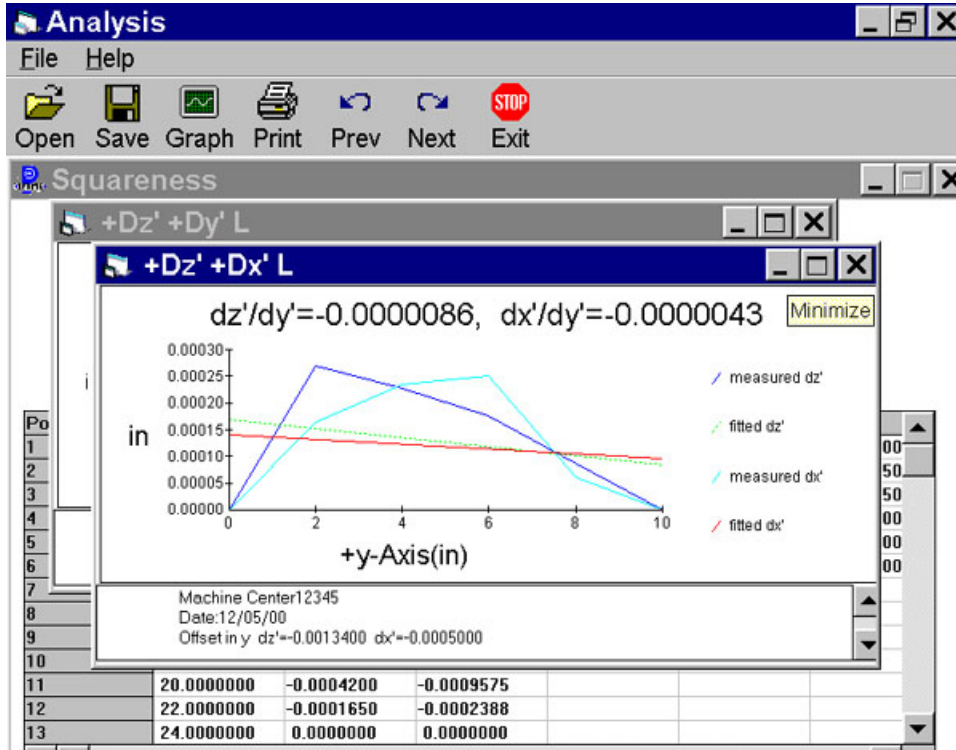


Fig. 7-7 A Plot of Adjusted Vertical and Horizontal Straightness. The Straight Line is the Least Square Fit.

The least square fitted line is a straight line with off-set and slope. Click on the **Averaged Straightness**, the table will show the averaged straightness values. Click on the graph to display the two averaged straightness plots shown in Fig. 7-8. Here the least square fitted line is rotated to be zero off-set and zero slope.

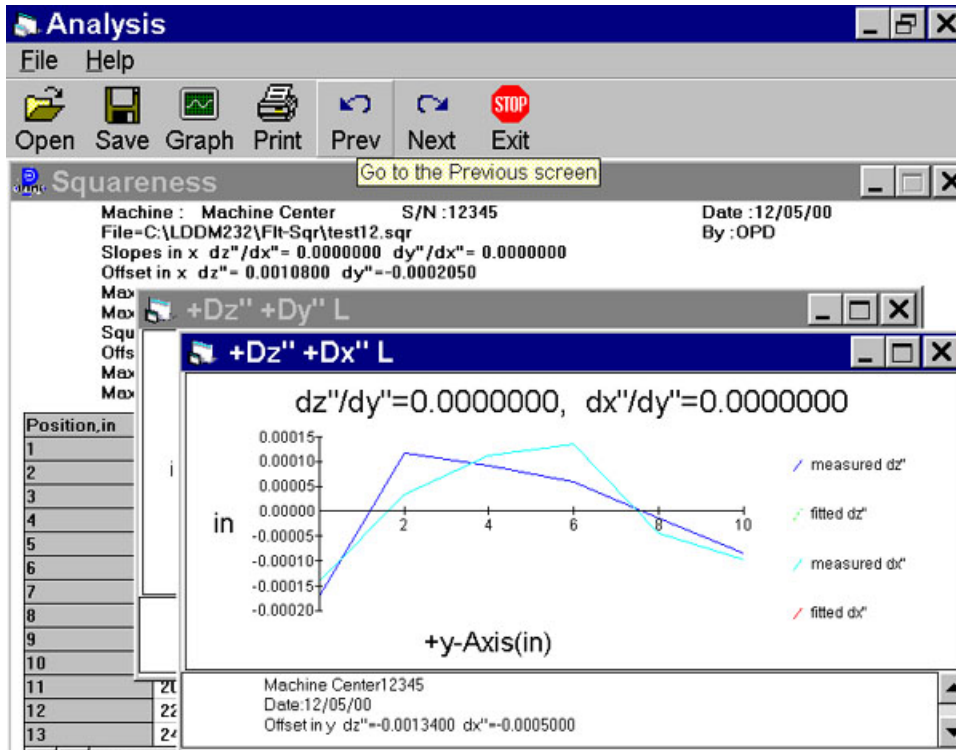


Fig. 7-8 A plot of Averaged Vertical and Horizontal Straightness. Here the Least Square Fit Line is at Zero and Parallel to the Axis of Travel.

The following icons have the following function in Analysis:



Open a new data file.



Save a data file.



Graph a data file (After graphing, you may also change the scaling of the graph by checking X on adjust grid).



Print a data graph (for printing data tables, use the Print option under the “File” heading)



Moves to the previous screen.



Moves to the next screen.



Exits the program.

8.0 Rotary Table Measurements

The rotary measurement setup is similar to the Straight / Angular measurement, except the starting position is always zero. The least increment is 1 degree with an increment of 1 degree up to 10 degree. Briefly, a dual-retroreflector is placed on top of a small rotary table supplied by Optodyne, which is in turn mounted on the test device, a rotary table or stage. The test device is programmed to move in incremental steps of 1 to 10 degrees. At the end of each step, the data will be recorded. Then rotate the small rotary table in the opposite direction to prevent laser beam break. At the end of the rotation the residual value will be recorded. Hence the rotational angle of the test device and the rotational angle (in the opposite direction) of the small rotary table are all recorded. The software will calculate the difference (error) data from both the forward and reverse angular measurements and will provide full data storage, analysis and plots. For more detailed setup, see user's guide section 12.

8.1 Rotary Table Measurement Main Display (Fig. 8-1)

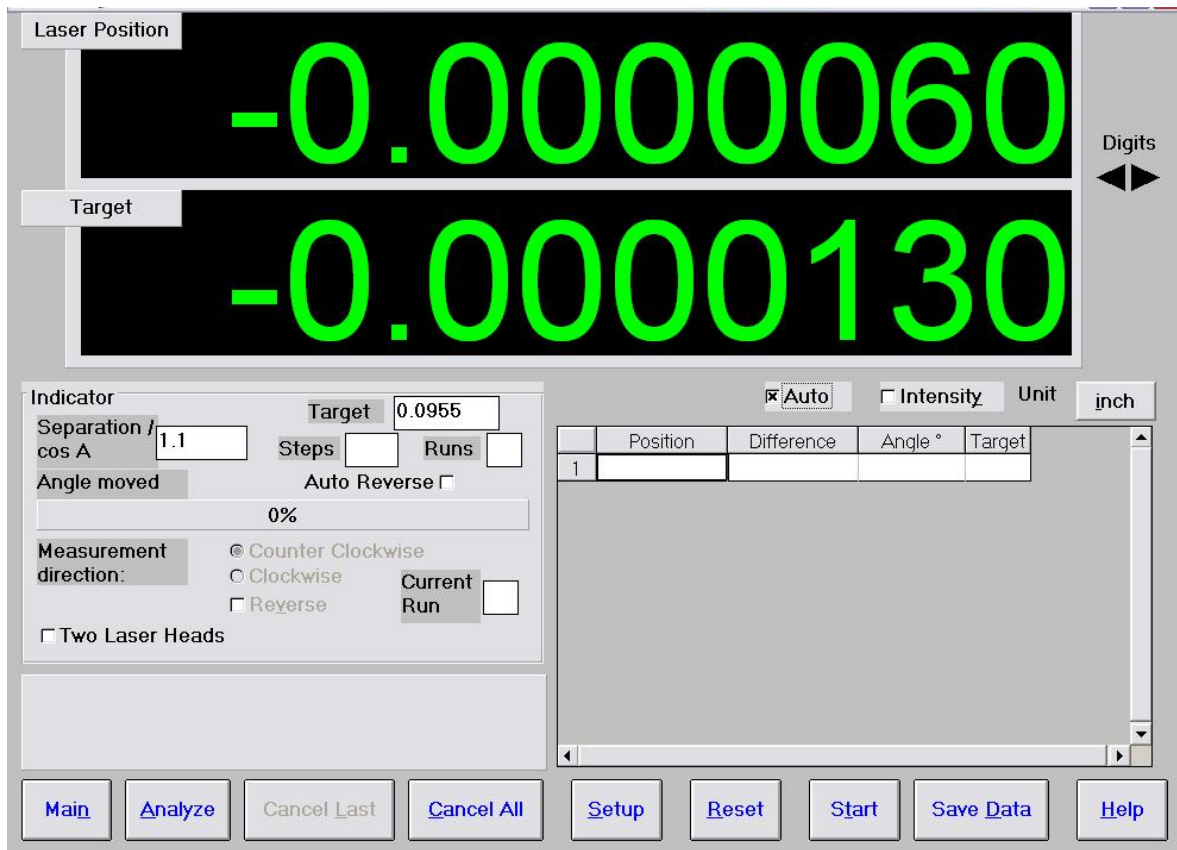


Fig. 8-1 Rotary Table Measurement Main Display

The display shows the linear distance traveled on the top line, and the difference between LDDM #1 and LDDM #2 for the second line. If the second line value is twice of the top line value, the center of rotation is exactly between the centers of the two retroreflector. (See user's guide section 12.5.4 for alignment procedure).

Choices on the Main Display are

Separation : This is the separation of the dual-retroreflector. Typical value is 1.105 in or 28 mm. More accurate value could be obtained by calibration.

Steps, Runs and Auto Reverse: These are for motorized turn table. For example, 3 bidirectional runs of 10 degrees increment, set steps=36, runs=3 and click on Auto Reverse. Maximum number of runs is 9. The saved data file is for a single run. For 5 runs, the data will be saved in 5 data files with same name, but with the run number added before the extension .rot.

Angle moved : This box show the angular movement of the rotary table. 50% is about 10 degree and 100% is about 20 degree. When the angle moved is more than 10 degree, there is a message asking the operator to move the retroreflector back to zero. However, as long as the laser intensity is okey, you can continue taking data.

Measurement direction : If you want counter clockwise rotation to be positive, click counter clockwise. Otherwise click clockwise. For bi-directional measurement, after you reached 360 degree and taken the data, click the "Reverse" button. Move the dual-retroreflector (small table) back to zero and move the stopper to the other side. Take the residual reading then continue in the reverse direction.

Two Laser Heads: Click this button, if two laser heads are used.

Auto : In the automatic data collection, click this to change to manual data collection. Click again to change back to automatic data collection.

8.2 Rotary Measurement Setup Screen

Click on the setup box, the screen will show the setup menu.

The screenshot shows a software window titled "Rotary Table Setup". It is divided into several sections:

- Identification:** A group box containing four text input fields: "Machine" (Machine Center), "S/N" (12345), "By" (OPD), and "Date" (04/02/98).
- Rotary Table Measurement:** A group box containing a "Laser head separation" field with the value "1.105" and the unit "inch". Below it are two radio buttons: "Manual" (unselected) and "Automatic" (selected).
- Auto measurement:** A group box containing two text input fields: "Trigger dwell" with the value "1" and the unit "sec", and "Vel Threshold" with the value ".01".
- Buttons:** A row of five buttons at the bottom: "Automatic Measurement", "New Config File", "Save Configuration", "Cancel", and "OK".

Fig. 8-2 Rotary Measurement Setup Screen

Identification: these are information for your own identifications.

Laser head separation : This is the same box as show in the previous screen. You may enter a more accurate value after the calibration.

Manual : The “start” button will turn into a “take” button after the measurement begins. At every collection point, this button will have to be clicked.

Automatic : The software will collect data every time the dual-retroreflector moved and stopped.

Trigger dwell : For automatic measurements, the settling time of the machine is entered here. Choose a value of at least 2 seconds less than the programmed machine dwell time.

Vel threshold : For automatic measurement, this is the threshold that the dual-retroreflector must drop underneath, so that a data point can be taken.

The total travel is set to 360 degree. For measurement less than 360 degree, a more accurate separate value should be used. The increment can be varied from 1 degree up to 10 degree. It has to be an integer of degree.

New Configuration : You may load previous configuration file if you have one for this particular machine.

Save Configuration : This updates the configuration file so that the data seen on the screen will appear each time LDDM for Windows is run.

8.3 Example of a Rotary Table Measurement

Before starting, please make sure all the hardware and software is installed properly.

- 1, Double click on Optodyne logo to get the main menu.
- 2, Click on rotary calibration, a screen with two LDDM readings will show up.
- 3, Click on “set up” to set up automatic data collection or manual data collection.
- 4, ‘Dwell time’ is the time delay between stage stopped and data collection. It may be zero or up to a few seconds.

“Velocity threshold” is the maximum vibration motion of the stage. Typically set to 0.001 to 0.00001. For noisy environment use large number.
- 5, Set the beam separation value to ----- (default 1.105).
- 6, For automatic data collection, click reset, then click start. The initial position will be recorded.
- 7, Move the stage to be calibrated to the first position (at least 1 degree, no more than 10 degree) then stop. The data will automatically be recorded after the dwell time.
- 8, Move the second stage in the opposite direction to zero. The data will automatically be recorded.
- 9, Continue steps 7 and 8 until reading 360 degrees.
- 10, Select “save data” to save data file with extension .ROT .
- 11, To analyze data, click on “Analyze” in the bottom or in the main menu.

- 12, Open the data file.
- 13, Click on “data selection” and select “angle”.
- 14, click on down arrow to get to the end of data file, or at 360 degrees. Double click and type 360. (For data file less than 360 degrees, double click the last target reading and type the actual angle in degrees). Move the cursor to target readings less than 360 degree and click again. The data file will move to the beginning and the “calibration” button will stand out.
- 15, Click on the “calibration” button. New data files will be calculated, and the new beam separation number will be calculated. (Record this number and enter in Step 5). The graph on the right hand side will be replotted.
- 16, Please note that data may be collected at 1 degree increments, 2 degree increments, up to 10 degree increments automatically. After 10 degrees the second stage must rotate in the opposite direction to zero and stop. The zero position data will be recorded automatically.
- 17, For hands off operation, the second rotary table with the dual-retroreflector needs a control signal either from the rotary table to be calibrated, or from a signal generator. Please make sure the time between movements is much large than the dwell time set in the data collection software.

8.4 Rotary Data Analysis Menu

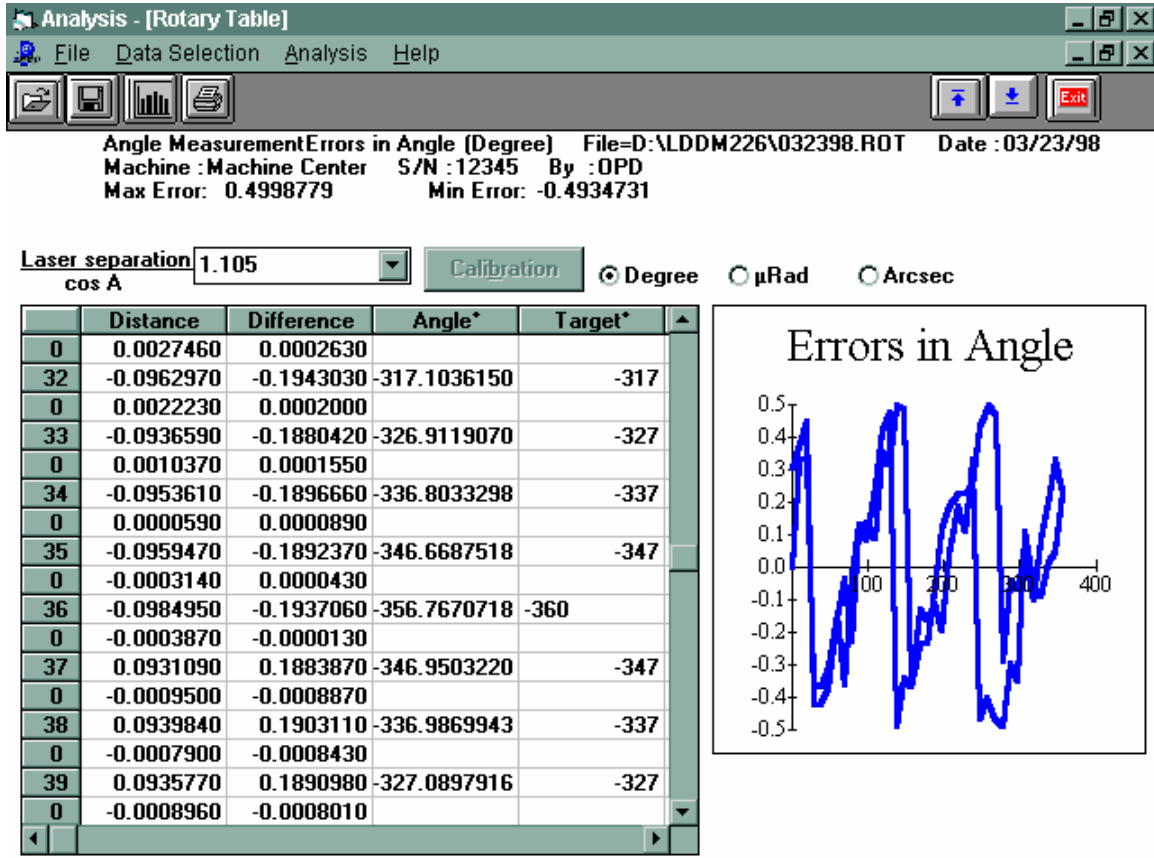


Fig. 8-3 Rotary Data Analysis Table

Under the “File Menu”, you can open a new data file, save a data file, set your printer type, set your printer style, or return to the “Main Menu”. When loading a file, choose the files with the extension of .ROT for rotary data. You can only print data tables using the print function under this heading.

To analyze data, go to the target readings and select the reading nearest to the 360 degrees. Double click and type 360. (For data file less than 360 degrees, double click the last target reading and type actual angle in degrees). Move the cursor to target readings less than 360 degree and click again. The calibration box will stand out. Click on the calibration, new data files will be calculated, and the new beam separation value will be calculated. (Record this value and enter the value in the beam separation box in the setup menu). The graph on the right-hand-side will be replotted as shown in Fig. 8-4 .

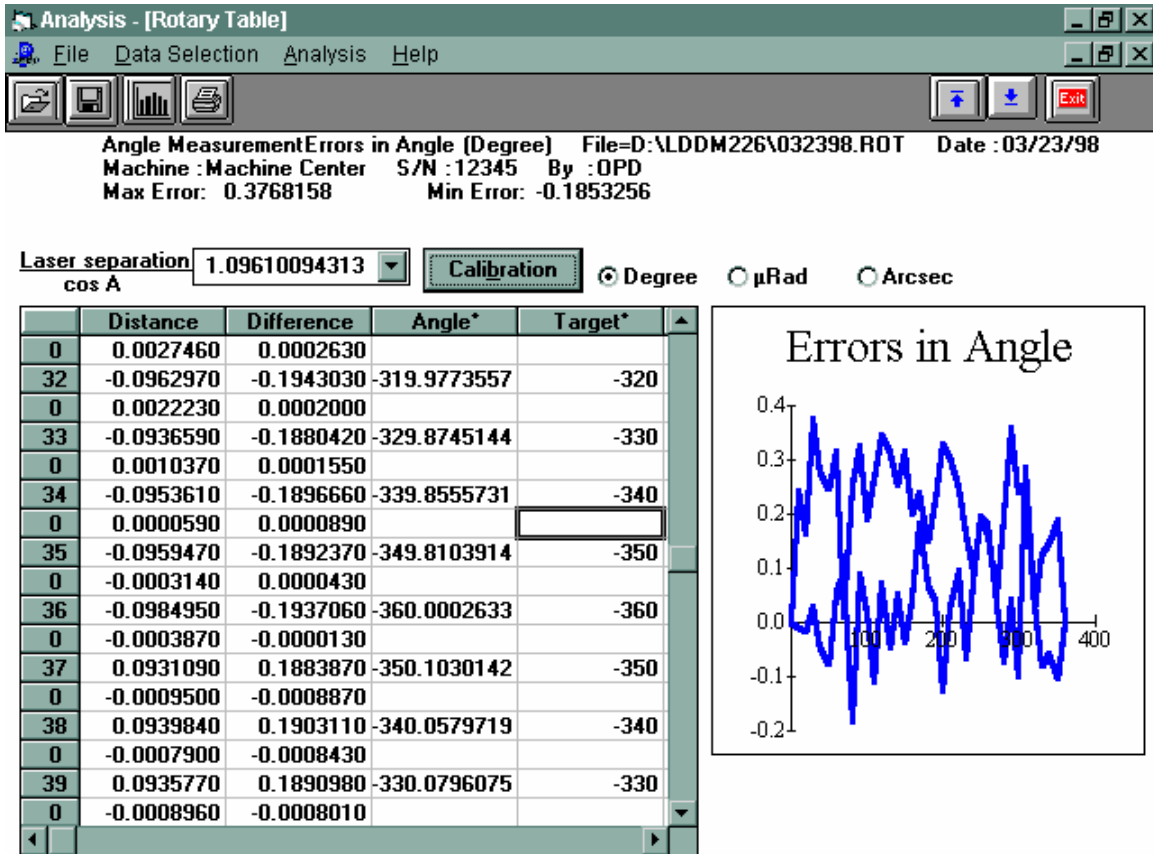


Fig. 8-4 Rotary Data Analysis Show Error Table

To print error table or error plot, move the cursor to “Analysis” and click on “error”. The error table is shown below:

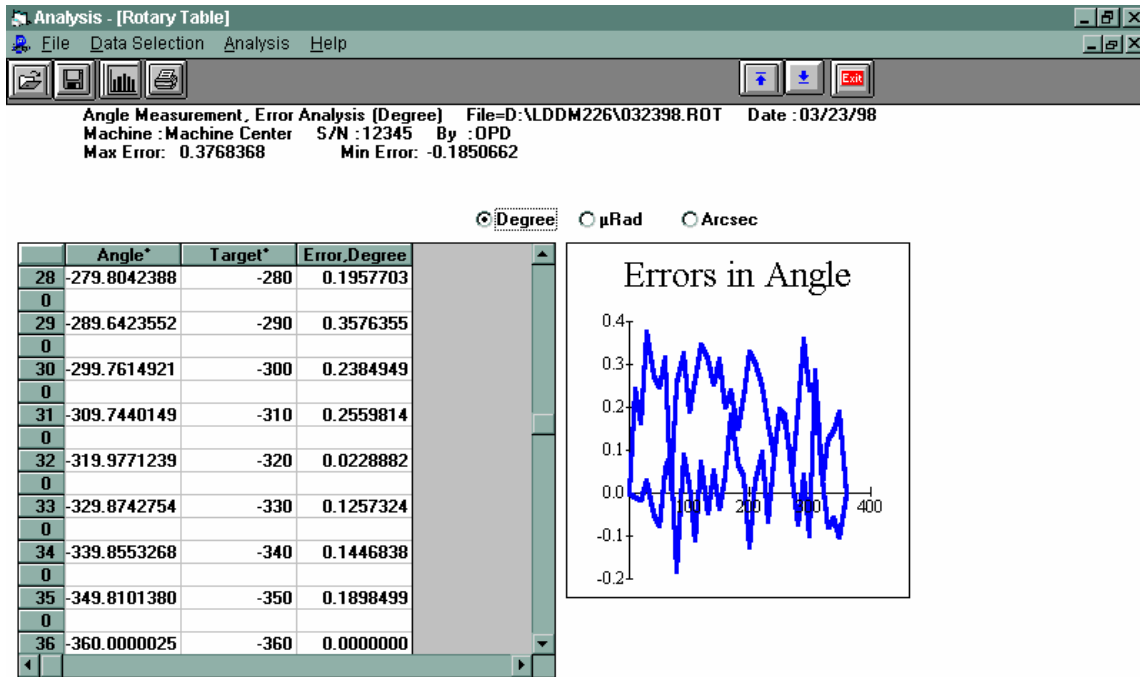


Fig. 8-5 Rotary Data Analysis Show Error table

To get a line plot, click on the graph icon. To print the graph, click on the printer icon. An error plot is shown in Fig. 8-6 .

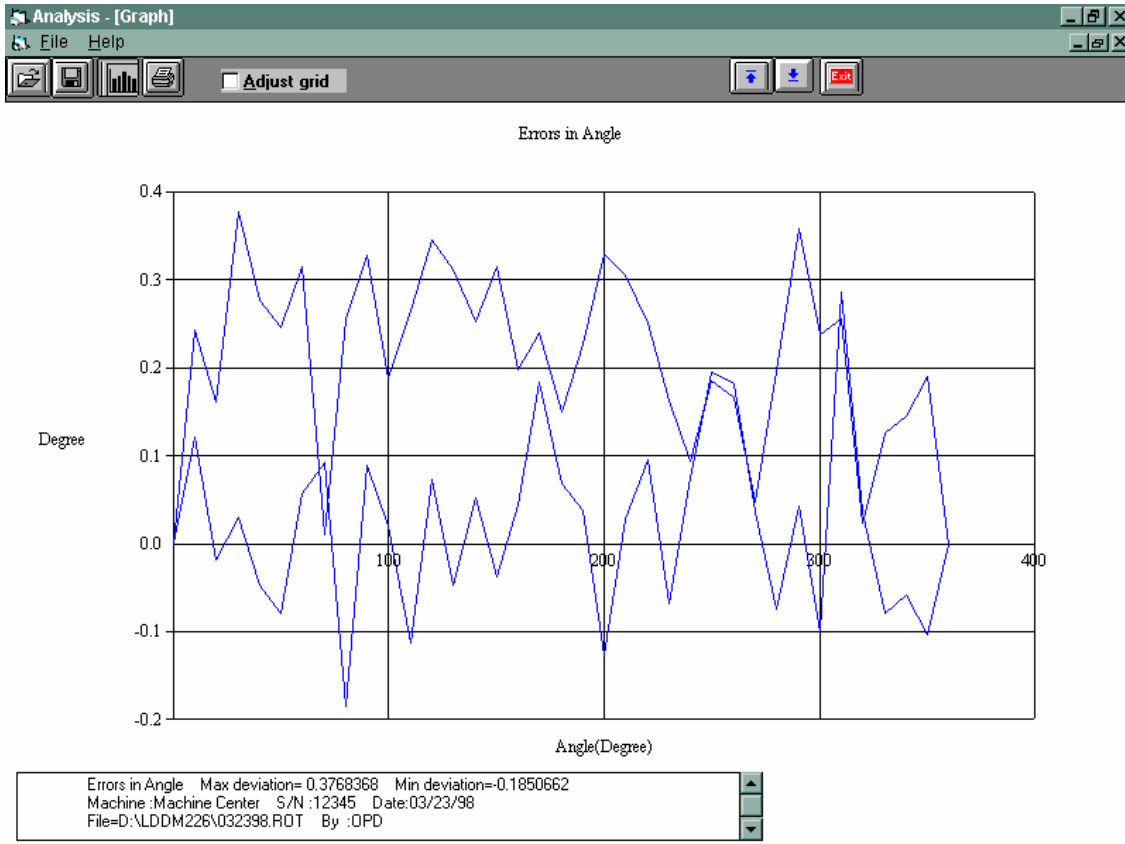


Fig. 8-6 Rotary Measurement Error Plot in Degree

9.0 Circular test (Laser/Ballbar)

9.1 General Description

For general description, windows, installation and starting LDDM program, see section 7.6.

9.2 2D Time Base Data Collection

The 2D time base collects data through a special PCMCIA card. The maximum data rate is 10,000 data/sec, and the maximum number of data point is 24,000 points/record. Click on the “2D time base” button in the main menu to get the data collection screen as shown in Fig.8-6. For two PCMCIA cards, the available address are: 350,110, 220,100 and 300.

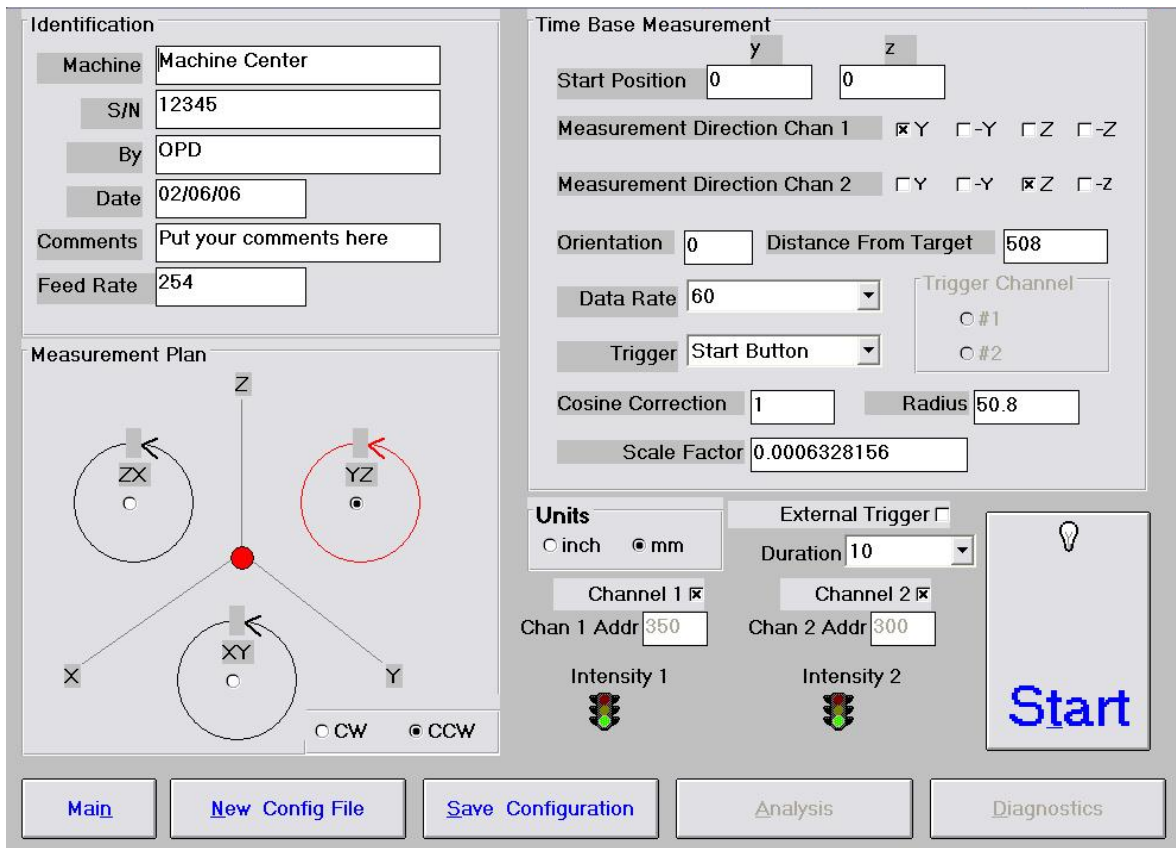


FIG. 9-1 2D TIME BASE DATA COLLECTION SCREEN

Choices on the data collection screen are as follows:

Identification: Input the machine type, serial number, operator, date, your comments or remarks and feed rate in/min or mm/min.

and direction of the circular path, either cw or ccw.

Time base measurement: Enter start position, measurement Direction (-x means the laser beam is pointing in the -x direction), and distance from the target. Click positive axis direction when the laser beam is pointing in the positive axis direction. The orientation is the angle between the measurement direction and the first-axis direction. The data rate is determined by the selected feed rate and radius (see section 8.5.3). Trigger mode is “start button” only. The displacement or velocity trigger will be added later. Click the External trigger if you have the external trigger option. The external trigger is used for external clock or external synchronized events, such as nonstop leadscrew calibration. Cosine correction is 1 for normal operation. It is $2\cos(\text{angle})$ for double pass and the angle is the angle between outgoing and return beams. The radius is the radius of the programmed circular path. The scale factor is 0.000024914 in or 0.000632816 mm. Click “in” for inch unit and “mm” for metric unit. Click both channels for 2 channel data collection.

Data Rate: Select a data rate up to 10,000 Hz.

Duration: Select a duration. The maximum duration is limited by the maximum size of the record, 24,000 data/record.

External trigger: For external trigger, click on “External Trigger” box. A special cable with external trigger connector is needed. The trigger pulses should be TTL standard, the pulse width larger than 30 μsec , and the rep rate less than 3000 Hz. For 2 channels, connect the trigger pulses to channel #1 and both channels will collect data synchronized with the trigger pulse. The data age is a few microseconds.

Intensity: The green light indicates the laser is aligned properly and the red light indicates the alignment is off. Block the laser beam to check whether the PCMCIA Card is installed properly.

Start/stop: Click “start” to start the data collection and “stop” to stop the data collection. After stop, enter the filename to save the data collected. The extension .2dr will be added automatically. After select a data rate, select a duration. If you want to stop data collection before the selected time duration, click “stop” to stop data collection.

9.3 Data Analysis

To analyze data, go to the main menu first then click on the “analysis”. Click on “file” to open a file with extension .2dr. The file usually is very large, please wait a while for the file to be ready. After the .2dr data shown on the screen, click on “data selection” and “displacement 1”.

The displacement values will be calculated and displayed as shown in Fig 9-2.

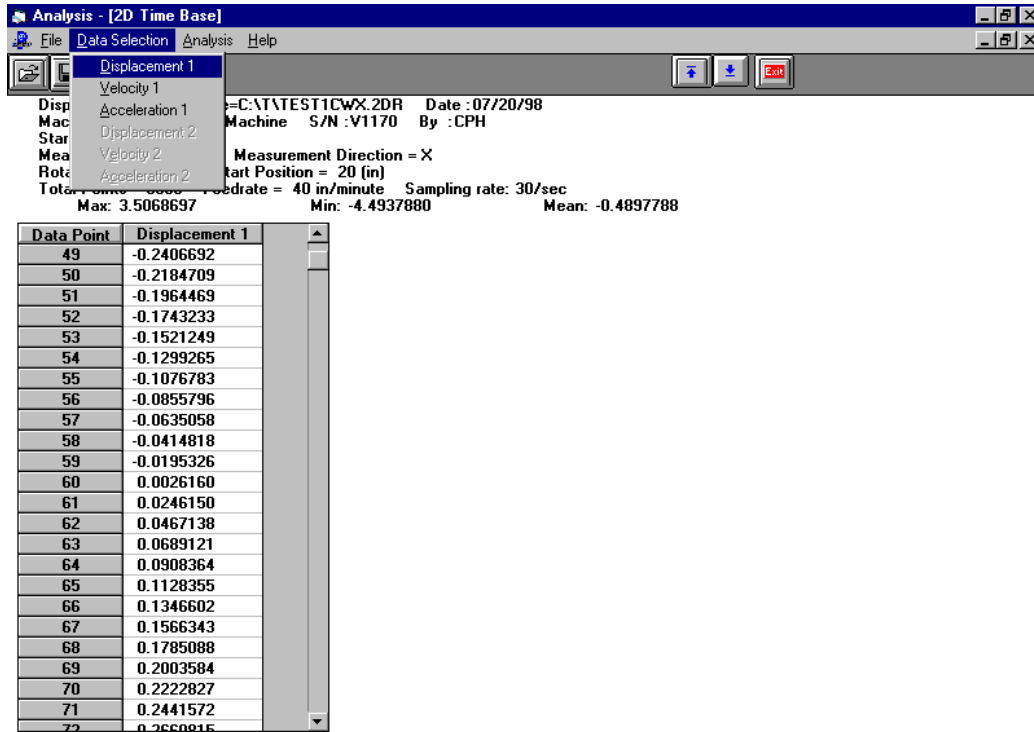


FIG.9-2 THE ANALYSIS SCREEN WITH DISPLACEMENT DATA

After the displacement values are displayed, click on the “graph” to plot the displacement. A typical plot of the displacement is shown in Fig 9-3

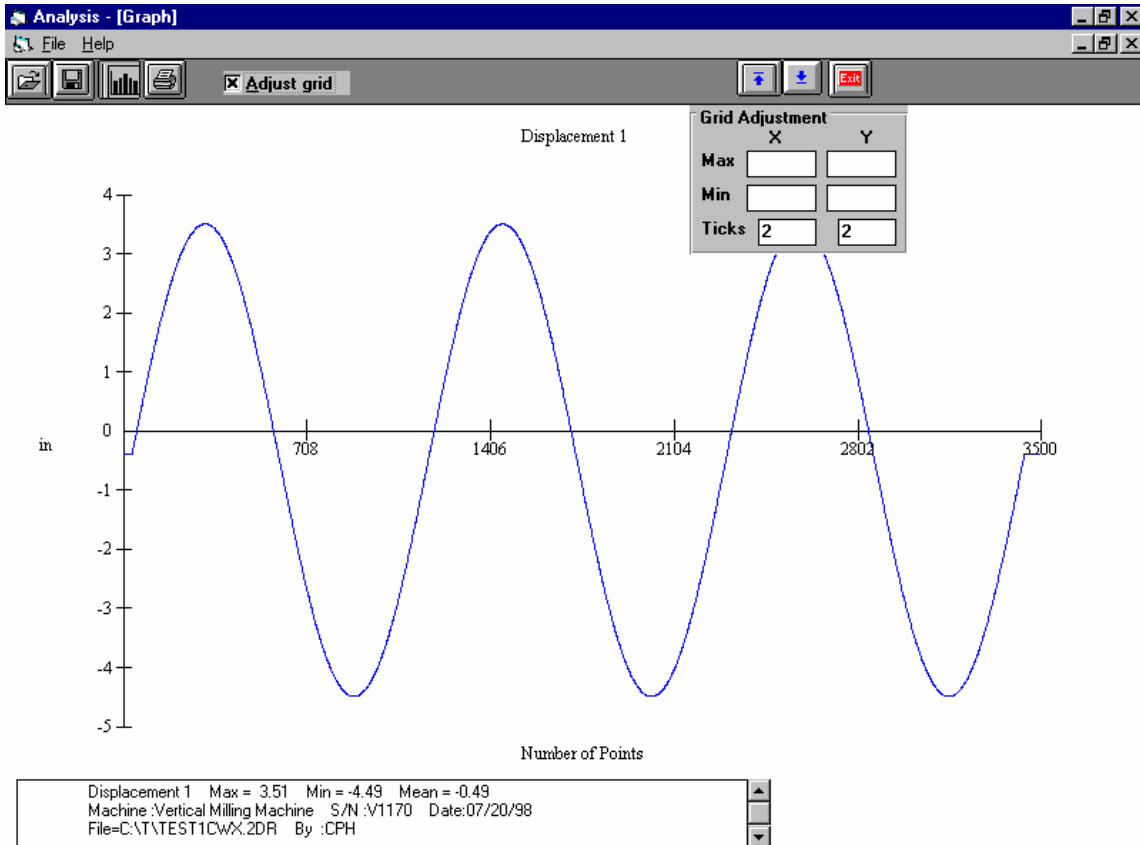


FIG. 9-3 A Typical Plot on Displacement Data

To generate a data file for polar plot, click on “file” and “save”. Select 2dd in the popup screen. Another popup screen asking the starting point and ending point of the data file. The starting point should be before the first maximum and the ending point should be at least 2 and ¼ cycles after the first maximum. If not enough data, a popup screen will indicate so. Enter a filename to save the data file. The extension .2dd will be added automatically. A popup screen will show the actual starting point, number of points per cycle, ending point, and the data file is for one or two cycles. After click on “Yes”, another screen will popup for the change of number of points per cycle. You may enter an integer either larger or smaller than the default value. Please make sure that all 4 2dd files have the same number of points per cycle. We believe, 360 points per cycle is adequate. Of course, more points provide more resolution, but it also need more storage space and larger processing time. The default value is the existing number of points per cycle. If there is no change, press “enter” or click on “ok”, then another screen popup to change the shift. You may enter any shift value between -10 to +10. The default shift is zero.

For some machine, the feed rate can not be controlled exactly, hence the number of points per cycle varies. It is more desirable to keep the number of points per cycle the same for all 4 files. Please note that to generate a complete circular path, 2 data files, one in the x-direction and the other in the y-direction (for xy-plan) are needed. The number

of points in these two data files should be the same. If one data file is 2 cycles and the other is 1 cycle, only one cycle of the data will be processed.

9.4 Circular Path

To generate a circular path, first to process all raw data files (.2dr) to generate the data files (.2dd).

Click on “analysis”, “circular”, “polar plot” and “ISO 230”, a screen will popup. The file cannot be entered by type the filename. Click on the right-hand-side to enter the files. The first line is cw, x-direction, the second line is cw, y-direction, the third line is ccw, x-direction and the fourth line is ccw, y-direction. For a complete circular path, 2 data files in the same cw or ccw rotation are needed. For both cw and ccw circular path, enter all 4 files. For most machine, click on “ok”. “sync” is for machines without velocity control. Please wait for the data files to be displayed on the screen. Click on “graph” to plot the circular path in polar plot as shown in Fig. 9-4.

Before the polar plot, a screen will popup and ask for the values of S1, S2, S3, S4, Rcw, Rccw, sc and scc. These shifts and rotations are used when the measurement directions are not perpendicular to each other or the measurement directions are not along any axis direction.

For the measurement of servo mismatch or squareness errors, it is desirable to measure in the directions 45 degree from the axis. Hence, in the polar plot enter Rcw and Rccw equal to 45 degree or – 45 degree.

Positive S shifts in the ccw direction and negative S shifts in the cw direction. S is the number of points to be shifted. It is zero or an integer. S1, S2, S3, and S4 are the shifts in cwx, cwy, ccwx and ccwy respectively. Positive R rotates in the ccw direction and negative R rotates in the cw direction. The maximum angle of rotation is +/- 180 degree. Rcw and Rccw are rotational angles for cw measurements and ccw measurements respectively. Sc and scc are shifts between cw and ccw rotations respectively.

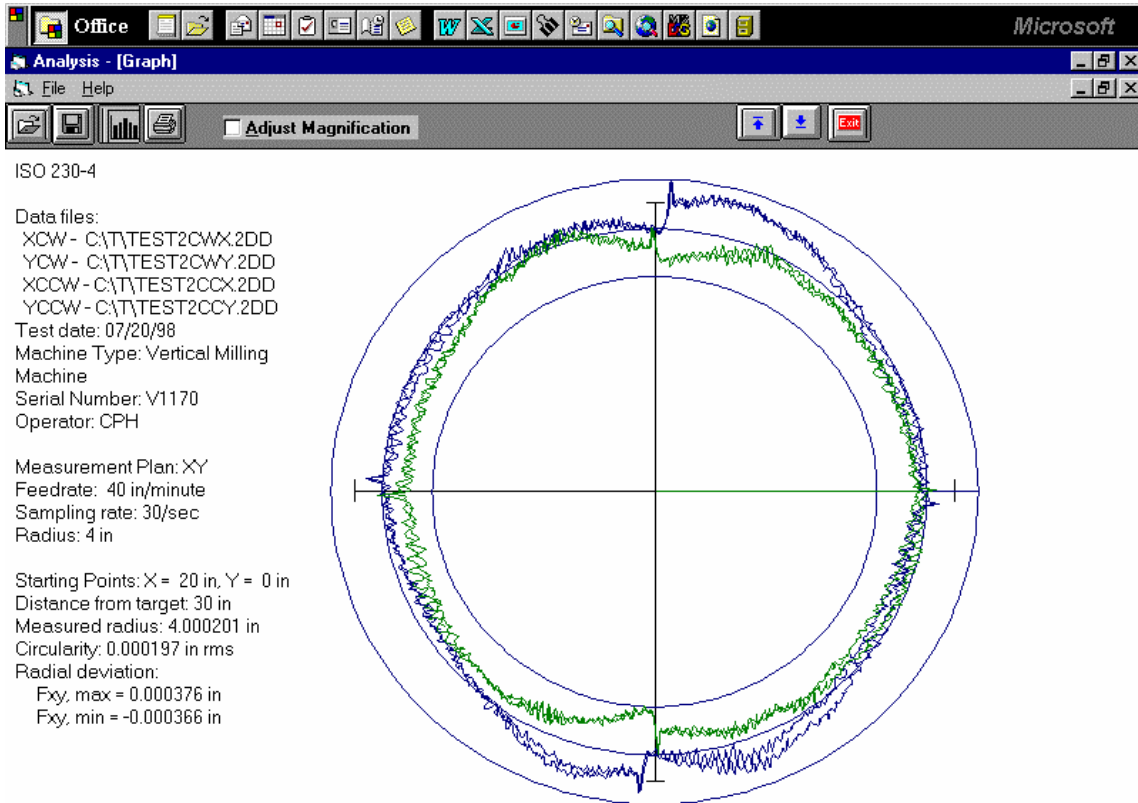


FIG. 9-4 A TYPICAL POLAR PLOT OF THE CIRCULAR PATH

There are 3 circles on the plot. The radius of the middle circle is the measured radius. The radius of the largest circle is the measured radius plus the $F_{xy,max}$ and the radius of the smallest circle is the measured radius minus the $F_{xy,min}$. Or the distance between the largest circle and smallest circle is equal to $F_{xy,max} - F_{xy,min}$. Click on the “adjust magnification” to change the magnification of the plot. The circularity is the rms value of the deviations from the measured radius.

To view more details such as vibration frequency, backlash values, reverse spikes, etc., click on “analysis”, “circular”, “polar plot”, “linear plot”, and “one of the 4 files”, then click on the “graph” button. A popup screen will let you input the starting point and the ending point of the plot. A typical linear plot is shown in Fig 9-5.

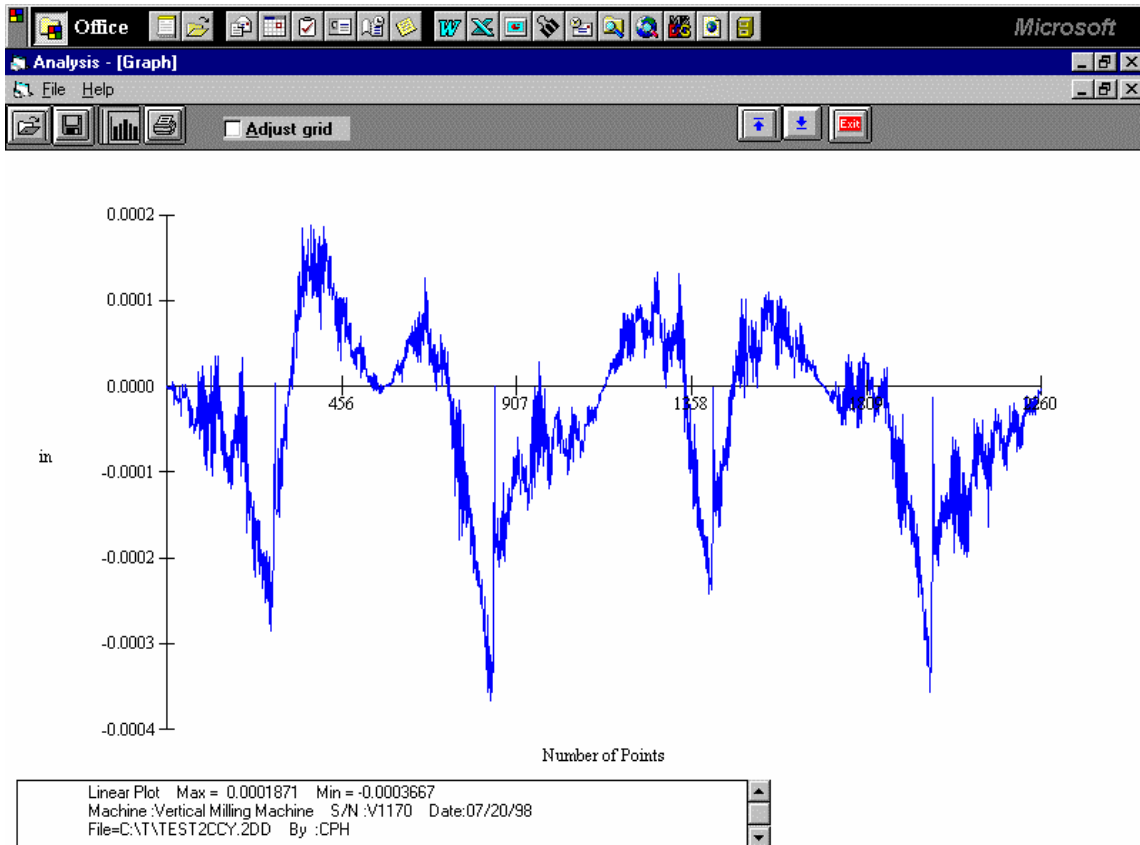


FIG. 9-5 A Typical Linear Plot of the Circuit Path

You may view more details in a region by enter the starting point and the ending point near the region of interests. You may also adjust the grid to change the vertical scale. Click on “Save” and select “xyfile”, then enter a file name in the popup screen, 4 files with extensions xcw, ycw, xcc, ycc will be generated. For multiple runs with the same setup, up to 3 runs can be entered and plotted in the same graph.

9.5 Output Data File for “Polarcheck” or “Polaranalyser” Software

To use a commercial analysis or diagnostic software, such as Polarcheck* or Polaranalyser, a compatible data file can be generated. In the previous section, before click on “graph” to plot the circular path in polar plot as shown in Fig.8.8, click on the “file”, then “save”, a screen will popup. Enter a filename and a file will be generated with extension .rtb.

This data file is similar to a telescoping ball-bar data file. The first 24 line header is machine information and parameters. Run count is how many 360 degree cycles. Max Targets is the number of points in 1 run or a 360-degree cycle. Direction -1 is cw and +1 is ccw. The best R is the actual measured radius. Since there is no center offset, hence the best X and Y are all zero. The first column is the point number and the second column is the deviation in the radial direction. EOF is end of file.

- * For more information, check the Polarcheck Analyser Web Site:
<http://kiila.me.tut.fi/projects/dbbbros.htm> or e-mail jouni.holsa@qplus.fi

A typical polar plot similar to Fig.9-4, but using the .rtb data file and the Polarcheck software, is shown in Fig.9-6.

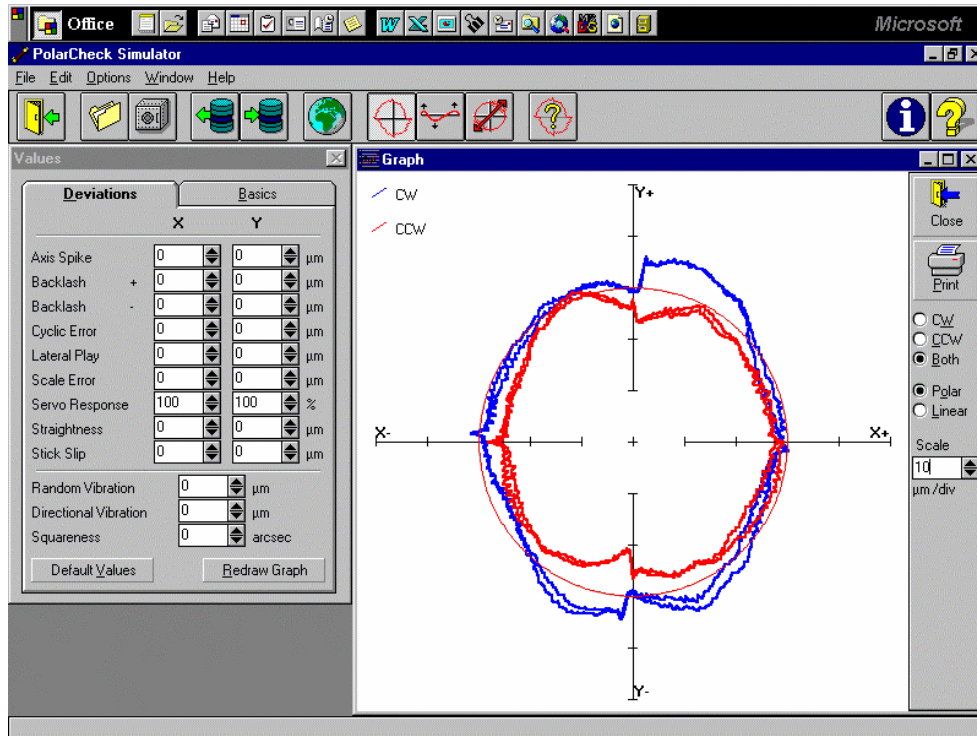


Fig. 9-6 A TYPICAL POLAR PLOT USING POLARCHECK

9.6 “rtb” Button to Generate Output File Directly

To generate an output file directly from 2dr files, click on the “rtb” button. A screen will popup and allow you to enter 4 2dr files. You may click on “ok” or “sync”. For most machines, click on “ok”. “sync” is for machines without velocity control. Enter the filename to save the output data file. To verify the output data, click on “graph” to view the polar plot. In case of error, use the procedure in the previous section.

9.7 Velocity, Acceleration and Other Measurements

As shown in section 9.3, the displacement values can be displayed or plotted. Click on the “velocity 1”, the velocity values are calculated and displayed. Click on the “graph” to plot the velocity profile. Similarly, the acceleration values can be calculated by click on the “Acceleration 1” button. To remove a spike or spikes, click on the “R-spike” button, and specify the starting point and the ending point, the spike or spikes between

the starting and ending point, will be removed and the displacement values recalculated. Please note that, remove the spikes may distort the circular path.

The 2D time base data collection can collect data up to 1000 Hz. It can also be used for many other applications, such as small increment displacement test, etc.

9.8 Feedforward and Velocity Feedback

For some controllers without the feedforward function or the feedforward function is not turned on, there is a notch on the velocity profile as shown in Fig. 9-7. These velocity notches may cause non-uniform cutting and effect the surface finish of the part.

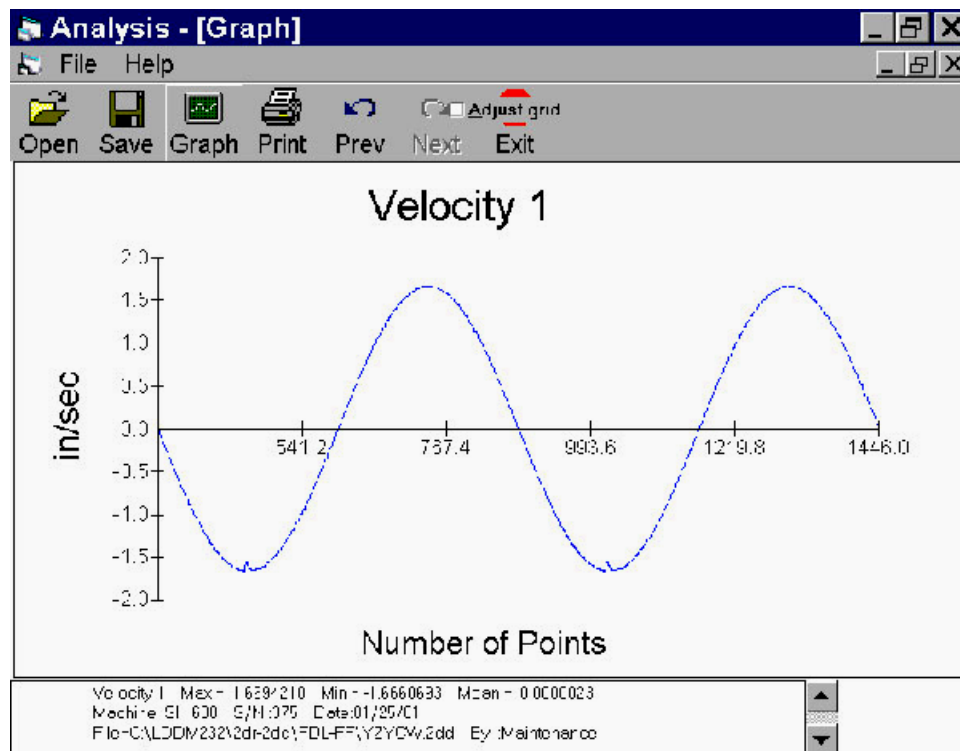


Fig. 9-7 A Plot of Velocity Profile without Feedforward. There are Notches near the Maximum Velocity in the Negative Direction.

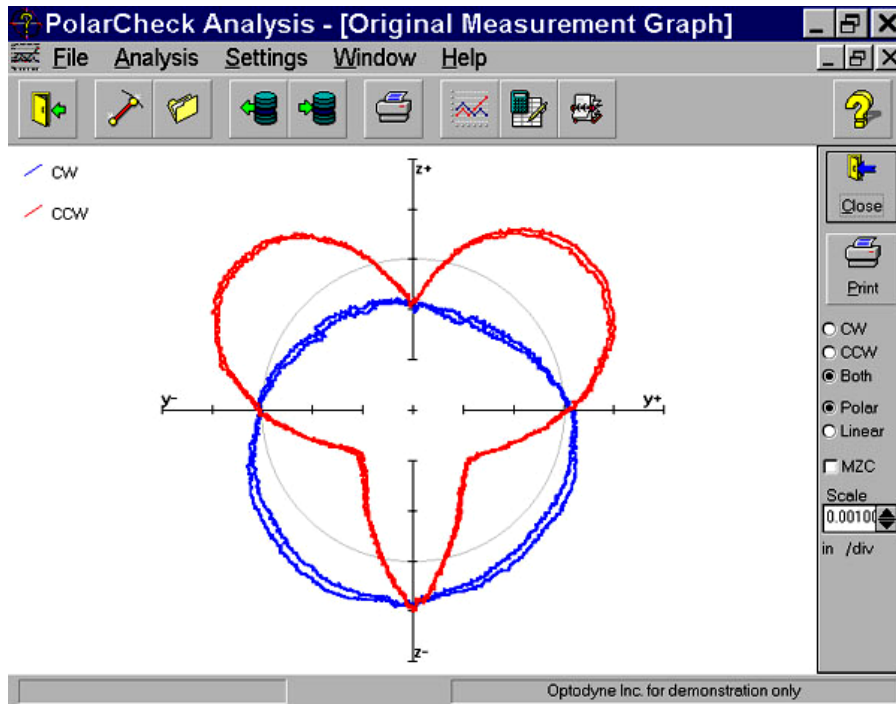


Fig. 9-8 A Polar Plot of the Circular Contouring Error without Feedforward

The large non-roundness shown in Fig. 9-8 is caused by the velocity notches. Once the feedforward function is turned-on, the velocity notches in Fig. 9-6 are removed and the polar plot shown in Fig. 9-9. The non-roundness is reduced considerably.

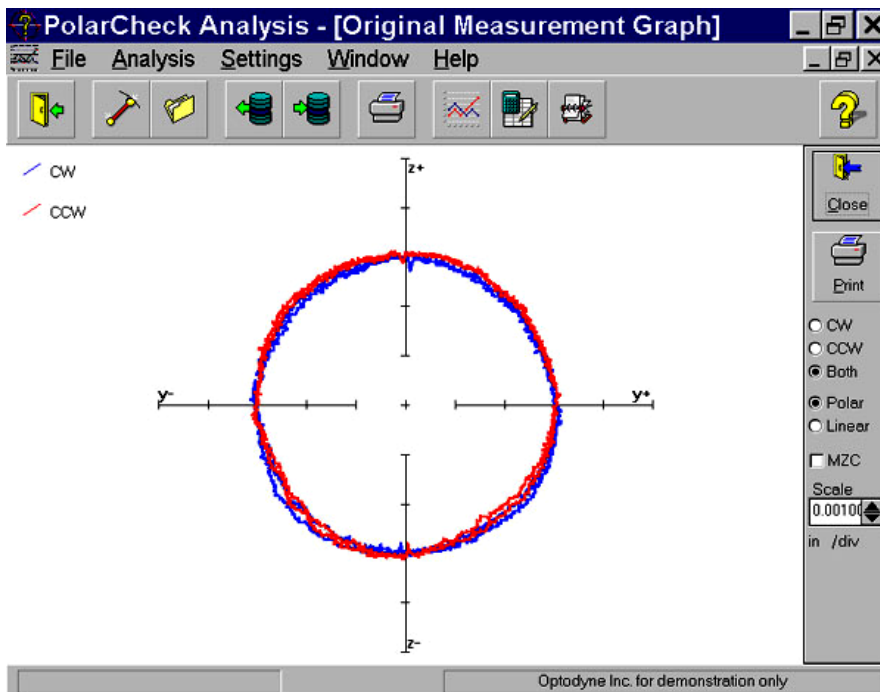


Fig. 9-9 A Polar Plot of the Circular Contouring Error with Feedforward

For some controllers, there is no velocity control, the velocity profile looks like triangular shape (see Fig. 9-10) instead of the sinusoidal shape. The polar plot, (see Fig. 9-11) shown large loop and the non-roundness is excessive large. This is because in the data processing,

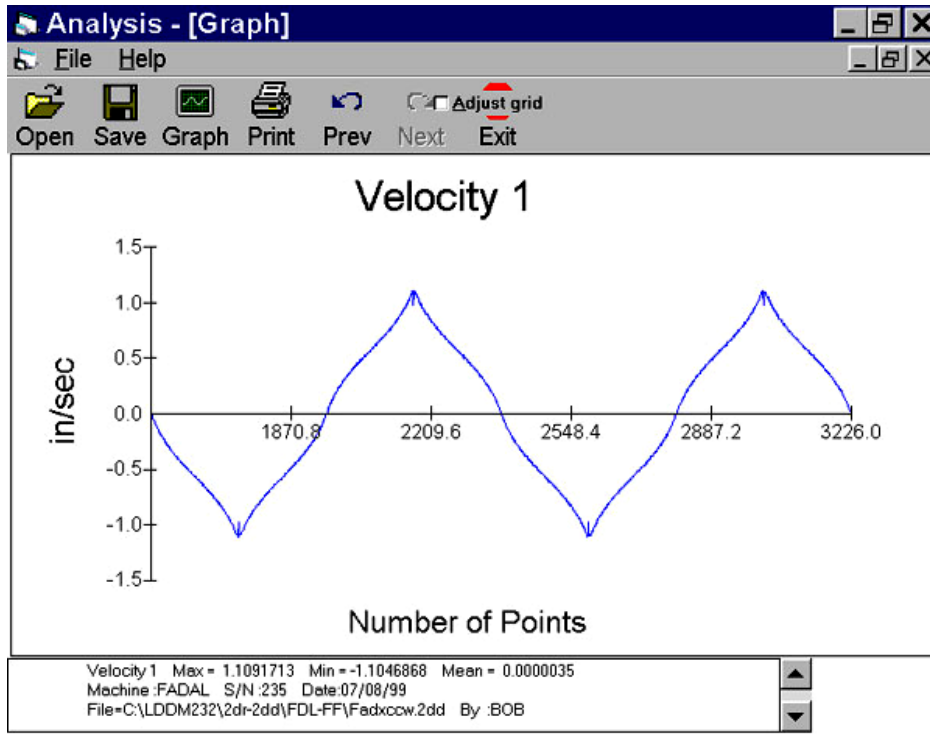


Fig. 9-10 A Plot of Velocity Profile without Velocity Feedback

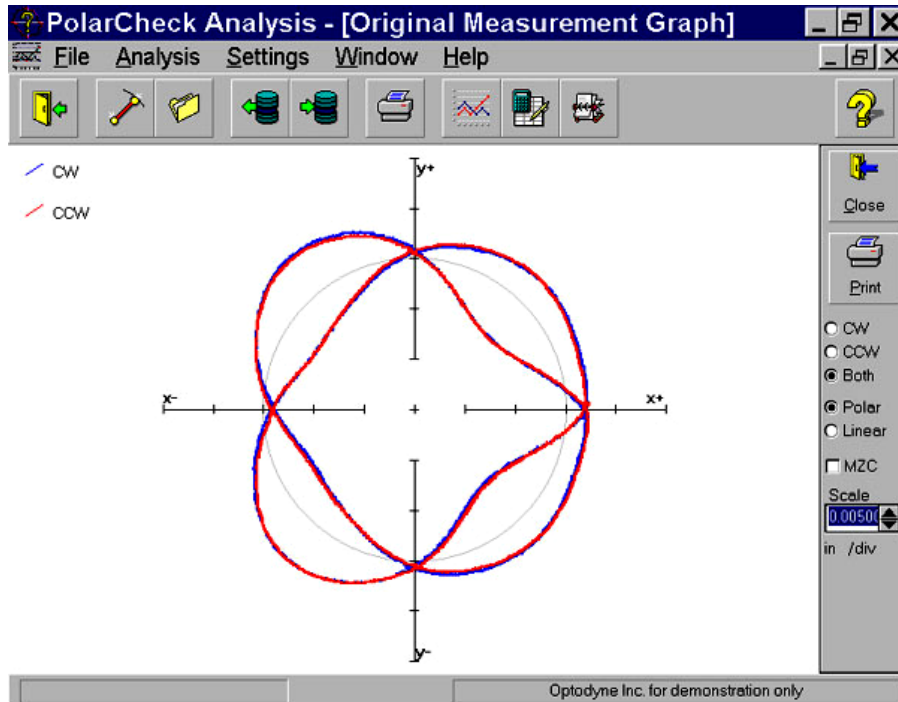


Fig. 9-11 A Polar Plot of the Circular Contouring Error without the Synchronized Data Processing

it is assumed that the velocity is uniform or sinusoidal. To fix this problem, a “sync” button is added in the “select Axis Data files” screen. The non-roundness is reduced as shown in Fig. 9-12.

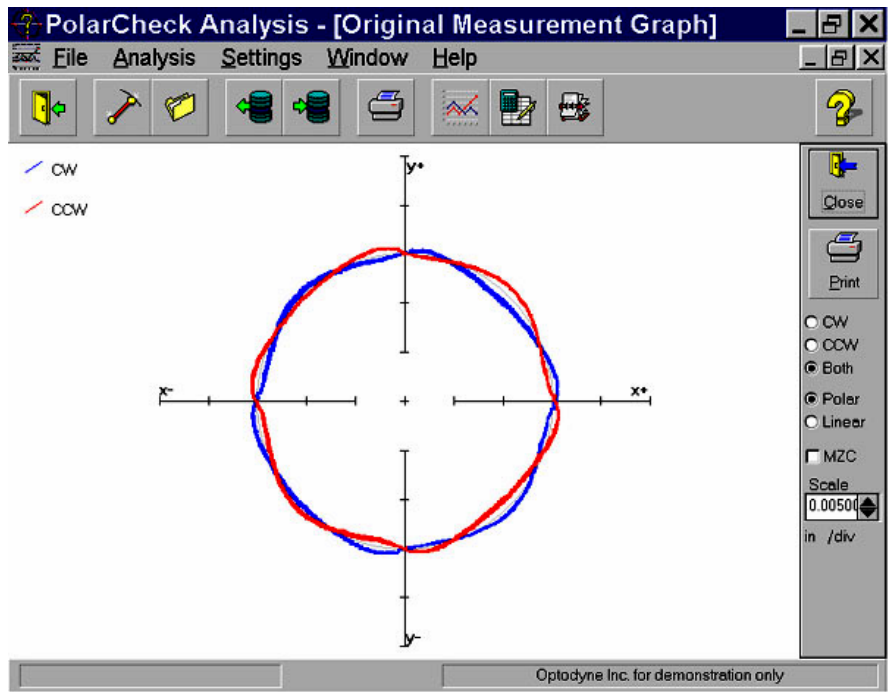


Fig. 9-12 A Polar Plot of the Circular Contouring Error with the Synchronized Data Processing