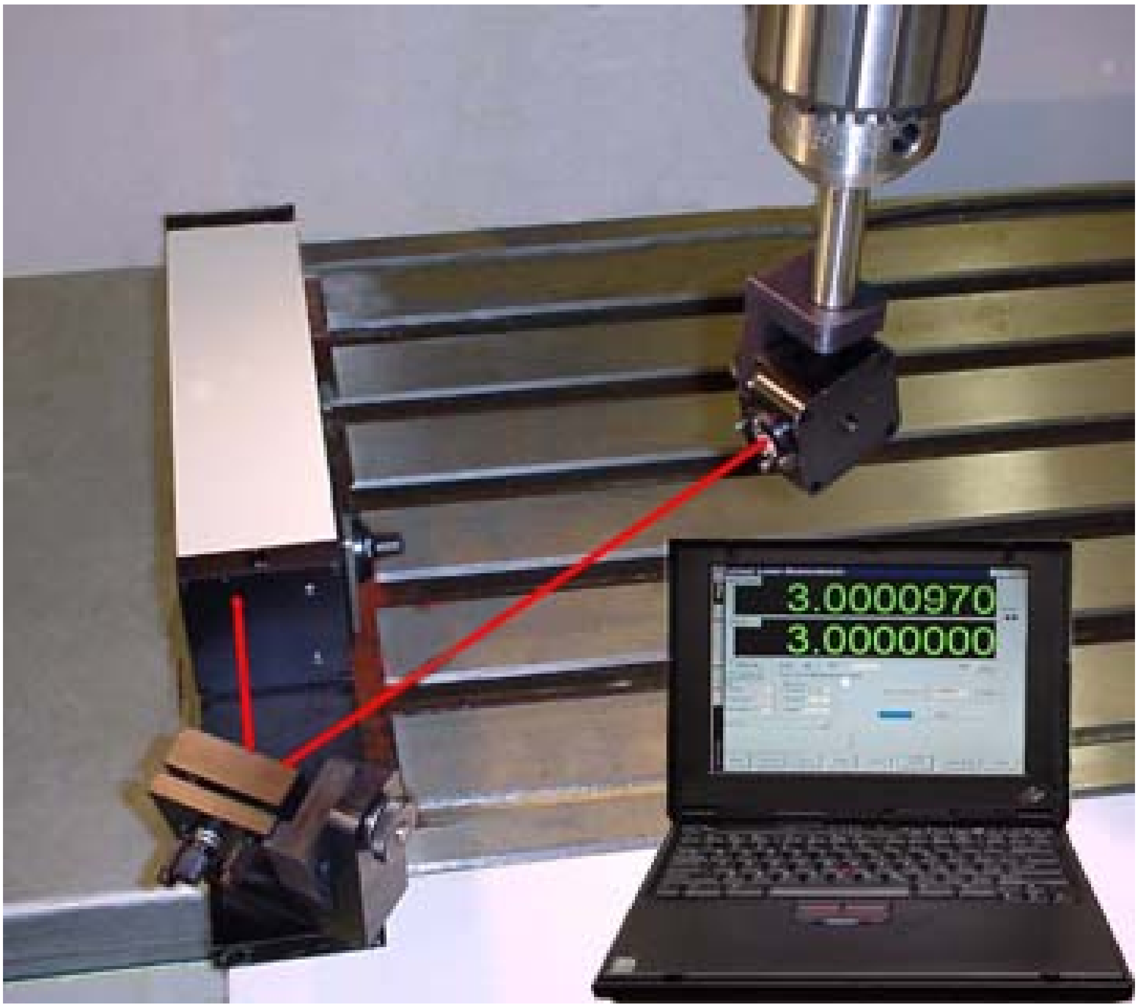
Laser Doppler Displacement Meter™
Laser Measurement System

User's Guide (MCV-500)



OPTODYNE, INC.
1180 Mahalo Place
Rancho Dominguez, CA 90220
Phone: 310-635-7481
Fax : 310-635-6301
Email : http//www.optodyne.com

Notice

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.

For technical assistance, please contact Optodyne's Service Department:

Optodyne, Inc.
Service Department
1180 Mahalo Place
Rancho Dominguez, CA 90220, USA
310-635-7481 (Telephone)
800-766-3920 (Toll Free in USA)
310-635-6301 (Fax)
www.optodyne.com

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 of its intended design. 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:

OPTODYNE, INC.
1180 Mahalo Place
Compton, CA 90220
USA
www.optodyne.com

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Part I. INTRODUCTION

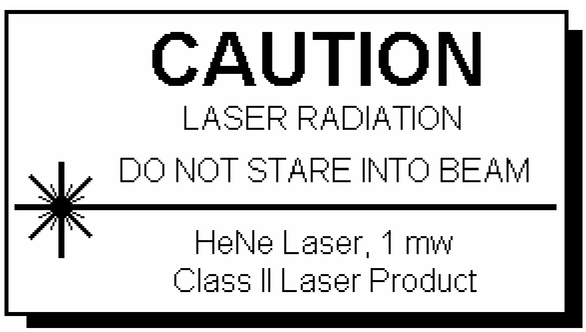
1.0 Before we begin

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. Retroreflector
4. Cable Assemblies
5. AC Power Cord
6. User's Guide
7. Accessories and Software

Please check the condition of all components. Fill out the Warranty Registration, section 5.4, 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 inform 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 the same 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 Notebook computer as shown in Fig. 2-1, LDDM™ System Block Diagram. Please note that because of the single aperture optical arrangement (same aperture for both the laser output beam and the return beam), the retroreflector and all the optical accessories are much smaller. Furthermore, using an optical adapter, a flat-mirror can be used as target.

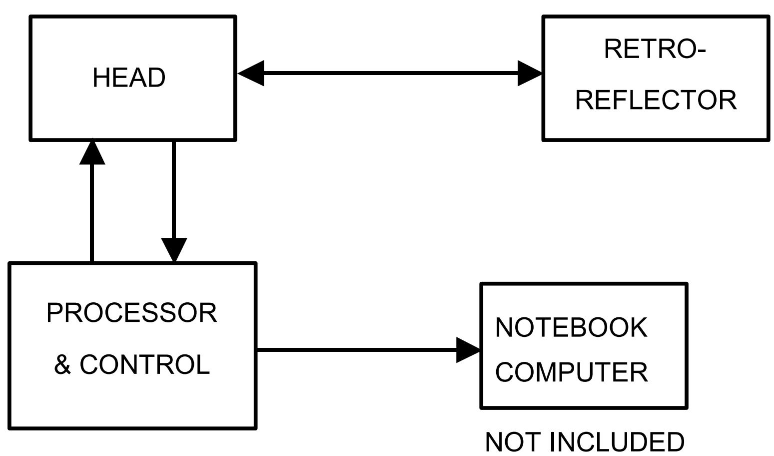


FIG. 2-1 SYSTEM BLOCK DIAGRAM OF LDDM
WITH A SINGLE APERTURE LASER HEAD

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. 2-5, 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 the same path , 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 Notebook PC through RS232. See Fig. 2-4, Processor Module, Physical Layout and Fig. 2-6, Processor Module, Block Diagram. Two Probes are provided for automatic temperature and pressure compensation. .

Notebook PC

A notebook computer with standard RS-232 interface can be used to display or collect data. Windows software is 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.

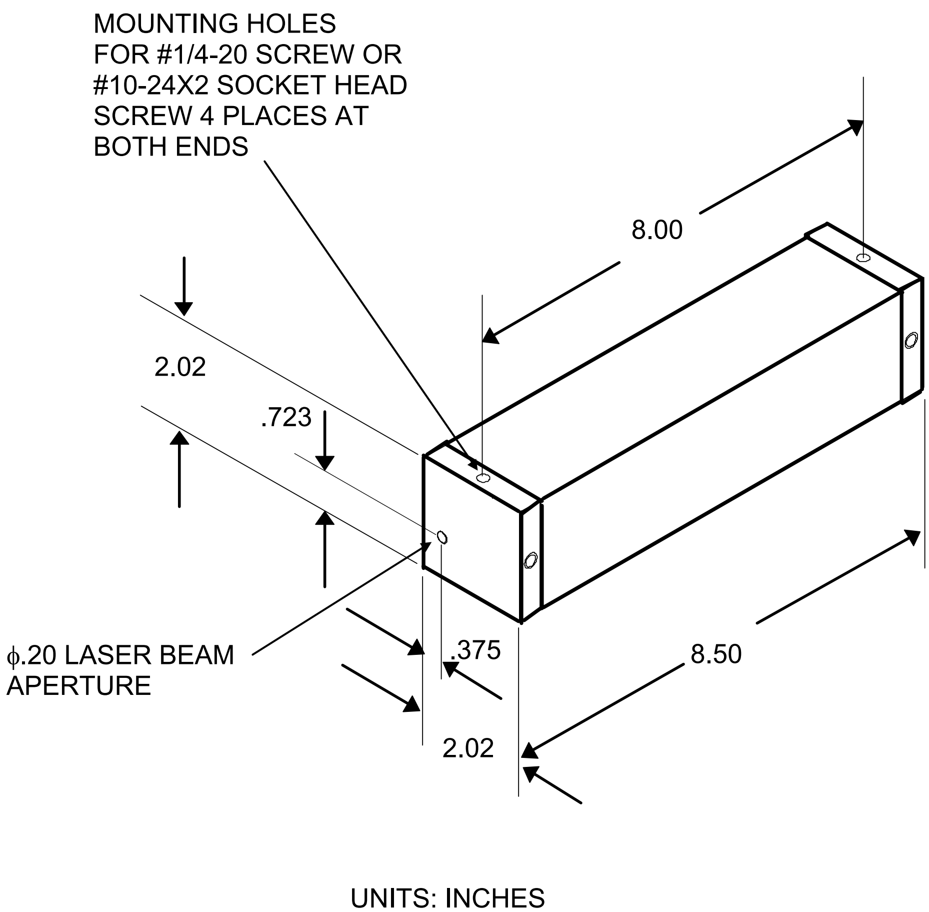
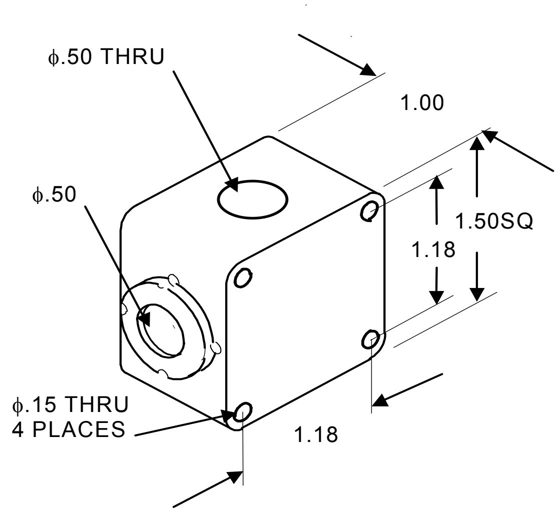
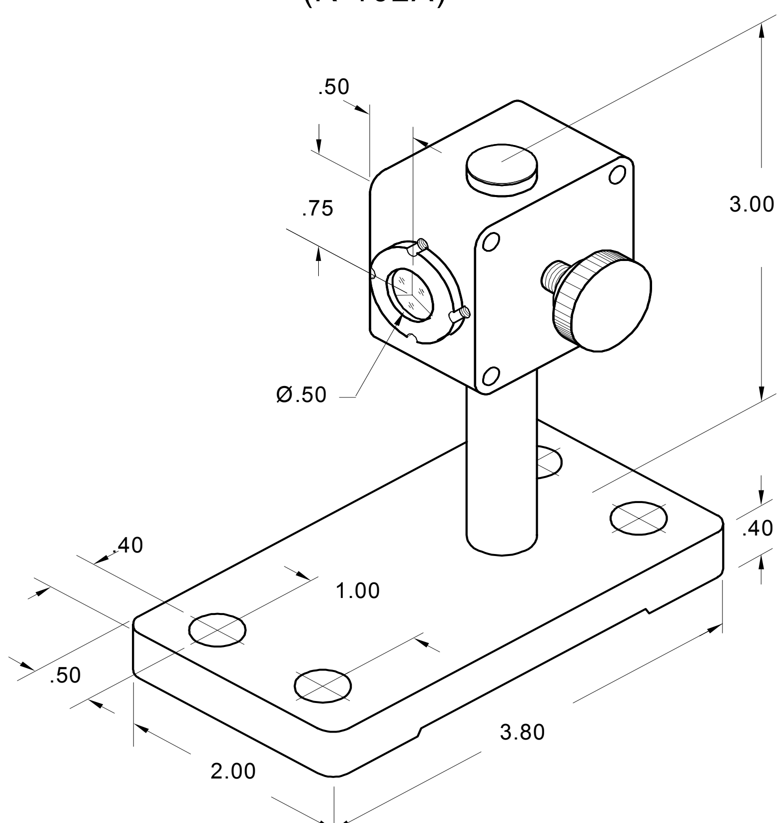


FIG. 2-2 LASER HEAD (L-109)
OUTLINE & MOUNTING DIMENSIONS



1/2” RETROREFLECTOR
(R-102A)



ø1/2" CORNER CUBE WITH POST AND BASE (R-102)

FIG. 2-3 1/2”RETROREFLECTOR

UNITS: INCHES

FIG. 2-4 PROCESSOR MODULE P-108D
OUTLINE DIMENSIONS

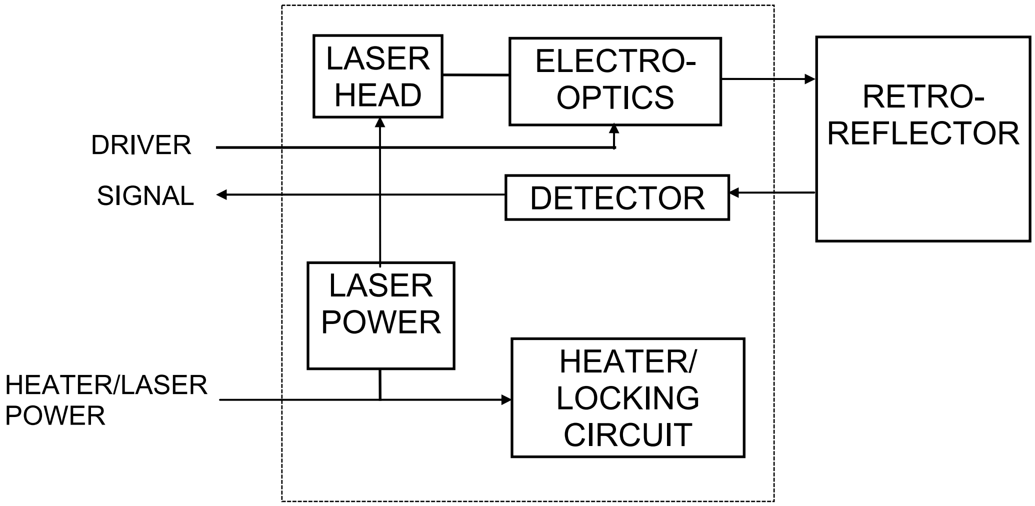


FIG.2-5 LASER HEAD MODULE, BLOCK DIAGRAM

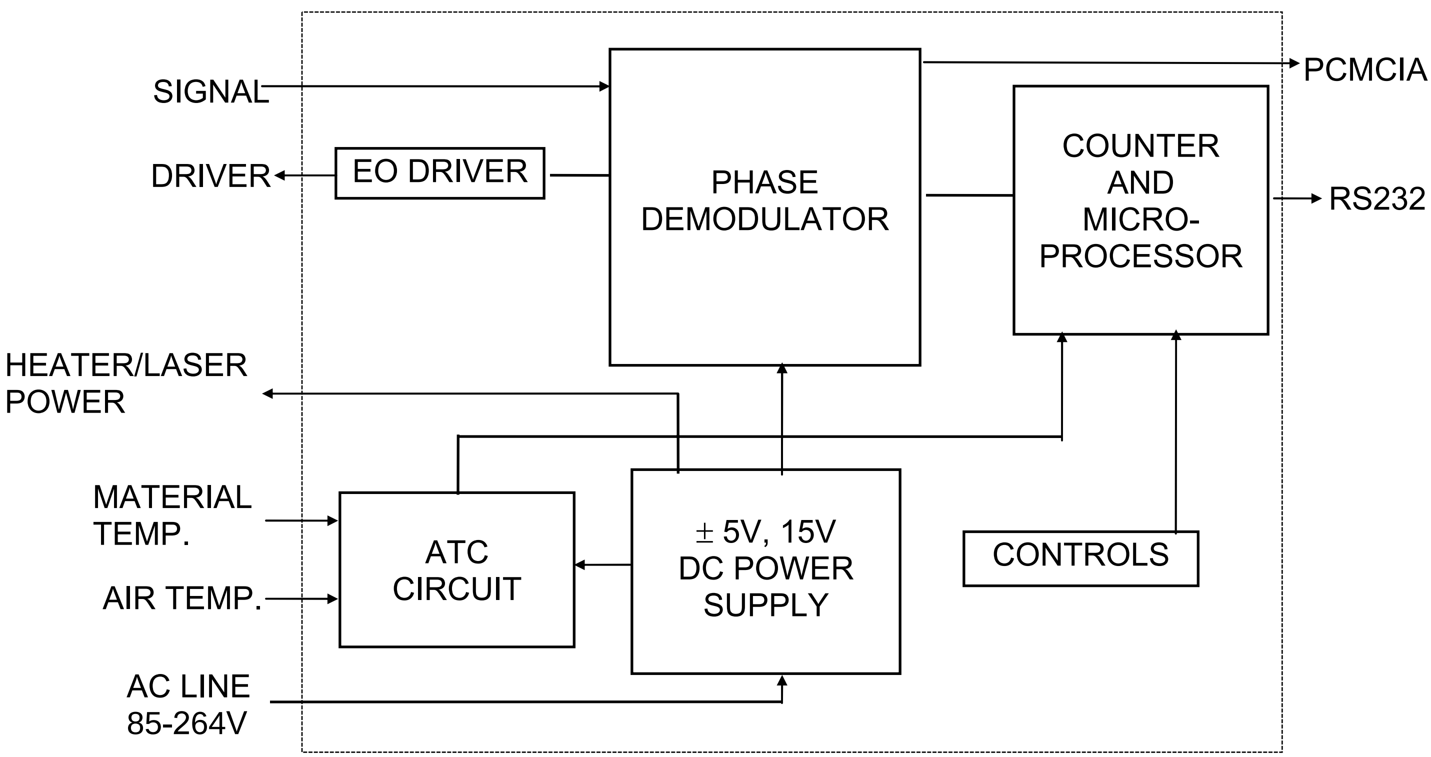


FIG. 2-6 PROCESSOR MODULE, BLOCK DIAGRM

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:

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

or:

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

Where Δf and $\Delta \theta$ are the frequency and phase shift and $\Delta \nu$ 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. 2-5, 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 Specifications

	Standard	Units
Laser Stability:	0.1	ppm
Resolution:	1	µin
	0.01	µm
Range:	0-50	ft
	0-15	meters
Axes:	one (Two axes available)	
Rate (max.):	144	inch/sec.
	216000	mm/min.

Outputs: computer interface, RS-232C (other interface available)

Operating Environment: Temperature 60 to 90 °F (15 to 32ºC).
Option 40 to 100 °F (5 to 37ºC).

Altitude: 0 to 10,000 feet (0 to 3000 m)

Humidity: 0 to 95 percent (non-condensing)

Components:	Width (in)	Height (in)	Length (in)	Weight (lb)
Laser Head	2 (50.8mm)	2 (50.8mm)	8.5 (215.9mm)	2 (0.9kg)
Retroreflector	Ø0.5 (12.7mm)		0.35 (8.9MM)	0.1(90gm)
Processor Module	8.0 (203.2mm)	3.5 (88.9mm)	9.6 (243.8mm)	5 (4.5kg)

Interconnection

Cables:	Number	Length
	3	12 ft (3.6m) and 8 ft (2.4m) (other lengths available)

Power Requirements: 85-264 VAC, 50-60HZ, 100W

Note: Specifications may change without notice.

3.0 Operation

3.1 General Applications

Applications for LDDM™, MCV-500 laser system fall into three categories: calibration and compensation of linear displacement errors, calibration and compensation of volumetric positioning errors (3 displacement errors, 6 straightness errors and 3 squareness errors), 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. Furthermore, the new patented vector method (see section 9) can be used to measure the 3 dimensional volumetric positioning errors. These measured volumetric 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. 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 monitor will show displacement. The value displayed will constantly change as the Retroreflector moves. When motion stops, the monitor will show the displacement of the Retroreflector at its current position. If motion resumes, the monitor will again constantly change to show each instantaneous position of the moving Retroreflector. If the Retroreflector moves back to its original position, where the monitor was zeroed, and the monitor 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 near 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 no laser beam 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/IEC 17025 by L.A.B. The certificate number is L1085.

5.4 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 S/N:______________ **Processor 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.

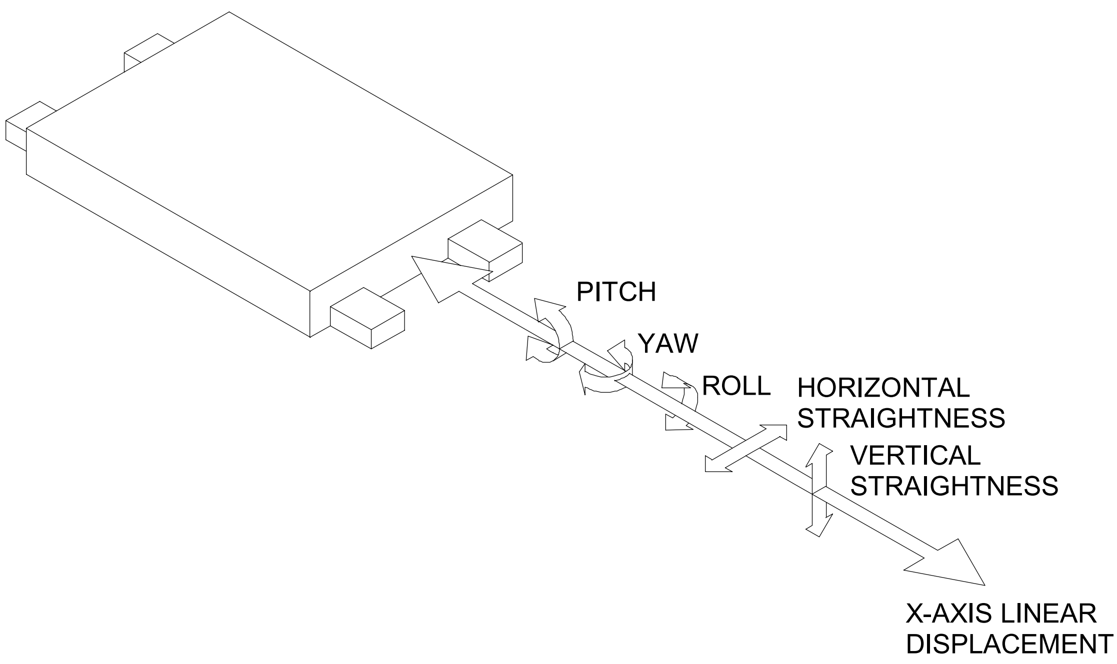


FIG. 6-1 LINEAR MOTION WITH SIX DEGREES OF FREEDOM

For a three-axis machine, there are 18 errors plus 3 for squareness, a total of 21 errors. Complete measurement of these errors is very time consuming. Body diagonal displacement error measurements have been recommended for a quick check of the volumetric accuracy. This is because it is sensitive to all the error components. However, if the errors measured are large, there is not enough information to identify the error sources.

Machine accuracy can be improved by measuring all these errors and then compensating for these errors, provided that the machine is repeatable. The key is how to measure these errors accuracy and quickly.

The laser vector measurement technique described in section 9 can measure the volumetric positioning errors, including 3 displacement errors, 6 straightness errors and 3 squareness errors, using the single-aperture and compact laser system in 4 setups and within a few hours.

6.2 Hardware and Accessories

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

6.2.1 Laser Head

L-109 Single-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. 2-2.

6.2.2 Processor Modules

P-108D 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 μin. There are RS-232 interface, automatic temperature and pressure compensation. A typical dimension of the processor module is shown in Fig. 2-4.

6.2.3 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 parallel to the input beam regardless of the angle of incidence. The standard retroreflector has a diameter of ϕ0.5 in. The dimensions of a Ø0.5 in. retroreflector is shown in Fig. 6-2. 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 Automatic temperature and pressure compensation

The ATC probe consists of an air temperature sensor, an air pressure sensor (inside the processor modul), and a material temperature sensor. The ATC electronics consist of a power supply to the probe and ADC to convert analog signal to digital signals. 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 monitor. The user needs to key in the material thermal expansion coefficient to calculate the correction factor (MTE) for the material thermal expansion. For a detailed description and calibration procedure, see Appendix H. The ATC probes are shown in Fig. 6-4.

6.2.5 Beam bender

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. 6-3.

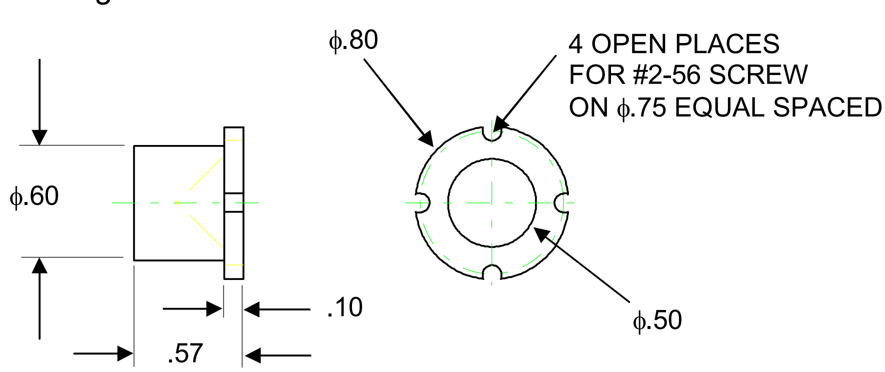


FIG.6-2 ϕ0.5" RETROREFLECTOR
DIMENSION & OUTLINE

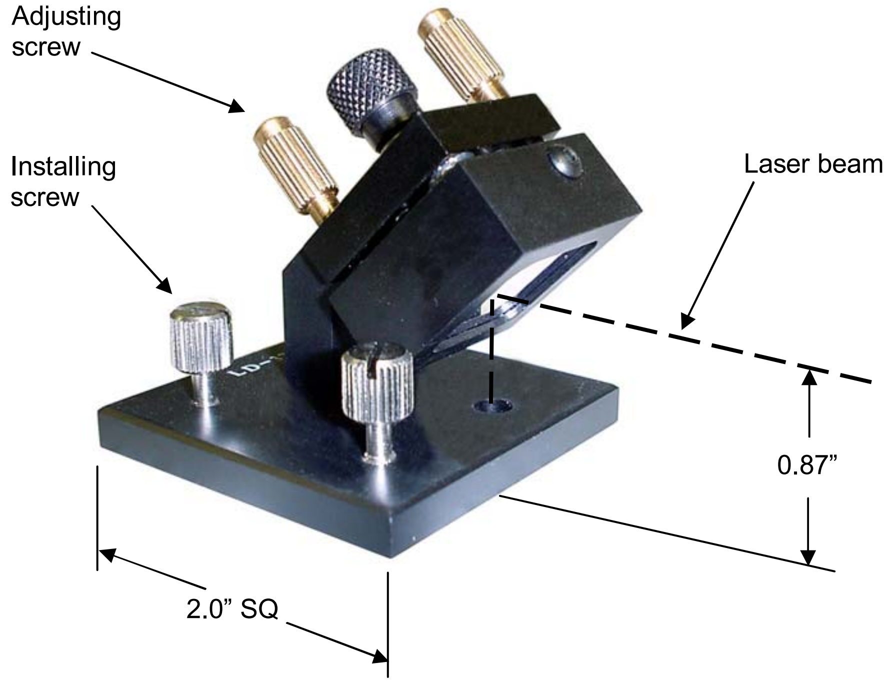


FIG. 6-3 90° BEAM BENDER (LD-37)

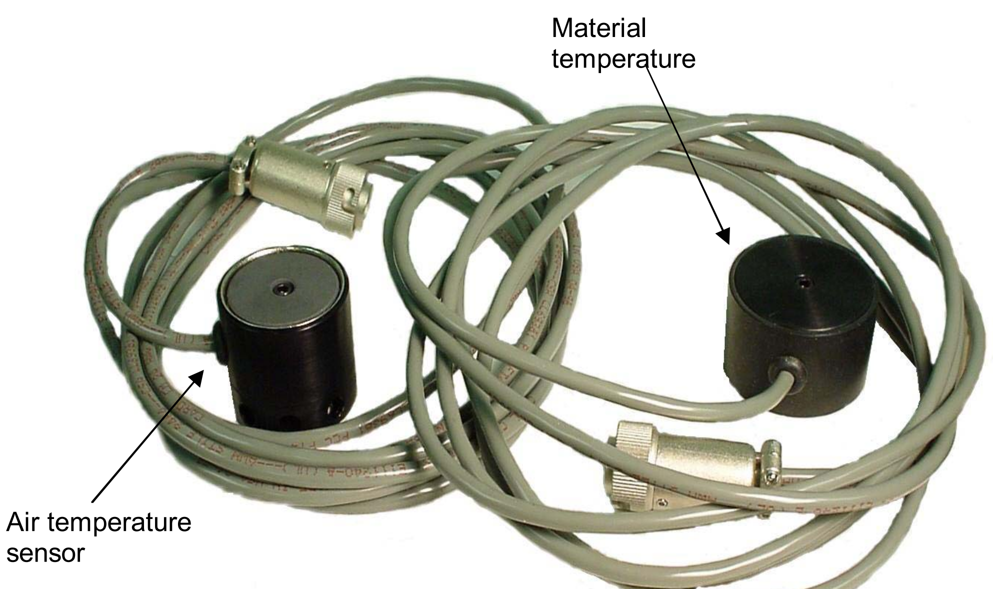


FIG.6-4 ATC PROBES

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 (see sections 7.9 and 9.9).

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, ”$\overline{B}$” and repeatability in the forward and reverse directions, “R^+” and “R^-” to define the machine accuracy.

For the ASME 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. The new ASME B5.54 standard is similar to ISO 230-2 standard.

"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 = -.)

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. Single Aperture Laser Head	L-109
b. Processor Module with RS-232 Interface	P-108D
c. Automatic temperature compensation Probes	IATCP
d. Ø05" Retroreflector	R-102
e. Metrology/Analysis Program	W-500
f. 90° beam Bender (Ø0.5")	LD-37
g. Magnetic Base	LD-03
h. Adapter Platform	LD-14D
i. 12 ft Cable Set	LD-21L
j. Carying Case	LD-20A
h. Notebook PC	Not supplied

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

FIG.7-1 CALIBRATION HARDWARE

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 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 μin (0.01 μm).

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)
Option 40 °F to 100 °F(5 °C to 37 °C)

7.4 Reference Material

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 along the entire measurement path.

7.5.2 Installation

7.5.2.1 Set up LDDM Program

To setup LDDM program from Windows 95/98, Windows Millennium, windows 2000, NT and XP.

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.

7.5.2.2 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 figure 7-10). Click on Linear for linear measurement. The measurement program will appear on your screen (see figure 7-11).

7.5.2.3 Setup Laser Head and Retroreflector

Attach the 90° beam bender (Fig. 7-2) to the front of the laser head. Make sure both exit beam and return laser beam are covered by the steering mirror on the 90° beam bender. To mount the laser head to the spindle, you may use the magnetic base (Fig. 7-3). The retroreflector and post (Fig. 7-5) can be mounted on the bed or on a magnetic base (Fig. 7-6). Make sure all screws are tight and the surface of the magnetic base is free of grease. Various other mounting techniques are shown in Fig. 7-7, Fig. 7-8, and Fig. 7-9.

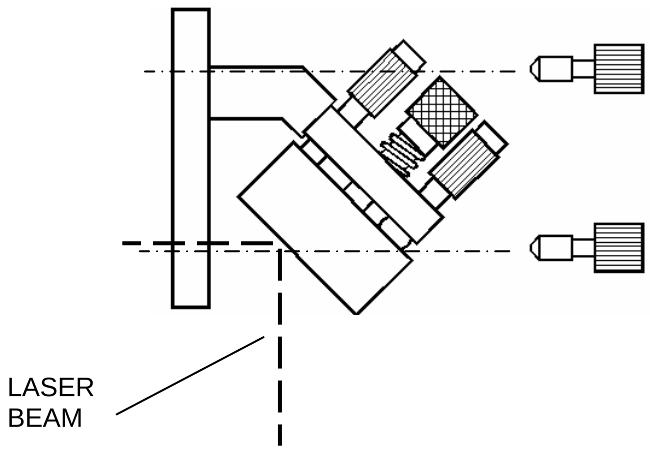


FIG. 7-2 90° BEAM BENDER
(LD-37)

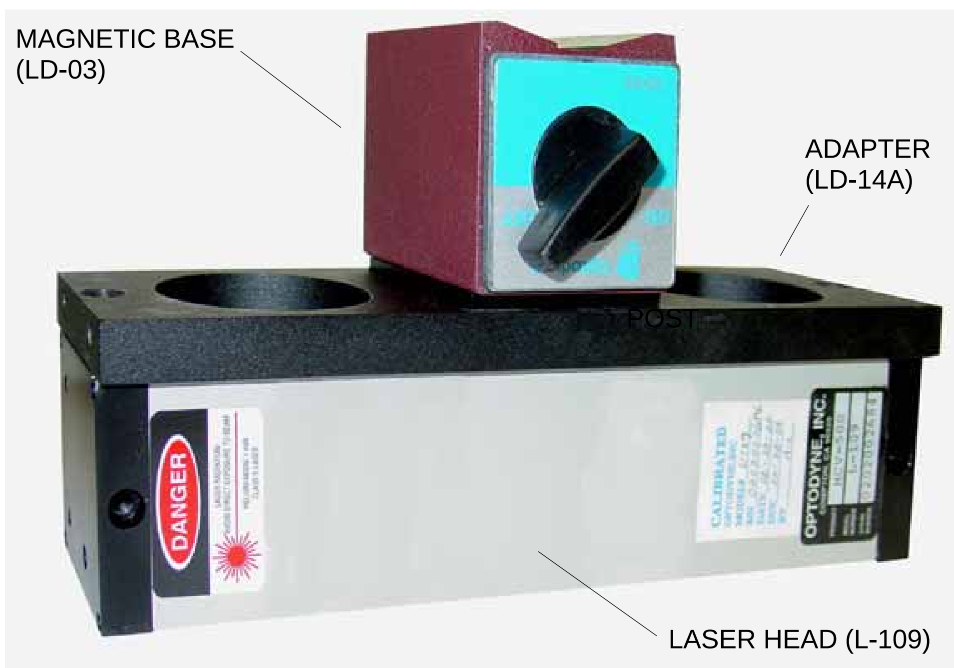


FIG. 7-3 SPINDLE MOUNT WITH
MAGNETIC BASE

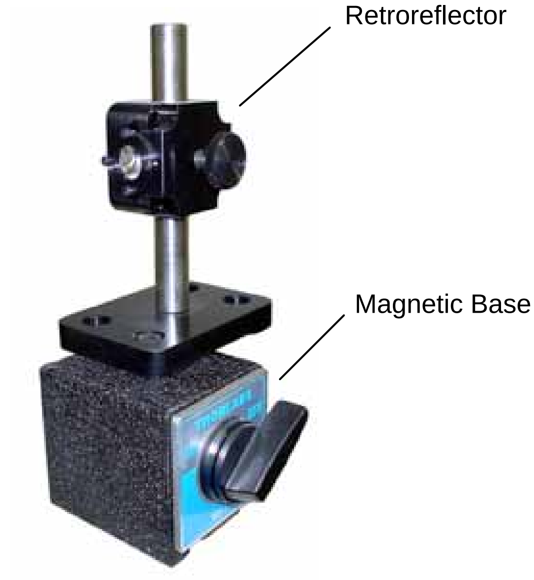


FIG. 7-4 RETROREFLECTOR
MOUNTED ON MAGNETIC BASE

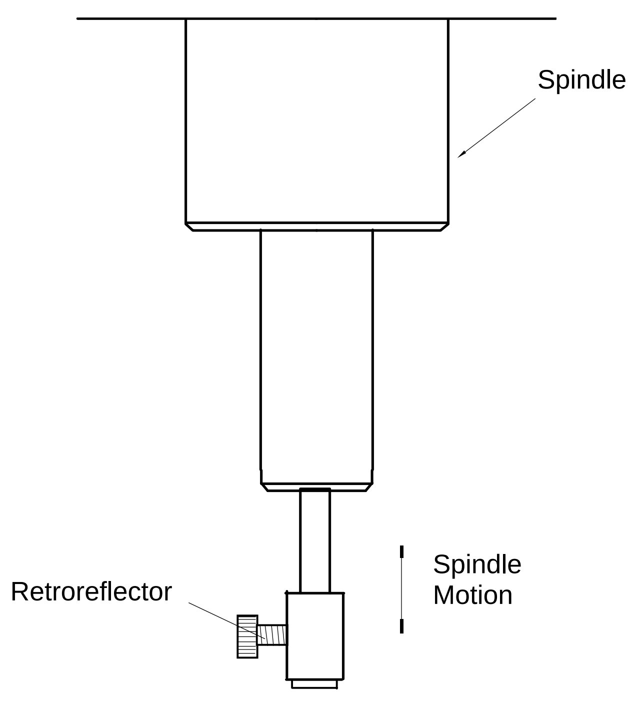


FIG. 7-5 RETROREFLECTOR MOUNTED
ON A SPINDLE

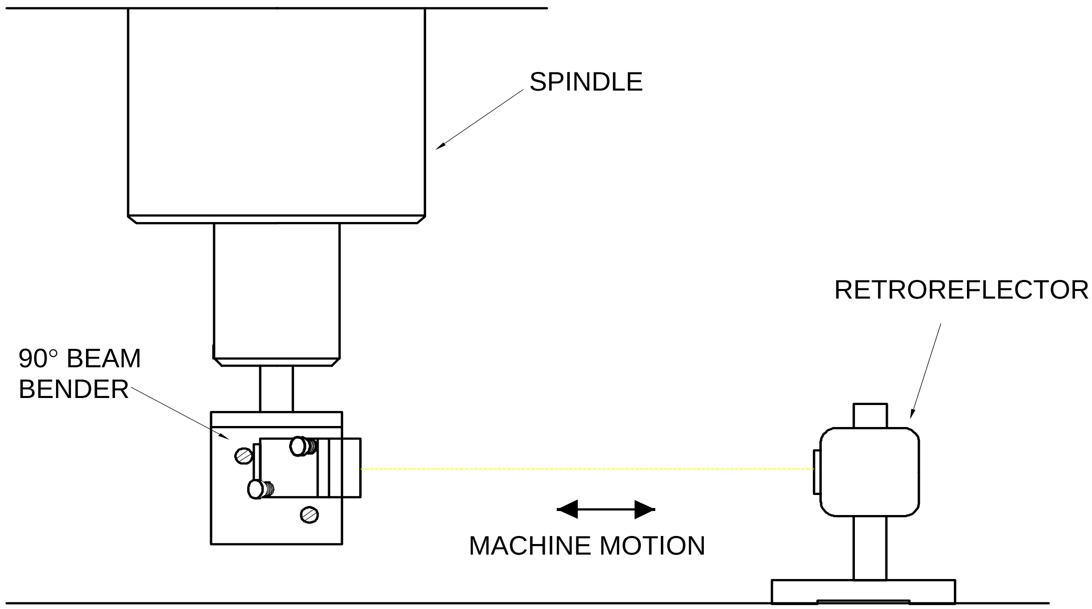


FIG. 7-6 LASER HEAD MOUNTED
ON A SPINDLE

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. 7-7, 7-8).

   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.

2. Setup the notebook PC and the Windows software to display the LDDM readings (see section 7.5.2.1 and 7.5.2.2).

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.

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 maximun.

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.

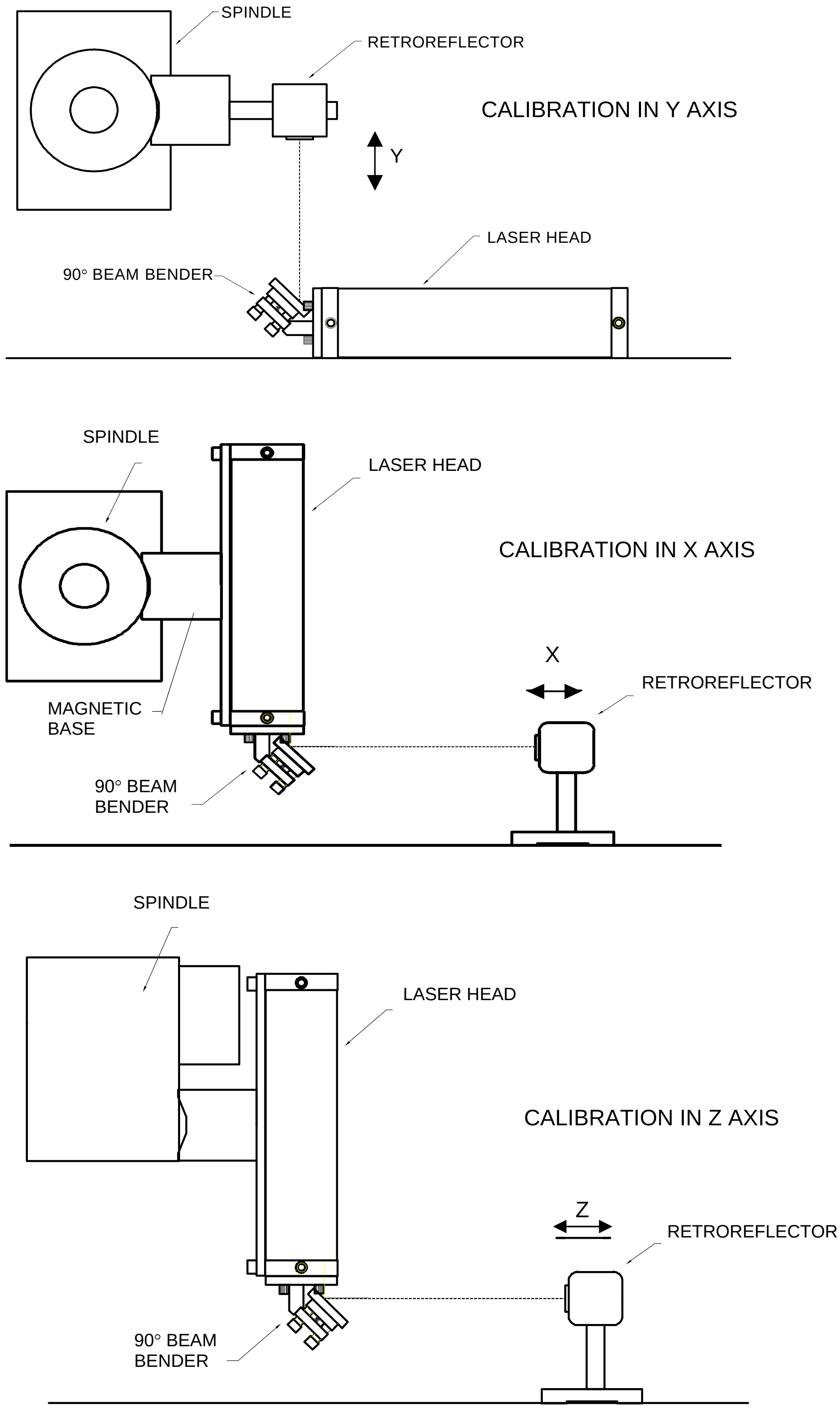


FIG. 7-7 CALIBRATION ON HORIZONTAL MILLING CENTER

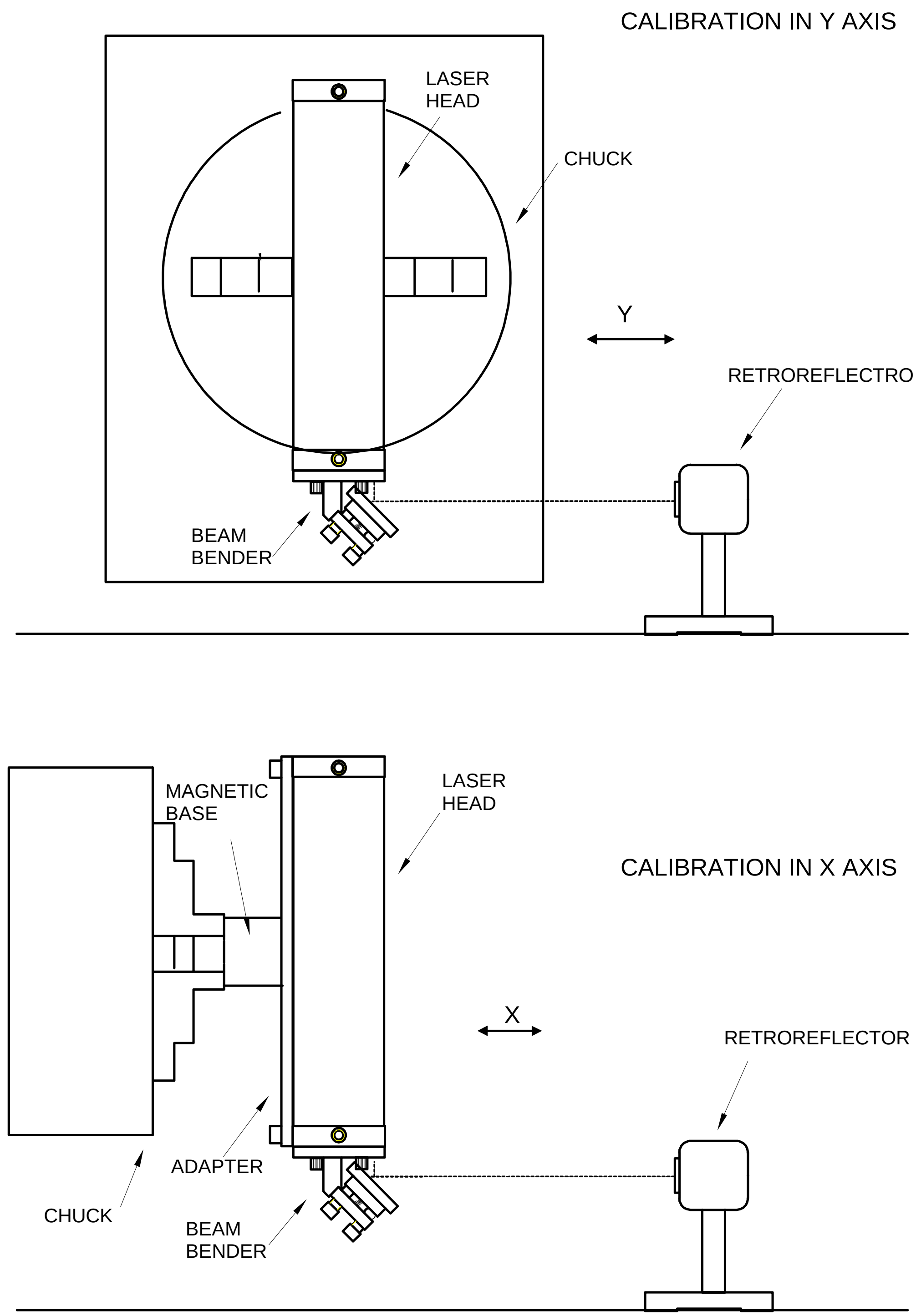


FIG. 7-8 CALIBRATION OF TURNING CENTER

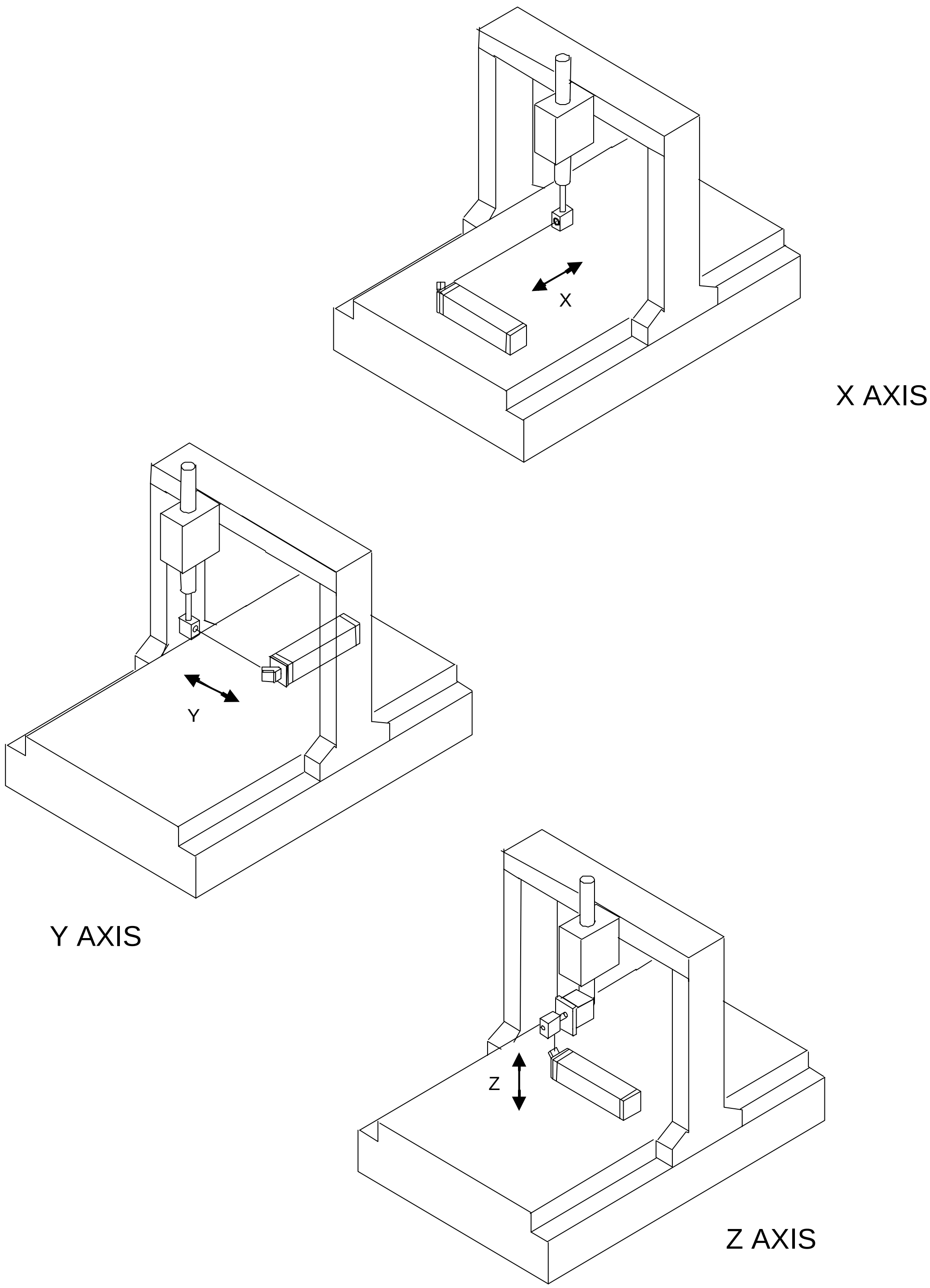


FIG.7-9 CMM CALIBRATION

7.6 Software Description

The Metrology program is used to determine the positioning discrepancy 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 measurement discrepancy. 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 Windows software to direct the operator through the setup and execution of measurement procedures. The software includes several default and operator selectable measurement parameters that are used by calibration equations. Interim or final reports can be created to show the results of any calibration procedure.

7.6.1 LDDM for Windows

Here 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.

Bolded characters

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

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.

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.

7.6.2 Installation

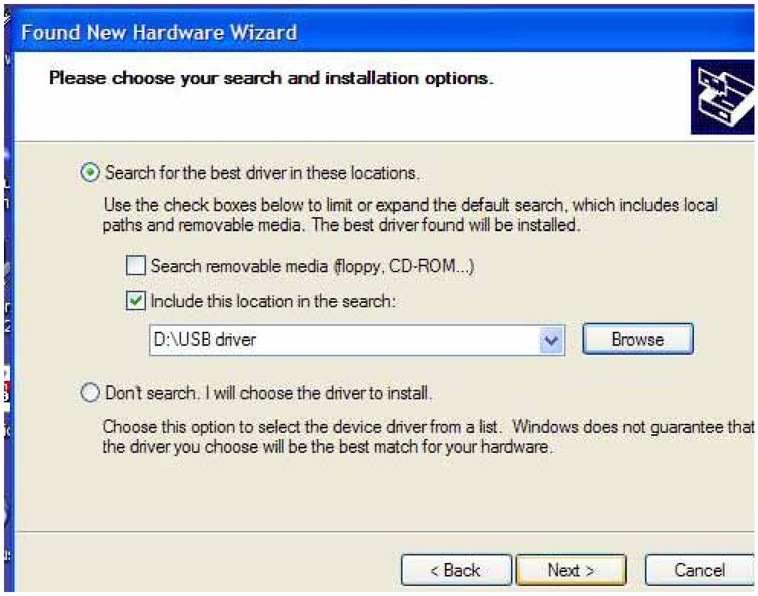
7.6.2.1 Instructions for USB Driver Installation

1. Turn on LDDM system and make sure the USB cable is connected between LDDM processor box and the USB port of computer.

2. Windows will detect USB ⇔ Serial and automatically start the Found New Hardware Wizard as shown below.

3. Select “Install from a list or specific location (Advanced)”. Click “Next” to continue.

4. Windows will ask you to specify where the USB drivers are located. Please select “include this location in the search”. Use “Browse” to find out the USB drivers in CD-ROM Drive. The driver should be located in D:\USB driver (where D: is the drive of your CD-ROM drive). Click “Next” to continue.



5. A Hardware Installation Windows will appear during setup. Simple press "Continue anyway" button to continue.

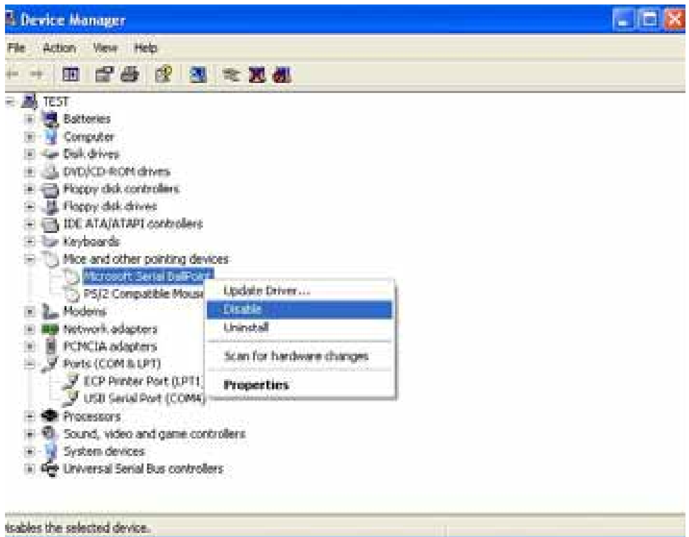
6. Windows will install the driver on the system. Click "Finish" button to process next step.

7. Installation of other drivers will start. Repeat step 2 through 6 to complete the installation process.

8. Windows will restart the computer before the new settings will take effect.

9. After computer reboot, open Device Manager in Control Panel as below:

The USB Serial port will always take the next available COM port.
LDDM systems will work on COM1 through COM4.
If a Mcrosoft Serial Ballpoint driver is loaded in the Mice and other pointing devices, please right-click to disable it. This will prevent Windows from keeping detecting LDDM as other pointing devices.



10. The installation of USB is completed and it is now ready to run LDDM Windows program.

Note: If computer could not recognize USB adapter after driver is installed. Simply turn off LDDM processor box and disconnect USB cable from the processor box. Plug USB cable back to the processor box and wait computer to detect USB adapter before turn on the processor box.

7.6.2.2 Instructions for PIOD24 PC Card Installation

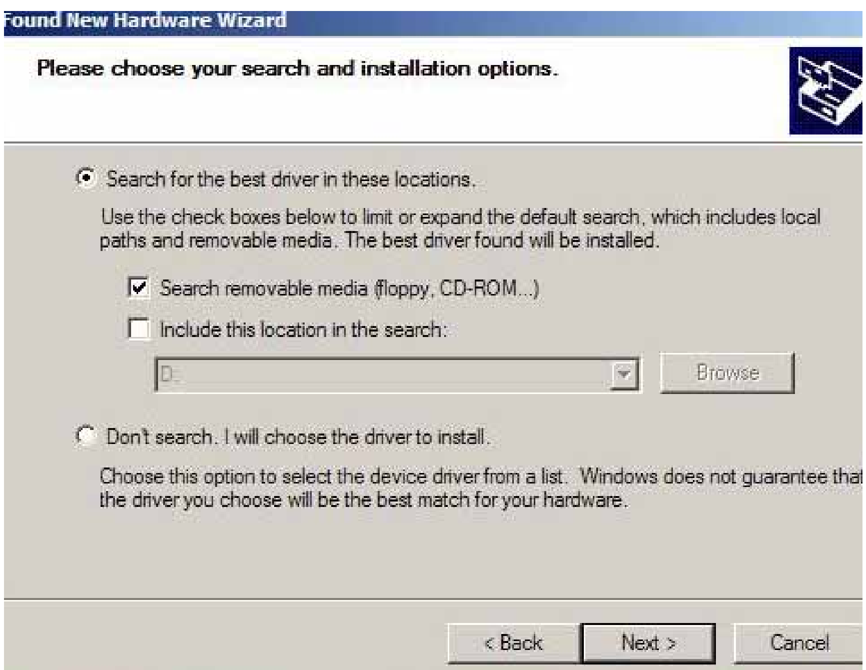
Insert PIOD24 PC Card to the PCMCIA slot.

Windows will detect **Kontron PC CARD (PCMCIA) PIOD24** and automatically start the **Found New Hardware Wizard** as shown below:

Select “Install from a list or specific location (Advanced)” and click “Next” to continue.

Next, system will ask you to choose installation options.

Please select “Search for the best driver in these locations.” and choose “Search removable media (floppy, CD-ROM…)”



Click “Next” proceed to next step and Windows will finish the installation process.

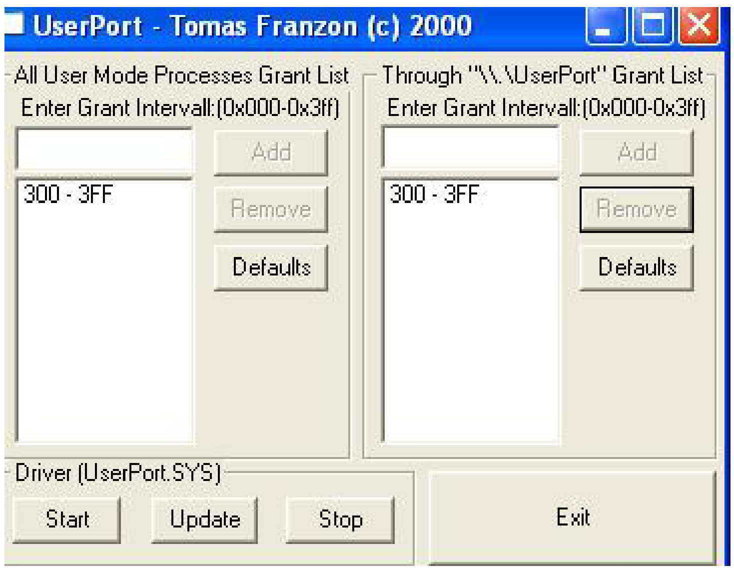
For Windows NT/2000 and XP users, an additional USERPORT driver is needed for PC card to run properly on these operating systems.

The driver can be installed in the following steps:

1. Copy D:\Userport\UserPort.sys to \Windows\system32\drivers
   (where D: is the location of LDDM CD ROM)

2. Copy D:\Userport\UserPort.exe to C:

3. Start UserPort.exe and add this I/O range 300-3FF as follows:



4. Remove the others and click Start to access this addresses you have chosen.

   The installation of Kontron PC card is completed.

7.6.2.3 Set up LDDM Program

To setup LDDM program from Windows 95/98 and Windows Millennium, Windows 2000 and Windows XP.

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.

7.6.2.4 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 figure 7-10). Click on Linear for linear measurement. The measurement program will appear on your screen (see figure 7-11).

7.6.3 Main Menu

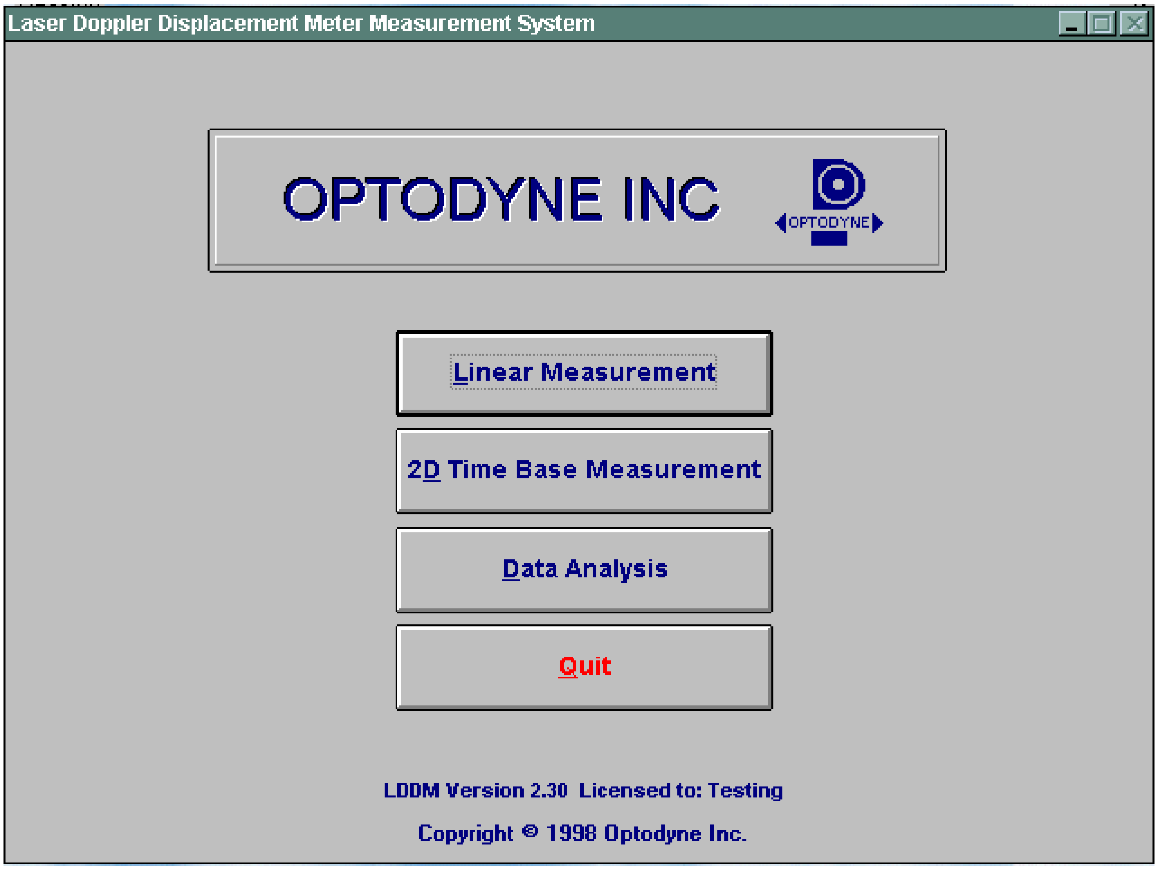


FIG.7-10 MAIN MENU

Click on **Linear** if you would like to take a linear measurement.
Click on **2D Time Base Measurement** for circular test or dynamic measurement
Click on **Quit** if you would like to exit the program.

7.6.4 Linear Measurement

After clicking the **Linear Measurement Box** on the Main Menu, you will be greeted by the Linear Measurement Data Screen (Fig. 7-11). If the LDDM is not connected properly, an error message box will appear indicating that the LDDM interface not found, either turn off or not connected. Please check your connections and the LDDM reading on the display should appear. If the dashed lines should persist, press the **In/mm** button.

A. Linear Measurement Main Display

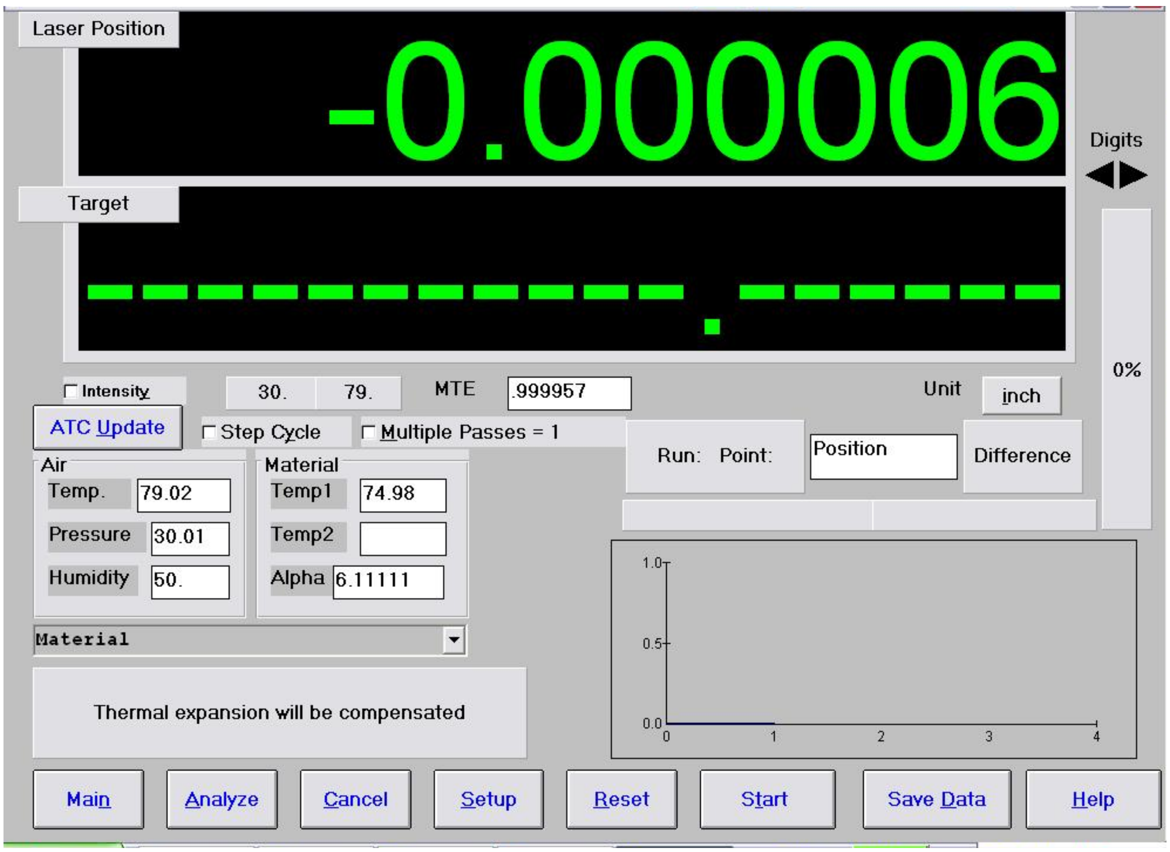


FIG.7-11 LINEAR MEASUREMENT MAIN DISPLAY

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 80% over your whole run. Press the intensity box again to return the system to its original state.

make sure that the intensity is at least 80% 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). 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 the respective values 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 displays 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.

Cancel: By pressing this button, the popup screen allows you to cancel the last data point taken during a run, or the second popup screen allows you to 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.

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.

B. Linear Measurement Setup Screen (Fig. 7-12)

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.

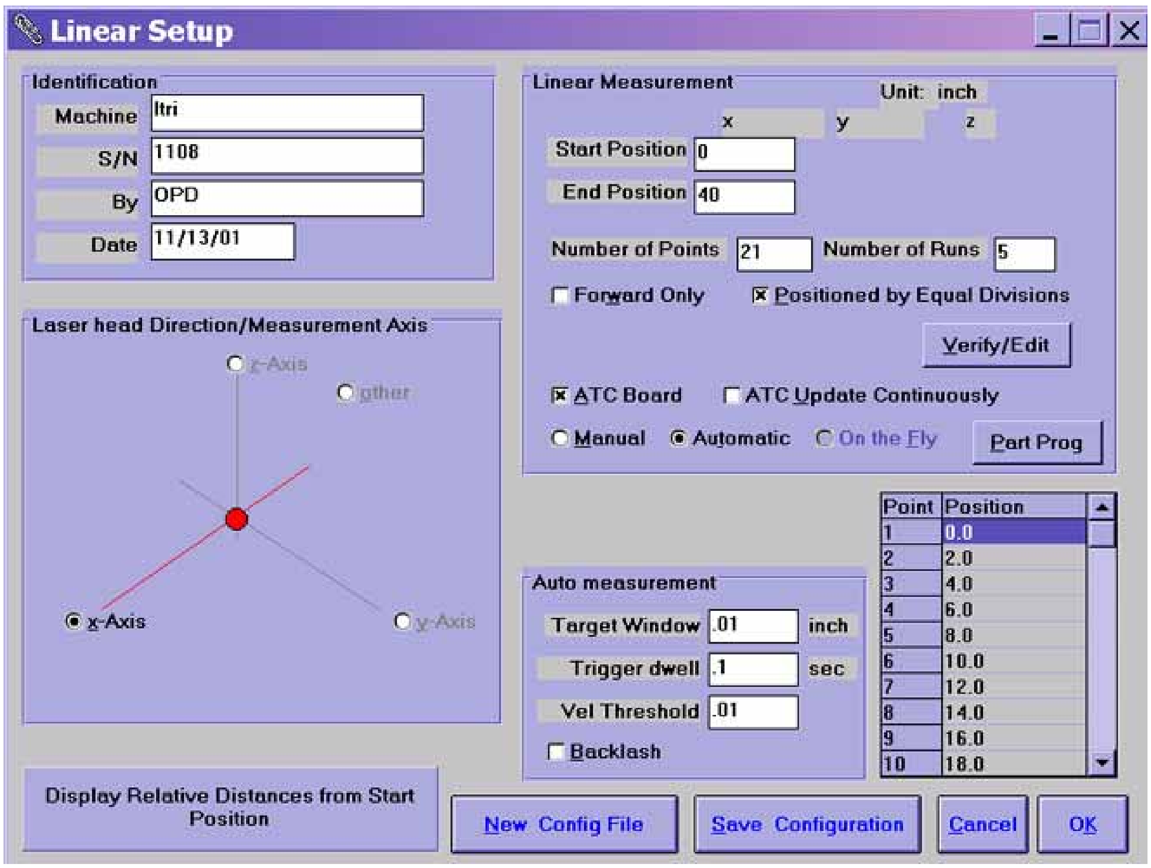


FIG.7-12 LINEAR MEASUREMENT SETUP SCREEN

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.

Linear Measurement:

Start Position: Enter the coordinate of the machine position that you are going to be starting at (for that given axis).

End Position: Enter the final coordinate of the machine position that you will be ending at (for that given axis). Please make sure that the end position is always large than the start position.

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.

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 Continuous Update: 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.

On-The-Fly: There is no On-The-Fly capability for the Linear Measurement.

Auto Measurement Box:

Part Prog: Click on this button to generate a sample part program to move the machine for the measurement. A screen will popup to enter the header (up to 5 lines) the dwell time, the backlash, the line ending (blank or ;) and the filename. The part program generated will have an extension .PPG.

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.

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. This allows the computer to finish the data collection before the machine start to move again.

Vel Threshold (automatic only): This is the threshold that the velocity of 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 Configuration: 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.

C. Example of a Linear Measurement

Linear Measurement Main Display (See Fig. 7-11):

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. 7-12):

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 or VDI, ISO and at least 3 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) Click on **ATC Continuous Update** if you want continuously update the ATC value during the 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. The extension .1CF indicates a configuration file.

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

Taking Data Points for a Linear Measurement (Fig. 7-13)

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. 7-13).

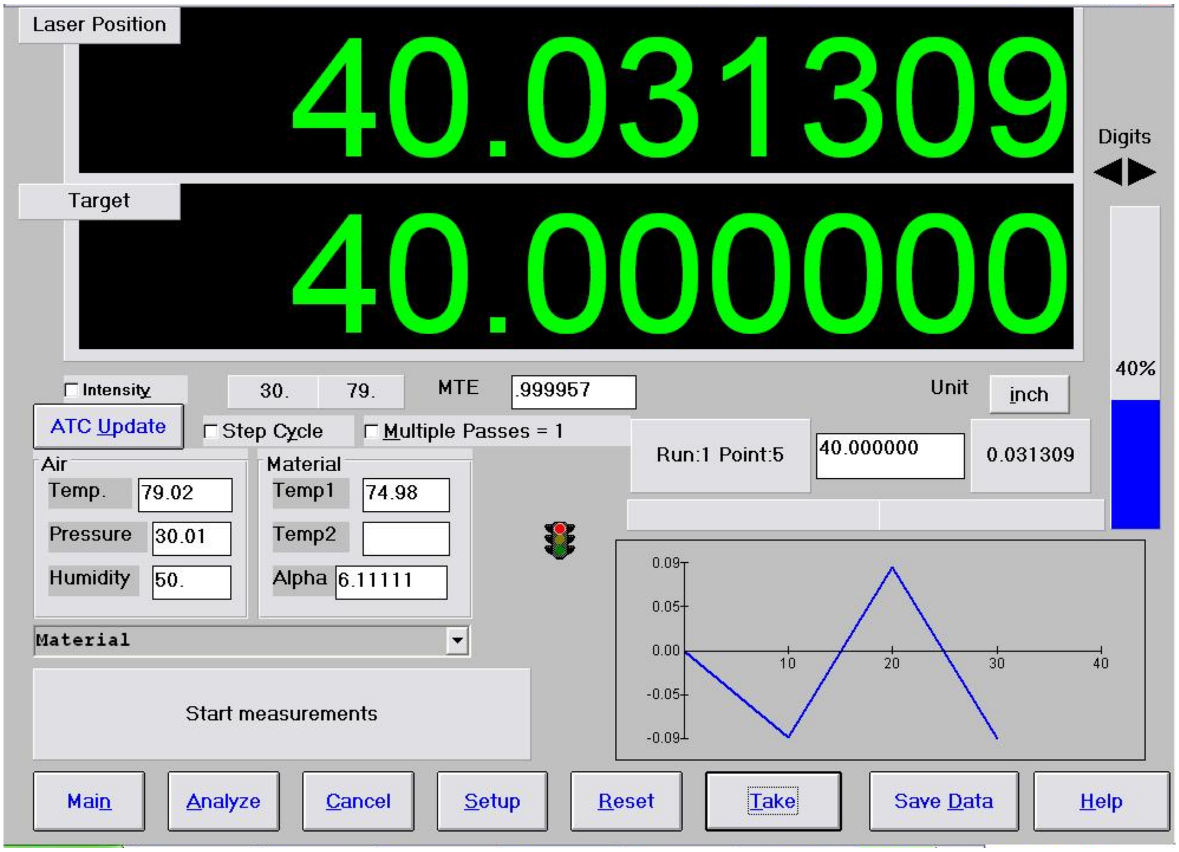


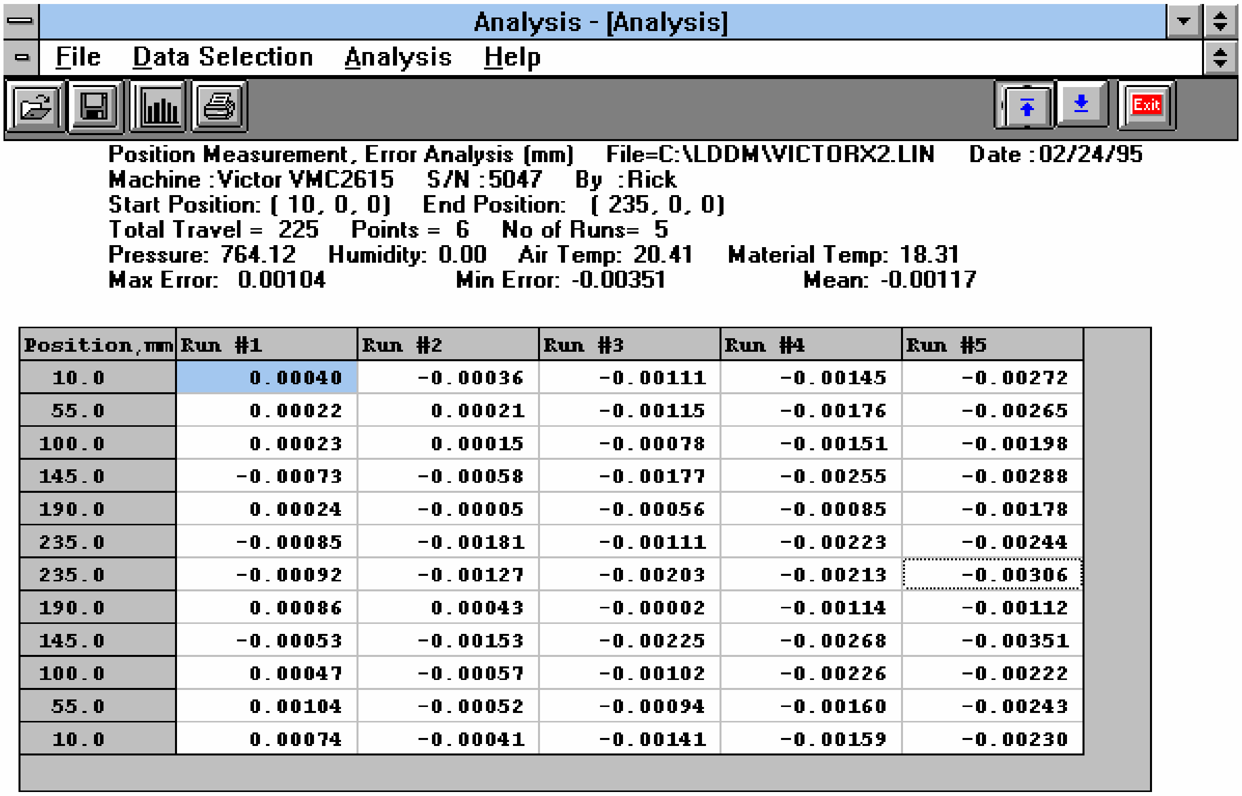
FIG.7-13 AUTOMATIC LINEAR DATA COLLECTION

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.

D. Linear Data Analysis Menu (Fig. 7-14)



Position,mm	Run #1	Run #2	Run #3	Run #4	Run #5
10.0	0.00040	-0.00036	-0.00111	-0.00145	-0.00272
55.0	0.00022	0.00021	-0.00115	-0.00176	-0.00265
100.0	0.00023	0.00015	-0.00078	-0.00151	-0.00198
145.0	-0.00073	-0.00058	-0.00177	-0.00255	-0.00288
190.0	0.00024	-0.00005	-0.00056	-0.00085	-0.00178
235.0	-0.00085	-0.00181	-0.00111	-0.00223	-0.00244
235.0	-0.00092	-0.00127	-0.00203	-0.00213	-0.00306
190.0	0.00086	0.00043	-0.00002	-0.00114	-0.00112
145.0	-0.00053	-0.00153	-0.00225	-0.00268	-0.00351
100.0	0.00047	-0.00057	-0.00102	-0.00226	-0.00222
55.0	0.00104	-0.00052	-0.00094	-0.00160	-0.00243
10.0	0.00074	-0.00041	-0.00141	-0.00159	-0.00230

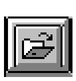
FIG.7-14 LINEAR MEASUREMENT DATA ANALYSIS TABLE

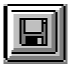
Under the **File Menu**, you can open a **new** data file, **save** a data file, set your **printer type**, set your **printer style**, or return to the **main menu**. When loading a file, choose the files with the extension of .LIN for linear. You can only **print data** tables using the print function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

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

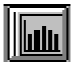
Under **Analysis**, you can choose **Error**, **NMTBA**, **NMTBA with Zero Shift, ISO-230-2(1988), ISO-230-2(1997), VDI 3441**, **ASME B5.54, and ASME B5.57,** for different types of data manipulation. After choosing **Error**, you will be given a choice on what you wish to see, **Runs #1-7**, and **forward** 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.

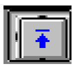


Save a data file.

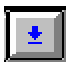


Graph a data file (After graphing, you may also change the scaling of the graph by checking X on adjust grid).

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.

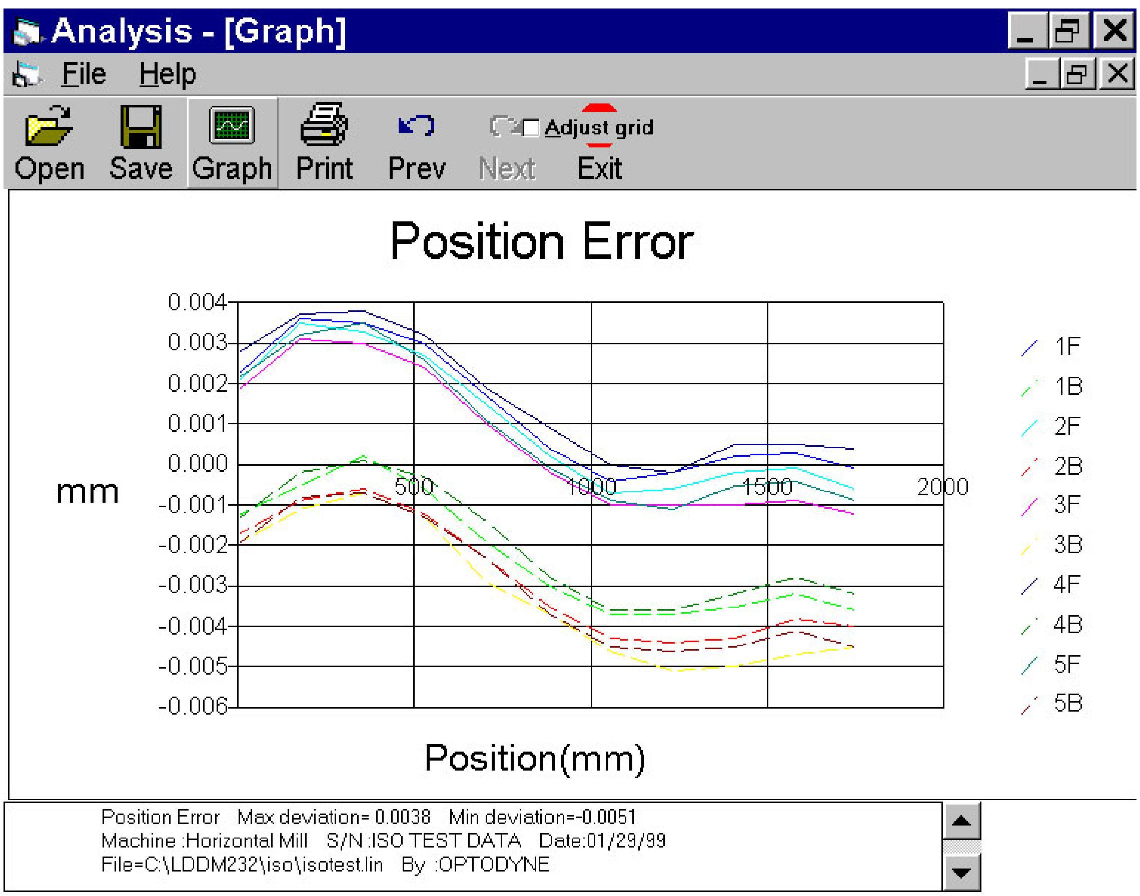


FIG.7-15 LINEAR MEASUREMENT DATA PLOT
(INDIVIDUAL PLOTS TOGETHER)

7.6.5 Angular Measurement

Using a dual-beam laser head(MCV-2002) or two laser heads(MCV-5000), the pitch and yaw angular errors of the machine can be measured. For a single laser head(MCV-500), if the machine is repeatable, the angular errors can be determine by 2 or 3 separate measurements along the same axis but at different Abbe offsets. [C. Wang & G. Liotto, “A theoretical analysis of a body diagonal displacement measurement and sequential step diagonal measurement” in proceedings of the LAMDAMAP Conference, Huddersfield, England, July 4, 2003.]

For example, for 3 measurements along X-axis at 3 different locations with known Abbe offsets m1, p1; m2, p2; and m3, p3, the measured results, DX1, DX2 and DX3 can be expressed as the followings.

DX1 = Dx(x) + m1*Ay(x) + p1*Az(x)
DX2 = Dx(x) + m2*Ay(x) + p2*Az(x)
DX3 = Dx(x) + m3*Ay(x) + p3*Az(x)

Where Dx(x) is the linear displacement error, Ay(x) and Az(x) are pitch and yaw angular errors respectively.

There are 3 sets of data DX1, DX2 and DX3 and 3 unknowns Dx(x), Ay(x) and Az(x). The solutions are,

Ay(x) = [(m3-m1)*(DX2-DX1)-(m2-m1)*(DX3-DX1)] / [(m3-m1)*(p2-P1) -(m2-m1)*(p3-p1)]
Az(x) = [(p3-p1)*(DX2-DX1)-(p2-p1)*(DX3-DX1)] / [(m3-m1)*(p2-P1) -(m2-m1)*(p3-p1)]
Dx(x) = DX1*(m2*p3-m3*p2)+DX2*(m3*p1-m1*p3)+DX3*(m1*p2 -m2*p1) / [(m3-m1)*(p2-p1)-(m2-m1)-(p3-p1)].

Similarly for the Y- and Z-axis, Ax(y), Az(y), Dy(y), Ax(z), Ay(z), and Dz(z) can all be determined.

Of course, the accuracy of the measurement is limited by the repeatabililty of the machine and the Abbe offset. For example, for a machine with repeatability of 0.0001”(2.5 µm) and the Abbe offset of 20”(500 mm), the accuracy of the angular measurement is 0.0001/20 = 0.000005 rad, or 1 arcsec which is good enough for most of the machines.

Same as a linear displacement measurement of an axis, here the position of the laser head (or laser beam) is recorded in the setup screen as shown in Fig. 7-16.

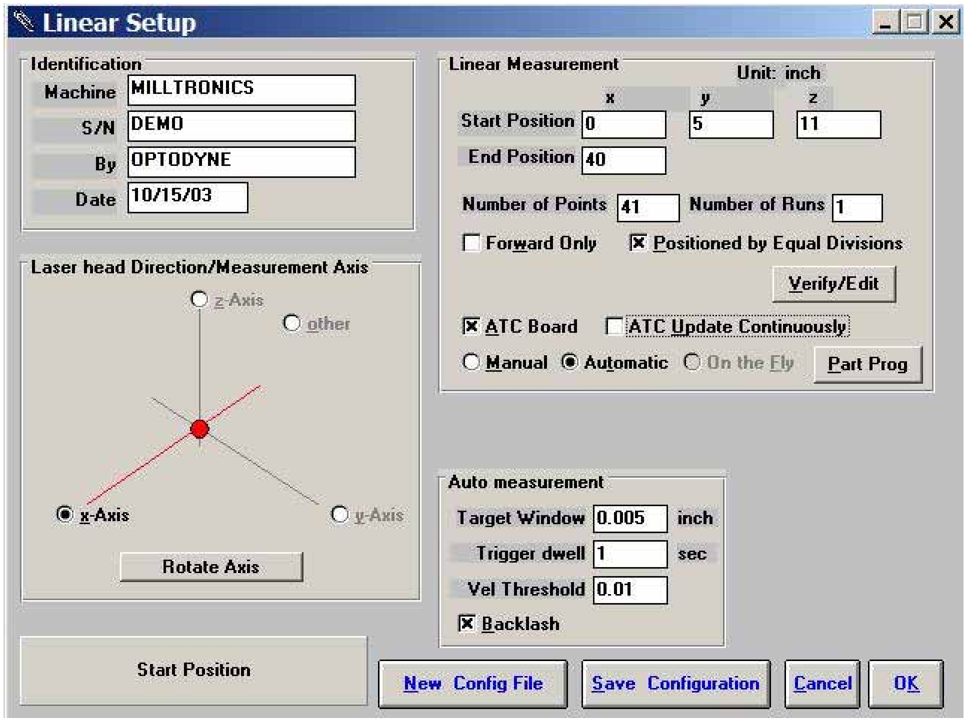


Fig. 7-16, A popup screen for user to enter the location of the laser beam.

Pushing the Part program button on the set up screen, you can have the ISO part program to move the machine by sub sequential steps in order to measure positioning error. Load the program in the CNC .
Aligning the laser beam parallel to the X axis movement. Take the first measurement positioning the machine at starting point and collect it pushing START button on the PC screen. Start the positioning program, the machine will move to the next point and stops for few seconds, the point will be collected automatically, the same as the sub sequential points. At the end of the measurement save the data .

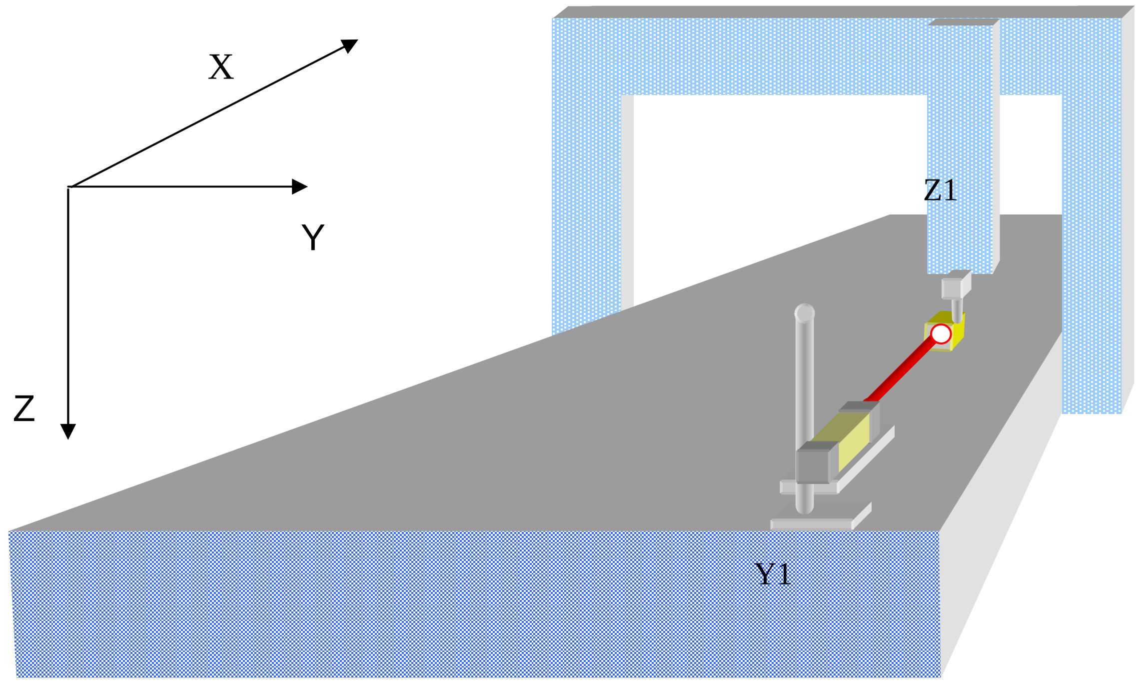


Fig 7-17 Example of laser position at the first measurement

Then relocate the laser head in a new location with different Abbe offset in in the horizontal direction.

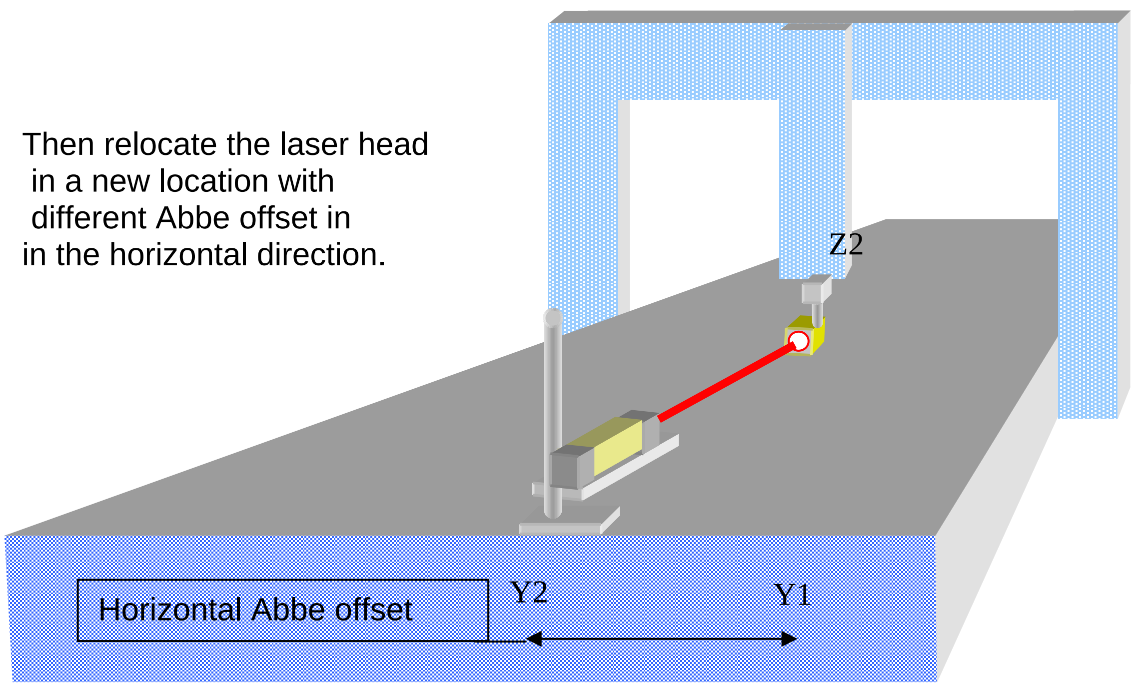


Fig 7-18 Example of laser position at the second measurement

and again another location with different Abbe offset in the vertical direction.

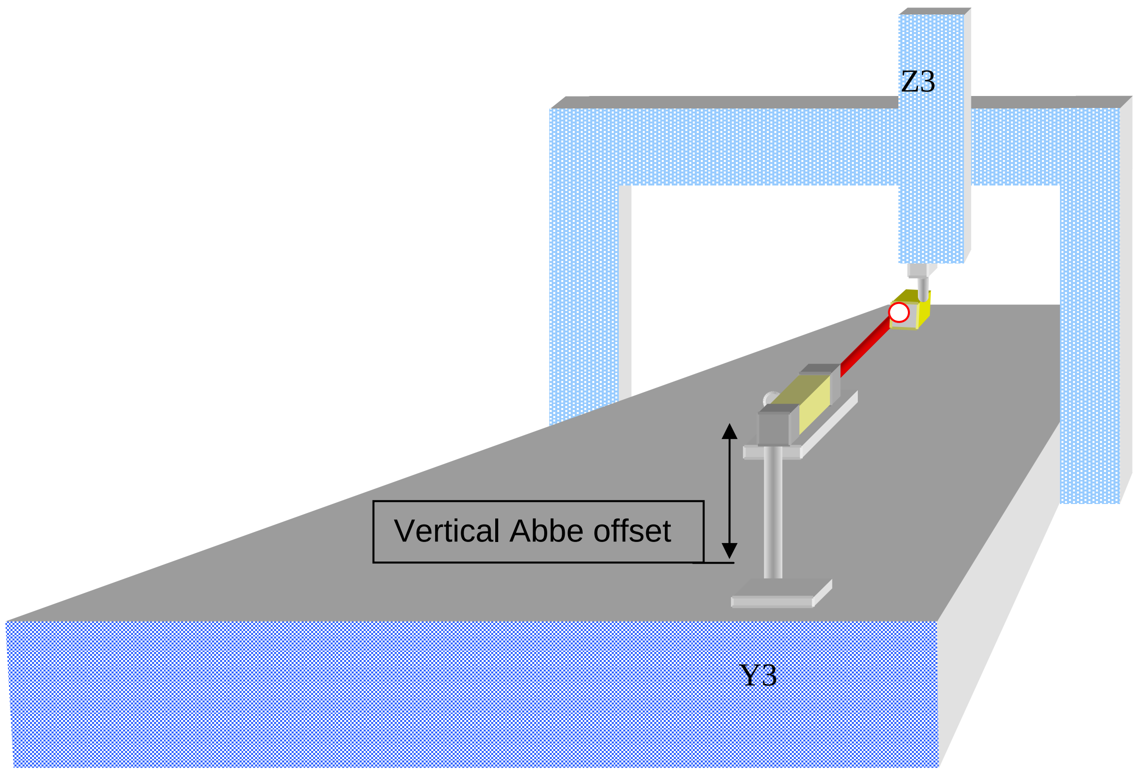


Fig 7-19 Example of laser position at the third measurement

A software is available to calculate the pitch & yaw angular errors based on three linear displacement data. Click on "Data Analysis", "File" and "Convert 3 Linear Files", a popup screen as shown in Fig. 7-20 , allow user to enter 3 linear files & coordinates.

Enter 3 linear files of the same axis, same starting and ending position and same number of points. The first coordinate and second coordinate are the two Abbe offsets at vertical and horizontal directions respectively. User needs to enter the output file names. The first file is equivalent to the linear displacement measured at the reference (both Abbe offsets are zero). The second file is equivalent to pitch angular errors with an offset equal to the vertical distance from the reference (user input the value). The third file is equivalent to yaw angular errors with an offset equal to the horizontal distance from the reference (user input the value). The angular errors can be analyzed by click on the "Straightness" button or open the straightness file.

For example, 3 linear displacement errors were measured on the X-axis with different Abbe offsets. #1 was measured at z=z1, y=y1, #2 was measured at z=z2, y=y2 and #3 was measured at z=z3, y=y3. Enter these 3 files with the values of 1st and 2nd coordinates. Enter the output file names and a vertical offset value
(typical 4" to 20" or 100mm to 500mm) and a horizontal offset value. The file name R.lin is the linear displacement error at the reference line. The file name V.str is the pitch angular error and file name H.str is the yaw angular error.

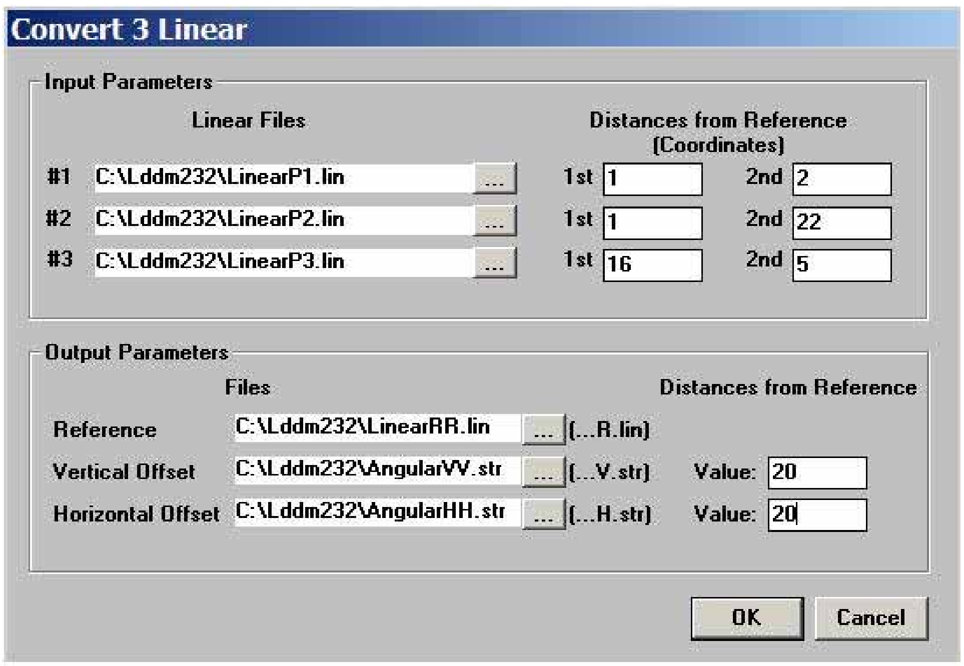


Fig. 7-20, A Popup Screen for User to Enter 3 Linear Displacement Files with Different Abbe Offsets and 3 Output File Names with 2 Different Abbe Offsets

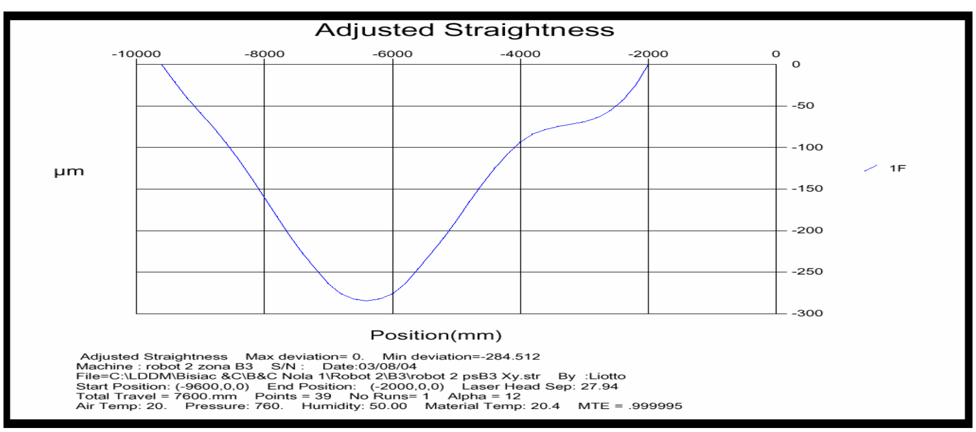


Fig. 7-21, A vertical straightness analyzed and calculated by LDDM software

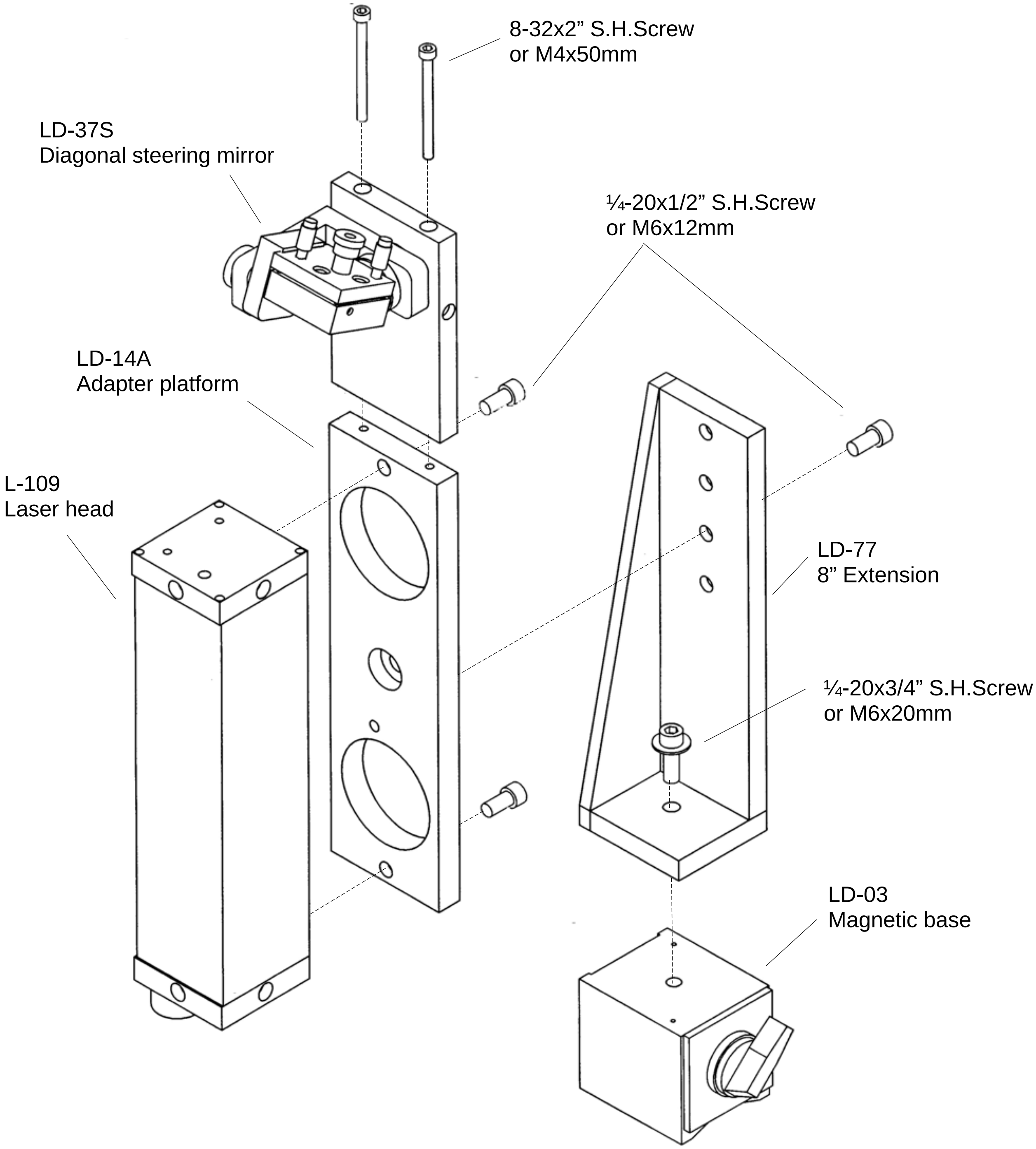


FIG 7-22 8” EXTENSION (LD-77) SET UP

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. Set up the desired configuration or load an existing configuration.

6. Move the machine to the starting point.

7. Reset the LDDM™ reading, click the start button. 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 click the taken button 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 (at least 2 x target window) 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 need to save the data. You may click the analysis button to analyze the data now or save the data now and to analyze the data later.

7.9 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.

7.9.1 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.

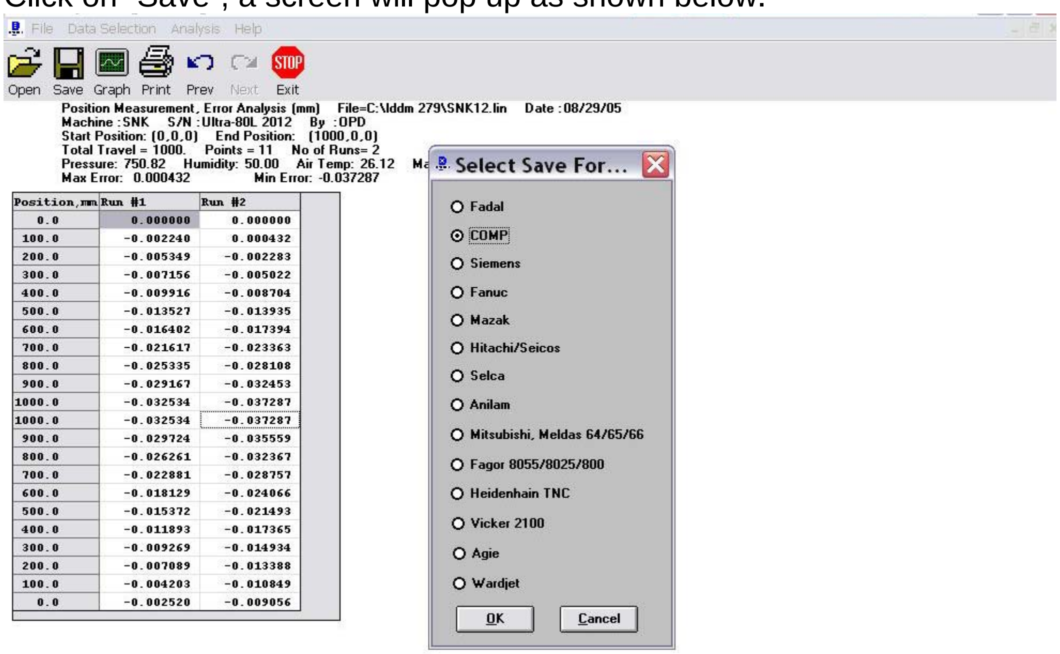


Fig. 7-23 Compensation File Selection Screen

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.

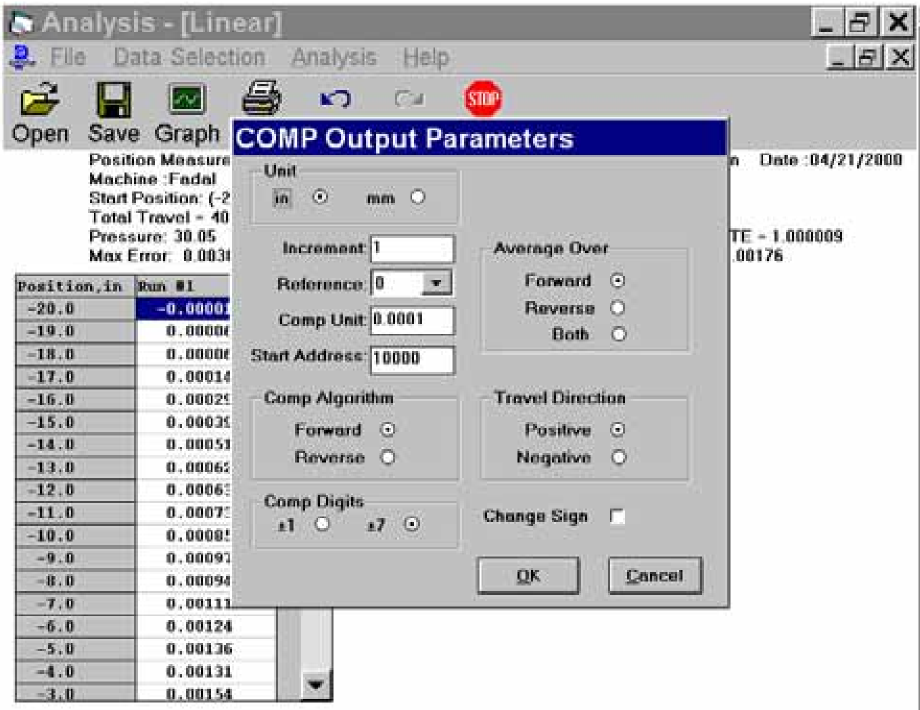


Fig. 7-24 Compensation Input Parameter Screen

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.

```
         Optodyne Linear Error Compensation Table

LDDM file: C:\LDDM232\fadal1Y.lin
First Comp Pt:      0.00       Data:          Avg All Forward Runs
Last Comp Pt:      20.00       Unit:                            in
Interval:          1.000       Travel Direction:          Negative
Comp Unit:        0.0001       Table Start Address:          10000
                               Comp Algorithm:             Forward

Machine: Fadal  Serial#: 1234  Axis: Y  04/21/2000
MTmp: 66.72162  ATmp: 70.32162  Alpha: 6.67  Baro: 30.05  Humid: 50.0
AxisLen: 20.00  #pts: 21  Runs: 1  MTE: 1  Run by: optodyne
Reference: 0.0000  # Cmp Pts: 21  AvResEr: 0.0000295  MaxResEr: 0.0000498
```

Target	LDDM Avg	Addr	CmpPos	Error	Cmp	CumCmp	CmpdVal
0.00	-0.0000055	10021	0.00	0.0000000	0	0.00000	0.0000000
1.00	0.0000500	10020	1.00	0.0000555	-1	-0.00010	-0.0000445
2.00	0.0000450	10019	2.00	0.0000505	0	-0.00010	-0.0000495
3.00	0.0001443	10018	3.00	0.0001498	0	-0.00010	0.0000498
4.00	0.0002889	10017	4.00	0.0002944	-2	-0.00030	-0.0000056
5.00	0.0003450	10016	5.00	0.0003505	-1	-0.00040	-0.0000495
6.00	0.0004560	10015	6.00	0.0004615	-1	-0.00050	-0.0000385
7.00	0.0005640	10014	7.00	0.0005695	-1	-0.00060	-0.0000305
8.00	0.0006277	10013	8.00	0.0006332	0	-0.00060	0.0000332
9.00	0.0006540	10012	9.00	0.0006595	-1	-0.00070	-0.0000405
10.00	0.0007650	10011	10.00	0.0007705	-1	-0.00080	-0.0000295
11.00	0.0008760	10010	11.00	0.0008815	-1	-0.00090	-0.0000185
12.00	0.0009442	10009	12.00	0.0009497	0	-0.00090	0.0000497
13.00	0.0009980	10008	13.00	0.0010035	-1	-0.00100	0.0000035
14.00	0.0011230	10007	14.00	0.0011285	-1	-0.00110	0.0000285
15.00	0.0012350	10006	15.00	0.0012405	-1	-0.00120	0.0000405
16.00	0.0013060	10005	16.00	0.0013115	-1	-0.00130	0.0000115
17.00	0.0013940	10004	17.00	0.0013995	-1	-0.00140	-0.0000005
18.00	0.0014560	10003	18.00	0.0014615	-1	-0.00150	-0.0000385
19.00	0.0015120	10002	19.00	0.0015175	0	-0.00150	0.0000175
20.00	0.0016549	10001	20.00	0.0016604	-2	-0.00170	-0.0000396

The machine information and parameters are shown in the first few lines.

The first column is the target position from data file and the second column is the averaged errors calculated from data file.

The third column is the address number.

The forth column is the comp position, determined by the comp increment for the controller.

The fifth column is the positioning error calculated at the comp position.

The sixth column is the differential comp values. For Siemens controller, it is limited to ±1 and for Fanuc controller, it is limited to ±7.

The seventh column is the absolute comp value with the least increment of comp unit.

The eighth column is the remaining errore after the compensation.

The AvResEr is the average positioning error after compensation, and the MaxResEr is the maximum positioning error after compensation.

Please consult the controller manual to determine the Pre amble, the prefix, the start address, the reference position, increment or absolute, comp algorithm, travel direction, comp interval and unit. We can provide a customer button to generate the comp file per your specification.

8.0 Circular Test (Laser/Ballbar)

8.1 Introduction

The circular test accessories (LB-500) are designed for circular test with an MCV-500 laser system. The single aperture MCV-500 laser system is based on laser dopplermetry. 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-500 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-500 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 10,000 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.

8.2 Hardware Required

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

a. Single Aperture Laser Head	L-109
b. Processor Module with RS-232 Interface	P-108D
c. 6” Flat-mirror w/steering	LD-71
d. Metrology/Analysis Program with Circular Path	W-500/w-500lb
e. Optical Adapter	LD-69
f. Magnetic Base	LD-03
g. Adapter Platform	LD-14D
h. 12 ft Cable Set	LD-21L
i. PC Card and Cable	IPC5-1000
j. Notebook PC	Not supplied

Option, 2-channel simultaneous data collection:

a. Single Aperture Laser Head (Quantity 2)	L-109
b. Processor Module with RS-232 Interface (2-channel)	P-108D
c. 6" Flat-mirror w/steering (Quantity 2)	LD-71
d. Metrology/Analysis Program with Circular Path	W-500/w-500lb
e. Optical Adapter (Quantity 2)	LD-69
f. Magnetic Base (Quantity 2)	LD-03
g. Adapter Platform (Quantity 2)	LD-14D
h. 12 ft Cable Set (Quantity 2)	LD-21L
i. PC Card and Cable (Quantity 2)	IPC5-1000
j. Notebook PC	Not supplied

FIG. 8-1 HARDWARE FOR LASER/BALLBAR

FIG. 8-2 LASER/BALLBAR CIRCULAR TEST SETUP

8.3 Operating Specifications

<u>Accuracy</u>:	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.
<u>Resolution</u>:	Standard resolution is 1 μin (0.01 μm). Option (0.001μm).
<u>Maximum Velocity</u>:	144 inch/sec (3600 mm/sec)
<u>Measurement Range</u>:	Up to 50 ft (15 m)
<u>Temperature Range</u>:	60°F to 90°F (15.5°C to 32°C) Option 40°F to 100°F (5°C to 37°C)

8.4 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)

8.5 Installation and Alignment

8.5.1 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.

8.5.2 Installation

8.5.2.1 Set up LDDM Program

See Section 7.5.2.1.

8.5.2.2 Starting LDDM Program

See Section 7.5.2.2.

8.5.2.3 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 (MCV-500). 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.

8.5.2.4 Setup Laser head and Flat-mirror target

Attach the optical adapter to the front of the laser head (Fig.8-3). Align the output beam by move the optical adapter up/down and left/right such that the output laser beam is pointing to the same position with and without the optical adapter. Tighten the two screws on the side. Mount the laser head with the optical adapter on the bed with a magnetic holder and the flat-mirror on the spindle directly or with a magnetic holder, as shown in Fig.8-4. 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.8.5) 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.

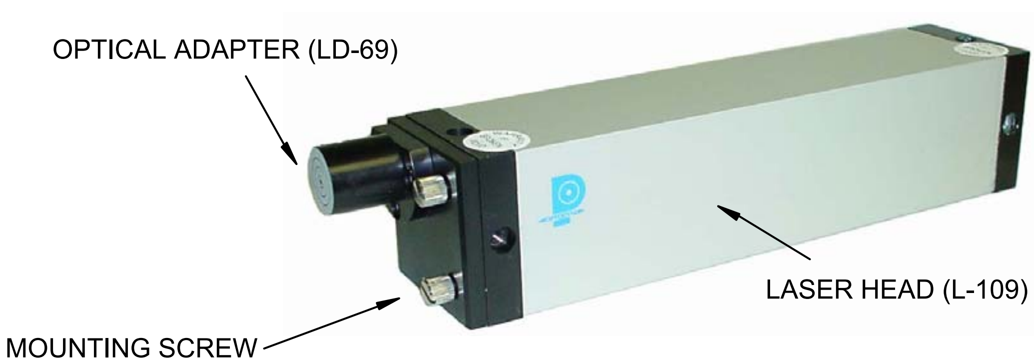


FIG. 8-3 LASER HEAD WITH OPTICAL ADAPTER

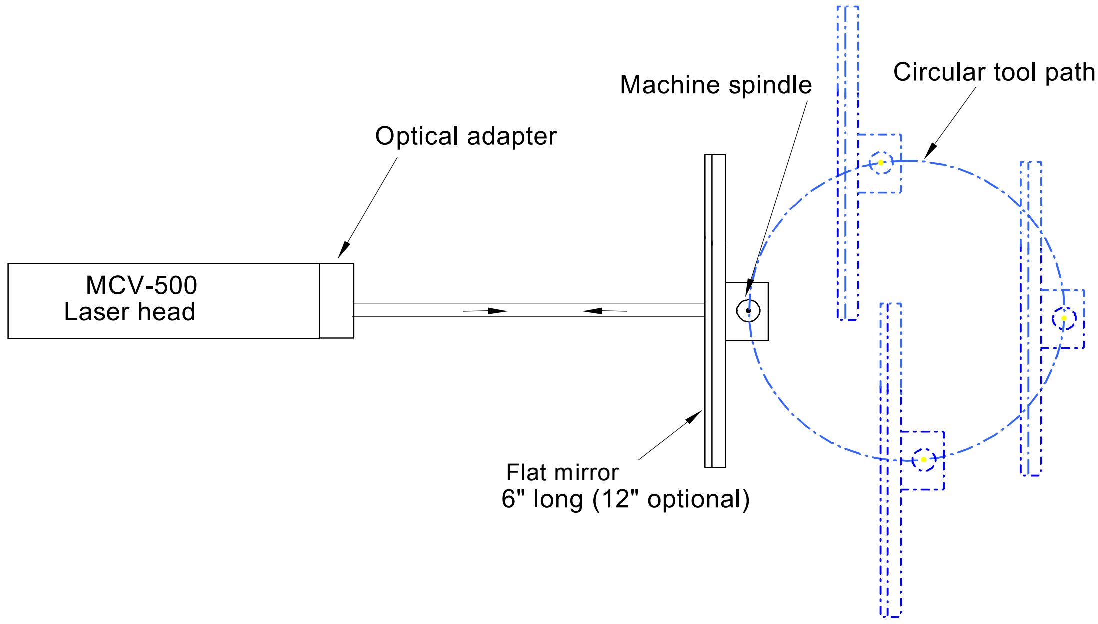


FIG. 8-4   SCHEMATIC OF LASER CIRCULAR TEST

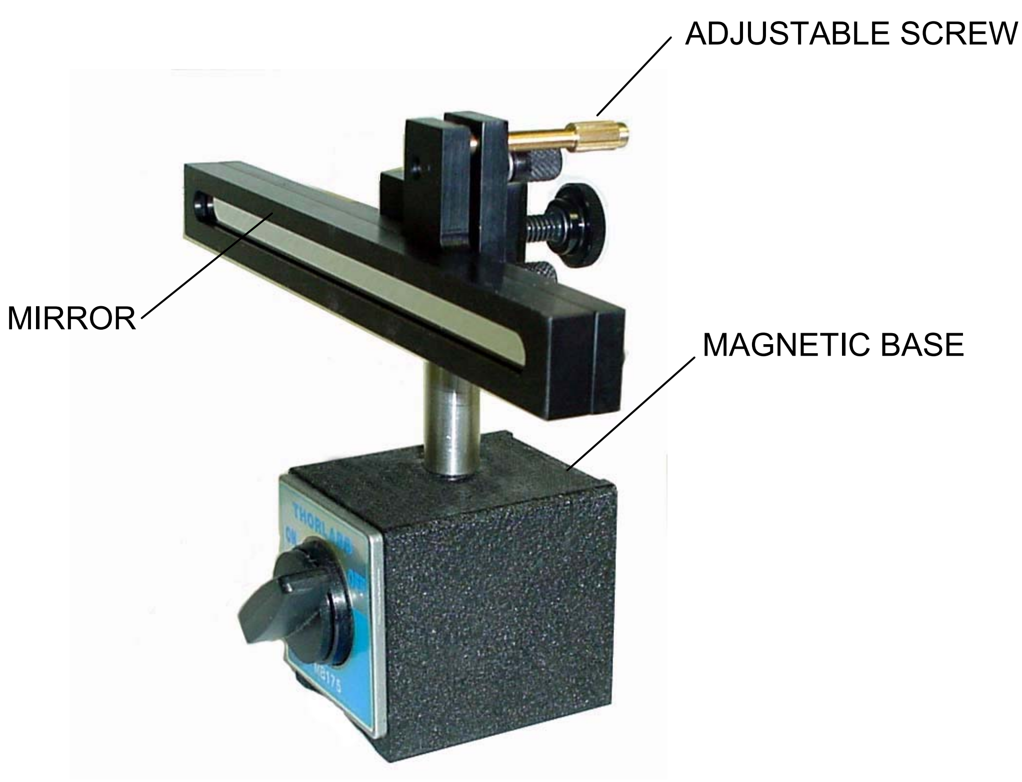


FIG. 8-5 FLAT-MIRROR TARGET WITH TWO ADJUSTABLE SCREWS

8.5.3 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.

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

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.

8.6 Software Description

8.6.1 General Description

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

8.6.2 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.

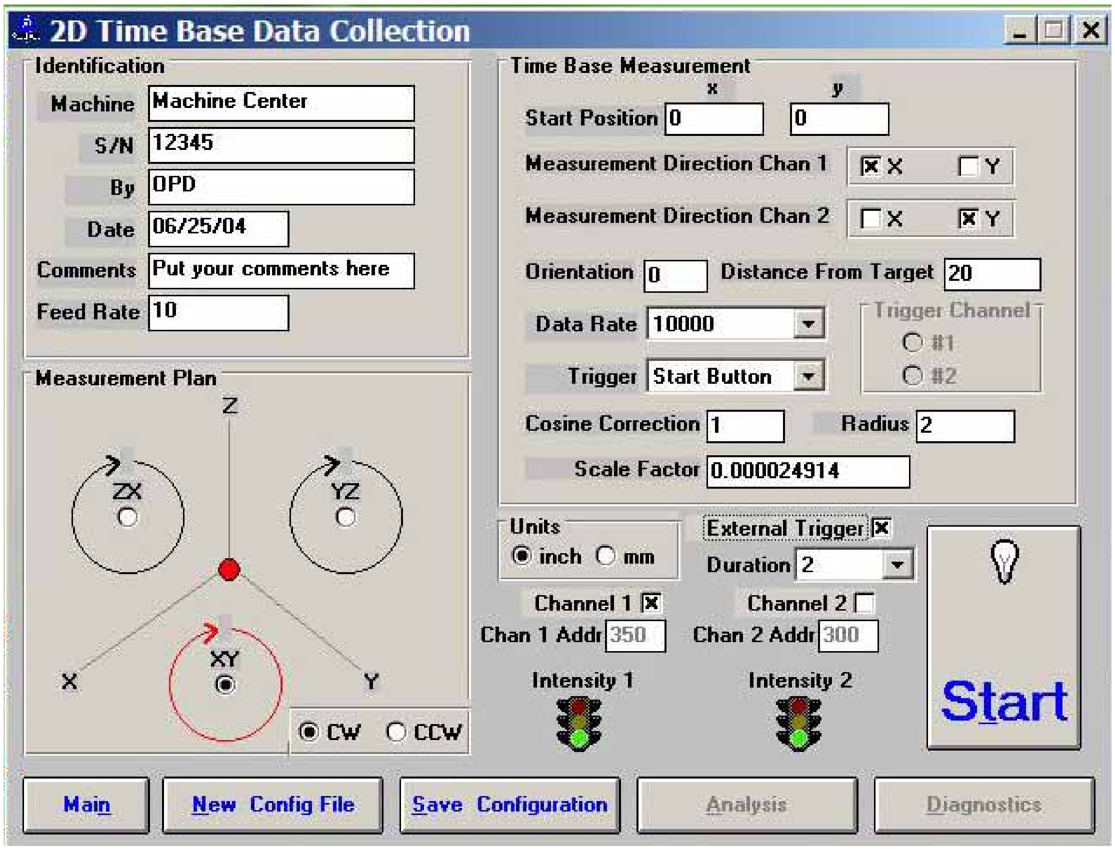


FIG. 8-6 2D TIME BASE DATA COLLECTION SCREEN

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 8.5.3). Trigger mode is "start button" only. The displacement or velocity trigger will be added later. Cosine correction is 1 for normal operation. It is 2cos(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.

8.6.3 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 8-7.

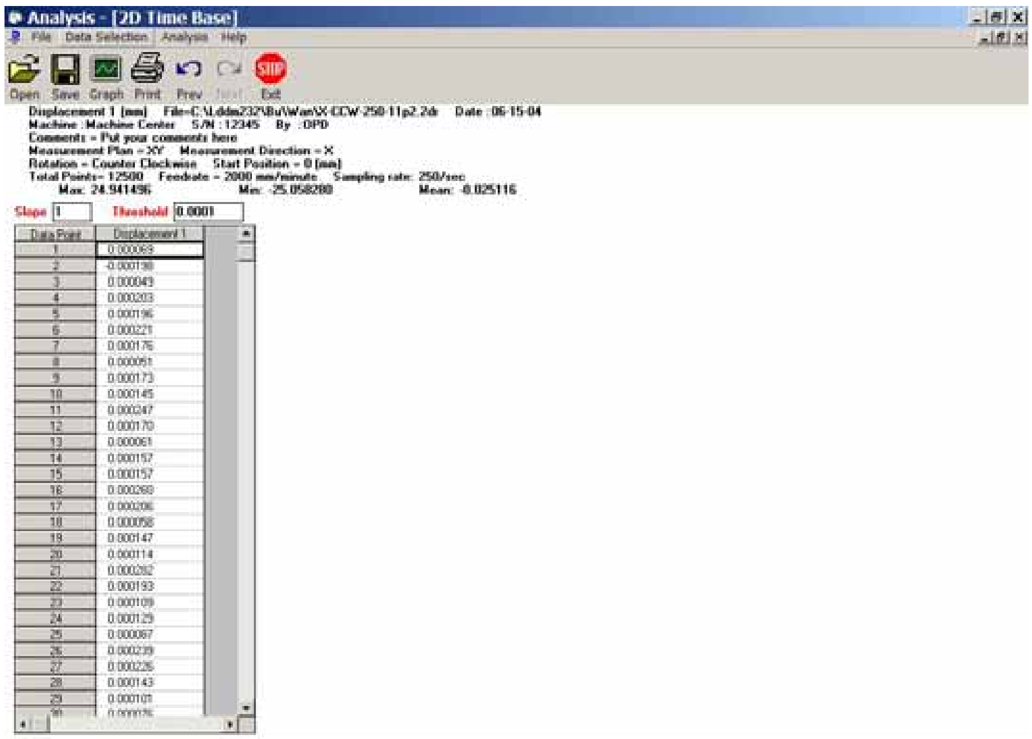


FIG.8-7 THE ANALYSIS SCREEN WITH DISPLACEMENT DATA

The parameters “Slope” and “Threshold” are used for the generation of 2dd files. The default values are slope = 1 (integer) and Threshold = 0.0001. For high data rate or noisy data, you may increase the slope or threashold.

After the displacement values are displayed, click on the “graph” to plot the displacement. A typical plot of the displacement is shown in Fig 8-8.

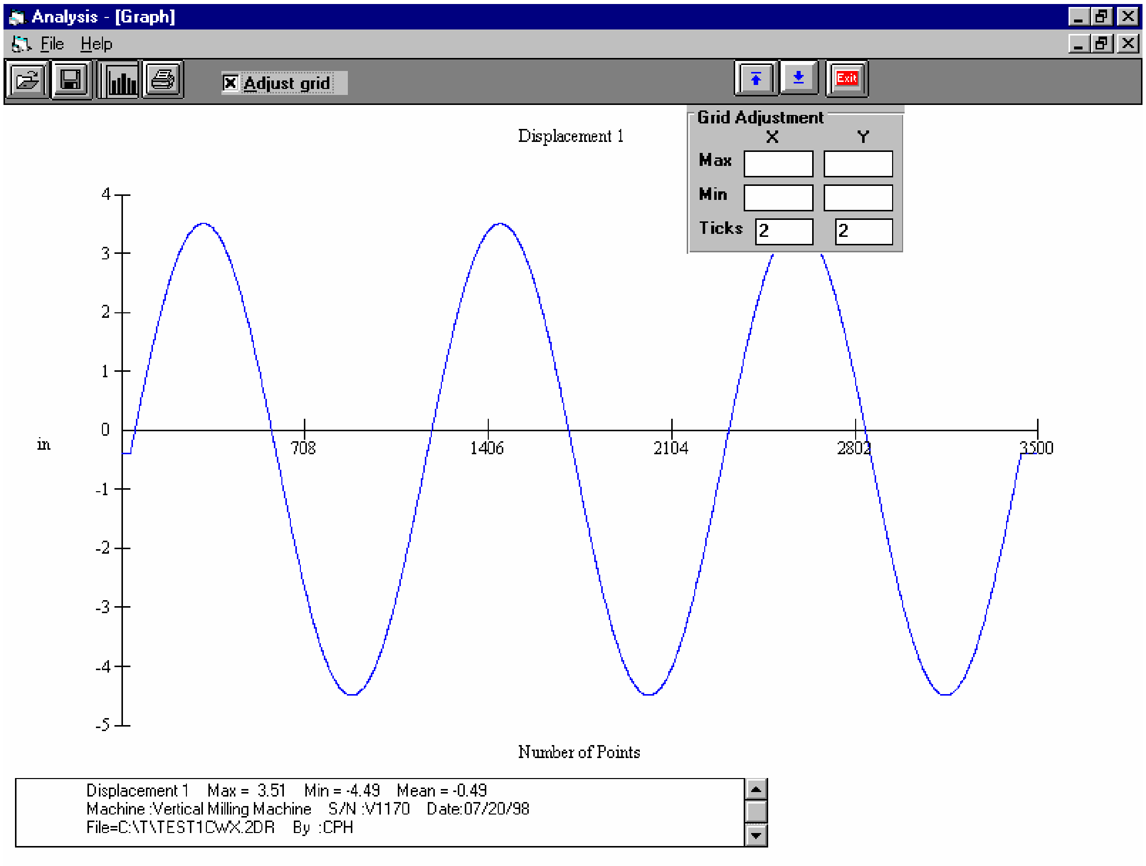


FIG. 8-8 A TYPICAL PLOT ON DISPLACEMENT DATA

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 ¼ 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.

8.6.4 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. 8-9.

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.

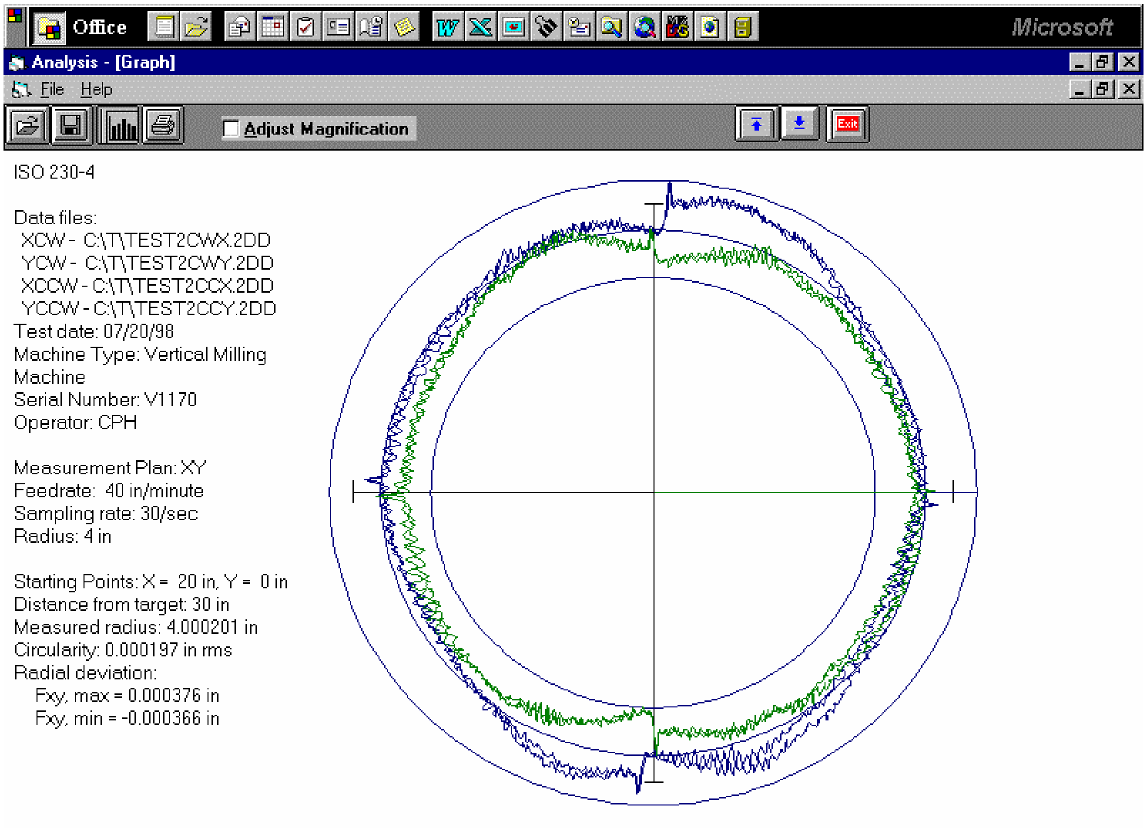


FIG. 8-9 A TYPICAL POLAR PLOT OF THE CIRCULAR PATH

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 Fxy,max and the radius of the smallest circle is the measured radius minus the Fxy,min . Or the distance between the largest circle and smallest circle is equal to Fxy,max – Fxy,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 8-10.

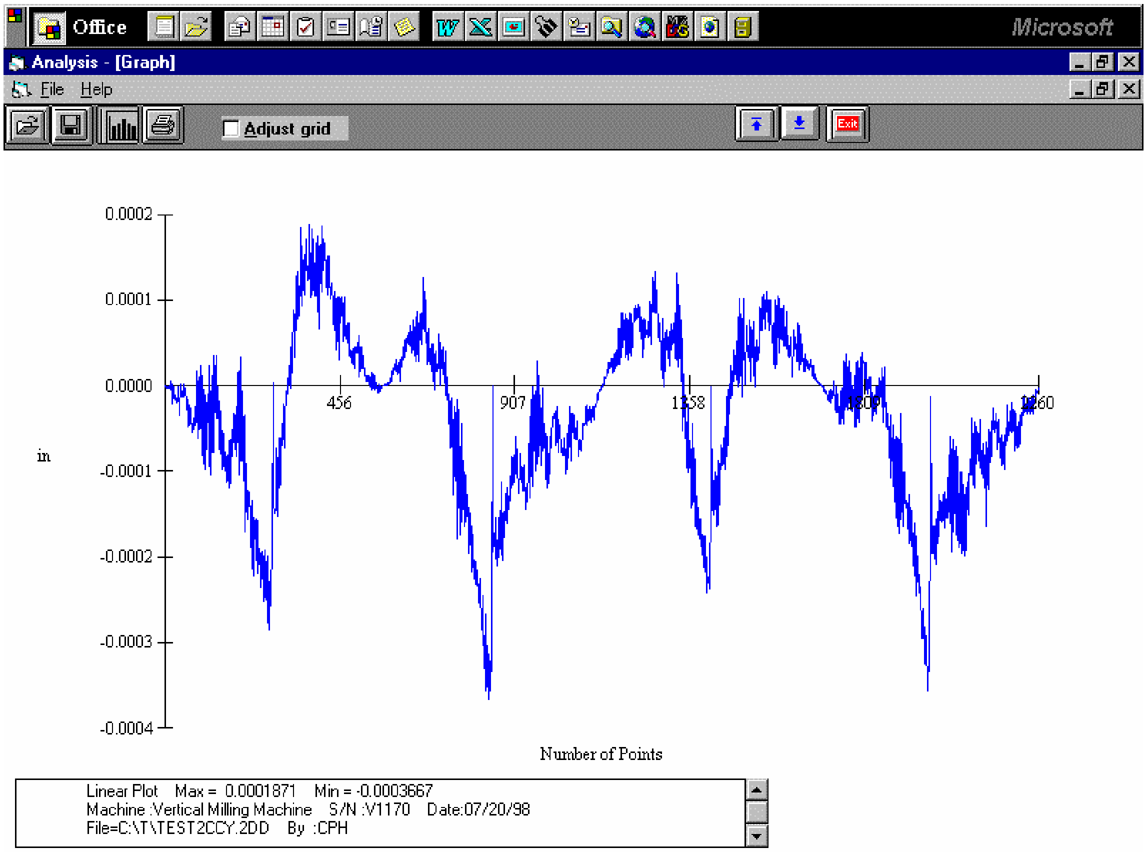


FIG. 8-10 A TYPICAL LINEAR PLOT OF THE CIRCULAR PATH

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.

8.6.5 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.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.

A typical polar plot similar to Fig.8-9, but using the .rtb data file and the Polarcheck software, is shown in Fig.8-11.

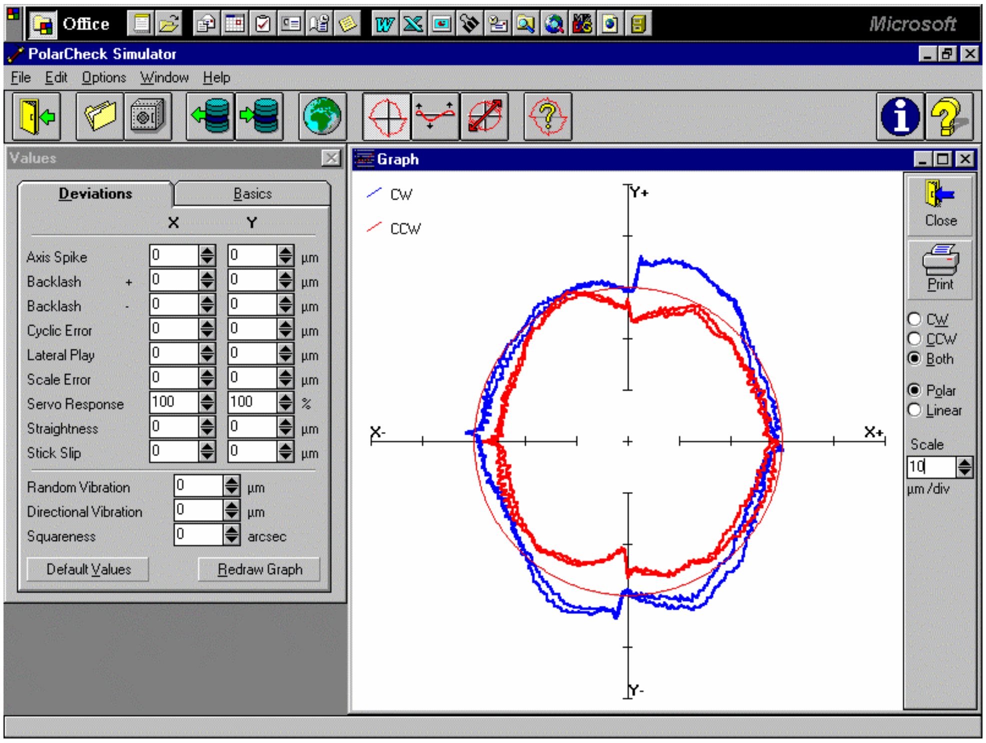


Fig. 8-11   A TYPICAL POLAR PLOT USING POLARCHECK

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

8.6.6 “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.

8.6.7 Velocity, acceleration and other measurements

As shown in section 8.6.3, 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.

8.6.8 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. 8-12. These velocity notches may cause non-uniform cutting and effect the surface finish of the part.

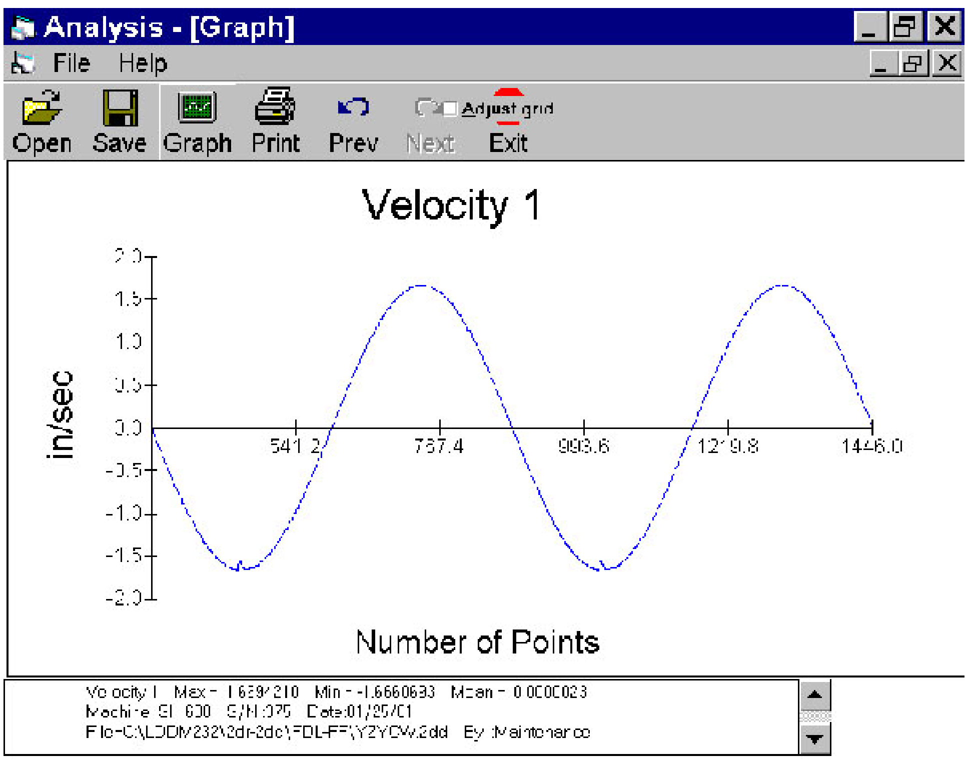


Fig. 8-12 A Plot of Velocity Profile without Feedforward. There are Notches near the Maximum Velocity in the Negative Direction.

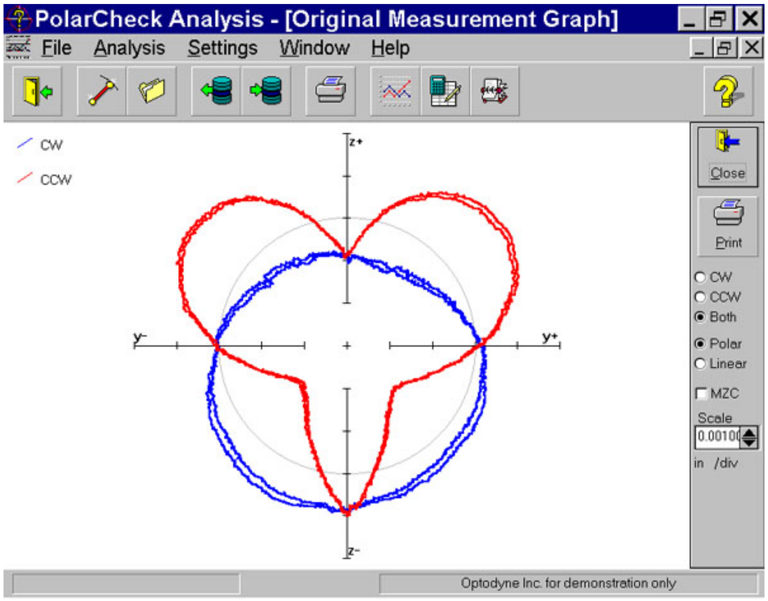


Fig. 8-13 A Polar Plot of the Circular Contouring Error without Feedforward

The large non-roundness shown in Fig. 8-13 is caused by the velocity notches. Once the feedforward function is turned-on, the velocity notchs in Fig. 8-12 are removed and the polar plot shown in Fig. 8-14. The non-roundness is reduced considerably.

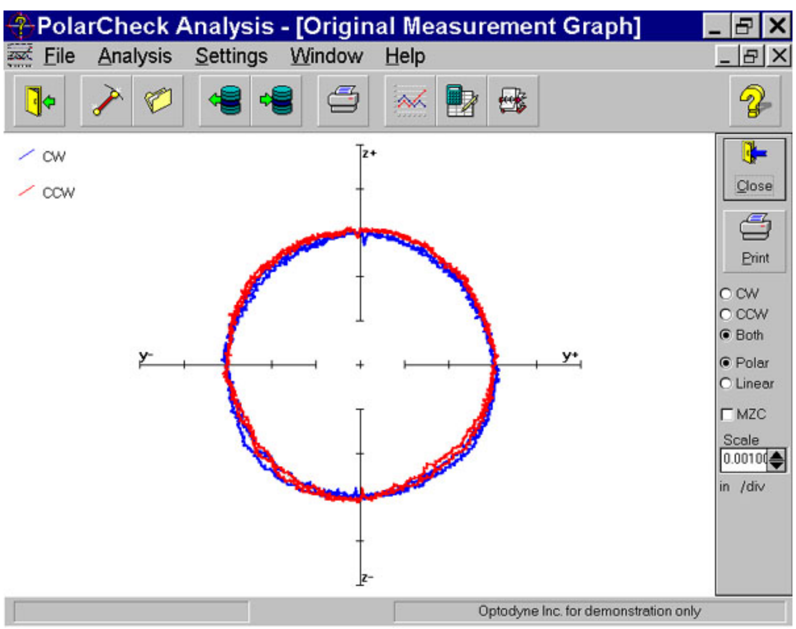


Fig. 8-14 A Polar Plot of the Circular Contouring Error with Feedforward

For some controllers, there is no velocity control, the velocity profile looks like triangular shape (see Fig. 8-15) instead of the sinusoidal shape. The polar plot, (see Fig. 8-16) shown large loop and the non-roundness is excessive large. This is because in the data processing,

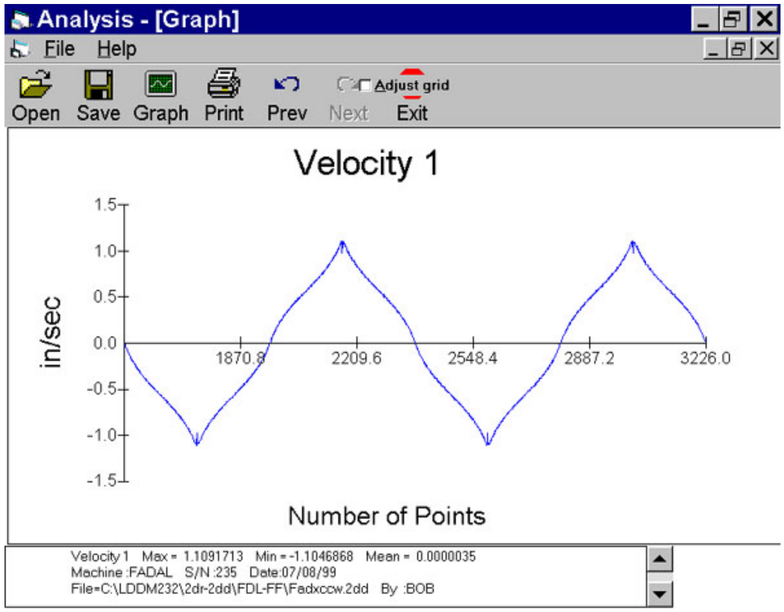


Fig. 8-15 A Plot of Velocity Profile without Velocity Feedback

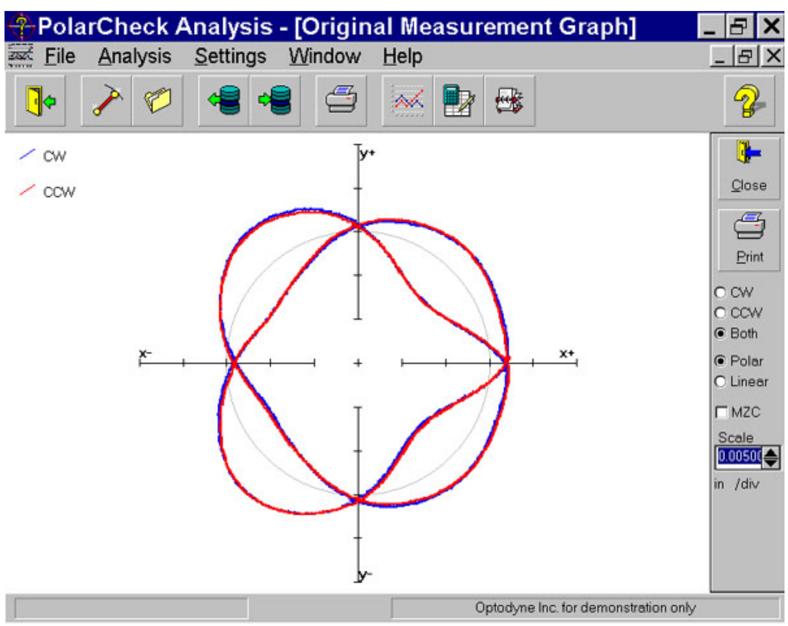


Fig. 8-16 A Polar Plot of the Circular Contouring Error without the Synchronized Data Processing

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. 8-17.

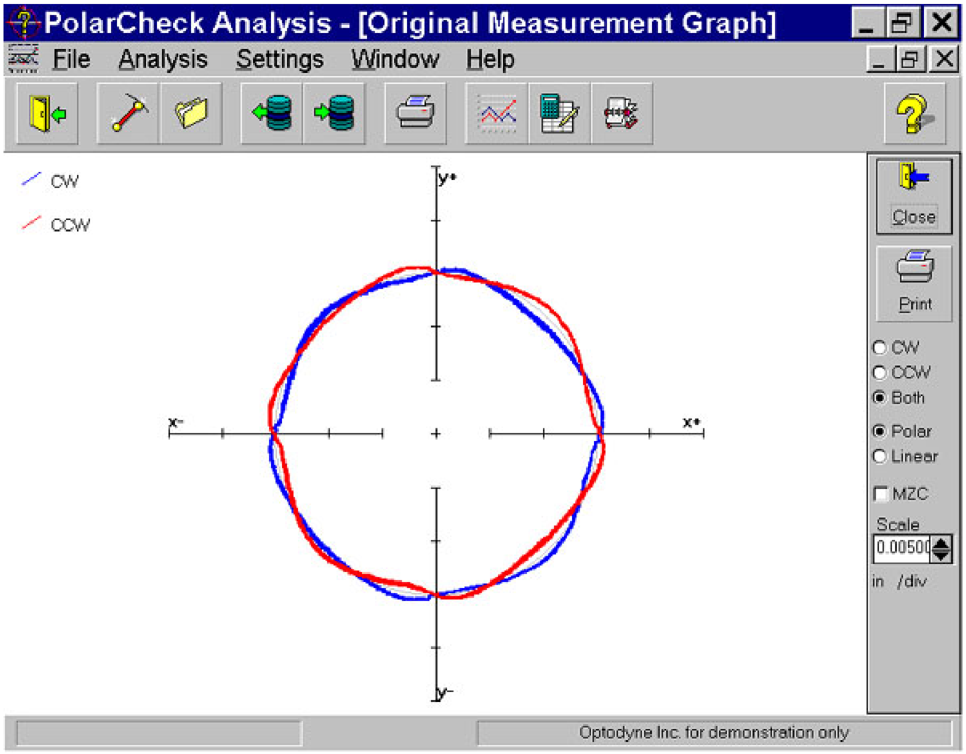


Fig. 8-17 A Polar Plot of the Circular Contouring Error with the Synchronized Data Processing

8.7 Accuracy and Error Sources

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

8.7.2 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.

8.7.3 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.

8.8 Taking a Measurement

8.8.1 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.

8.8.2 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.

8.8.3 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 in, F=40 in/min, then $\frac{100}{18} < S \leq \frac{1000}{18}$ or select the data rate between 4 to 60.

5. Trigger—start button only
Cosine Correction—Single pass = 1
Double pass = 2cosθ

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

Radius of circular path—should be less than ½ 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.

8.8.4 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 ¼ cycle data points, starting before a first maximum and ending at ¼ cycle or more after the third maximum. (For 1 cycle, select the ending point ¼ 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.

8.9 Diagnostics

8.9.1 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.

8.9.2 Common errors

1. Backlash step:
   A step along one axis indicates lost motion from backlash or play. An outward step may 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 tilted 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.

8.9.3 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.

9.0 Vector Measurement or Sequential Diagonal Measurement

9.1 Introduction

The performance or accuracy of a CNC machine tool or a coordinate measuring machine (CMM) is determined by the linear displacement errors, straightness errors, squareness errors, angular errors and non-rigid body errors. A complete measurement of these errors is very complex and time consuming. The body diagonal measurements have been recommended for a quick check on the volumetric accuracy. However, there is not enough information to identify the error sources.

The characterization of a machine's movement is very complex. For each axis of motion, there are 6 degrees of freedom, linear in X, straightness in Y, and Z-direction, pitch, yaw and roll angles. For a 3-axis machine, there are 18 errors plus 3 for squareness, a total of 21 errors. The machine accuracy can be improved by measuring all these errors and then to compensate these errors, providing that the machine is repeatable.

The vector measurement technique or the sequential step diagonal measurement technique is developed by Optodyne (Patent Pending). It can measure all these volumetric errors by using a Laser Doppler Displacement Meter (LDDM) system.

The laser diagonal measurement method has been recommended by many standards such as the ASME B5.54, and ISO 230-6, for a quick check of the volumetric performance of machine tools. However, the conventional laser diagonals require measurements moving all three axes simultaneously along a body diagonal and collecting data at each preset increment. It is well known that any of the 21 errors (3 linear position errors, 6 straightness errors, 9 angular errors and 3 squareness errors) will show up in the diagonal measurement. Hence it is a good method to check the inaccuracy of a machine tool. However, there is not enough information to identify the error sources.

The new vector method or sequential step diagonal measurement method, moves the X, Y, and Z-axis in sequence and collects data after each axis is moved. Hence the position errors due to the movement of each axis can be separated. The collected data can be processed as deviations measured in the body diagonal direction due to X-axis movement, Y-axis movement and Z-axis movement respectively. Hence, the linear errors and straightness errors of all three axes can be determined.

For conventional laser diagonal measurement, the displacement is a straight line along the body diagonal. However, for the sequential laser diagonal measurement, the displacement is along the X-axis, then along the Y-axis, and then along the Z-axis. The trajectory of the target or retroreflector is not a straight line, and the lateral movement is rather large. Hence conventional laser interferometers will be out of alignment with such large lateral displacement.

The single aperture MCV-500 laser system is based on the laser Dopplermetry. Hence, a flat-mirror can be used as a target. It is noted that with a flat mirror as the target, any displacement parallel to the flat-mirror will not displace the return laser beam and will not effect the measurement. Hence the displacement along the laser beam direction is measured.

For a large aspect ratio machine, the working volume can be divided into several volumes. The vector measurement can be performed in each volume and the data stitched together. For example, for a machine working volume of 240 in x 80 in x 60 in, it can be divided into 3 work volumes of 80 in x 80 in x 60 in.

9.2 Hardware Required

The basic hardware and software required for the vector measurement are listed below:

a. Single Aperture Laser Head	L-109
b. Processor Module with RS-232 Interface	P-108D
c. Automatic Temperature Compensation Probes	IATCP
d. 3"x4" Flat-mirror w/steering	LD-71S
e. MCV-500 Windows Program with Sequential Diagonal Data Collection and Processing	W-500/W-500SD
f. Optical Adapter	LD-69
g. Magnetic Base	LD-03
h. Adapter Platform	LD-14D
i. 12 ft Cable Set	LD-21L
j. Cross Link	LD-44
k. Diagonal Steering Mirror	LD-37S
l. Notebook PC	Not supplied

Some of the hardware is shown in Fig.9-1.

FIG. 9-1 VECTOR MEASUREMENT HARDWARE

9.3 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 µin (0.01 µm). Option(0.001 µm)
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) Option 40°F to 100°F or (5°C to 37°C)

9.4 Reference Material

Appendix H, ATC and Calibration

Appendix J, Accuracy

C. P. Wang, “Laser Vector Measurement Technique for the Determination and Compensation of Volumetric Position Errors, Part I: Basic Theory,” Rev. Sci. Instrum. Vol. 71, pp. 3933-3937 (October 2000).

John Janeczko, Bob Griffin and C. P. Wang, “Laser Vector Measurement Tequenique for the Determination and Compensation of Volumetric Position Errors, Part II: Experimental Verification,” Rev. Sci. Instrum. Vol. 71, pp. 3938-3941 (October 2000).

9.5 Installation and Alignment

9.5.1 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 the machine bed and the flat-mirror on the spindle. If the machine bed is too small, mount the laser head on an extension bar tight to the machine bed. Never use a tripod to mount the laser head. The tripod may introduce an error.
   CAUTION! Never turn on the spindle of the CNC while the flat-mirror is 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 diagonal path. It is a good practice to steer the flat-mirror back and forth and stopped at the middle of the peak intensity.

9.5.2 Installation

9.5.2.1 Set up LDDM Program

See Section 7.5.2.1.

9.5.2.2 Starting LDDM Program

See Section 7.5.2.2.

9.5.2.3 Setup Laser Head and Flat-mirror Target

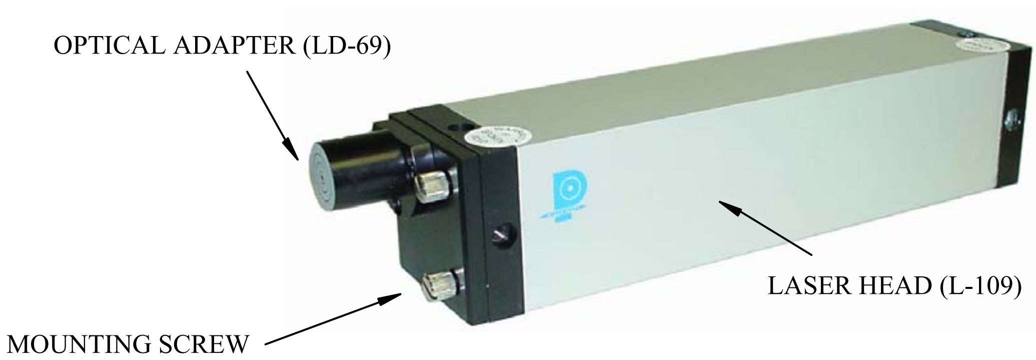


FIG. 9-2 LASER HEAD WITH OPTICAL ADAPTER

Attach the optical adapter to the front of the laser head (Fig.9-2). Align the output beam by moving the optical adapter up/down and left/right such that the output laser beam is pointing to the same position with and without the optical adapter. Tighten the two screws on the side. Mount the laser head with the optical adapter and the diagonal steering mirror on the bed with a magnetic holder and the flat-mirror on the spindle directly or with a magnetic holder, as shown in Fig.9-3. Point the laser beam in the first diagonal 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 diagonal path. The standard flat-mirror is 3” x 4”. It will cover a movement of less than 2”. For large movement, a larger flat-mirror is available.

Finally, adjust the two screws on the mounting of the flat-mirror (Fig.9-4) such that the return laser beam enters the aperture of the optical adapter. The beam intensity should be above the minimum requirement along the entire diagonal path. Otherwise, fine adjust the flat-mirror again. For some machine a cross-link (LD-44) is needed to rotate the flat-mirror to be perpendicular to the laser beam.

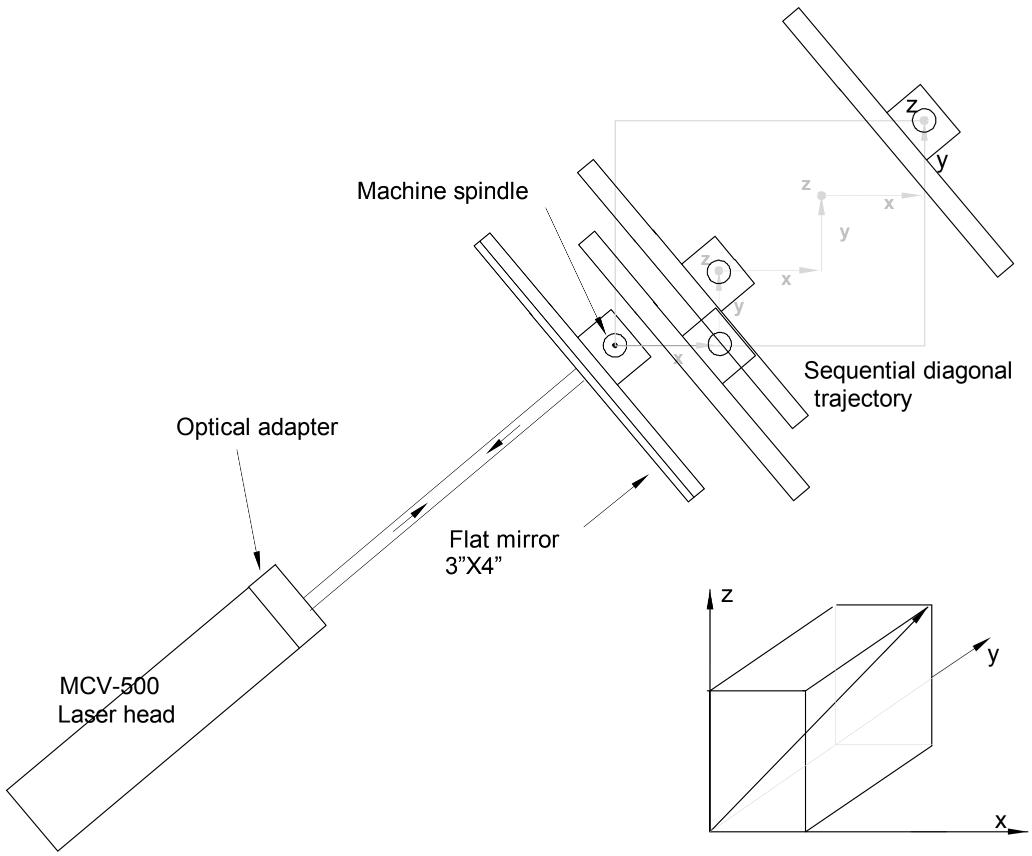


FIG. 9-3 SCHEMATICS OF SEQUENTIAL DIAGONAL MEASUREMENT

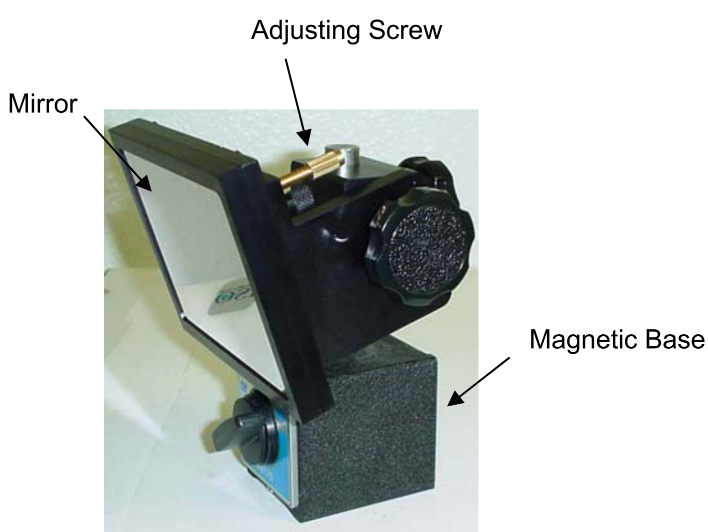


FIG. 9-4 FLAT-MIRROR TARGET WITH TWO ADJUSTABLE SCREWS

9.5.3 Parts Programs

To align the diagonal path from X_s = 0, Y_s = 0, Z_s = 0 to X_e= 40 in, Y_e = 30 in and Z_e = 20 in, a sample G-code parts program is:

```
G20 G90
N1 G91 G00
     X40.0 Y30.0 Z20.0
     MO
     X-40.0 Y-30.0 Z-20.0
     M0
     M99
```

For Sequential step data collection along the same diagonal, a sample G-code parts program is:

```
G91 G00
    G00 X-0.07 Y-0.07 Z-0.07
    G00 X0.07 Y0.07 Z0.07
M0
    M98 P107 L20
    G00 X0.07 Y0.07 Z0.07
    G00 X-0.07 Y-0.07 Z-0.07
M0
   M98 P108 L20
M0
M99

OP107
G91 G00
   X20 G4P4
   Y1.5 G4P4
   Z1.0 G4P4
   M99

OP108
   G91 G00
   Z-1.0 G4P4
   Y-1.5 G4P4
   X-2.0 G4P4
   M99
```

9.5.4 Description of Sequential Diagonal Path

Program the machine spindle to move a diagonal path within the working volume. Start from one corner at the base plan and move to the opposite corner at the top plan. There are 8 body diagonals. We define the 8 body diagonals by the positive or negative axis movement. For example, ppp means from the starting corner (smallest machine coordinates) to the opposite corner (largest machine coordinates), all the 3 axes move with positive increments. The npn means from the starting corner (smallest machine y-coordinate and largest x-axis and z-axis coordinate) to the opposite corner (largest machine y-coordinate and smallest x- and z-coordinate), the y-axis moves with positive increment and the x- and z-axis move with negative increments. The 8 body diagonals are ppp, npp, pnp, ppn, nnn, pnn, npn and nnp. The last 4 body diagonals are the same corners as the first 4 diagonals except the directions are reversed. Hence, there are only 4 body diagonal directions with forward movement and reverse movement (bidirectional).

More specifically, first define the starting point (Xs,Ys,Zs) and the end point (Xe,Ye,Ze). The working volume is defined by (Xe-Xs) * (Ye-Ys) * (Ze-Zs). The number of increments per axis is n and the total number of increments is 3n. The measurement increments Dx, Dy, and Dz , which is limited by the size of the flat-mirror, and the number of steps per axis n, are determined by the following relations:
Dx = (Xe-Xs)/n, Dy = (Ye-Ys)/n, and Dz = (Ze-Zs)/n.

Program the machine spindle movement in XYZ sequence. That is, starting from (Xs,Ys.Zs), move Dx in x-direction with feed rate F (usually between 20% to 80% of maximum feed rate), stop for a dwell time of T sec (usually 1 to 10 seconds depends on the machine structure), then move Dy in y-direction with the same feed rate and stop for the same dwell time, then move Dz in z-direction with the same feed rate and dwell time. Continue the sequence until the opposite corner is reached. There are n steps per axis and a total of 3n steps. For this diagonal, since all of the 3 increments are positive, we call this ppp, and the reverse nnn. For the second diagonal, npp or the reverse pnn, change the starting point to (Xe,Ys, Zs) and the increments to –Dx, Dy, and Dz. Similarly, the third diagonal npn the starting point is (Xe,Ys, Ze) with increments –Dx, Dy, and –Dz.
For the forth diagonal ppn the starting point is (Xs,Ys,Ze) with increments Dx, Dy, and –Dz .

To generate a sample part program to move the machine for the sequential diagonal measurement, click on the “Part Prog” button on the setup screen. The part program generated will have an extension .PPG.

Please note, here all of the sequences are XYZ. For angular measurements, there are 6 different sequences, namely, XYZ,YZX, ZXY, XZY, ZYX, and YXZ.

9.6 Software Description

9.6.1 General Description

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

9.6.2 Sequential Step Diagonal Data Collection

The sequential step diagonal data collection is in the linear measurement program. After clicking on the **Linear Measurement** box on the main menu, you will be greeted by the linear measurement data screen (Fig. 7-11). See section 7.6 for the descriptions of all the functions.

Click on the **Setup** box, the LDDM setup screen will be displayed as shown in Fig. 7-12a. First , click on the **Other** button, a square button **Sequential** will appear under the **Other** button. Click on the **Sequential** button for sequential data collection. Click on the **Double Pass** button only when you are using the double pass optics.

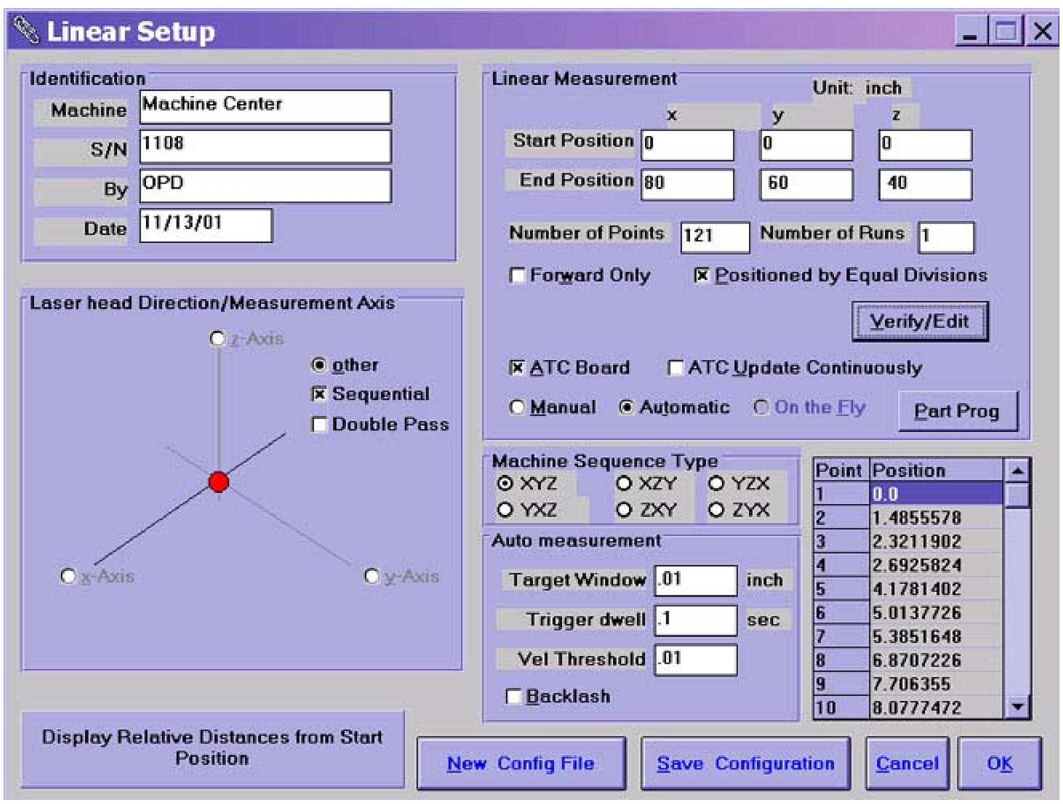


Fig. 7-12a Sequential Step Diagonal Measurement Setup Screen

Enter the start position and end position of X, Y, and Z. Here, always enter the start and end position of the first move in X, the start and end positions of the second move in Y, and the start and end positions of the third move in Z. If the end position is larger than the start position, it corresponds to p, otherwise it corresponds to n. Enter the number of points N = 3n + 1, where n is an integer, the number of steps per axis. Click the **Verify/Edit** button to verify the increments. The positions shown are always positive with positive increments.

Click the **Part Program** button to generate a sample part program. A screen shown in Fig. 7-12b will popup.

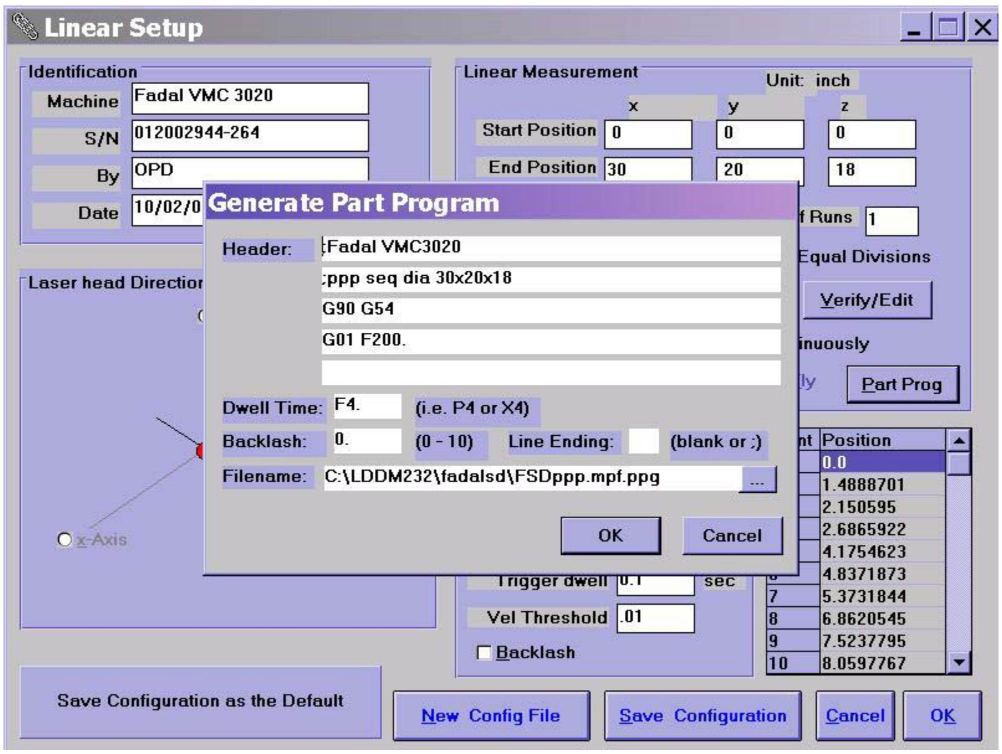


Fig. 7-12b A Popup Screen to Enter Input Parameters
and file Name of a Part Program

The header (up to 5 lines) will be reproduced at the beginning of the part program. G90 is absolute coordinate, G54 is parts coordinate, G01 is linear movement and F200 is feed rate at 200 in/min. The dwell time must be larger than the software dwell time. For most controllers, enter P4. and F4. is for Siemens controller. Enter 0.02 on backlash to remove backlash. Different controllers may use different character to end a line. For most controllers, just leave it blank. Click on the right-hand button to enter a filename and its location. The output file will have an extension .PPG.

Select the machine sequence type by click on the corresponding button if available. Only angular measurements need to make the selection. For the measurement here the sequence is always XYZ.

9.6.3 Example of a Volumetric Measurement

Linear Measurement Main Display (See Fig. 7-11):

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. 7-12):

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) Click the "other" and "sequential" button.

6) Enter the **machine coordinates** of the working volume 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 increments per axis, enter 31.

8) Enter the **number of runs**.

9) Press the **Verify/Edit** button to see the increments.

10) Choose **Forward Only** or **Bi-Directional** runs.

11) Click on the **ATC board** if you have one.

12) Choose your type of measurement:

Manual

you may: A) Hit the **enter key** at each point, or
B) 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:

Generate Points Program: Click this button to generate Parts Program in G-code.

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.

13) 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:

A) Click on the file name and press **OK**

B) Double click on the file name

C) Type the name of the file name, example: **LDDM.1CF** and hit enter. The extension .1CF indicates a configuration file.

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

Taking Data Points for a Linear Measurement (Fig. 7-13)

15) Input the **Humidity Value**.

16) 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.

17) 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.

18) Move your flat-mirror target 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).

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.

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

20) 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.

21) To analyze the data click on the **Analyze button**. When it prompts you, unload the module.

9.6.4 Linear Data Analysis Menu

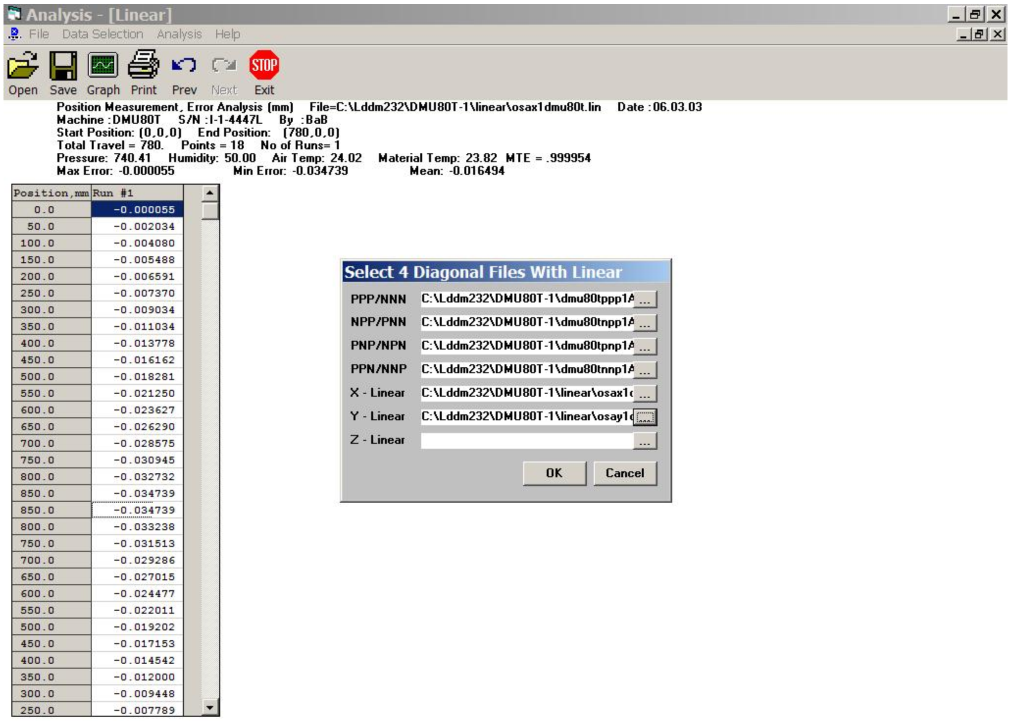


FIG. 9-5 SEQUENTIAL DIAGONAL DATA ANALYSIS SCREEN

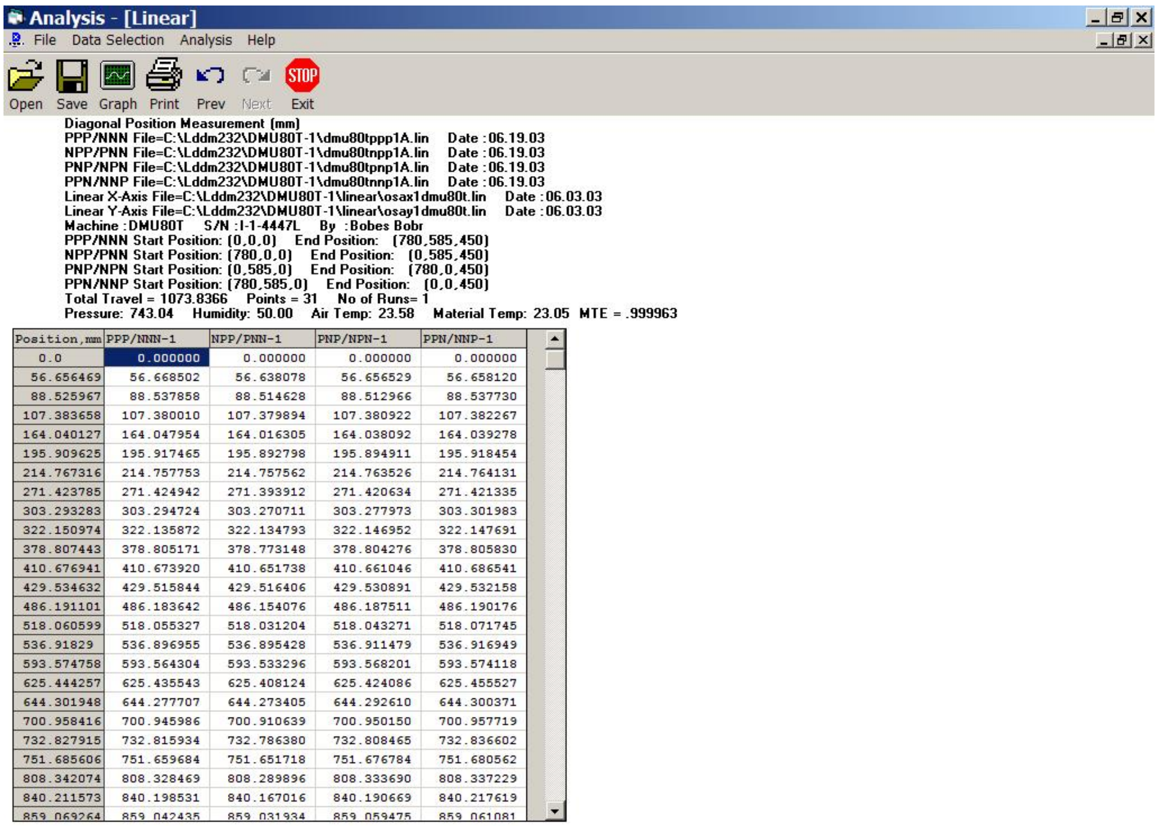
Under the **File Menu**, you can open a **new** data file, **save** a data file, set your **printer type**, set your **printer style**, or return to the **main menu**. When loading a file, choose the files with the extension of .LIN for linear. You can only **print data** tables using the print function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

1) Click “file” and “open” to open a .LIN file first.

2) Under the **Data Selection** heading, you can only choose **Displacement** when looking at a linear (.LIN) file, or “4 diagonals”. After click on the “4 diagonals with Linear”, a screen “Select 4 Diagonal Files with Linear” will popup (see FIG. 9-5). Enter the 4 diagonal files. There are 4 types of diagonal files, ppp/nnn, npp/pnn, pnp/npn and ppn/nnp. The file can not be entered by type the filename. Click on the right hand button to enter the correct type of diagonal file to the corresponding line. The program will process the data with at least one diagonal file and assume all the other diagonals are zeros. For a correct analysis, all 4 diagonal files must be entered. For a non-isotropic machine, sometimes it is necessary to input 2 linear displacement files with the same travel distances.

Under **Analysis**, you can choose **Error.** After choosing **Error**, you will be given a choice on what you wish to see, squareness, x-axis, y-axis, and z-axis, Diagonal. Click with the mouse button on which runs you wish to see.

3) After all 4 diagonal files are selected, the screen will shown the collected diagonal position data as shown in FIG. 9-6.



Analysis - [Linear]

File Data Selection Analysis Help

Open Save Graph Print Prev Next Exit

Diagonal Position Measurement (mm)
PPP/NNN File=C:\Lddm232\DMU80T-1\dmu80tppp1A.lin Date :06.19.03
NPP/PNN File=C:\Lddm232\DMU80T-1\dmu80tnpp1A.lin Date :06.19.03
PNP/NPN File=C:\Lddm232\DMU80T-1\dmu80tpnp1A.lin Date :06.19.03
PPN/NNP File=C:\Lddm232\DMU80T-1\dmu80tnnp1A.lin Date :06.19.03
Linear X-Axis File=C:\Lddm232\DMU80T-1\linear\osax1dmu80t.lin Date :06.03.03
Linear Y-Axis File=C:\Lddm232\DMU80T-1\linear\osay1dmu80t.lin Date :06.03.03
Machine :DMU80T S/N :I-1-4447L By :Bobes Bobr
PPP/NNN Start Position: (0,0,0) End Position: (780,585,450)
NPP/PNN Start Position: (780,0,0) End Position: (0,585,450)
PNP/NPN Start Position: (0,585,0) End Position: (780,0,450)
PPN/NNP Start Position: (780,585,0) End Position: (0,0,450)
Total Travel = 1073.8366 Points = 31 No of Runs= 1
Pressure: 743.04 Humidity: 50.00 Air Temp: 23.58 Material Temp: 23.05 MTE = .999963

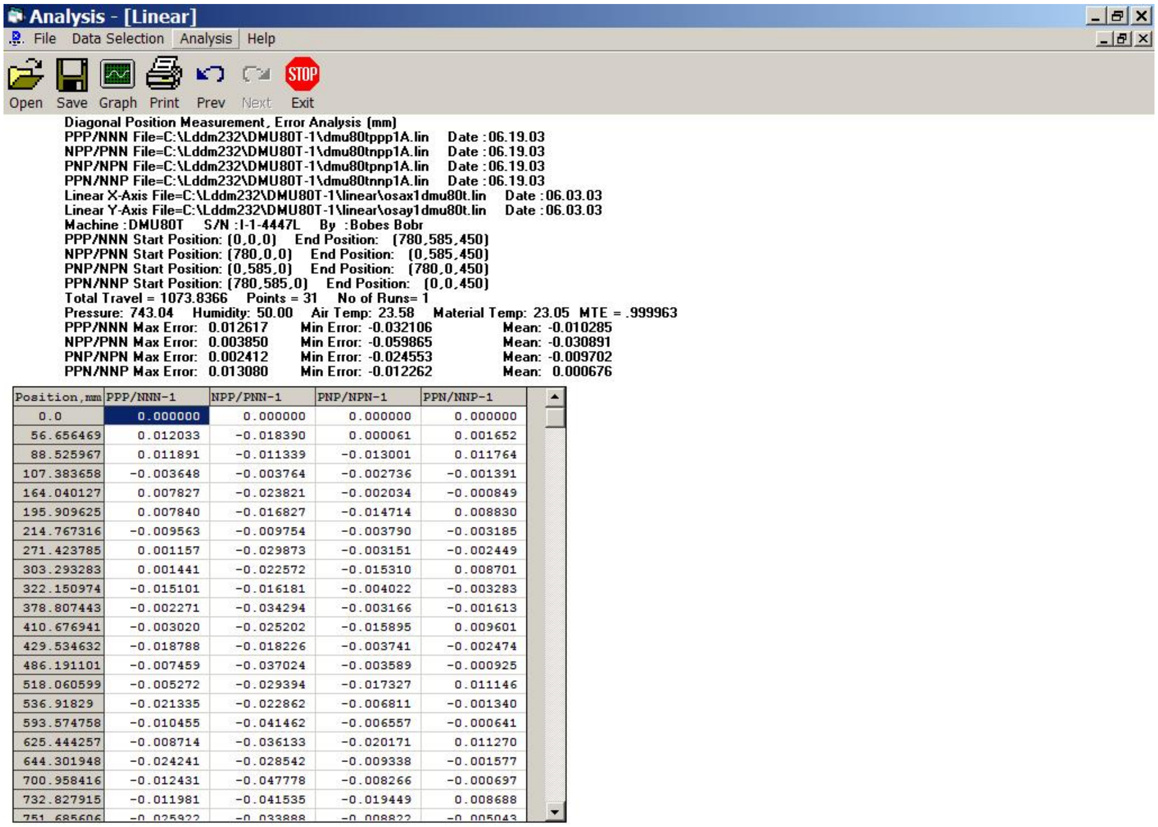
Position,mm	PPP/NNN-1	NPP/PNN-1	PNP/NPN-1	PPN/NNP-1
0.0	0.000000	0.000000	0.000000	0.000000
56.656469	56.668502	56.638078	56.656529	56.658120
88.525967	88.537858	88.514628	88.512966	88.537730
107.383658	107.380010	107.379894	107.380922	107.382267
164.040127	164.047954	164.016305	164.038092	164.039278
195.909625	195.917465	195.892798	195.894911	195.918454
214.767316	214.757753	214.757562	214.763526	214.764131
271.423785	271.424942	271.393912	271.420634	271.421335
303.293283	303.294724	303.270711	303.277973	303.301983
322.150974	322.135872	322.134793	322.146952	322.147691
378.807443	378.805171	378.773148	378.804276	378.805830
410.676941	410.673920	410.651738	410.661046	410.686541
429.534632	429.515844	429.516406	429.530891	429.532158
486.191101	486.183642	486.154076	486.187511	486.190176
518.060599	518.055327	518.031204	518.043271	518.071745
536.91829	536.896955	536.895428	536.911479	536.916949
593.574758	593.564304	593.533296	593.568201	593.574118
625.444257	625.435543	625.408124	625.424086	625.455527
644.301948	644.277707	644.273405	644.292610	644.300371
700.958416	700.945986	700.910639	700.950150	700.957719
732.827915	732.815934	732.786380	732.808465	732.836602
751.685606	751.659684	751.651718	751.676784	751.680562
808.342074	808.328469	808.289896	808.333690	808.337229
840.211573	840.198531	840.167016	840.190669	840.217619
859.069264	859.042435	859.031934	859.059475	859.061081

FIG. 9-6 4 SEQUENTIAL DIAGONAL POSITION MEASUREMENT DATA TABLE

4) Click on **Analysis** then **Error**, the screen will show the 4 diagonal position measurement errors as shown in FIG. 9-7. Click on **Graph** to plot or **Print** to print.

5) Click on **Analysis** then **3 Squareness**, the screen will shown the 3 squareness errors in the XY-plan, YZ-plan and ZX-plan as shown in FIG. 9-8.

6) Click on **Analysis** then **X-axiz**, the screen will shown the linear position errors, vertical straightness and horizontal straightness in the X-axis as shown in FIG. 9-9.



Diagonal Position Measurement, Error Analysis (mm)
PPP/NNN File=C:\Lddm232\DMU80T-1\dmu80tppp1A.lin Date :06.19.03
NPP/PNN File=C:\Lddm232\DMU80T-1\dmu80tnpp1A.lin Date :06.19.03
PNP/NPN File=C:\Lddm232\DMU80T-1\dmu80tpnp1A.lin Date :06.19.03
PPN/NNP File=C:\Lddm232\DMU80T-1\dmu80tnnp1A.lin Date :06.19.03
Linear X-Axis File=C:\Lddm232\DMU80T-1\linear\osax1dmu80t.lin Date :06.03.03
Linear Y-Axis File=C:\Lddm232\DMU80T-1\linear\osay1dmu80t.lin Date :06.03.03
Machine :DMU80T S/N :I-1-4447L By :Bobes Bobr
PPP/NNN Start Position: (0,0,0) End Position: (780,585,450)
NPP/PNN Start Position: (780,0,0) End Position: (0,585,450)
PNP/NPN Start Position: (0,585,0) End Position: (780,0,450)
PPN/NNP Start Position: (780,585,0) End Position: (0,0,450)
Total Travel = 1073.8366 Points = 31 No of Runs= 1
Pressure: 743.04 Humidity: 50.00 Air Temp: 23.58 Material Temp: 23.05 MTE = .999963
PPP/NNN Max Error: 0.012617 Min Error: -0.032106 Mean: -0.010285
NPP/PNN Max Error: 0.003850 Min Error: -0.059865 Mean: -0.030891
PNP/NPN Max Error: 0.002412 Min Error: -0.024553 Mean: -0.009702
PPN/NNP Max Error: 0.013080 Min Error: -0.012262 Mean: 0.000676

Position,mm	PPP/NNN-1	NPP/PNN-1	PNP/NPN-1	PPN/NNP-1
0.0	0.000000	0.000000	0.000000	0.000000
56.656469	0.012033	-0.018390	0.000061	0.001652
88.525967	0.011891	-0.011339	-0.013001	0.011764
107.383658	-0.003648	-0.003764	-0.002736	-0.001391
164.040127	0.007827	-0.023821	-0.002034	-0.000849
195.909625	0.007840	-0.016827	-0.014714	0.008830
214.767316	-0.009563	-0.009754	-0.003790	-0.003185
271.423785	0.001157	-0.029873	-0.003151	-0.002449
303.293283	0.001441	-0.022572	-0.015310	0.008701
322.150974	-0.015101	-0.016181	-0.004022	-0.003283
378.807443	-0.002271	-0.034294	-0.003166	-0.001613
410.676941	-0.003020	-0.025202	-0.015895	0.009601
429.534632	-0.018788	-0.018226	-0.003741	-0.002474
486.191101	-0.007459	-0.037024	-0.003589	-0.000925
518.060599	-0.005272	-0.029394	-0.017327	0.011146
536.91829	-0.021335	-0.022862	-0.006811	-0.001340
593.574758	-0.010455	-0.041462	-0.006557	-0.000641
625.444257	-0.008714	-0.036133	-0.020171	0.011270
644.301948	-0.024241	-0.028542	-0.009338	-0.001577
700.958416	-0.012431	-0.047778	-0.008266	-0.000697
732.827915	-0.011981	-0.041535	-0.019449	0.008688
751.685606	-0.025922	-0.033888	-0.008822	-0.005043

FIG. 9-7 4 SEQUENTIAL DIAGONAL POSITION ERROR TABLE

7) Click on **Graph**, a screen will popup for you to select the plots. A plot of linear position errors, vertical straightness and horizontal straightness is shown in FIG. 9-11. Click on [icon] to get back to the analysis screen. To save the data file, click on **file** and **save**. The data will be saved under filename.SDX.

Analysis - [Linear]

File Data Selection Analysis Help

Diagonal Position Measurement, 3 Squareness Analysis (mm)
PPP/NNN File=D:\LDDM234\PPPNC.LIN Date :01/25/99
NPP/PNN File=D:\LDDM234\NPPNC.LIN Date :01/26/99
PNP/NPN File=D:\LDDM234\NPNNC.LIN Date :01/26/99
PPN/NNP File=D:\LDDM234\PPNNC.LIN Date :01/25/99
Machine :Horizontal Mill S/N :Diagonal 1 By :OPTODYNE
PPP/NNN Start Position: (-240, 253, 160) End Position: (260, 753, 660)
NPP/PNN Start Position: (260, 253, 160) End Position: (-240, 753, 660)
PNP/NPN Start Position: (260, 253, 660) End Position: (-240, 753, 160)
PPN/NNP Start Position: (-240, 253, 660) End Position: (260, 753, 160)
Total Travel = 866.0254 Points = 61 No of Runs= 1
Pressure: 752.7 Humidity: 50.00 Air Temp: 22.41 Material Temp: 22.66 MTE = .999979
Mean Value: -0.017453

Squareness in	XY-plan	YZ-plan	ZX-plan
Radian	0.000035	-0.000031	-0.000014
Arcsec	7.19	-6.53	-2.89
Degree	0.002	-0.002	-0.001

FIG. 9-8 MEASURED SQUARNESS ERRORS

Analysis - [Linear]

File Data Selection Analysis Help

Diagonal Position Measurement, X-Axis Analysis (mm)
PPP/NNN File=D:\LDDM234\PPPNC.LIN Date :01/25/99
NPP/PNN File=D:\LDDM234\NPPNC.LIN Date :01/26/99
PNP/NPN File=D:\LDDM234\NPNNC.LIN Date :01/26/99
PPN/NNP File=D:\LDDM234\PPNNC.LIN Date :01/25/99
Machine :Horizontal Mill S/N :Diagonal 1 By :OPTODYNE
PPP/NNN Start Position: (-240, 253, 160) End Position: (260, 753, 660)
NPP/PNN Start Position: (260, 253, 160) End Position: (-240, 753, 660)
PNP/NPN Start Position: (260, 253, 660) End Position: (-240, 753, 160)
PPN/NNP Start Position: (-240, 253, 660) End Position: (260, 753, 160)
Total Travel = 866.0254 Points = 61 No of Runs= 1
Pitch: 0.0, 0.0 Yaw: 0.0, 0.0 Roll: 0.0, 0.0 Mean: 0.0, 0.0
S1: 0.0, 0.0 S2: 0.0, 0.0 S3: 0.0, 0.0
Pressure: 752.7 Humidity: 50.00 Air Temp: 22.41 Material Temp: 22.66 MTE = .999979
Mean Value Forward: PPP/NNN = 0.024595 NPP/PNN = -0.012806 PNP/NPN = -0.050996 PPN/NNP = 0.002047
Mean Value Reverse: PPP/NNN = 0.02496 NPP/PNN = -0.013431 PNP/NPN = -0.050196 PPN/NNP = 0.001386

Modify Pitch, Yaw, Roll & Mean

x-axis Position,mm	Linear Error	Vertical Straightness	Horizontal Straightness
0.0	0.0	0.0	0.0
25.0	0.002099	0.000506	0.000227
50.0	0.003207	0.00102	-0.001582
75.0	0.004789	0.0011	-0.001064
100.0	0.004183	0.000764	-0.00247
125.0	0.004575	-0.000054	-0.001927
150.0	0.003616	-0.0007	-0.002847
175.0	0.00262	-0.001671	-0.002556
200.0	-0.000483	-0.00132	-0.00336
225.0	-0.002791	-0.001554	-0.003328
250.0	-0.005629	-0.001073	-0.003999
275.0	-0.006673	-0.00124	-0.003082
300.0	-0.009847	-0.001574	-0.003193
325.0	-0.00885	-0.001849	-0.002931
350.0	-0.007389	-0.001587	-0.002801
375.0	-0.004406	-0.001259	-0.001934
400.0	-0.003104	-0.000254	-0.00075

FIG. 9-9 LINEAR POSITION ERROR, VERTICAL STRAIGHTNESS AND HORIZONTAL STRAIGHTNESS IN THE X-AXIS

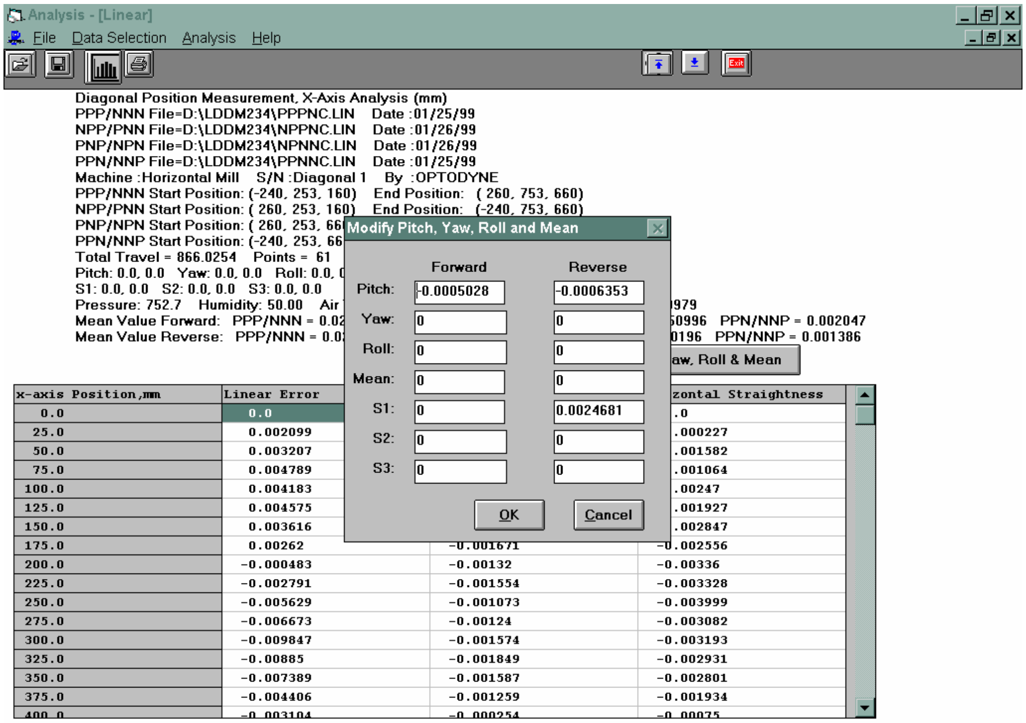


FIG. 9-10 A POPUP SCREEN TO SHOW THE PARAMETER VALUE OR TO CHANGE THE PARAMETER VALUE

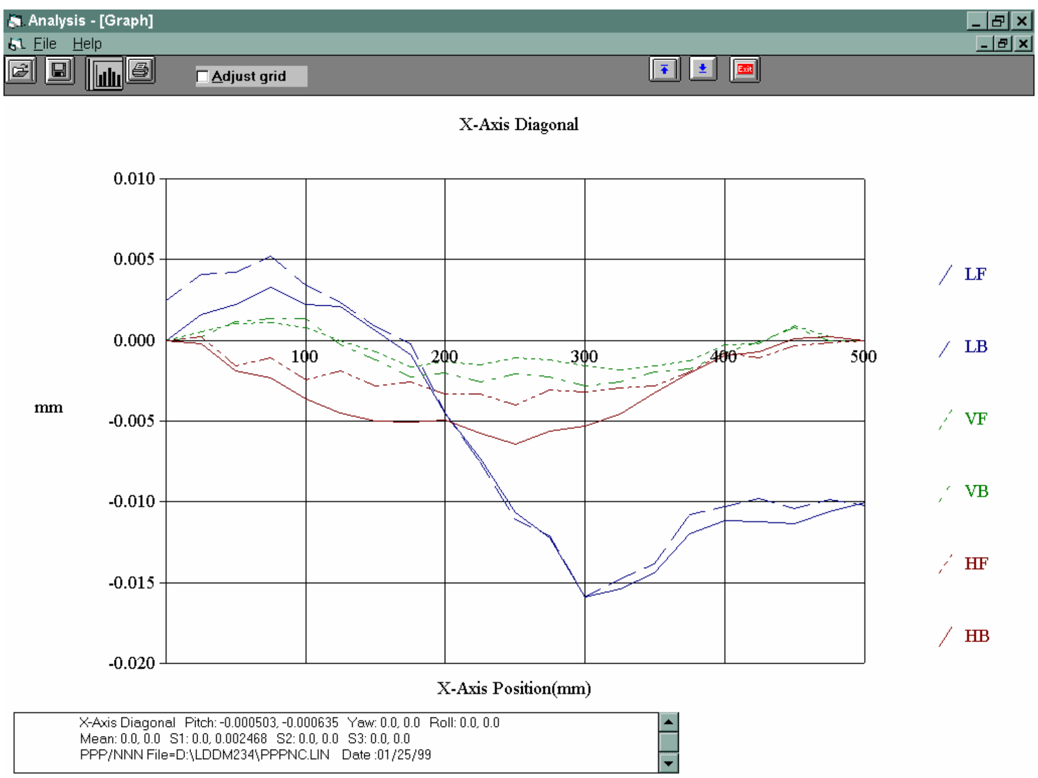


FIG. 9-11 A PLOT OF LINEAR POSITION ERRORS, VERTICAL STRAIGHTNESS AND HORIZONTAL STRAIGHTNESS OF X-AXIS

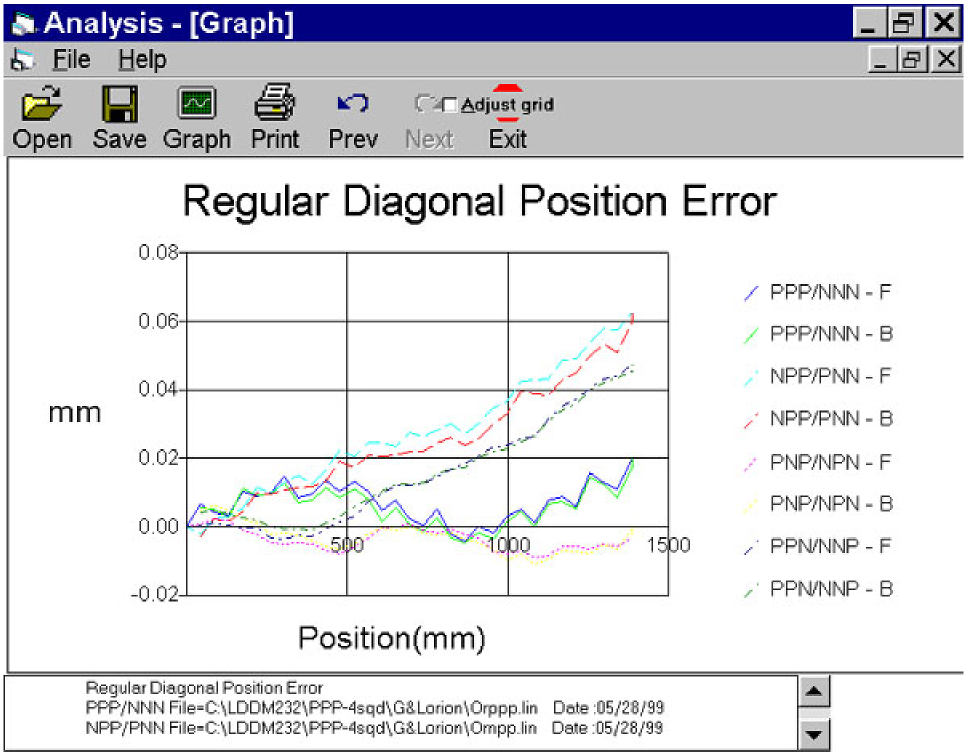


FIG. 9-12a A Plot of 4 Body Diagonal Displacement Errors without Volumetric Compensation

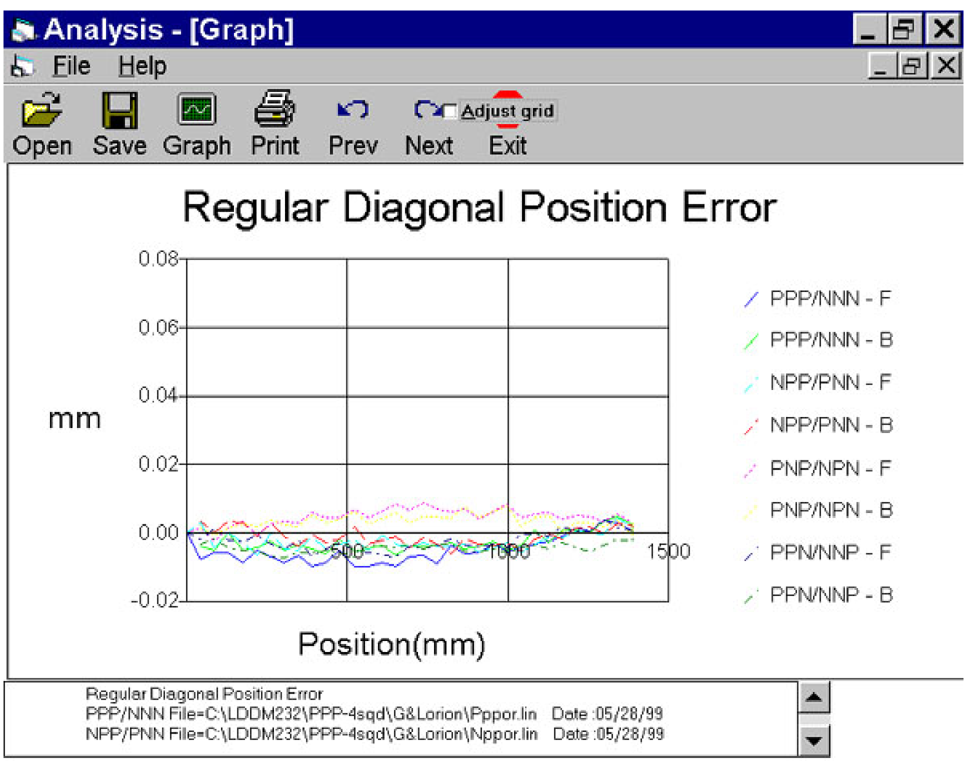


FIG. 9-12b A Plot of 4 Body Diagonal Displacement Errors with Volumetric Compensation

8) Similarly, click on **Y-axis** for Y-axis errors and click on **Z-axis** for Z-axis errors.

9) click on **Analysis**, then **Diagonals**, the screen will shown the regular diagonal errors as shown in FIG. 9-12. Click on **Modify Slope & Offset**, a popup screen will allow you to modify the slope values and the off-set values of each diagonal data. The purpose of these modifications is for simulation only. To save the data file, click on **file** and **save**. The data will be saved under filename.SDD.

9.6.5 Stitching several volumetric errors together

For large aspect ratio machine, the work volume can be divided into several work volumes with smaller aspect ratio as shown in Fig. 9-13.

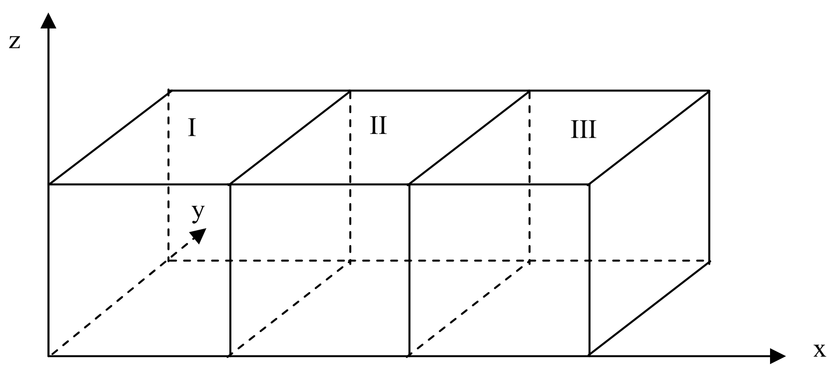


Fig. 9-13 Working Volume of a Large Aspect Ratio Machine

The vector measurement can be performed in each volume, I, II and III, and the final volumetric errors can be stitched together by the principle of continuity. That is, the error values at both sides of the boundary should be the same. For example, the error values at the end of I or the start of II should be the same. Also errors at the end of II or the start of III should be the same.

First enter 4 files in the volume I, click on the "error"' "x-axis", and "modify pitch, yaw & roll"' a screen will popup to show the parameter volues as shown in fig. 9-10. Record the values of pitch forward, pitch reverse and s1 reverse. Then enter 4 files in the volume II, click on the "error", "x-axis" and "modify pitch, yaw & roll"' a screen will popup to show the parameter values. Set

(s1 Forward) = (pitch forward in I) * (number of points – 1)
and (s1 Reverse) = (default s1 Reverse) + (pitch reverse in I) * number of points

Similarly, in volume III, set
(s1 Forward) = (pitch forward in II) * (number of points – 1)

and (s1 Reverse) = (default s1 Reverse) + (pitch reverse in II) * number of points.

9.6.6 Other Software Functions

There are many software functions available as shown in Fig 9-13b. The "3 Straightness" allow you to process 3 straightness files(.bsx, .bsy and .bsz) and to generate volumetric compensation files. The "Statistical Analysis" allows you to perform statistical analysis on the volumetric positioning error data files such as .sdx, .sdy, .sdz and .sdd files, and on the rotary table calibration data .ANG files.

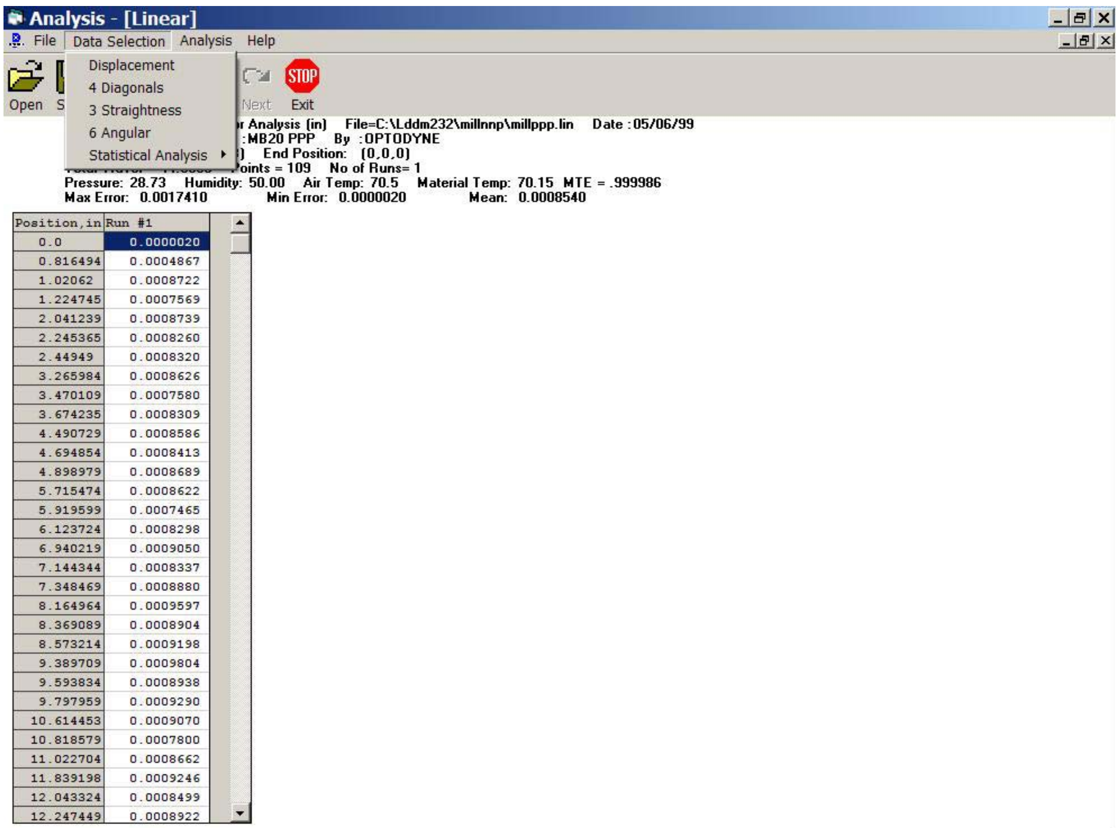


Fig. 9-13b A pull down Manu shows the 3 Straightness and Statistical Analysis options

9.6.6 Verification of Volumetric Positioning Accuracy

The laser body diagonal displacement measurement has been recommended by many standards such as the ASME B5.54, and ISO 230-6, for a quick check of the volumetric accuracy of machine tools. Hence, measuring the four body diagonal displacement with the volumetric compensation, can be used to verify the volumetric positioning accuracy of the machine. For many machine tool controllers, the volumetric compensation features are not available. However, higher volumetric positioning accuracy can still be achieved by compensate the part program.

To demonstrate this, the part programs for the 4 body diagonal movement can be compensated (corrected for the machine volumetric positioning errors). Then use these compensated part program to perform the body diagonal displacement measurement and the volumetric errors should be reduced considerably, providing the machine is repeatable.

To generate the compensated part program, after the step 8 of section 9.6.4, click on **Comp Part Program** and enter the filename of the body diagonal movement part program. A compensated part program will be generated with the same filename .VCM. The extension .VCM is automatically added.

9.7 Accuracy and Error Sources

For a linear measurement accuracy, see Section 7.7. Here are some additional error sources for the sequential step diagonal measurement.

1) Laser beam alignment error:
   When the laser beam direction and the diagonal direction are not exactly parallel, there is a cosine error. Assume the angle between the laser beam direction and the diagonal direction is Φ, the error is proportional to the square of Φ and the distance traveled. For an alignment error of 1 mm over 1 m, the maximum error is less than 0.5 μm.

2) Flat-mirror alignment error:
   When the flat-mirror target is not exactly perpendicular to the laser beam, there is an error due to the lateral motion of the flat-mirror. Assume the angle between the laser beam and the normal of the flat-mirror is θ , the error is proportional to the θ and the step size D. For an alignment error of 0.5 mm over 1 m, the angle θ is equal to 0.5 mrad. Assume a step size of 50mm, the maximum error is less than 25 μm. This error is relatively large. However, because this error is a constant and non-accumulative, it can be removed by data processing.

3) Error due to machine angular motion:
   Since the intersection of the laser beam and the flat-mirror may not be the center of rotation of the machine angular motion. Large error may be generated by the angular motion of the machine. It is noted that using different sequences, the angular motion of the machine can be determined. Also, the relation between the machine angular motion and the corresponding error terms are definitive, there no additional unknown introduced. Hence we can still solve all the angular errors with a little complexity.

9.8 Taking a Measurement

1. Decide which diagonal 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. Set up the desired configuration or load an existing configuration.

6. Move the machine to the starting point.

7. Reset the LDDM™ reading, click the start button. 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 click the taken button 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 (at least 2 x target window) 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 need to save the data. You may click the analysis button to analyze the data now or save the data now and to analyze the data later.
13. Repeat the same for the second diagonal, the third diagonal and the forth diagonal.

9.9 Generating a Volumetric Compensation File

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

9.9.1 Comp file generation

To generate comp files, same as shown in section 9.6.4, first calculate the errors on x-axis, y-axis and z-axis. Then click on file and save, a screen will popup for you to select the format of the comp file for different controllers.

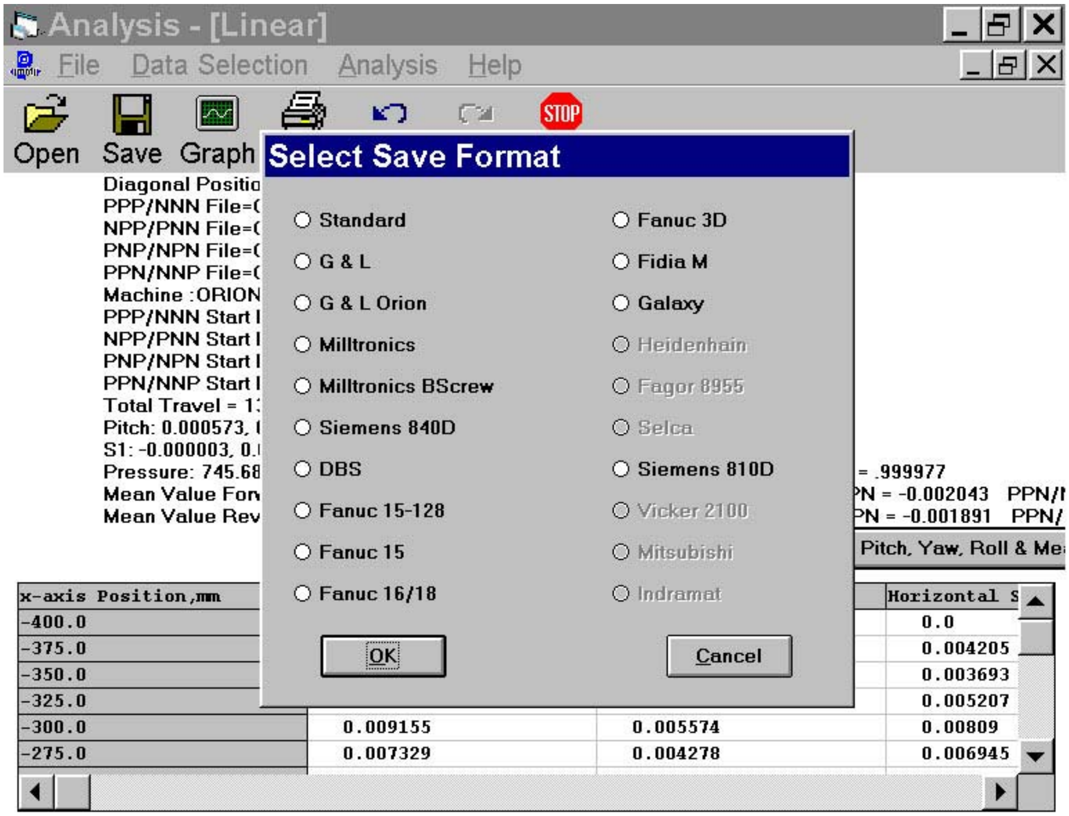


Fig. 9-14a Volumetric Compensation File Selection Screen

As shown in the popup screen, click “Standard” for standard format, the file extension are .sdx for x-axis, .sdy for y-axis and .sdz for z-axis. For Giddings and Lewis controller, the file extensions are .GDX for x-axis, .GDY for y-axis and .GDZ for z-axis. For milltronics, the file extensions are .ijF and .ijR, where i = 1 is x-axis, i= 2 is y-axis, i = 3 is z-axis, j = 1 is x-direction, j = 2 is y-dirextion and j = 3 is z-direction. F is forward direction and R is reverse direction. For Siemens840D, the file extension is . SAG.

Click on “DBS”, a second screen will popup as shown below

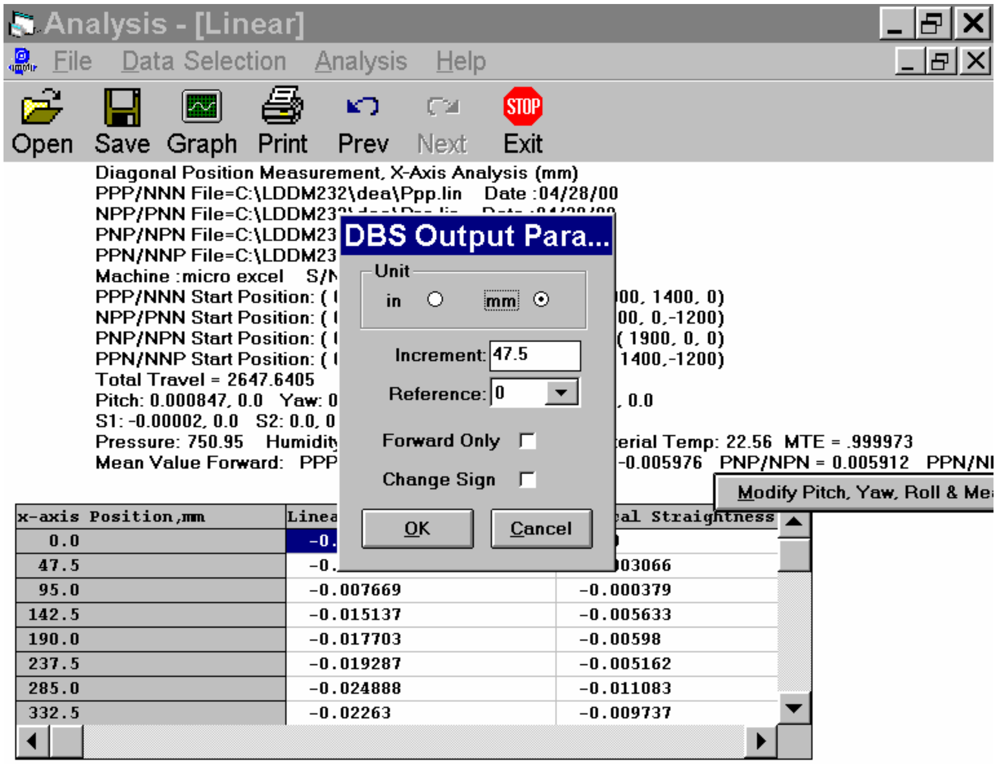


Fig. 9-14b Output Parameter Selection Screen for DBS

Select the units, and increment, a comp file will be generated with the extension .BSX for x-axis, .BSY for y-axis and .BSZ for z-axis.

Please note, make sure the **modify** button is clicked for each axis, before save the data. Consult the controller manual to determine the preamble, the prefix, the start address, the reference position, increment, and unit. We can provide a customer button to generate the comp file per your specification.

Click on “Fanuc 15-128”, a screen will popup as shown below:

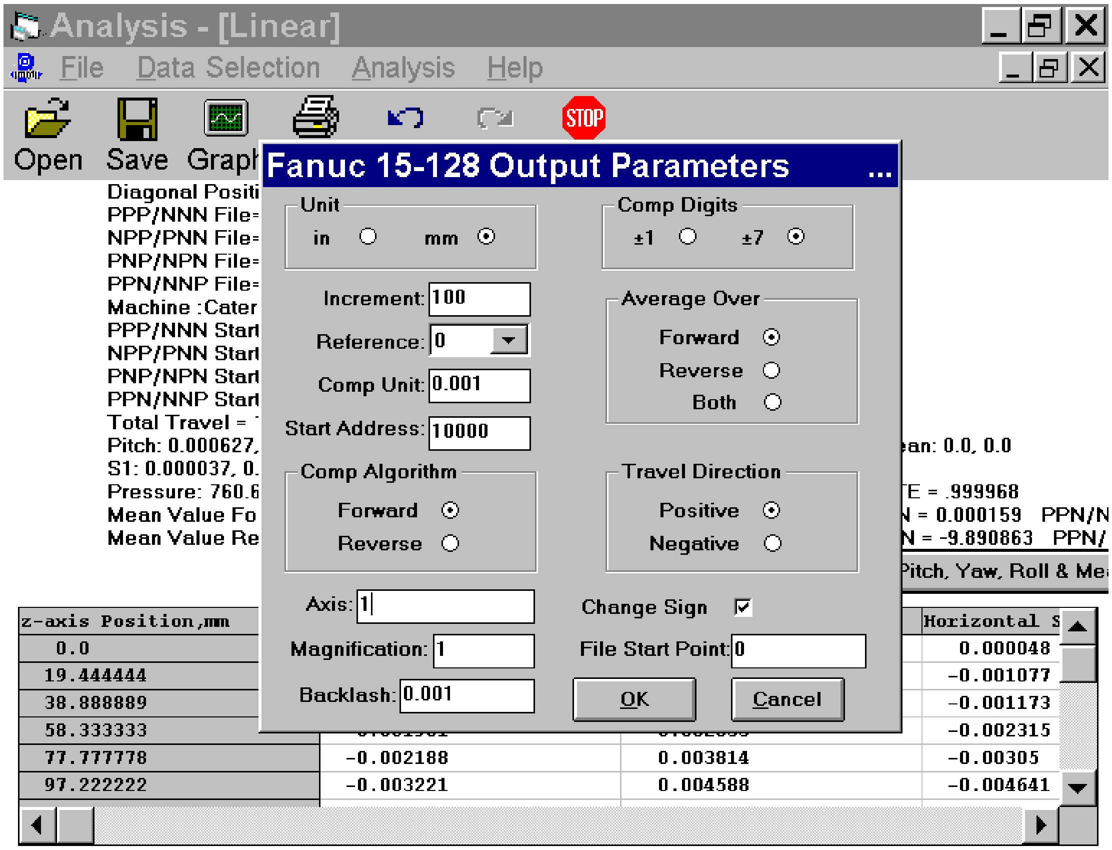


Fig. 9-15 Output Parameter Selection Screen for Fanuc 15-128

Select the units, the increment, reference point, and the comp unit. Keep the default values, Start Address = 10000, Comp Algorithm = Forward, Comp Digits = ±7, Travel Direction = positive, Change Sign = checked. Change the file start point only when the comp data points are larger than 100 and smaller than 128. This comp file is for Fanuc 15 with 128-point option. The file extension is .FN6.

Similarly, click on “**Fanuc 15**” to generate the standard Fanuc 15, 4-point straightness comp file. The file extension is .FN7. Click on “Fanuc 16/18” to generate the standard Fanuc 16/18, 4-point straightness comp file. The file extension is .FN8. Click on “**Fanuc 3D**” to generate the 3-D comp file for Fanuc 15 with 3-D option. The file extension is .FN9. To view the compensation file, click on “file” and “**Start Notepad**”, then enter the file name. Please consult GE Fanuc for detailed parameter file format and upload/download procedures.

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.

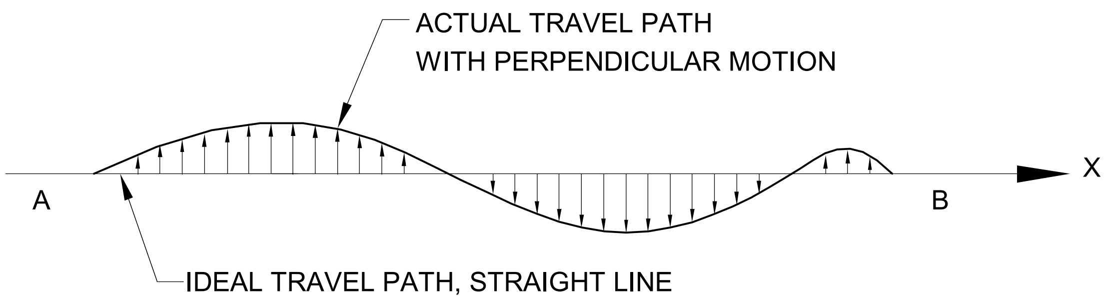


FIG. 10-1 DEFINITION OF STRAIGHTNESS

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.

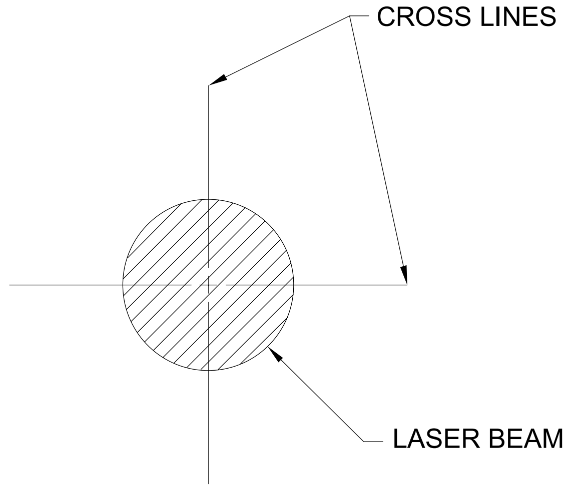


FIG. 10-2 LASER BEAM AND CROSS-LINE TARGET

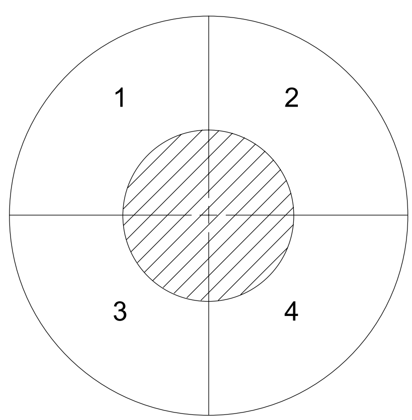


FIG. 10-3 QUAD-DETECTOR AND LASER BEAM

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° ± 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.

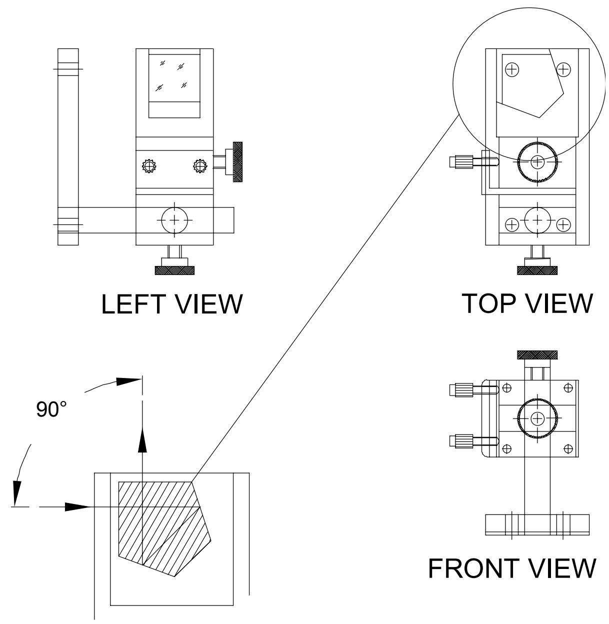


FIG. 10-4 SCHEMATIC OF A PENTA-PRISM

10.2 Hardware Required

The basic hardware and software required for squareness & straightness measurement are the following:

a. MCV-500 Laser Head	L-109
b. Processor Box	P-108D
c. Quad-Detector	LD-42
d. Optical Square	LD-16
e. Diagonal Steering Mirror	LD-37S
f. Magnetic Base	LD-03
g. Adapter Platform	LD-14A
h. 12 ft. cable set	LD-21L

10.3 Operation Specifications

Accuracy:	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 ±3% of displayed value for deviation less than 0.01 inch and is ±5% for deviation less than 0.04 inch.
Resolution:	0.0001 inch and 0.00001 inch selectable (0.001 mm and 0.0001 mm selectable)
Straightness Deviation Range:	±0.04 inch (± 1 mm)
Maximum Distance:	Up to 16 ft. (4.8 m)
Temperature Range:	60°F to 90°F or (15.5°C to 32°C) Option 40°F to 100°F or (5°C to 37°C)

10.4 Reference Material

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" (or M6x1 35mm) 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.

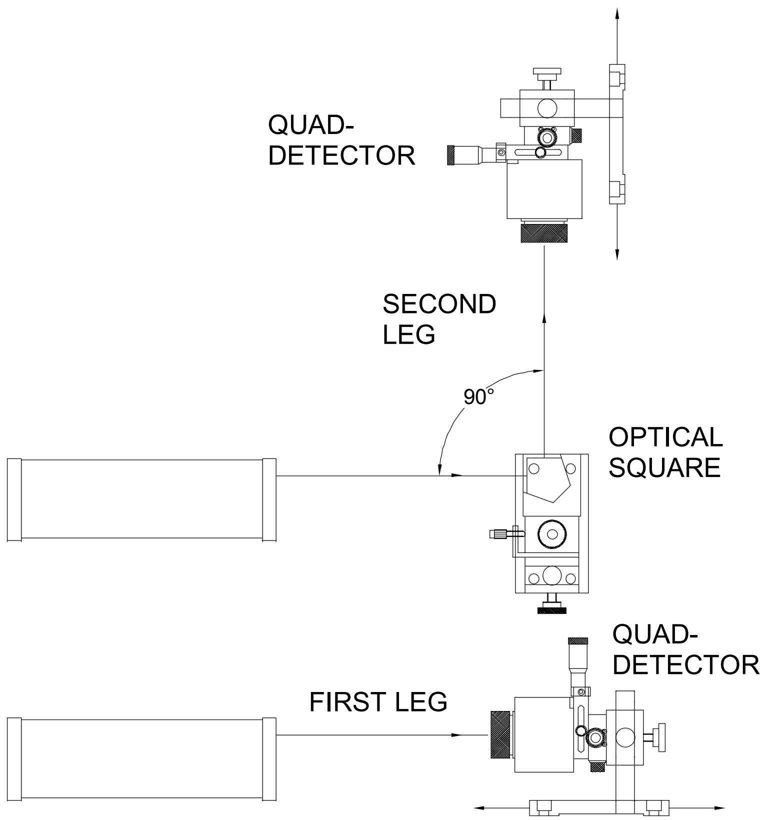


FIG. 10-5 SQUARENESS MEASUREMENT SETUP

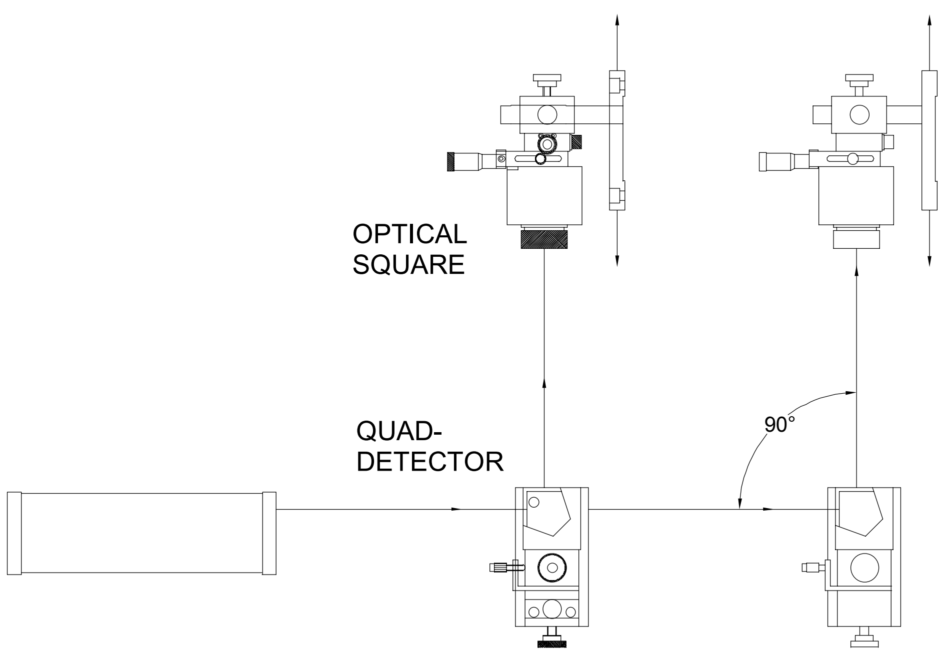


FIG. 10-6 PARALLELISM MEASUREMENT SETUP

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 con 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 an 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 or 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, sot 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°), 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 or 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 axis 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 is answered properly, the software will calculate the squareness deviation for the proper quadrant.

10.6 Software Description

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.

10.6.1 Squareness Measurement Main Display (Fig. 10-7)

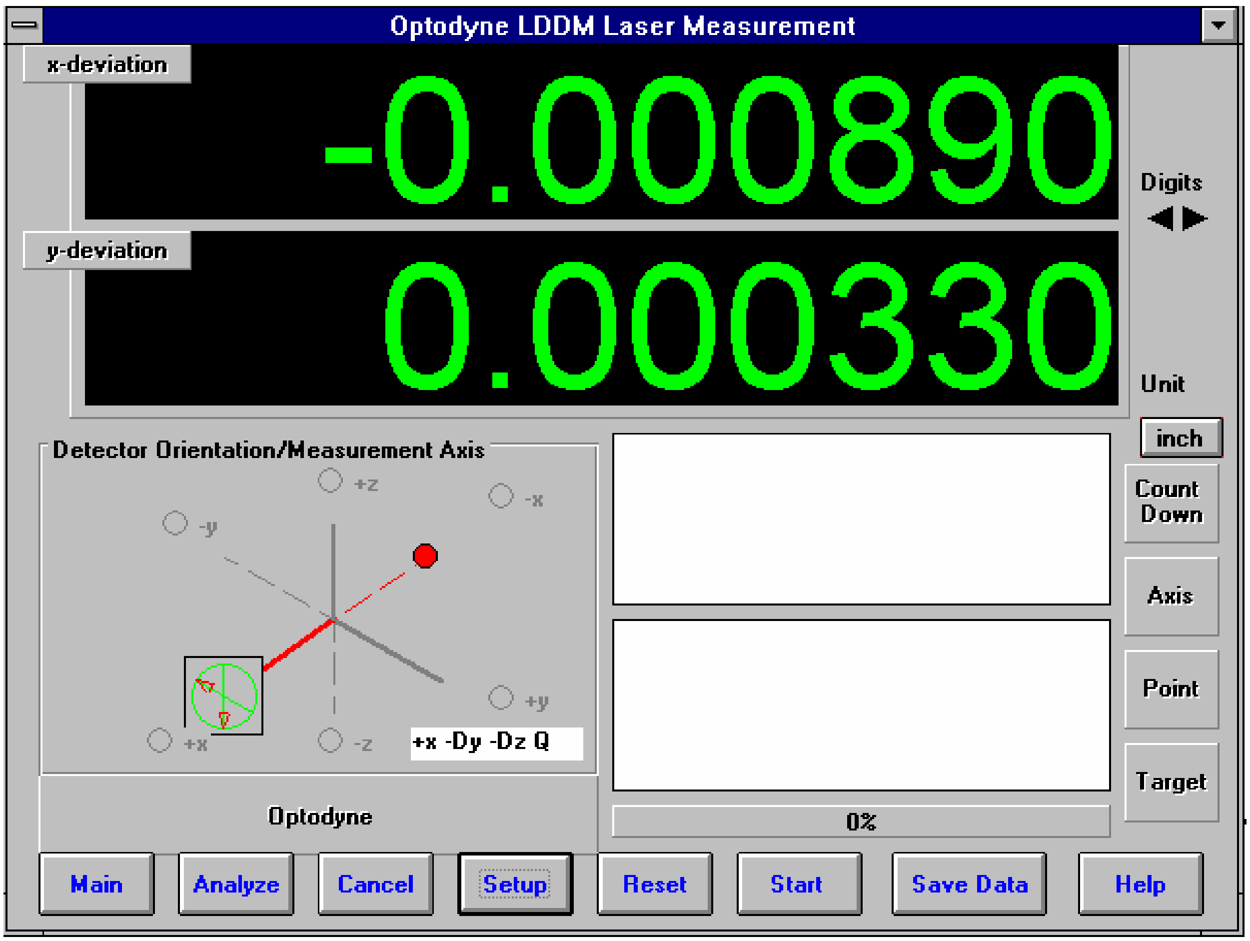


Fig. 10-7 Squareness Main Display

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/Measurement 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 ±x, ±y, and ±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.

10.6.2 Squareness Measurement Setup Screen (Fig. 10-8, 10-9)

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.

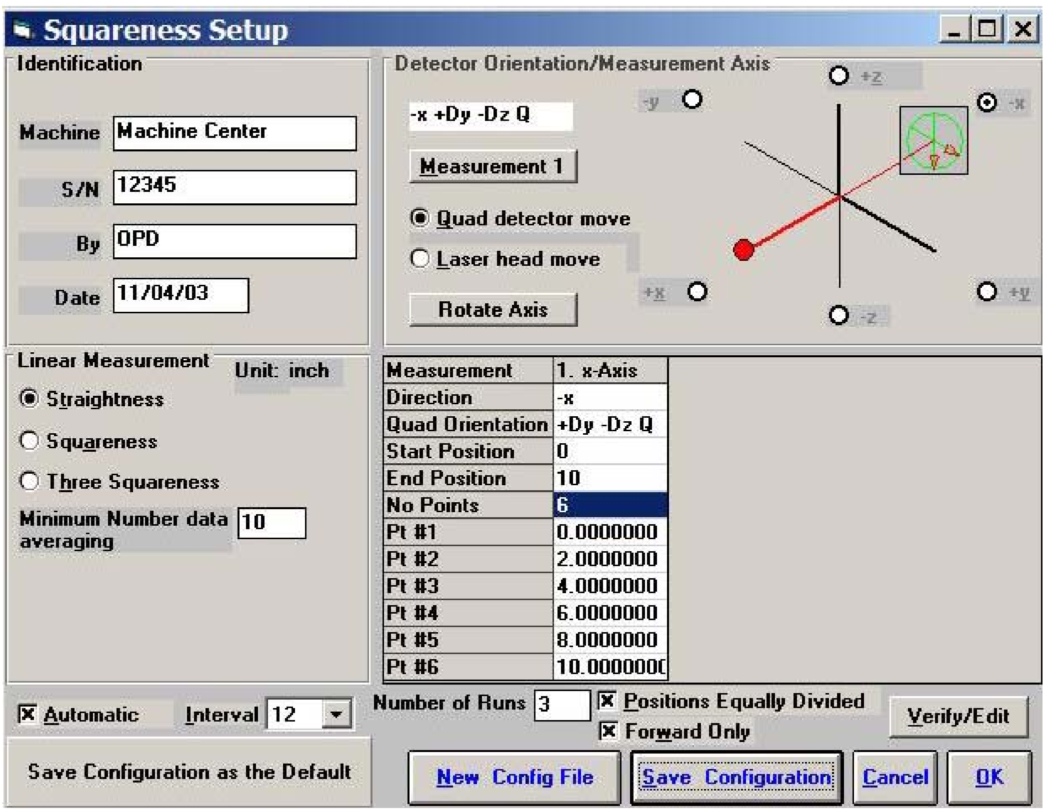


Fig. 10-8 Squareness Measurement Setup Screen

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.

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 you 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** error 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.
Measurement 2: This is the second measurement for squareness measurement. Click the "Measurement 2" and no on "Setup complete" to get back to measurement 1.

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-directional 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:

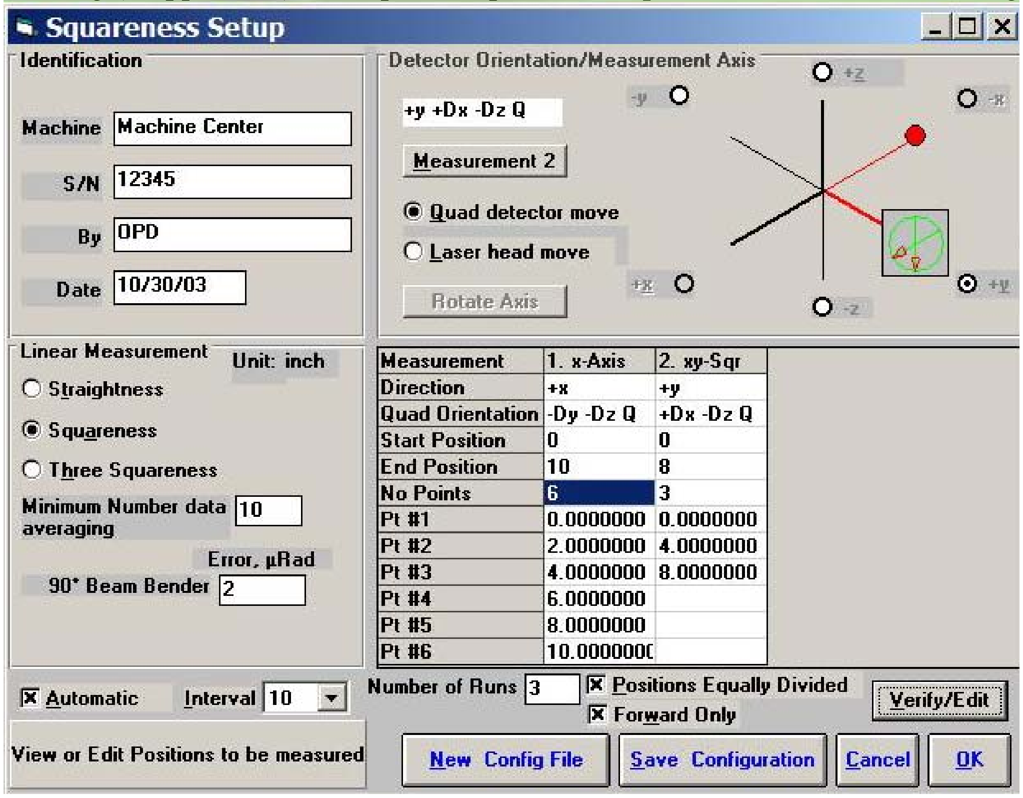


Fig. 10-9 Squareness Measurement Setup Screen (Leg 2)

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.4CF 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.

10.6.3 Example of a Squareness Measurement

1) At the main menu, click the left mouse button on **Squareness**.
Squareness Measurement Main Display (Fig. 10-7)

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. 10-8, 10-9)

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 Data Points for a Squareness Measurement (Fig. 10-10)

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**.

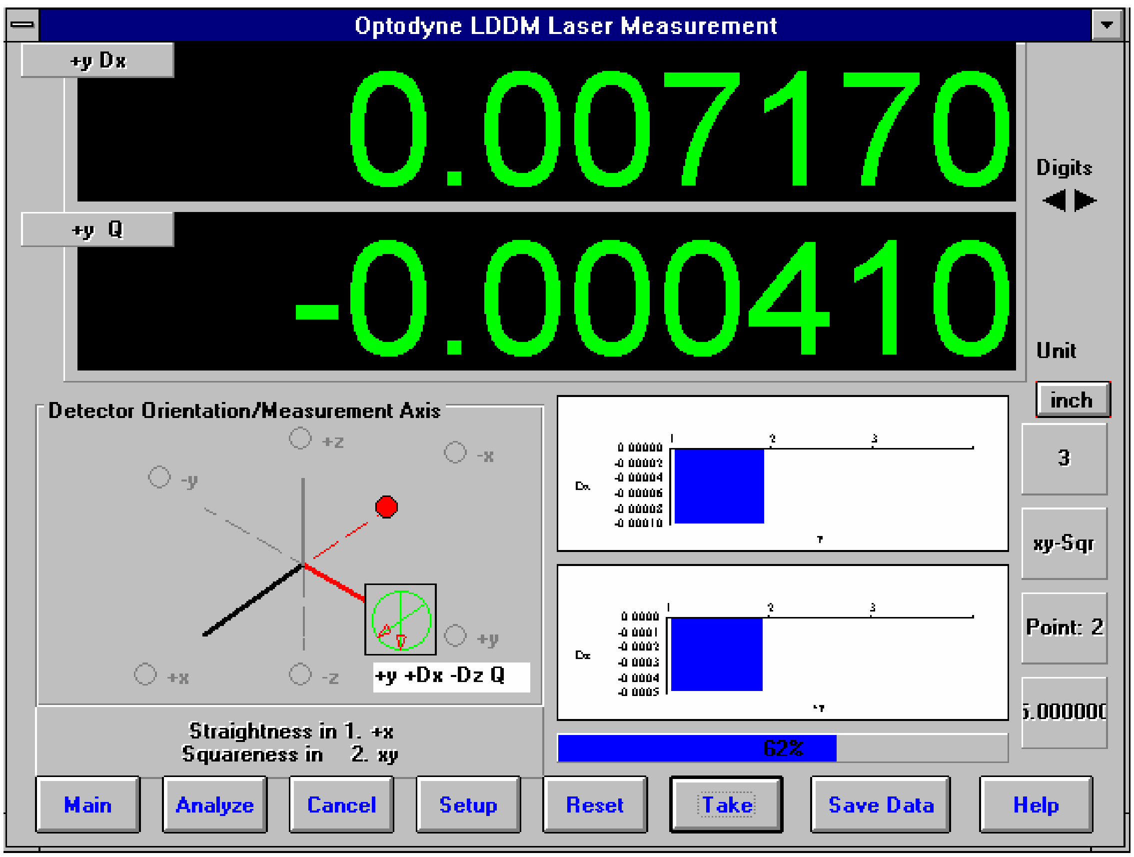


Fig. 10-10 Manual Squareness Data Collection

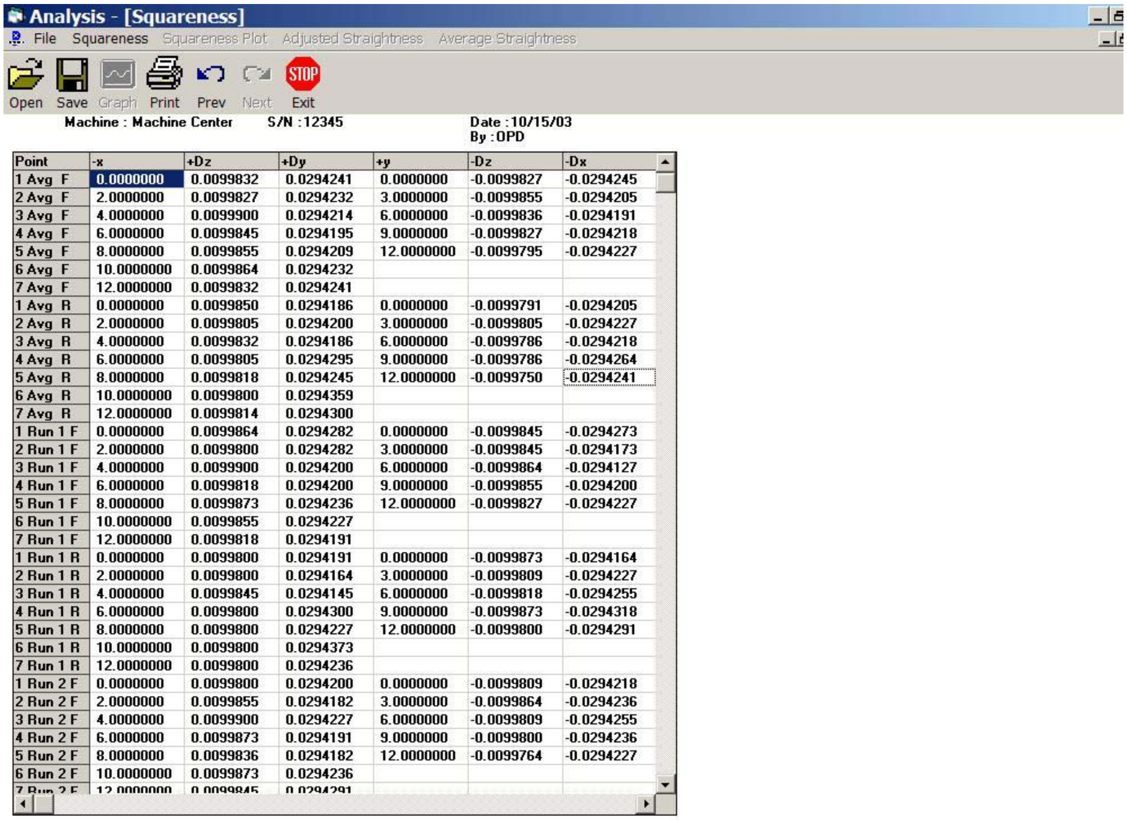
20) Setup your second axis and press the **Start Axis 2** button, repeat 19.

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).

10.6.4 Squareness Data Analysis (Fig. 10-11, 10-12)



Point	-x	+Dz	+Dy	+y	-Dz	-Dx
1 Avg F	0.0000000	0.0099832	0.0294241	0.0000000	-0.0099827	-0.0294245
2 Avg F	2.0000000	0.0099827	0.0294232	3.0000000	-0.0099855	-0.0294205
3 Avg F	4.0000000	0.0099900	0.0294214	6.0000000	-0.0099836	-0.0294191
4 Avg F	6.0000000	0.0099845	0.0294195	9.0000000	-0.0099827	-0.0294218
5 Avg F	8.0000000	0.0099855	0.0294209	12.0000000	-0.0099795	-0.0294227
6 Avg F	10.0000000	0.0099864	0.0294232			
7 Avg F	12.0000000	0.0099832	0.0294241			
1 Avg R	0.0000000	0.0099850	0.0294186	0.0000000	-0.0099791	-0.0294205
2 Avg R	2.0000000	0.0099805	0.0294200	3.0000000	-0.0099805	-0.0294227
3 Avg R	4.0000000	0.0099832	0.0294186	6.0000000	-0.0099786	-0.0294218
4 Avg R	6.0000000	0.0099805	0.0294295	9.0000000	-0.0099786	-0.0294264
5 Avg R	8.0000000	0.0099818	0.0294245	12.0000000	-0.0099750	-0.0294241
6 Avg R	10.0000000	0.0099800	0.0294359			
7 Avg R	12.0000000	0.0099814	0.0294300			
1 Run 1 F	0.0000000	0.0099864	0.0294282	0.0000000	-0.0099845	-0.0294273
2 Run 1 F	2.0000000	0.0099800	0.0294282	3.0000000	-0.0099845	-0.0294173
3 Run 1 F	4.0000000	0.0099900	0.0294200	6.0000000	-0.0099864	-0.0294127
4 Run 1 F	6.0000000	0.0099818	0.0294200	9.0000000	-0.0099855	-0.0294200
5 Run 1 F	8.0000000	0.0099873	0.0294236	12.0000000	-0.0099827	-0.0294227
6 Run 1 F	10.0000000	0.0099855	0.0294227			
7 Run 1 F	12.0000000	0.0099818	0.0294191			
1 Run 1 R	0.0000000	0.0099800	0.0294191	0.0000000	-0.0099873	-0.0294164
2 Run 1 R	2.0000000	0.0099800	0.0294164	3.0000000	-0.0099809	-0.0294227
3 Run 1 R	4.0000000	0.0099845	0.0294145	6.0000000	-0.0099818	-0.0294255
4 Run 1 R	6.0000000	0.0099800	0.0294300	9.0000000	-0.0099873	-0.0294318
5 Run 1 R	8.0000000	0.0099800	0.0294227	12.0000000	-0.0099800	-0.0294291
6 Run 1 R	10.0000000	0.0099800	0.0294373			
7 Run 1 R	12.0000000	0.0099800	0.0294236			
1 Run 2 F	0.0000000	0.0099800	0.0294200	0.0000000	-0.0099809	-0.0294218
2 Run 2 F	2.0000000	0.0099855	0.0294182	3.0000000	-0.0099864	-0.0294236
3 Run 2 F	4.0000000	0.0099900	0.0294227	6.0000000	-0.0099809	-0.0294255
4 Run 2 F	6.0000000	0.0099873	0.0294191	9.0000000	-0.0099800	-0.0294236
5 Run 2 F	8.0000000	0.0099836	0.0294182	12.0000000	-0.0099764	-0.0294227
6 Run 2 F	10.0000000	0.0099873	0.0294236			
7 Run 2 F	12.0000000	0.0099845	0.0294291			

Fig. 10-11 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 = 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 negtive 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.

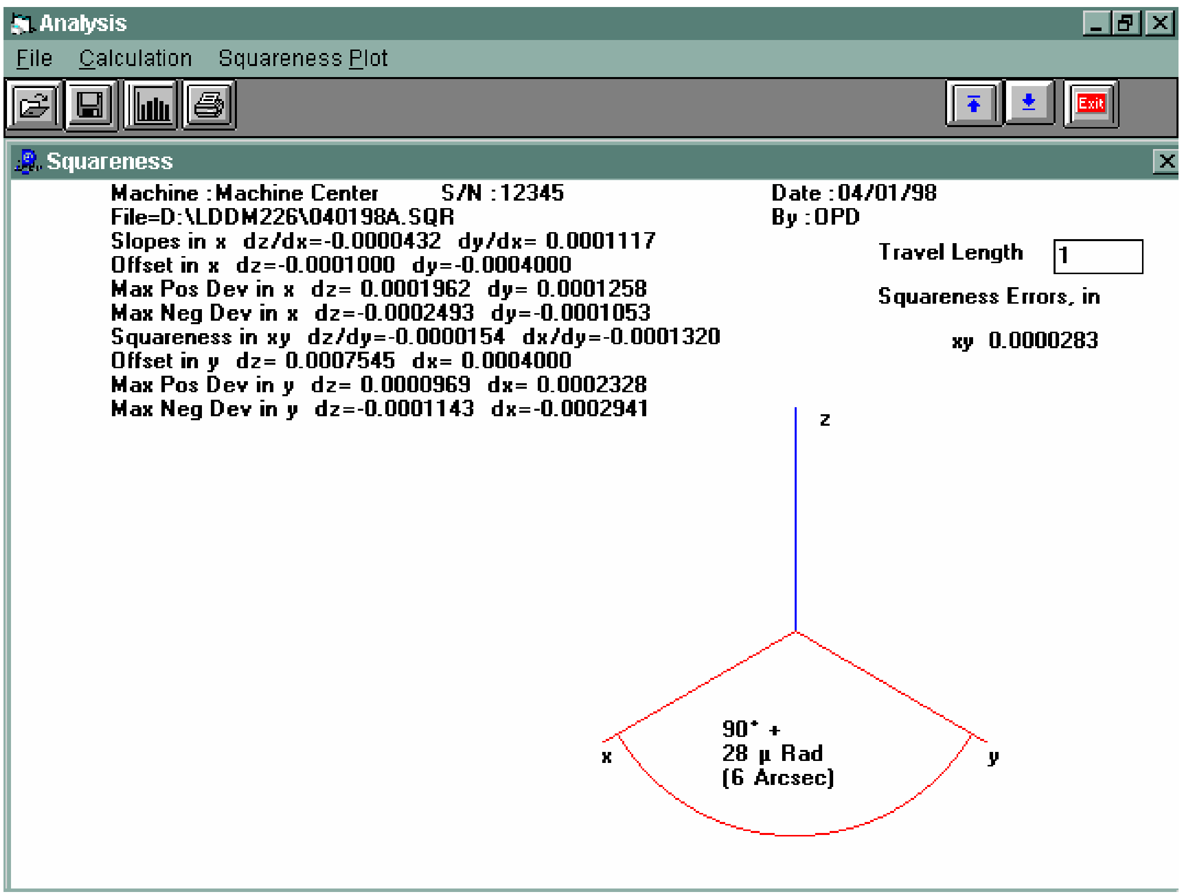
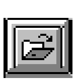
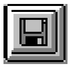


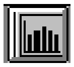
Fig. 10-12 Squareness Measurement Data Plot

The following icons have the following function in Analysis:

 Open a new data file.

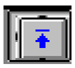


Save a data file.

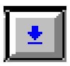


Graph a data file (After graphing, you may also change the scaling of the graph by checking X on adjust grid).

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



Moves to the previous screen.

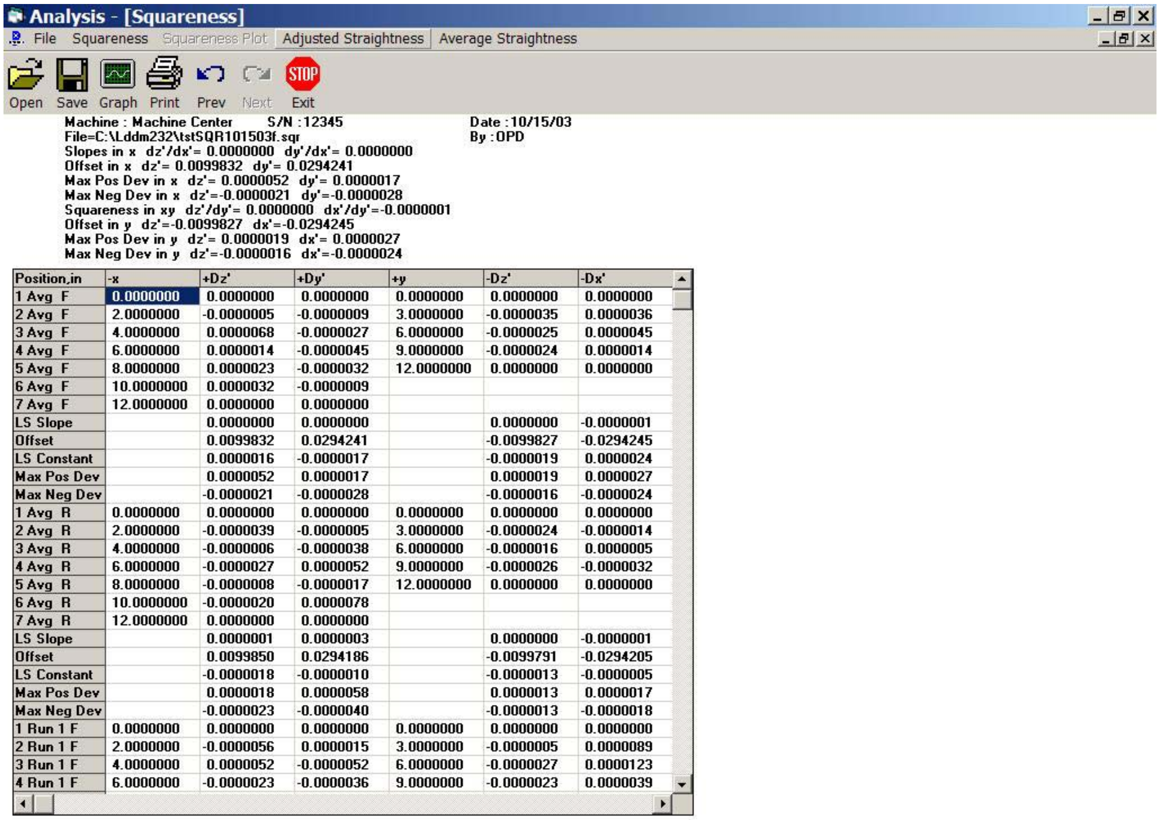


Moves to the next screen.

Exits the program.

10.6.5 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 10-12b. Here both end points are zero.



Position,in	-x	+Dz'	+Dy'	+y	-Dz'	-Dx'
1 Avg F	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
2 Avg F	2.0000000	-0.0000005	-0.0000009	3.0000000	-0.0000035	0.0000036
3 Avg F	4.0000000	0.0000068	-0.0000027	6.0000000	-0.0000025	0.0000045
4 Avg F	6.0000000	0.0000014	-0.0000045	9.0000000	-0.0000024	0.0000014
5 Avg F	8.0000000	0.0000023	-0.0000032	12.0000000	0.0000000	0.0000000
6 Avg F	10.0000000	0.0000032	-0.0000009			
7 Avg F	12.0000000	0.0000000	0.0000000			
LS Slope		0.0000000	0.0000000		0.0000000	-0.0000001
Offset		0.0099832	0.0294241		-0.0099827	-0.0294245
LS Constant		0.0000016	-0.0000017		-0.0000019	0.0000024
Max Pos Dev		0.0000052	0.0000017		0.0000019	0.0000027
Max Neg Dev		-0.0000021	-0.0000028		-0.0000016	-0.0000024
1 Avg R	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
2 Avg R	2.0000000	-0.0000039	-0.0000005	3.0000000	-0.0000024	-0.0000014
3 Avg R	4.0000000	-0.0000006	-0.0000038	6.0000000	-0.0000016	0.0000005
4 Avg R	6.0000000	-0.0000027	0.0000052	9.0000000	-0.0000026	-0.0000032
5 Avg R	8.0000000	-0.0000008	-0.0000017	12.0000000	0.0000000	0.0000000
6 Avg R	10.0000000	-0.0000020	0.0000078			
7 Avg R	12.0000000	0.0000000	0.0000000			
LS Slope		0.0000001	0.0000003		0.0000000	-0.0000001
Offset		0.0099850	0.0294186		-0.0099791	-0.0294205
LS Constant		-0.0000018	-0.0000010		-0.0000013	-0.0000005
Max Pos Dev		0.0000018	0.0000058		0.0000013	0.0000017
Max Neg Dev		-0.0000023	-0.0000040		-0.0000013	-0.0000018
1 Run 1 F	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
2 Run 1 F	2.0000000	-0.0000056	0.0000015	3.0000000	-0.0000005	0.0000089
3 Run 1 F	4.0000000	0.0000052	-0.0000052	6.0000000	-0.0000027	0.0000123
4 Run 1 F	6.0000000	-0.0000023	-0.0000036	9.0000000	-0.0000023	0.0000039

Fig. 10-12a Typical Data Screen Shows the Multiple Run Data

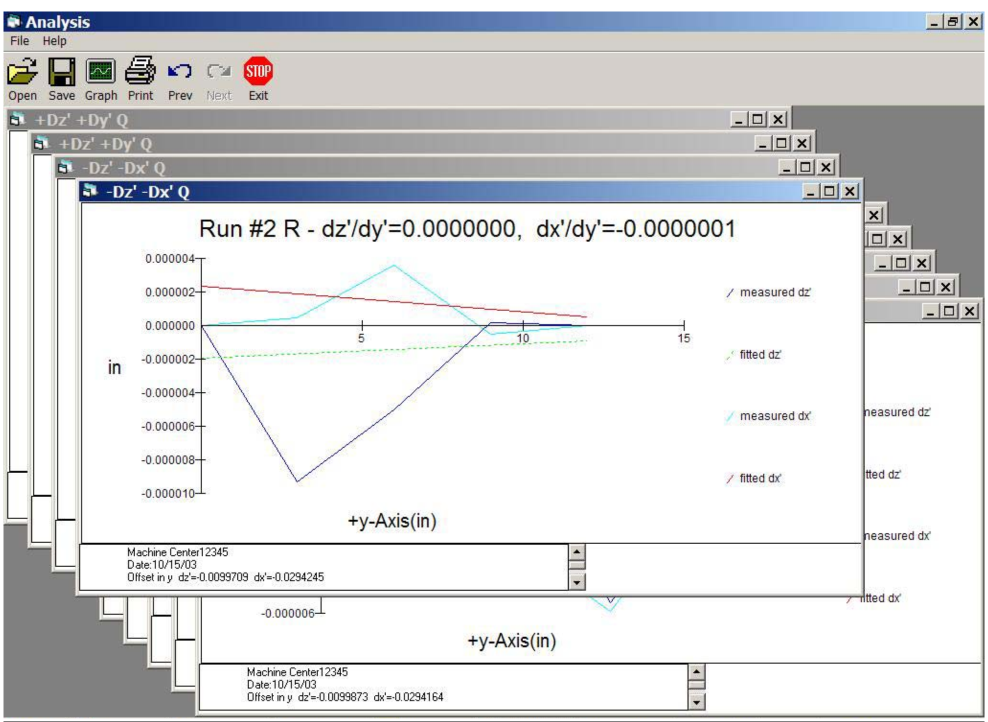


Fig. 10-12b A Plot of Adjusted Vertical and Horizontal Straightness.
The Straight Line is the Least Square Fit.

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. 10-12c. Here the least square fitted line is rotated to be zero off-set and zero slope.

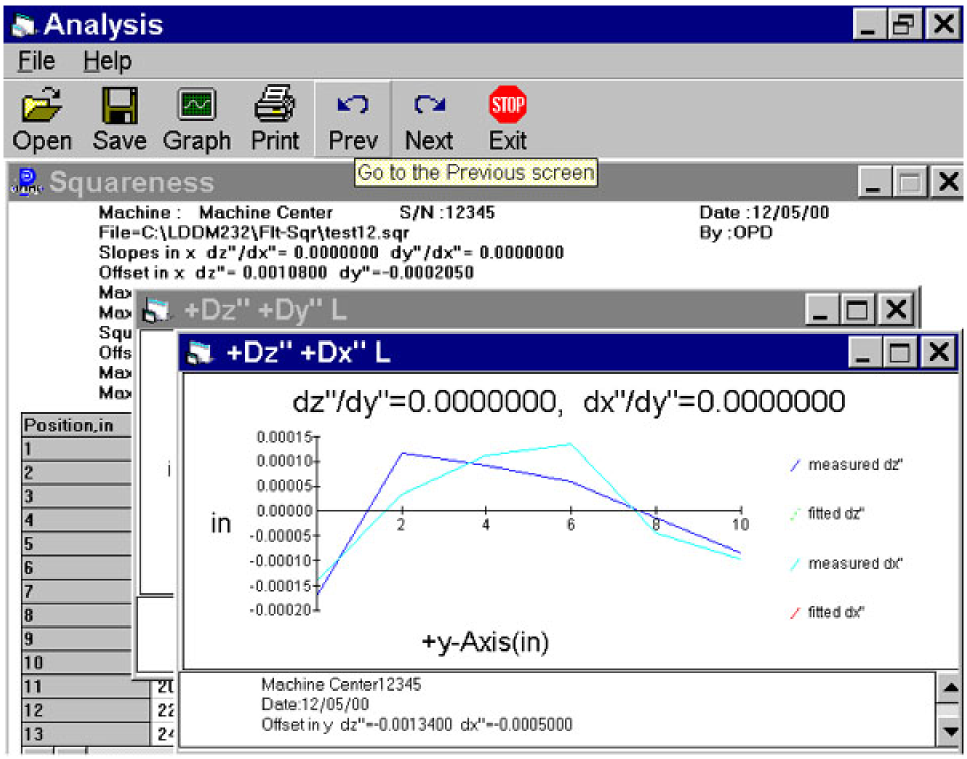


Fig. 10-12c A plot of Averaged Vertical and Horizontal Straightness. Here the Least Square Fit Line is at Zero and Parallel to the Axis of Travel.

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. 10-13. Similar measurements for Y-axis and Z-axis are shown in Fig. 10-14 and 10-15. 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. 10-16 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. 10-17. Squareness in other planes is shown in Fig. 10-18 and 10-19.

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. 10-18 and 10-19).

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.

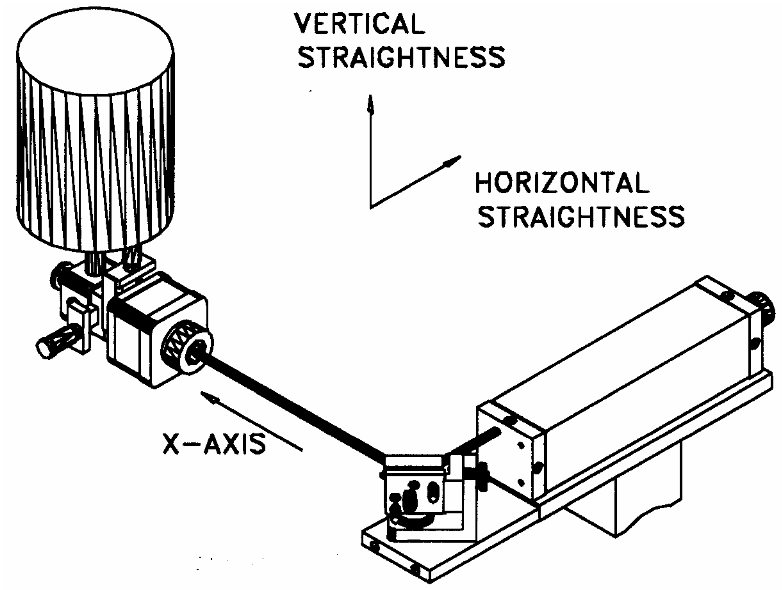


FIG. 10-13 HORIZONTAL AND VERTICAL STRAIGHTNESS OF X-AXIS

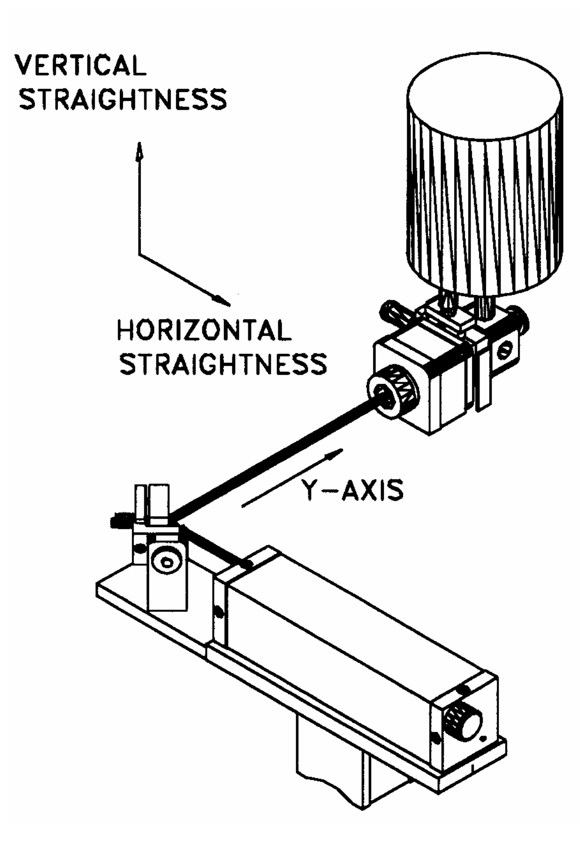


FIG. 10-14 HORIZONTAL AND VERTICAL STRAIGHTNESS OF Y-AXIS

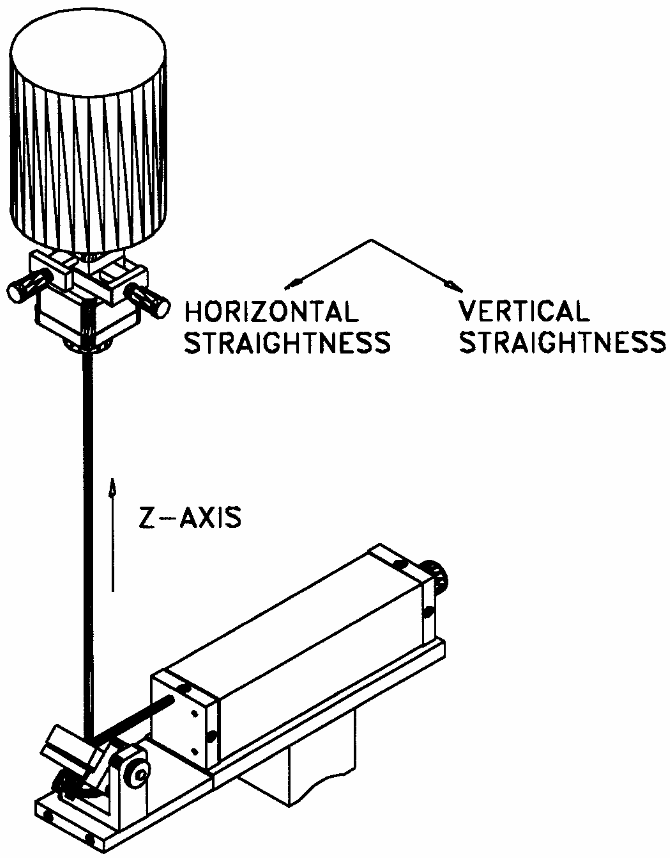


FIG. 10-15 HORIZONTAL AND VERTICAL STRAIGHTNESS OF Z-AXIS

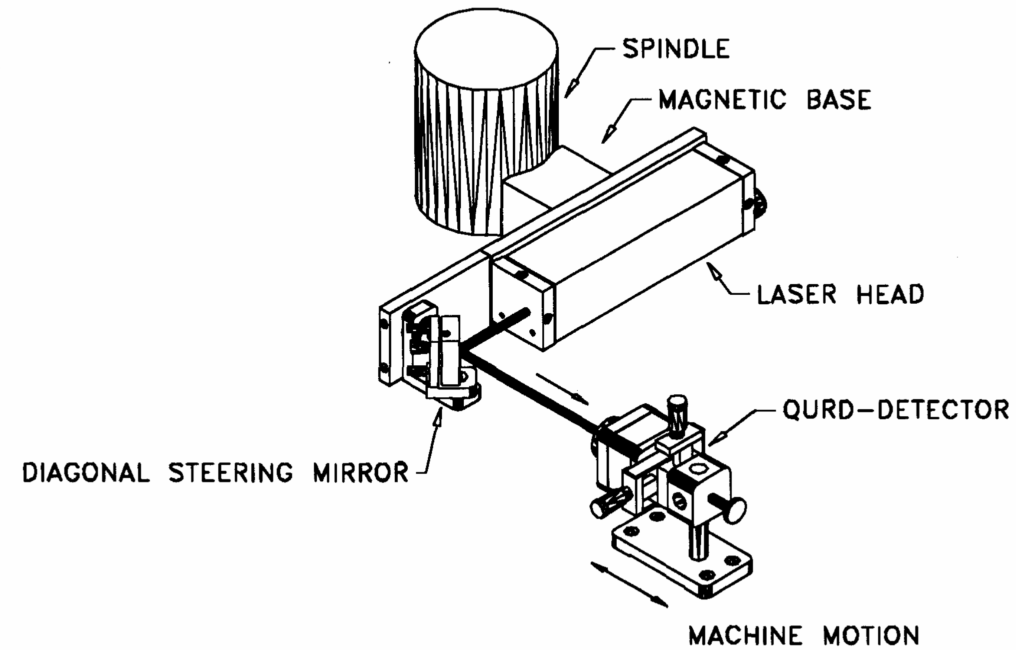


FIG. 10-16 SPINDLE MOUNT

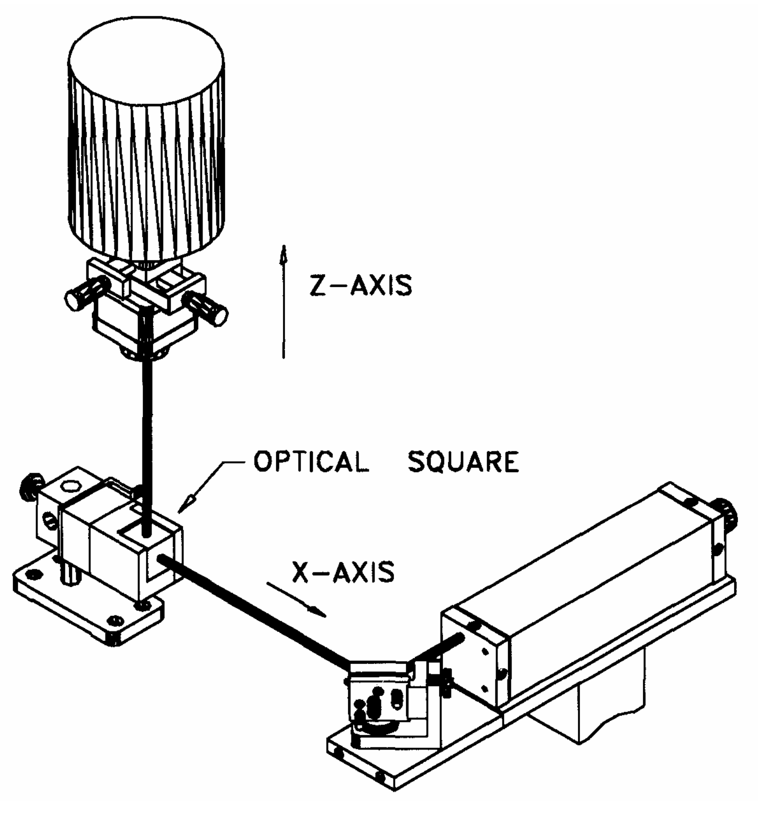


FIG. 10-17 SQUARENESS IN X-Z PLANE

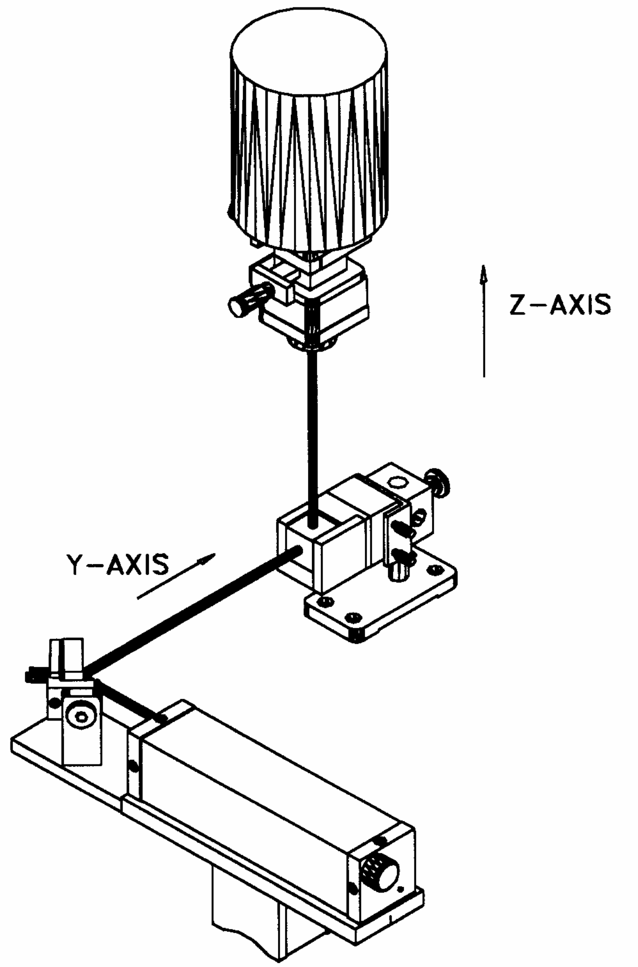


FIG. 10-18 SQUARENESS IN Y-Z PLANE

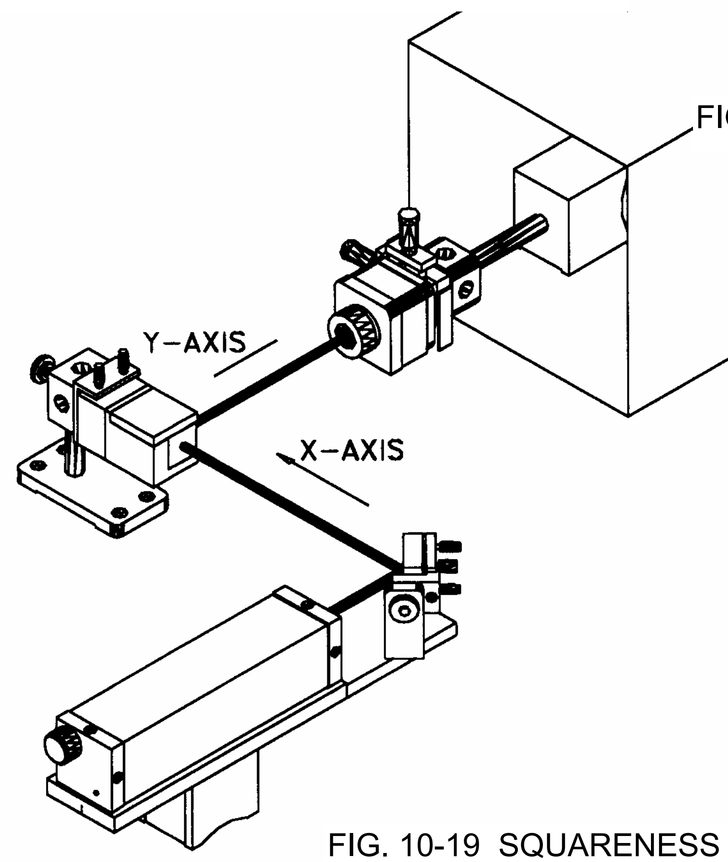


FIG. 10-19 SQUARENESS IN X-Y PLANE

11.0 Measurement of Spindle Error Motion

11.1 Introduction and Basic Theory

The major spindle error motion is caused by the alignment of the spindle rotational axis, the centerline of the tool holder and the centerline of the tool. All of these should be coaxial. Any deviation from coaxial will generate eccentric error motion. Other causes of the radial and axial error motions are the spindle bearings, structure error motion, etc.

Conventional measurement techniques using a precision spindle tester, capacitor transducers and an oscilloscope are complex and heavy. The precision spindle tester is very heavy and need periodic calibration. The capacitor transducers are limited by the sensitivity, range and non-linearity.

The spindle test accessories (DI-500) are designed for spindle error motion measurement with an MCV-500 laser system. The single aperture MCV-500 laser system is based on laser Dopplermetry. Hence, with a focus lens, a polished spherical surface can be used as a target. Mount the polished sphere on a spindle, the distance between the laser head and the surface of the sphere can be measured. The spindle error motion can be determined by measure the variations of the distance during spindle rotation.

For spindle error motion in a fixed sensitive direction, pointing the laser beam in a fixed direction and measure the variation of the distance between the laser head and the surface of the sphere during rotation. For spindle error motion in a rotational sensitive direction, use two laser heads, one pointing in the X-direction and one pointing in the Y-direction. Or use only one laser head, first pointing in the X-direction and measure the distance variation. Then repeat the same measurement with the laser head pointing in the Y-direction. A typical setup is shown in Fig. 11-1 and 11-2.

As compared with conventional techniques, the advantages of the laser measurement method are: (1) higher accuracy and resolution, (2) larger standoff distance, (3) easy setup and operation, (4) no need for a heavy precision tester and periodical calibration, and (5) save cost and time.

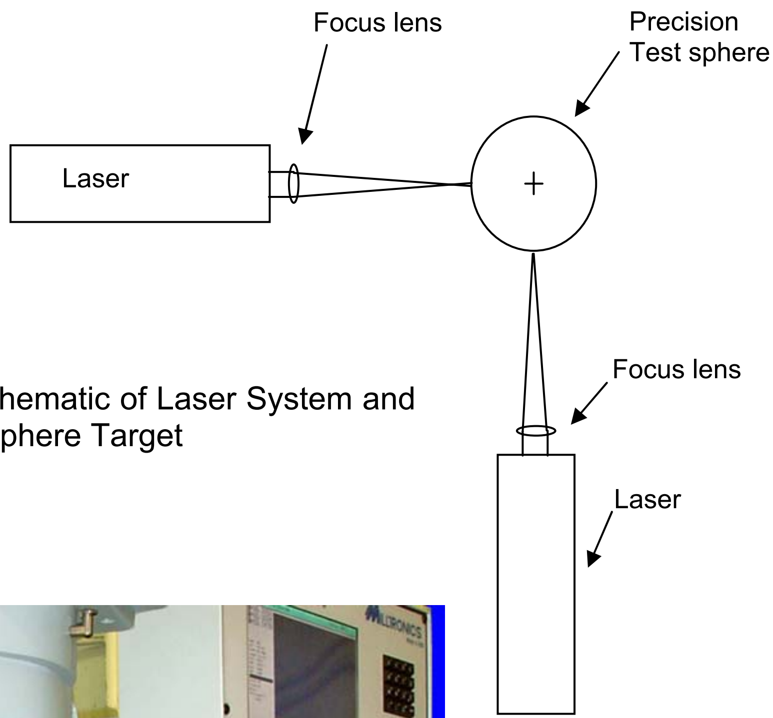


Fig.11-1 A Schematic of Laser System and the Sphere Target

Fig. 11-2 A Photo of a Typical Setup for the Measurement of Spindle Error Motion

11.1.1 Measurement of Spindle Offset

First point the laser in the X- or Y- direction, align the spherical surface to the focus point, and the reflected laser beam entered the aperture. As shown in Fig. 11-3, first align the sphere to the center of rotation by adjusting the 4 fine thread screws and make sure there are no changes in the laser readings or the readings are varied less than the background noise or vibration. Then rotate the tool holder together with the sphere tester 180 degrees. As shown in fig. 11-4, after rotating the tool holder together with the sphere tester 180 degrees, the offset is twice the offset between the spindle axis of rotation and the tool centerline. Manually rotate the spindle from X to -X and from Y to -Y. The maximum difference in X direction is ΔX_M and in Y direction is ΔY_M. The offset between the spindle axis of rotation and the tool center Δ can be determined by

$$\Delta = 0.25 * SQRT[\Delta X_M * \Delta X_M + \Delta Y_M * \Delta Y_M], \qquad \text{Eq. 1}$$

$$\varphi = Arctan [\Delta Y_M / \Delta X_M]. \qquad \text{Eq. 2}$$

The accuracy of this measurement is limited by the roundness of the sphere, typically 0.5 µm.

11.1.2 Measurement of the Total Spindle Error Motion

To measure the total spindle error motion, rotate the spindle and record the two laser systems readings, $\Delta X(t)$ and $\Delta Y(t)$, over several revolutions.

The total spindle error motion at a constant rotational speed can be expressed as a function of the angle θ and the number of cycles i.

$$r_i(\theta) = r_f + dr(\theta) + dr_i(\theta), \; i = 1,2,3,\ldots.N \qquad \text{Eq. 3}$$

where r_f is the fundamental error motion, $dr(\theta)$ is the residual error motion, $dr_i(\theta)$ is the asynchronous error motion, θ is the rotational angle, and N is the total number of cycles.

Here r_f is due to the offset between the spindle axis of rotation and the center of the tool, $dr(\theta)$ is due to the spindle bearing, the non-roundness of the sphere, and other synchronous error motion, and $dr_i(\theta)$ is due to the structure error motion or other asynchronous error motion. Once the total spindle error motion $r_i(\theta)$ is measured, the r_f, $dr(\theta)$, $dr_i(\theta)$ can be determined by the following relations.

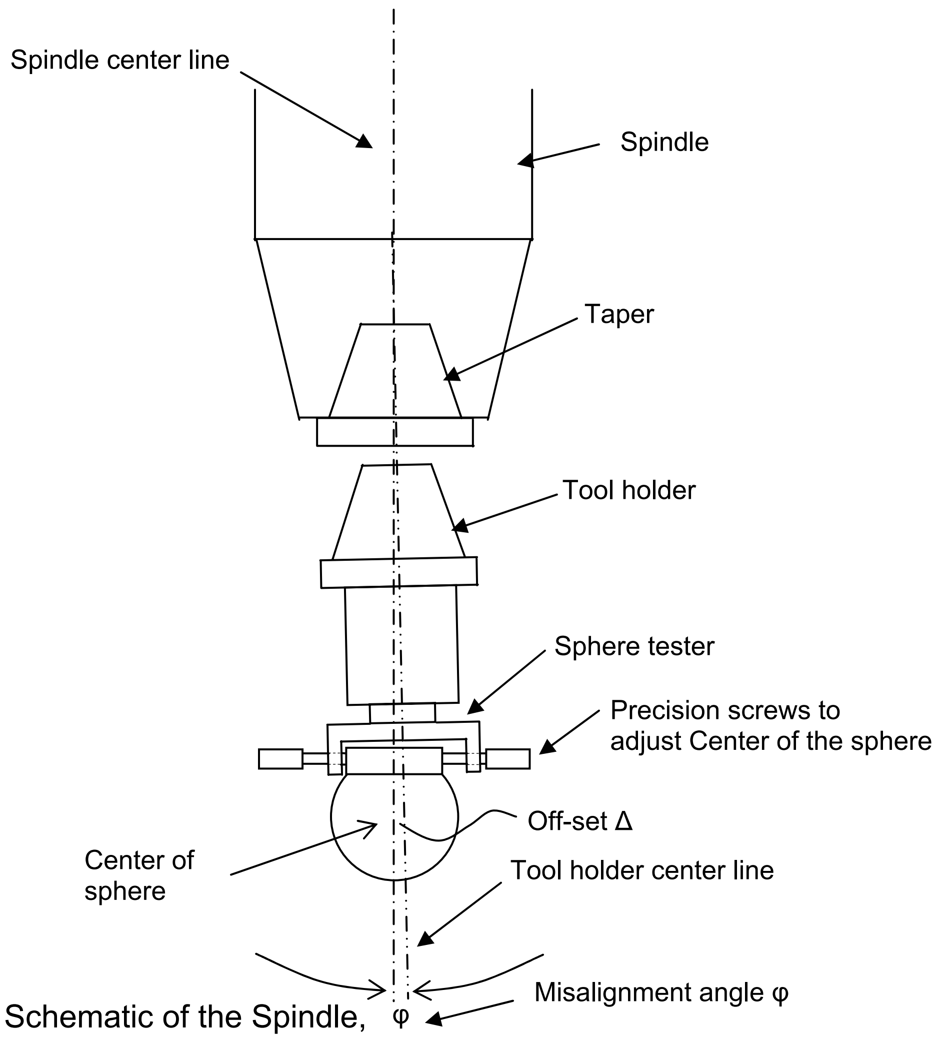


Fig. 11-3 A Schematic of the Spindle, the Tool Holder, and the Sphere Tester

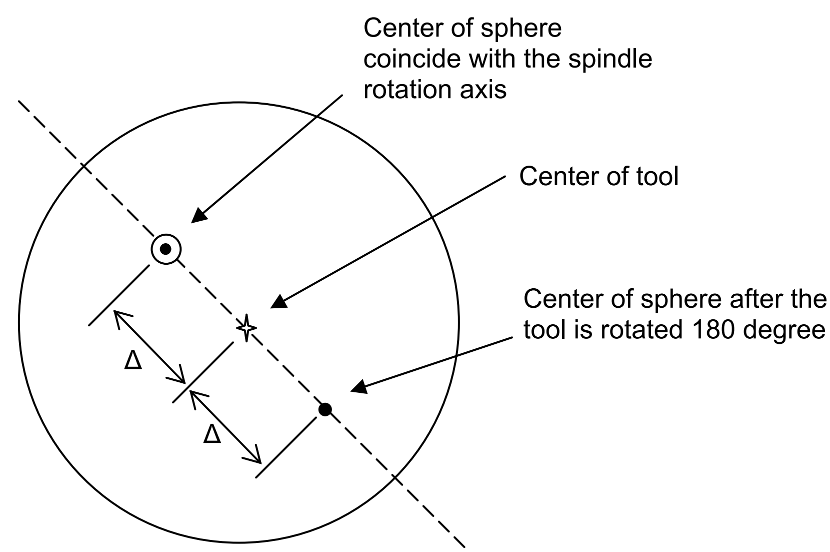


Fig. 11-4 A Schematic Illustrate the Effect of Rotating the Tool Holder by 180 Degree

$r_f = << r_i(\theta) >_i >_\theta$ Eq. 4

$dr(\theta) = < r_i(\theta) >_i - r_f$ Eq. 5

where $< >_i = \Sigma_i [\ ]/N$ is the average over N cycles
and $< >_\theta = \Sigma_\theta \{\ \}/2\pi$ is the average over 2π angle.

Based on the ASME B89.3.4M-1985 standard, the error motion values are defined as the followings.
Total error motion value = $Max_{i,\theta}\{ r_i(\theta) \} - Min_{i,\theta}\{ r_i(\theta) \}$
Average error motion value = $Max_\theta\{ r_f + dr(\theta) \} - Min_\theta\{ r_f + dr(\theta)\}$
Fundamental error motion value = r_f
Residual error motion value = $Max_\theta\{ dr(\theta) \} - Min_\theta\{ dr(\theta)\}$
Asynchronous error motion value = $Max_\theta\{ Max_i[r_i(\theta)] – Min_i[r_i(\theta)\}$,
Where $Max_i[\ ]$ is the maximum value over N cycles, $Min_i[\ ]$ is the minimum value over N cycles, $Max_\theta\{\ \}$ is the maximum value over angles θ, and $Min_\theta\{\ \}$ is the minimum value over angles θ.

For machine tool applications, there is a sensitive direction of spindle motion, defined as that component of axis motion that occurs in a direction that is directly toward or away from a cutting tool. There are two types of sensitive directions, one is the fixed sensitive direction, in which the work-piece is rotated by the spindle and the point of machining is fixed such as a lathe. The other is the rotating sensitive direction, in which the work-piece is fixed and the point of machining rotates with the spindle such as a milling machine.

There are 6 degrees of spindle error motion. However, only three of them are relevant. These are the radial error motion, tilt error motion and axial error motion. The radial error motion is the error motion in a direction normal to the z-axis. The tilt error motion is the error motion in an angular direction relative to the z-axis. The axial error motion is the error motion co-linear with the z-axis.

For the tilt measurement, repeat the radial error motion measurement at a different height L. The tile α(θ) can be expressed as

$\alpha(\theta) = [r(\theta) \text{ at } L - r(\theta) \text{ at zero}] / L$ Eq. 6

For axial error motion, use a mirror to bend the laser beam upward and point the focus of the laser beam to the center of rotation. The measured laser displacement in the z-direction is the axial error motion Z(θ).

11.2 Hardware Required

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

a. Single Aperture Laser Head	L-109
b. Processor Module with RS-232 Interface	P-108D
c. Focus Lens (100mm)	LD-47C
d. Metrology/Analysis Program with Spindle Analysis	W-500/W-500DI
e. 1.5" Diameter Sphere with Adjustable Center	LD-76
f. Magnetic Base	LD-03
g. Adapter Platform	LD-14A
h. 12 ft Cable Set	LD-21L
i. PC Card and Cable	IPC5-1000
j. Notebook PC	Not supplied

Option, 2-channel simultaneous data collection:

a. Single Aperture Laser Head (Quantity 2)	L-109
b. Processor Module with RS-232 Interface (2-channel)	P-108D
c. Focus Lens (100mm) (Quantity 2)	LD-47C
d. Metrology/Analysis Program with Spindle Analysis	W-500/W-500DI
e 1.5" Diameter Sphere with Adjustable Center	LD-76
f. Magnetic Base (Quantity 2)	LD-03
g. Adapter Platform (Quantity 2)	LD-14A
h. 12 ft Cable Set (Quantity 2)	LD-21L
i. PC Card and Cable (Quantity 2)	IPC5-1000
j. Notebook PC	Not supplied

11.3 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 μin (0.01 μm).
Maximum Velocity:	160 inch/sec (4000 mm/sec)
Stand off Distance	0.5” to 4” (10 mm to 100 mm)
Temperature	60°F to 90°F or (15.5°C to 32°C) Option 40°F to 100°F or (5°C to 37°C)

11.4 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, February 2001.

J. Bryan, R. Clonser and E. Holland, “Spindle accuracy”, American Machinist, Dec. 4, 1967.

Axes of rotation, methods for specifying and testing, An American National Standard, ASME B89.3.4M-1985 by American Society of Mechanical Engineers, 1985.

Methods for performance evaluation of computer numerically controlled machining centers, An American National Standard, ASME B5.54-1992 by the American Society of Mechanical Engineers, 1992.

11.5 Installation and Alignment

11.5.1 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. Never use a tripod to mount the laser head. The tripod may introduce an error.

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 spherical surface.

4. Vibration and loose connections must be minimized by proper mounting. Make sure that all supports and cables are completely stationary.

5. The output laser beam and the spherical target must be aligned properly such that the beam intensity is above the minimum requirement along the entire revolution. Move the sphere up or down slightly to avoid a scratch or a rough spot on the sphere. However, if there are too many scratches or rough spots, the sphere needs to be re-polished.

11.5.2 Installation

11.5.2.1 Set up LDDM Program

See Section 7.5.2.1.

11.5.2.2 Starting LDDM Program

See Section 7.5.2.2.

11.5.2.3 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 (MCV-500). 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.

11.5.2.4 Setup Laser Head and Spherical Target

Attach the focus lens to the front of the laser head (Fig.11-5). Tighten the two screws on the side. Mount the laser head with the focus lens on the bed with a magnetic holder and the spherical target on the spindle, as shown in Fig.11-2.

Finally, adjust the spindle position such that the return laser beam enters the aperture of the focus lens. The green light on the data collection screen should be on. Rotate the spindle and make sure the green light is always on. Otherwise, move the spindle up or down slightly. If there are too many scratched, re-polish the sphere.

To repolish the sphere, rotate the sphere at about 100 rpm and use a flat metal surface (1/4” wide and 3” to 5” long) and soft tissue. Applied a small amount of the polishing paste (Diamond Lapping Compound, grad 1, super-fine finishing) on the soft tissue and press slightly the flat metal surface with soft tissue & paste against the equator of the sphere. During polishing, there is more scattered light due to the polishing paste. After the polishing, the scattered light should be reduced. Continue polishing until there is no rough spot or scratches and there is no jump in laser displacement value over one revolution.

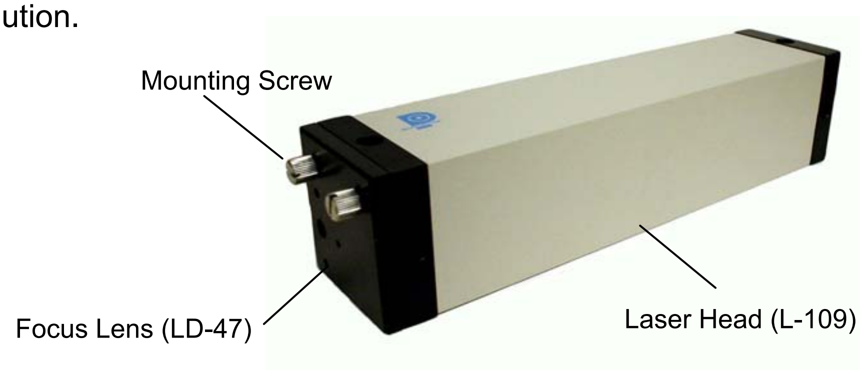


FIG. 11-5 LASER HEAD WITH FOCUS

11.5.3 Measurement of Spindle Offset

The spindle offset is the distance between the spindle axis of rotation and the tool center.

As shown in Fig. 11-3, first point the laser in the X- or Y- direction, align the spherical surface to the focus point, and the reflected laser beam entered the aperture. As shown in Fig. 11-3, first align the sphere to the center of rotation by adjusting the 4 fine thread screws and make sure there are no changes in the laser readings or the readings are varied less than the background noise or vibration. Then rotate the tool holder together with the sphere tester 180 degrees. As shown in Fig. 11-4, after rotating the tool holder together with the sphere tester 180 degrees, the offset is twice the offset between the spindle axis of rotation and the tool centerline. Manually rotate the spindle from X to -X and from Y to -Y. The maximum difference in X direction is ΔX_M and in Y direction is ΔY_M. The offset between the spindle axis of rotation and the tool center Δ can be determined by

$$\Delta = 0.25 * SQRT[\Delta X_M * \Delta X_M + \Delta Y_M * \Delta Y_M], \qquad \text{Eq. 1}$$

$$\varphi = \text{Arctan } [\Delta Y_M / \Delta X_M]. \qquad \text{Eq. 2}$$

The accuracy of this measurement is limited by the roundness of the sphere, typically 0.5 μm.

11.5.4 Measurement of the Radial Spindle Error Motion

The radial error motion is the error motion in a direction normal to the Z-axis.

To measure the total spindle error motion, rotate the spindle and record the two laser systems readings, X(t) and/or Y(t), over several revolutions using the dynamic measurement as illustrated in section 11.8. The radial spindle error can be obtained by two perpendicular and simultaneous readings or more simply but with good approximation with only one reading only and generating the 90 degree error file by software calculation, assuming that the radial spindle error is axial symmetric.

11.5.5 Measurement of Tilt Error Motion

The tilt error motion is the error motion in an angular direction relative to the z-axis.

For the tilt measurement, repeat the radial error motion measurement at a different height L. The tilt () can be expressed as

$$\alpha(\theta) = [r(\theta) \text{ at } L - r(\theta) \text{ at zero}] / L \qquad \text{Eq. 6}$$

11.5.6 Measurement of Axial Error Motion

The axial error motion is the error motion co-linear with the z-axis.

As shown in Fig. 11-3, align the sphere to the center of rotation by adjusting the 4 fine thread screws and rotating the spindle manually, make sure there are no changes in the laser readings or the readings are varied less than the background noise or vibration.

For axial error motion, use a mirror to bend the laser beam upward and point the focus of the laser beam to the center of rotation. The measured laser displacement in the z-direction is the axial error motion $Z(\theta)$.

Before to take the measurement as shown in Fig. 11-3, align the sphere to the center of rotation by adjusting the 4 fine thread screws and rotating the spindle manually, make sure there are no changes in the laser readings or the readings are varied less than the background noise or vibration.

11.6 Software Description

11.6.1 General Description

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

11.6.2 2D Time Base Data Collection

See section 8.6.2

11.6.3 Data Analysis

See section 8.6.3

11.6.4 Spindle Error Motion

To analyze the spindle error motion, first to process all raw data files(.2dr) to generate the ASCII data files(.2dd).

Click on “Analysis” and “Spindle”, a screen will popup. The file cannot be entered by type the filename. Click on the right-hand-side to enter the files. The axis 1 may be X-direction or Y-direction. The axis 2 must be perpendicular to the axis 1. In general, the axis 1 and axis 2 data were taken separately, the period or number of points per cycle must be calculated. The phase shift value should be ¼ of the number of points per cycle. If only one axis data is available, leave the axis 2 blank and the axis 2 will be generated by using the axis 1 file and shift by 90 degree.

After click on “Ok”, a new screen will popup, as shown in Fig. 11-6.

Enter the starting point number and ending point number. The minimum points per cycle is set at 50 and the orientation angle at 0. The zero angle is the X-axis in the positive direction. To rotate an angle φ, CW, enter φ degree in the orientation angle. Average parameters P1 and P2 are the number of points of the average. The default value is 1. Multiplier is the scale factor of axis 1 And axis 2. They can be positive or negative. The default value is 1. The off-set is the value add to the data file. The default value is 0.

After click on “Ok”, then enter the axis 2 phase shift. The default value is zero. The table can display up to 20 cycles. The first column is the angle. The rest of the columns are averaged over all cycles, maximum and minimum over all cycles, values of cycle 1, 2, …, 20. Click on "graph" to generate Polar or linear plots. The definition of various errors are defined in section 11.5.4.

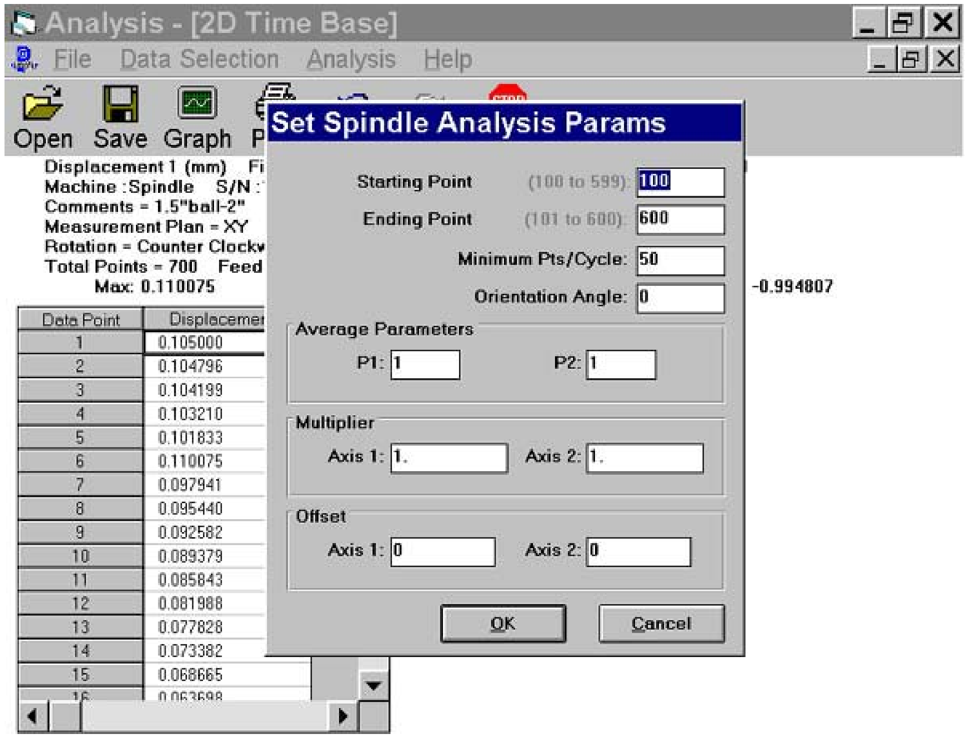


Fig. 11-6 A Popup Screen to Select the Spindle Analysis Parameters

11.7 Accuracy and Error Sources

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

11.7.2 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 spindle measurement. 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.

11.7.3 Scratches or Rough Spots

If there is a large scratch or a rough spot on the surface, the return laser beam may be scattered or deformed. This may cause lost of intensity momentary. A sudden increase or decrease in reading will occurs and cause error readings. The sphere may be moved up or down a few microns to avoid rough spots. Please make sure the reading returns to the same after a 360 degree rotation.

11.8 Taking a Dynamic Measurement

11.8.1 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 installed 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 rpm, the data rate, and the direction of measurement..

11.8.2 Alignment

1 Mount the laser head on the bed and pointing the laser beam in the x-direction or Y-direction (within a few degrees).
2 Mount the sphere on the spindle and align the sphere by moving the spindle. Make sure the return beam enters the laser aperture and the green light on the data collection screen is on over the entire 360 degree rotation. Make sure the reading return to the same after a 360 degree rotation.

11.8.3 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 0 for on axis direction. Enter data from 1 to 10,000 data/sec. Select the rpm and the data rate S[data/sec] such that a minimum of 50 points per cycle. The maximum size of the file is 24,000 points. For example, at 10 rpm and 15 data/sec, the points per cycle is 90. Similarly at 1000 rpm and 1000 data/sec, the points per cycle is 60.
5. Trigger—Start button only
   Cosine Correction—Single pass = 1
   Scale factor = 0.000024914 in.
   Channel number – 1 or 2
   Intensity – Green means okay
   Red means out of alignmen
   Start – Press start to start collecting data and press end to stop.
   Maximum data file is 24,000 data points.
   Maximum display is 10,000 data points.
   Start the spindle motion first, then press start.

Collect at least 10 cycles of data.

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

11.8.4 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. Please note any large jumps and the point numbers.
4. 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. Or a “Displacement Error Occurred” screen will popup. Click “Ok” to save data.
7. Click on “Analysis”, “Spindle”. A “Select Axis Data Files” screen will pop up. Enter the files by clicking on the right-hand buttons.
8. A “Set Spindle Analysis Parameters” screen will popup. Enter the starting point number, ending point number, average parameters, multipliers, and off-set. Make sure there is no large jump between the starting and the ending point.
9. A “Select Data to Display” screen will popup. Select the cycles and click “Ok”.
10. Click on “Graph” to plot the spindle error motion in polar plot or linear plot.

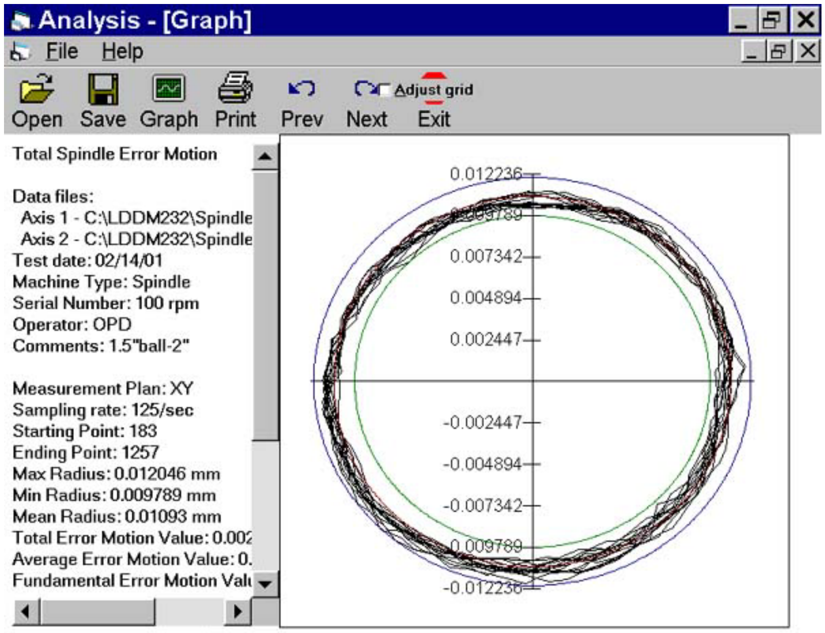


Fig. 11-7 A Polar Plot of the Spindle Error Motion

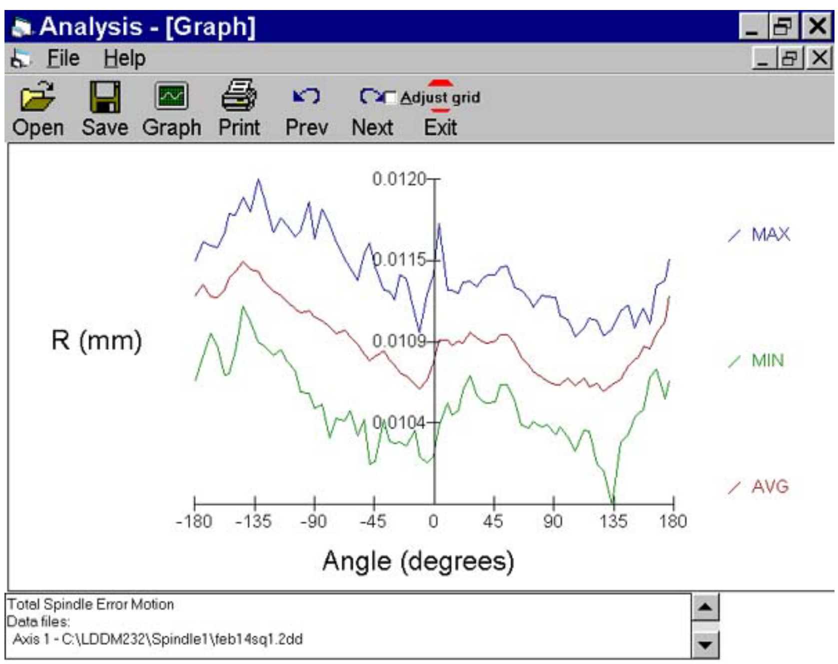


Fig. 11-8 A Linear Plot (Polar plot that is broken open and plotted from –180º to 180º with a magnified scale for easy viewing) Amplifies the Readings Showing the Average, Maximum and Minimum Error Motion

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 changes 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 a 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.

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, 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) Option 40-100°F (5-37°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)	

Material Temperature: One material temperature sensor is standard.

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 traceablilty.

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 ±10%.

The laser frequency 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 know as Material Thermal Expansion Compensation (MTE) and is defined as:

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

where

α = thermal expansion coefficient

$\Delta t = T - 68°F$

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 μm/°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 θ = 1 mrad (3 arcmin), the cosine error is 0.5 ppm.

For example, with the following variables:

controlled environment T = ±0.5°C

total machine travel	L = 50 in.
dead-path	D = 3 in.
misalignment angle	θ = 1 mrad
machine guideway pitch angle	ϕ = 25 μrad
Abbé offset	s = 1 in.
material thermal expansion coefficient	α = 6.5 ppm
laser wavelength error	1 μin

The following errors would result:

The atmospheric compensation error:	1ppm x 50 in x 0.5°C = 25 μin.
The material thermal expansion:	6.5ppm x 50in x 0.5°C=162.5 μin.
The dead-path error:	1ppm x 3 in x 0.5°C = 1.5 μin.
The Abbé error:	1 in x 25 μrad = 25 μin.
The cosine error:	(1 mrad)^2/2 x 50 in = 25 μrad.

The total error, E would then be:

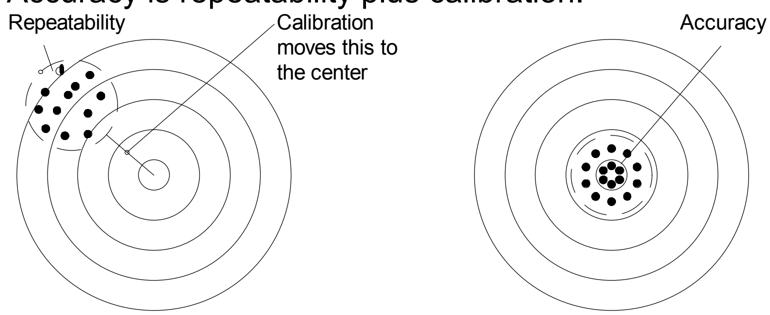
$$E = \sqrt{50^2 + 1^2 + 25^2 + 162.5^2 + 1.5^2 + 25^2 + 25^2}$$
$$\cong 175\ \mu\text{in.}$$

To achieve optimum measurement accuracy it is recommended that:

1. Whenever possibly make the measurement in a tightly controlled environment and use appropriate compensation methods 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	Accuracy is repeatability plus calibration. 
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, υ, the observed frequency shift, Δf is directly proportional to υ. Discovered by Christian Doppler, 1842.

$$\Delta f = f_0 \cdot \frac{\upsilon}{c}$$

where f_0 is the original frequency and c is the speed of light.

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 interpolated.

Gage Block An LDDM™ system is available to retrofit a supermicrometer for gage block measurement or calibration. The resolution is 3 µin. 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:

$$X = \frac{c}{2 \cdot f_0} \cdot \left(N + \frac{\varphi}{2 \cdot \pi} \right)$$

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 x 10^{-6}.

Standard Deviation — The software on the statistical package will calculate averaged value:

$$\overline{X} = \frac{1}{N} \cdot \left(\sum_{i=1}^{N} X_i \right)$$

and the standard deviation:

$$\sigma = \sqrt{\frac{1}{N-1} \cdot \sum_{i=1}^{N} \left(X_i - \overline{X} \right)^2}$$

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 µin 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) *Erotic 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 ±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).

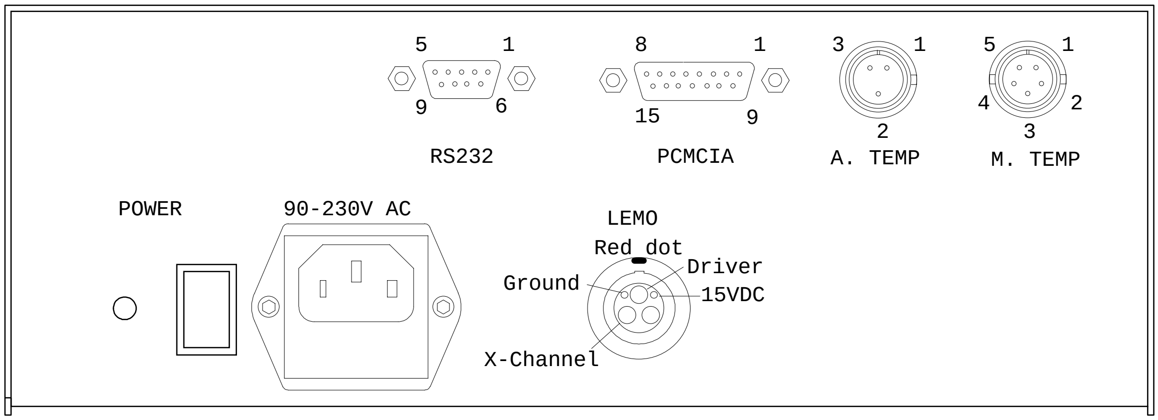
B) *Erratic reading:* One of the detector may be bad.
Replace the Quad-detector by the ATC.
If reading also erratic, reload firmware or replace IC. If reading okay, repair the quad-detector.

V) PCMCIA Card

A) *No communication:* Software problem, reload the driver and reassign port.
Bad cable or bad connection.

B) *Wrong readings* Bad output or bad cable.
Apply a 0 to 5V signal wave to Pin10 RD, all 8 bit Pin1-8 ADC should be read.
Use an oscilloscope to check Pin11 DNCNT and Pin12 UPCNT. They are TTL 30-50 nsec pulses.
Pin9 ERROR, high okay and low error.

RS232		PCMCIA		A. TEMP		M. TEMP	
2	RXD	1-8	ADC	1	RTD1	1	RTD1
3	TXD	9	ERROR	2	RTD2	2	RTD2
5	GND	10	RD	3	RTD2	3	RTD2
		11	DN CNT			4	N/C
		12	UP CNT			5	N/C
		13	GND				



PIN ASSIGNMENT, MCV-500

:

Appendix P – Fadal

Generation of displacement Error (pitch error) 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.

Compensation Files for Fadal Controllers

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.

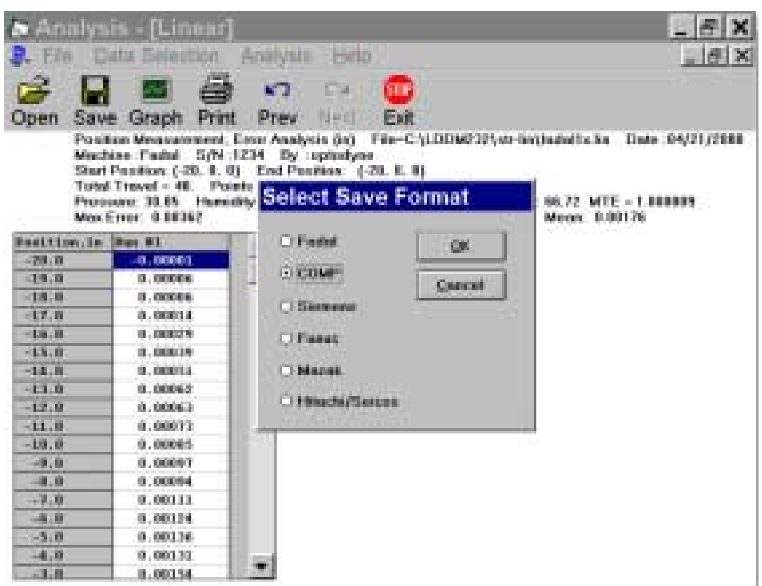


Fig. P-1 Compensation File Selection Screen

Click on “Fadal”, “ok”, and enter a filename, a comp file with extension .svx, .svy or .svz for Fadal controllers will be generated. A typical compensation file is shown below:

```
%
SVX,-19,0
SVX,-18,0
SVX,-17,1
SVX,-16,2
SVX,-15,3
SVX,-14,5
SVX,-13,6
SVX,-12,6
SVX,-11,7
SVX,-10,8
SVX,-9,9
SVX,-8,9
SVX,-7,11
SVX,-6,12
SVX,-5,13
SVX,-4,13
SVX,-3,15
SVX,-2,16
SVX,-1,16
SVX,0,16
SVX,1,18
SVX,2,19
SVX,3,20
SVX,4,19
SVX,5,22
SVX,6,23
SVX,7,24
SVX,8,23
SVX,9,26
SVX,10,27
SVX,11,28
SVX,12,26
SVX,13,30
SVX,14,31
SVX,15,32
SVX,16,30
SVX,17,34
SVX,18,36
SVX,19,36
SVX,20,32
SVX,10000,000
SVX,10001,0
SVWX
SVW,10000
%
```

Appendix Q – Fanuc 3D

Volumetric Positioning Errors Compensation Files

Many machine tool controllers can provide volumetric positioning error compensations for repeatable linear position and straightness errors on each linear axis of motion. For most controllers, there are compensations for linear errors (or pitch errors) and straightness error (or cross errors, or droop errors). To generate a new compensation file, first set up the compensation to zero and set up the LDDM™ laser measurement system to measure the sequential step diagonals at an increment corresponding to the compensation file requirement. Second, use the software to collect the sequential step diagonal error data and to generate a volumetric error table. Third, key in the new compensation file based on the volumetric positioning error table. Finally, use the LDDM™ laser measurement system again to measure the body diagonal displacement errors with the new compensation file to make sure that the volumetric errors have been compensated.

Compensation File for Fanuc 15 Controllers with 3D Compensation

This 3D comp file is for the Fanuc 15-MA (A02B-0261-J693) or 15-MB (MA) (A02B-0162-J693) controllers with three dimensional error compensation features. The traditional pitch error compensation compensates the error on a position in accordance with the position data of one axis. The 3D compensation compensates the error on a position in accordance with the position data and the compensation data of 3 axes.

To generate comp files, same as shown in section 9.6.4, first calculate the errors on x-axis, y-axis and z-axis. Then click on “file” and “save”, a screen as shown in Fig. Q-1 will popup for you to select the format of the comp files for various controllers.

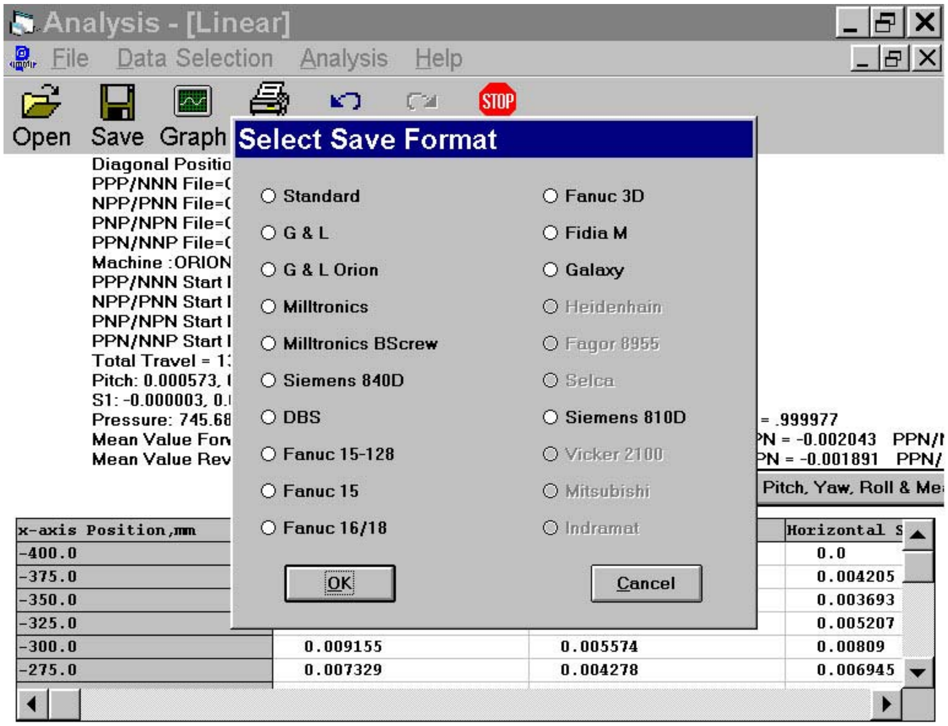


Fig. Q-1 Compensation File Selection Screen

Click on “Fanuc 3D”, a parameter screen will popup as shown in Fig. Q-2 bellow:

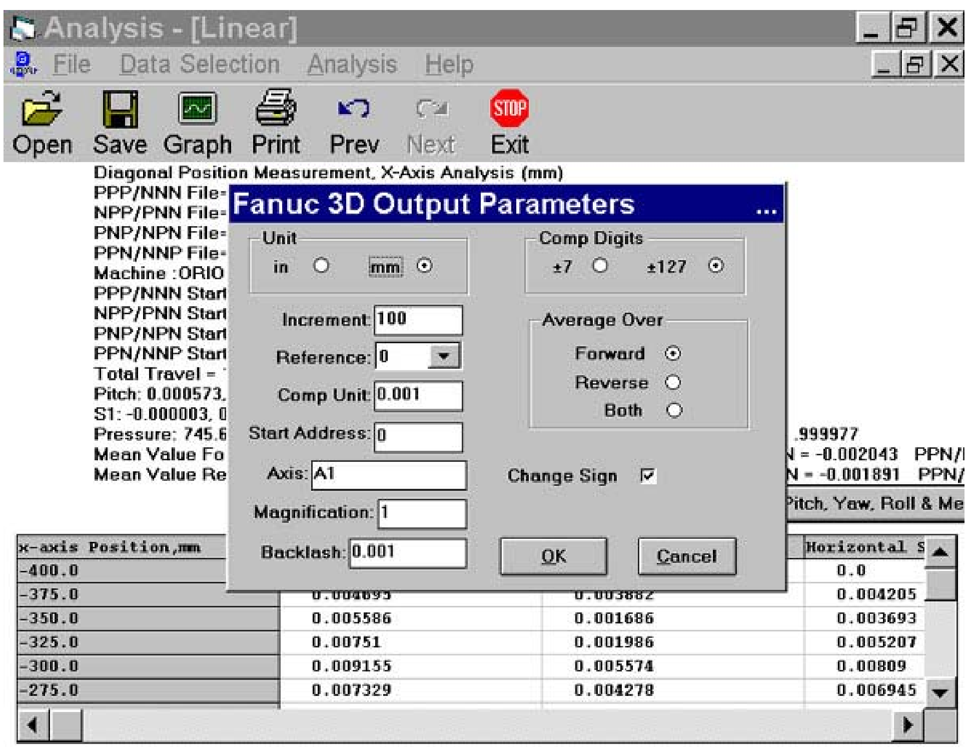


Fig. Q-2 Fanuc 3D Output Pararmeters Screen

Select the units, the increment, reference point, and the comp unit. Keep the default values, Start Address = 0, Comp Digits = ±127, Change Sign = checked. This comp file is for Fanuc 15. The file extension is .FN9.

A typical compensation file is shown bellow:

```
%
N5440P1
N5441P2
N5442P3
N5443P9
N5444P5
N5445P9
N5446P0
N5447P0
N5448P0
N5449P1
N5450P1
N5451P1
N5452P100
N5453P200
N5454P100
%
%
N100001A1P0A2P0A3P0
N100002A1P-9A2P-6A3P-8
N100003A1P-13A2P-6A3P-9
N100004A1P-15A2P-9A3P-10
N100005A1P-15A2P-4A3P-7
N100006A1P-19A2P-4A3P-5
N100007A1P-19A2P-4A3P-5
N100008A1P-17A2P1A3P-2
N100009A1P-18A2P0A3P0
N100010A1P1A2P2A3P0
N100011A1P-8A2P-3A3P-8
N100012A1P-11A2P-4A3P-9
N100013A1P-13A2P-6A3P-10
N100014A1P-14A2P-2A3P-7
N100015A1P-18A2P-2A3P-5
N100016A1P-18A2P-2A3P-5
N100017A1P-16A2P3A3P-2
N100018A1P-17A2P2A3P0
N100019A1P3A2P-10A3P0
N100020A1P-6A2P-16A3P-8
N100021A1P-9A2P-17A3P-9
N100022A1P-11A2P-19A3P-10
N100023A1P-12A2P-15A3P-7
N100024A1P-15A2P-14A3P-5
N100025A1P-16A2P-14A3P-5
N100026A1P-14A2P-10A3P-2
N100027A1P-15A2P-10A3P0
N100028A1P-1A2P-7A3P-2
N100029A1P-10A2P-13A3P-10
N100030A1P-13A2P-14A3P-12
N100031A1P-16A2P-16A3P-12
N100032A1P-16A2P-11A3P-9
N100033A1P-20A2P-11A3P-7
```

```
…
…
…
…
…
…
N100356A1P22A2P-29A3P-20
N100357A1P18A2P-29A3P-18
N100358A1P18A2P-29A3P-18
N100359A1P20A2P-24A3P-14
N100360A1P19A2P-25A3P-13
N100361A1P40A2P-16A3P-18
N100362A1P31A2P-22A3P-26
N100363A1P28A2P-23A3P-28
N100364A1P26A2P-25A3P-28
N100365A1P25A2P-21A3P-25
N100366A1P21A2P-20A3P-23
N100367A1P21A2P-20A3P-24
N100368A1P23A2P-16A3P-20
N100369A1P22A2P-16A3P-18
N100370A1P41A2P-14A3P-18
N100371A1P32A2P-20A3P-26
N100372A1P29A2P-21A3P-28
N100373A1P27A2P-23A3P-28
N100374A1P26A2P-19A3P-25
N100375A1P23A2P-18A3P-23
N100376A1P22A2P-18A3P-24
N100377A1P24A2P-14A3P-20
N100378A1P23A2P-14A3P-18
N100379A1P43A2P-27A3P-18
N100380A1P34A2P-32A3P-26
N100381A1P31A2P-33A3P-28
N100382A1P29A2P-35A3P-28
N100383A1P28A2P-31A3P-25
N100384A1P25A2P-31A3P-23
N100385A1P24A2P-31A3P-24
N100386A1P26A2P-26A3P-20
N100387A1P25A2P-27A3P-18
N100388A1P39A2P-24A3P-21
N100389A1P30A2P-29A3P-29
N100390A1P27A2P-30A3P-30
N100391A1P25A2P-32A3P-31
N100392A1P24A2P-28A3P-27
N100393A1P20A2P-27A3P-26
N100394A1P20A2P-28A3P-26
N100395A1P22A2P-23A3P-22
N100396A1P21A2P-24A3P-21
N100397A1P36A2P-35A3P-18
N100398A1P27A2P-40A3P-26
N100399A1P24A2P-41A3P-28
N100400A1P22A2P-43A3P-28
N100401A1P21A2P-39A3P-25
N100402A1P18A2P-39A3P-23
N100403A1P18A2P-39A3P-24
N100404A1P20A2P-34A3P-20
N100405A1P18A2P-35A3P-18
%
```

Appendix R LDDM Laser System Simulator

The LDDM laser system data collection software can only work with a complete laser system or a simulator. To learn the data collection software or to demonstrate the data collection features, it is more economical to use the LDDM laser simulator. The simulator can simulate a dual-beam laser system with temperature and pressure sensors or quad-detectors. A photograph of the simulator is shown below (Fig. R1).

Fig. R1 Control Panel of the LDDM Laser System Simulator

The speed of the motion is controlled by a 4 position dial switch. The maximum speed, position 4, is 4.5 in/sec (6750 mm/minute). The position 3 is 0.28 in/sec (420 mm/minute), the position 2 is 0.018 in/sec (25 mm/minute) and the position 1 is 0.001 in/sec (1.6 mm/minute). The speed of the second axis, y-axis, is a factor of 65536 lower. The direction of the motion is controlled by the toggle switch, X positive or negative and Y positive or negative. To start the motion, switch to RUN and to stop switch to STOP. The speed and direction can be changed during motion.

There are 4 dials A, B, C and D. A is for air pressure, counter clockwise change the pressure from 0 to 35.5 inHg. B is for air temperature, counter clockwise change the air temperature from 33 ºF to 120 ºF. C and D are for the material temperature 1 and 2 respectively. The ranges are the same as B. To set to standard condition, dial B clockwise to the end. The pressure will read 29.9 inHg and the temperature will read 68 ºF.

For squareness or straightness data collection, set A, B, C and D to the mid-range. The A, B, C and D control the quad-detector output. The ranges are from 0 to 1000. To start, turn-on the AC power, connect the RS-232 cable to the notebook PC, set all 4 dials, A, B, C and D to the mid-range and speed to position 3. Click on the LDDM Logo and start the LDDM software. For linear measurement, click on “Linear”. Adjust A to set the air pressure to near 29.9 inHg, adjust B and C to the room temperature. Click on “reset” to update the pressure and temperature readings. Click on the “setup” and enter the measurement parameters. For automatic data collection, use RUN/STOP and X positive/negative to reach the target position. Speed position 1 may be needed to simulate a more accurate machine.

For dual-beam laser system, click on “straightness” and adjust air pressure or air temperature as before. For automatic data collection, keep X in the same direction and change Y to positive and negative during motion.

For squareness measurement, set A, B, C and D in the mid-range. Rotate a very small amount to indicate straightness deviations. Similarly, the surface flatness and rotary table calibration can also be simulated. However, it is more difficult to control the readings. If you have a display, you may connect to the displace connector to displace the readings.

APPENDIX T. Time Based Data Collection with a Synchronization Pulse

For the 2 D time base data collection, click on “start” to start the data collection and click on “stop” to stop the data collection. However, for many application, more précised timing or to synchronize the data with the event is important. To achieve the synchronization, a push button or a TTL trigger pulse is used to start the event and also to generate a step in the displacement.

The required hardware for this synchronization pulse is an option. It consists of two new connectors, one for positive step and one for negative step, on the processor module. Connect a push button switch or a TTL signal to the connector, a step of 1 count or 0.000025” or 0.0006 mm will be added to the displacement counter. Usually, for a push button switch, there may be many pulses generated due to bouncing of the switch. Use the first pulse or the first step for the timing.

A typical synchronization step is show in Fig. 1. Here, the step is located at the point number 391. The second and third steps are due to the switch bouncing. Use only the first one for timing and ignore the rest of the steps. Since the synchronization step is only 0.000025”, sometimes it is difficult to find the small step. You may click on the “velocity” to generate the velocity plot as shown in Fig. 2, to locate the synchronization pulse.

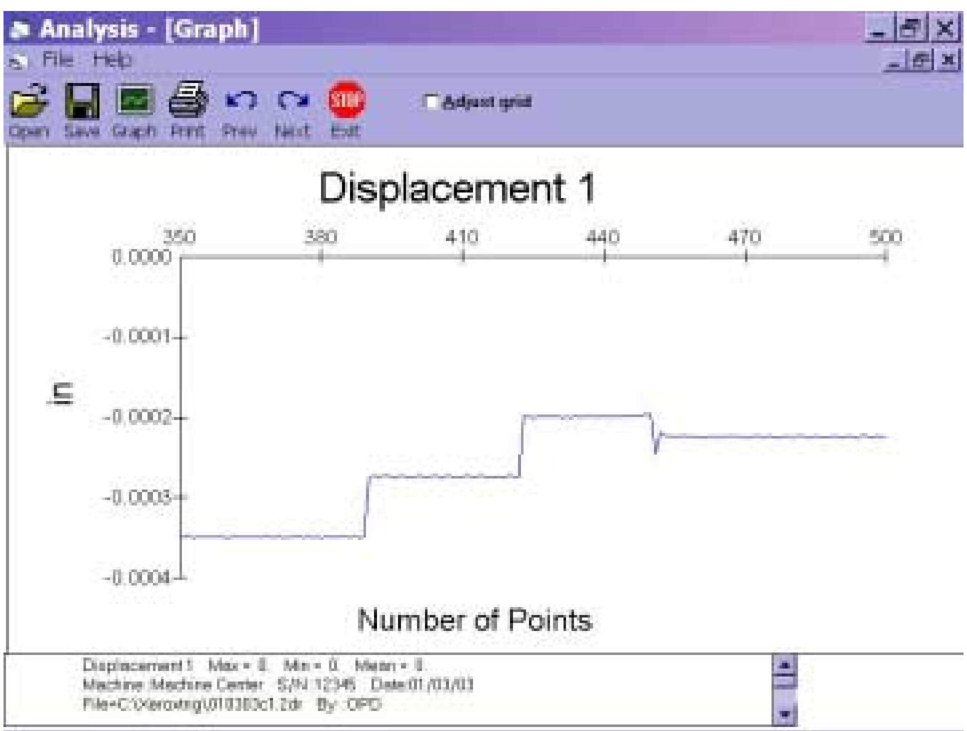


Fig. 1, A Synchronization Displacement Step at Point Number 391.

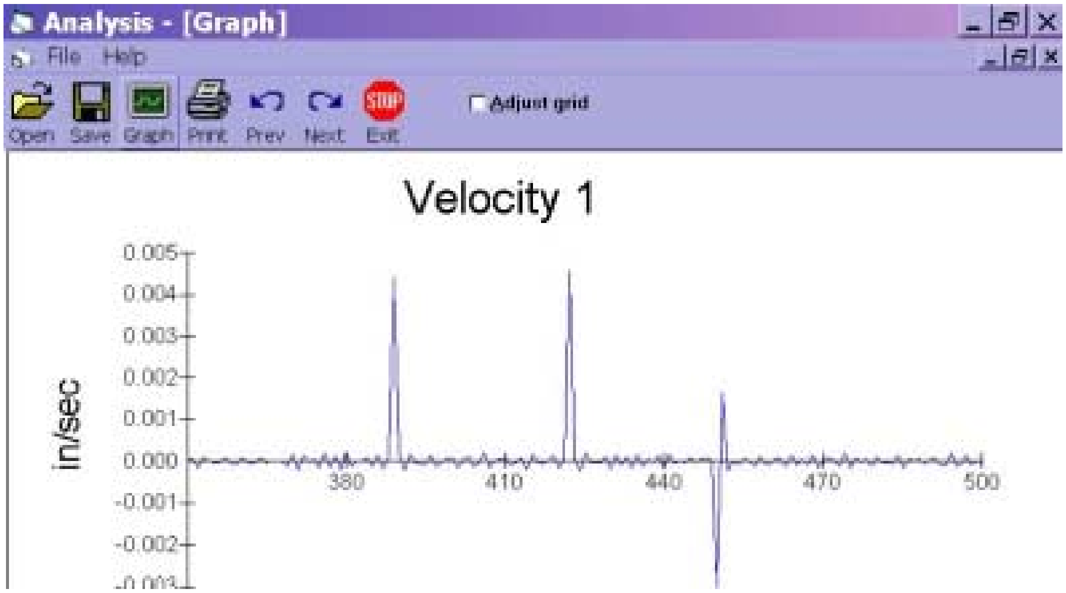
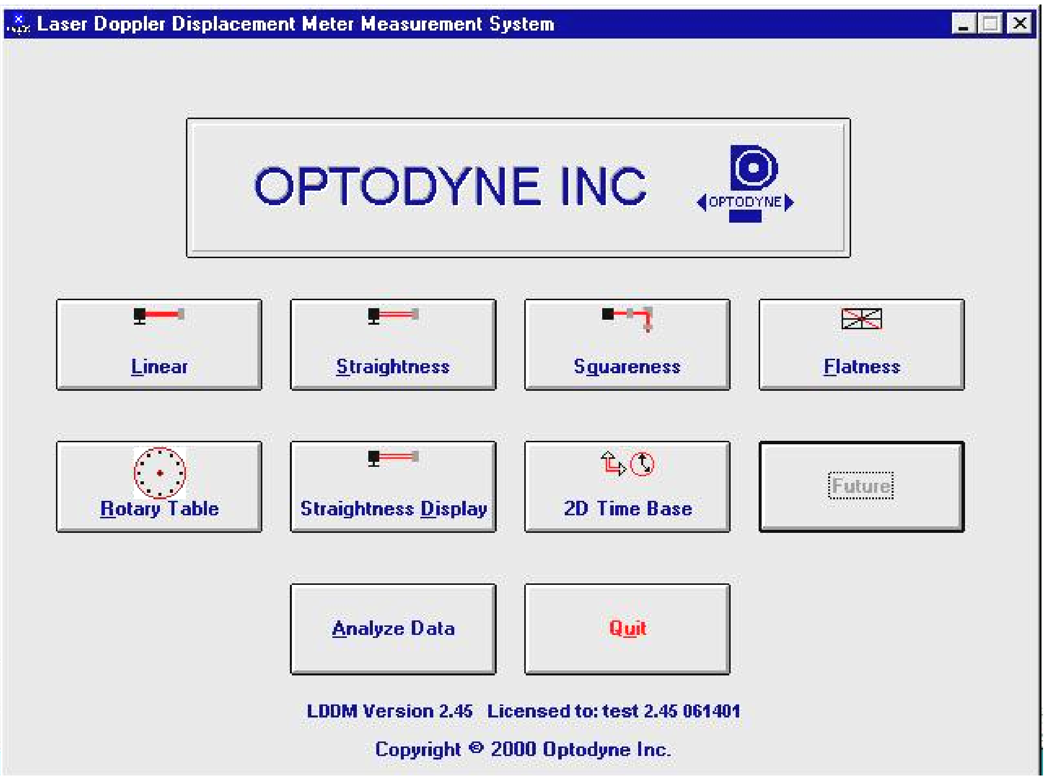


Fig. 2, A Synchronization Velocity Pulse at Point Number 391.

OPTODYNE, INC.
1180 Mahalo Place
Compton, CA 90220
310-635-7481

LASER DOPPLER DISPLACEMENT METER

LDDM FOR WINDOWS
Version 3.0
SOFTWARE MANUAL



Optodyne, Inc.
1180 Mahalo Place
RANCHO DOMINGUEZ,
CA 90220
310-635-7481

For technical assistance, please contact Optodyne's Service Department:

Optodyne, Inc.
Service Department
1180 Mahalo Place
RANCHO DOMINGUEZ,
CA 90220, USA
310-635-7481 (Telephone)
800-766-3920 (Toll Free in US)
310-635-6301 (Fax)
www.optodyne.com

Table of Contents

List of Figures

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.

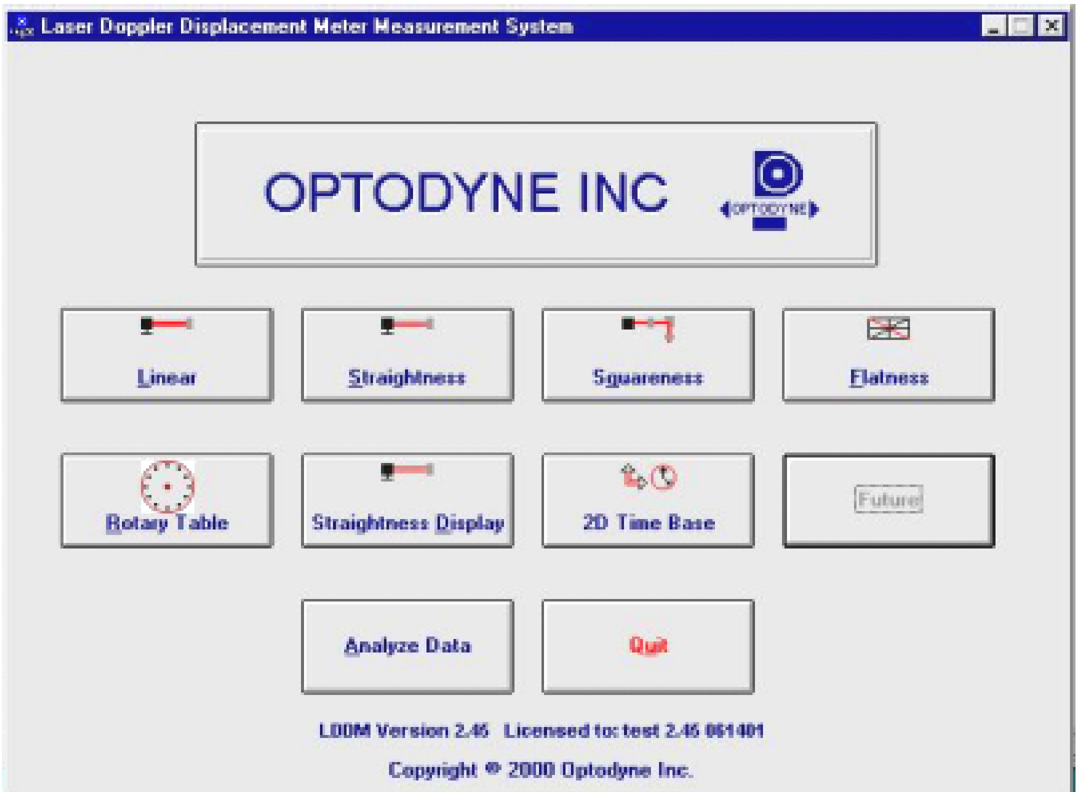


Fig. 3-1 Main Menu

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

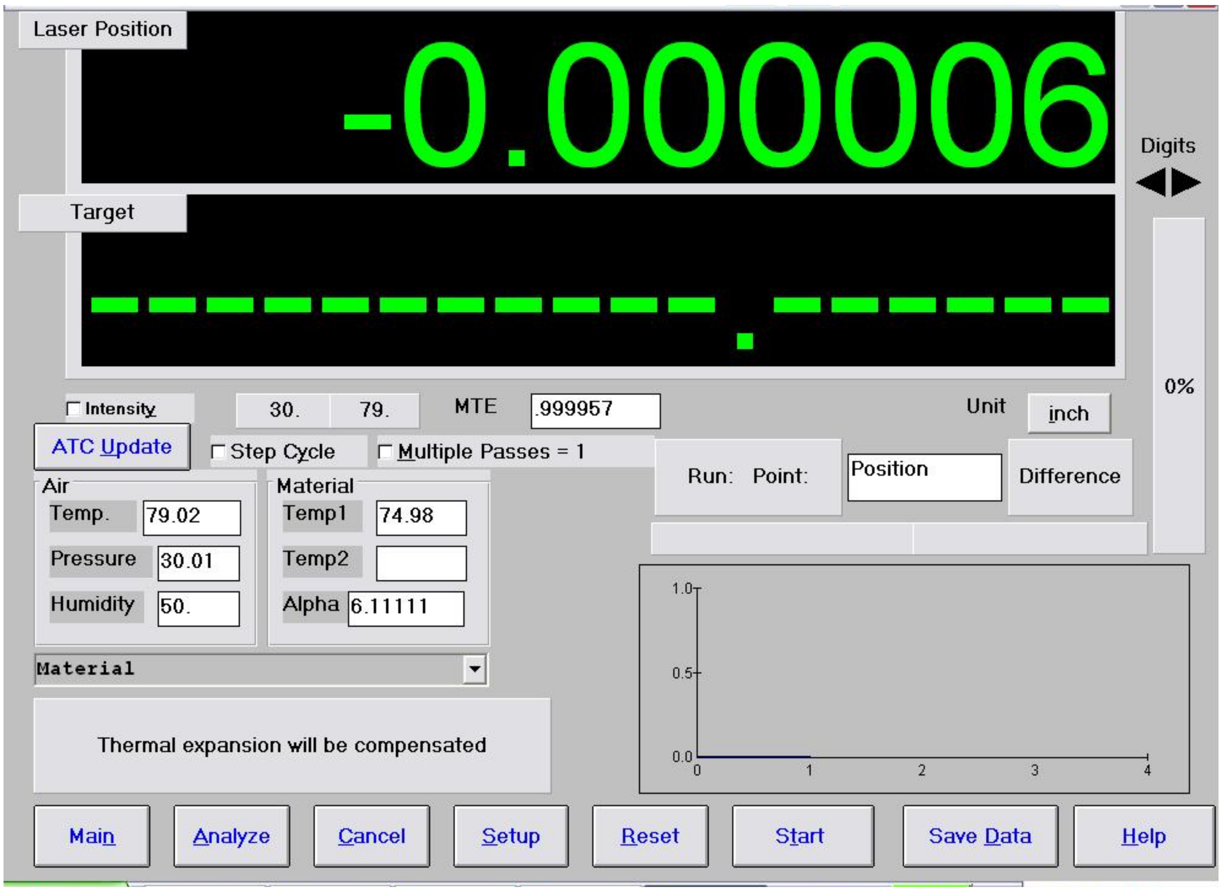


Fig. 4-1 Linear Measurement Main display

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.

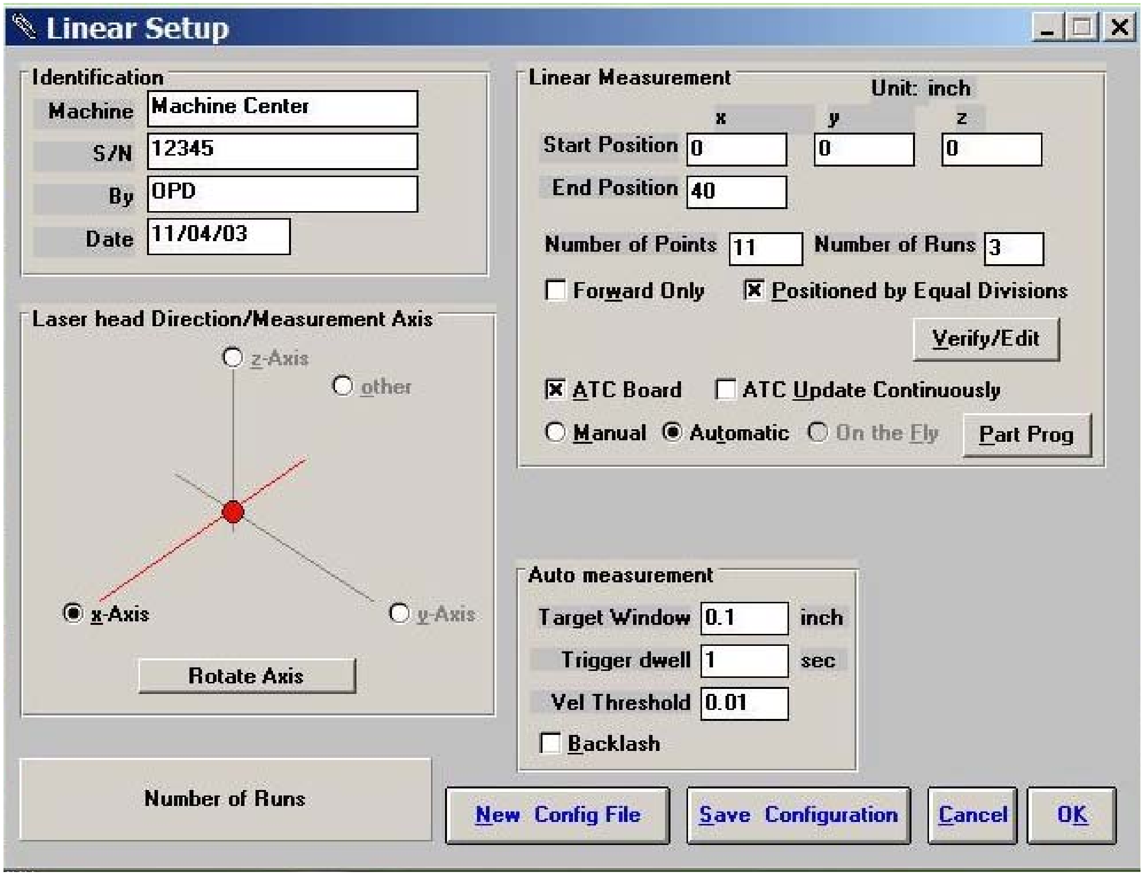


Fig. 4-2 Linear Measurement Setup Screen

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)

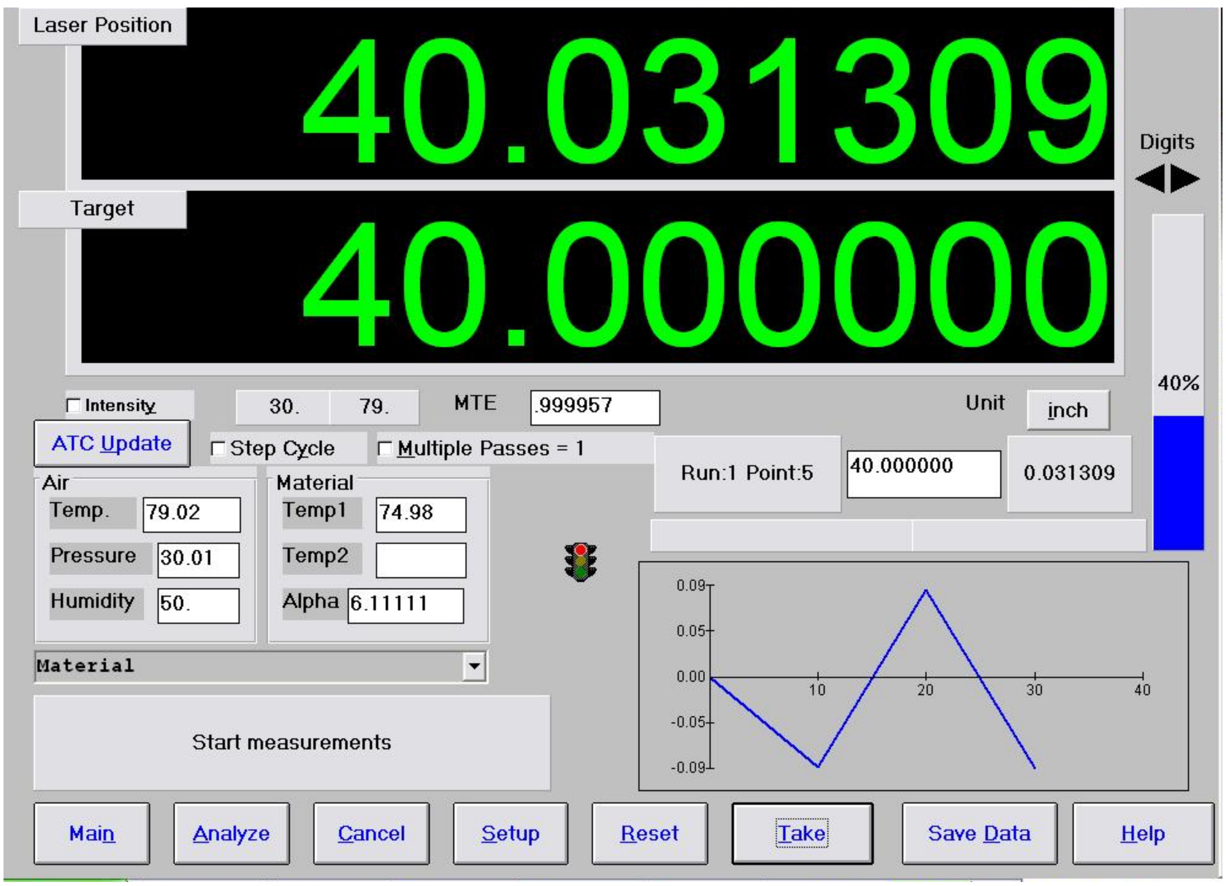
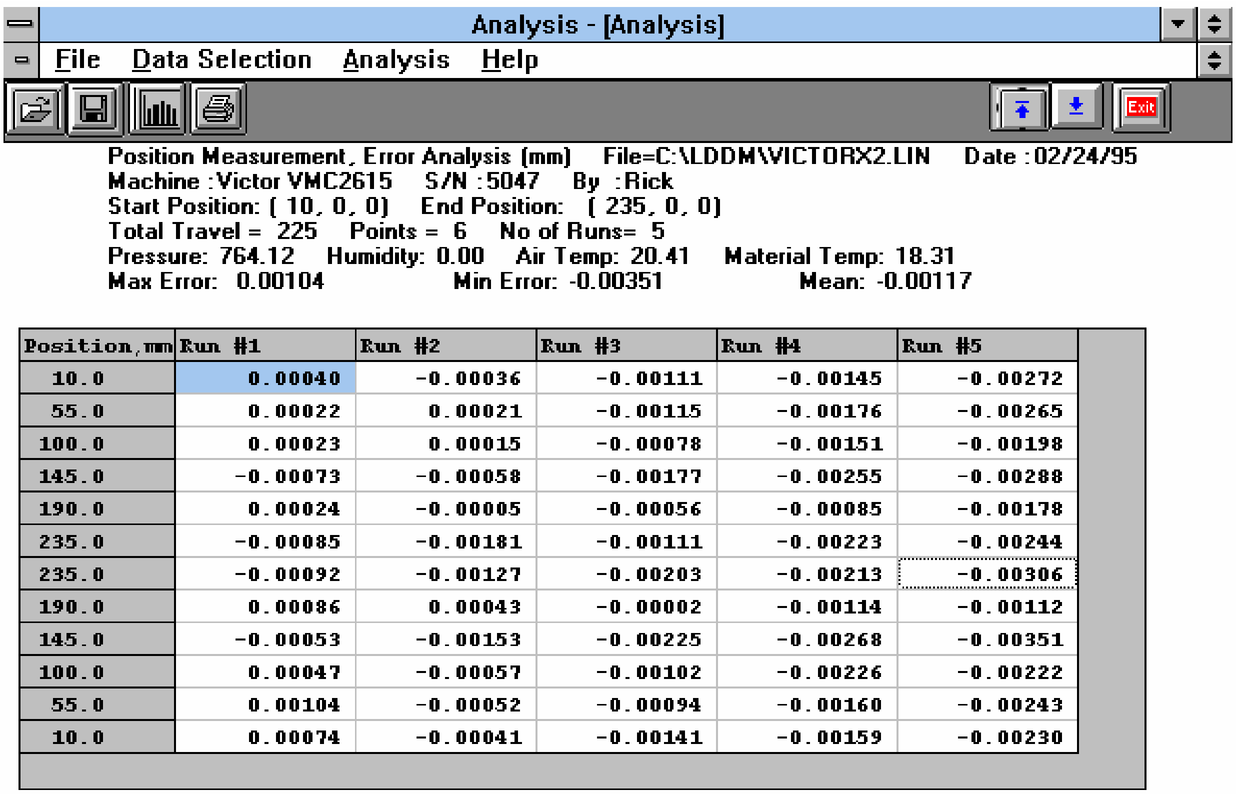


Fig. 4-3 Automatic Linear Data Collection

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)



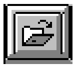
Position,mm	Run #1	Run #2	Run #3	Run #4	Run #5
10.0	0.00040	-0.00036	-0.00111	-0.00145	-0.00272
55.0	0.00022	0.00021	-0.00115	-0.00176	-0.00265
100.0	0.00023	0.00015	-0.00078	-0.00151	-0.00198
145.0	-0.00073	-0.00058	-0.00177	-0.00255	-0.00288
190.0	0.00024	-0.00005	-0.00056	-0.00085	-0.00178
235.0	-0.00085	-0.00181	-0.00111	-0.00223	-0.00244
235.0	-0.00092	-0.00127	-0.00203	-0.00213	-0.00306
190.0	0.00086	0.00043	-0.00002	-0.00114	-0.00112
145.0	-0.00053	-0.00153	-0.00225	-0.00268	-0.00351
100.0	0.00047	-0.00057	-0.00102	-0.00226	-0.00222
55.0	0.00104	-0.00052	-0.00094	-0.00160	-0.00243
10.0	0.00074	-0.00041	-0.00141	-0.00159	-0.00230

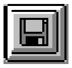
Fig. 4-4 Linear Measurement Data Analysis Table

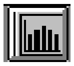
Under the **File Menu**, you can open a **new** data file, **save** a data file, set your **printer type**, set your **printer style**, or return to the **main menu**. When loading a file, choose the files with the extension of .LIN for linear. You can only **print data** tables using the print function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

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

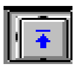
Under **Analysis**, you can choose **Error**, **NMTBA**, **NMTBA with Zero Shift**, **VDI 3441**, **ISO**, **ASME B5.54** or **ASME B5.57** for different types of data manipulation. After choosing **Error**, you will be given a choice on what you wish to see, **Runs #1-7**, and **forward** or **backward**.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

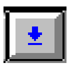
 Open a new data file.

 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.

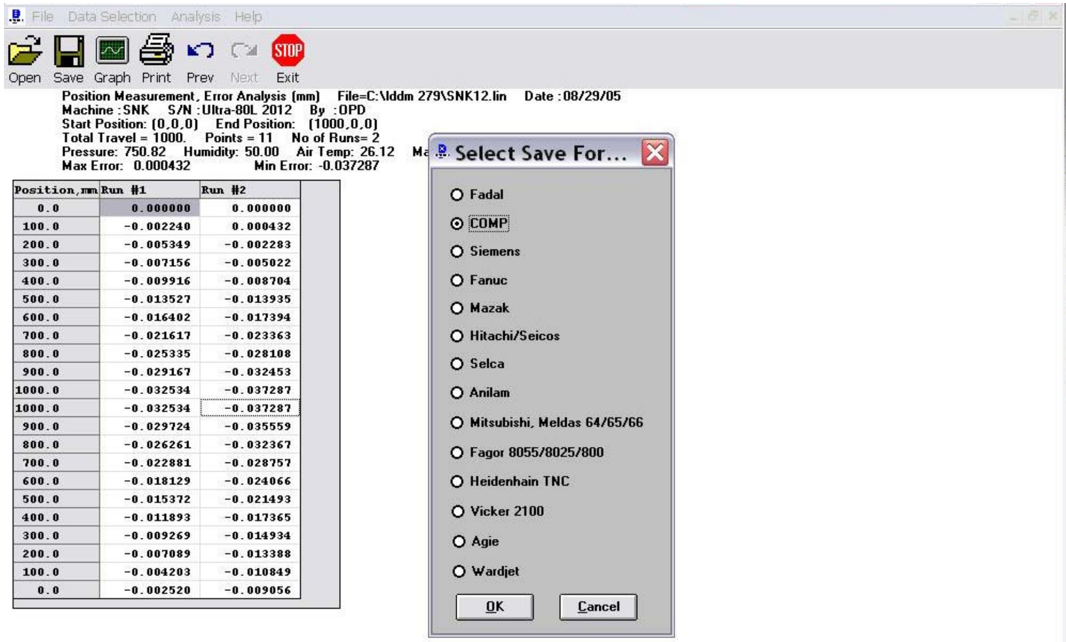


Fig. 4-5 Compensation File Selection Screen

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.

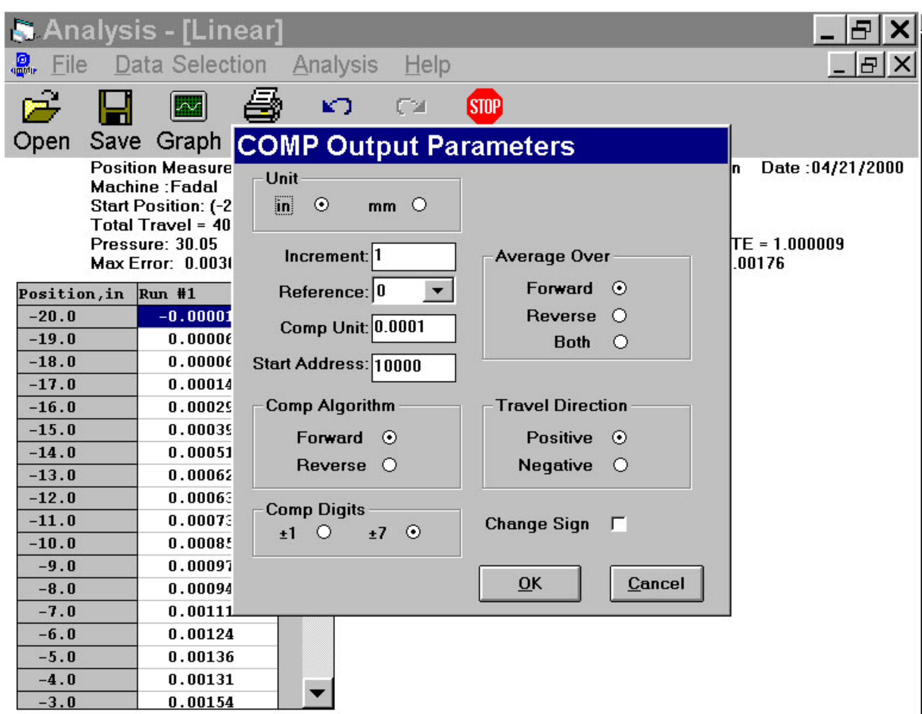


Fig. 4-6 Compensation Input Parameter Screen

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.

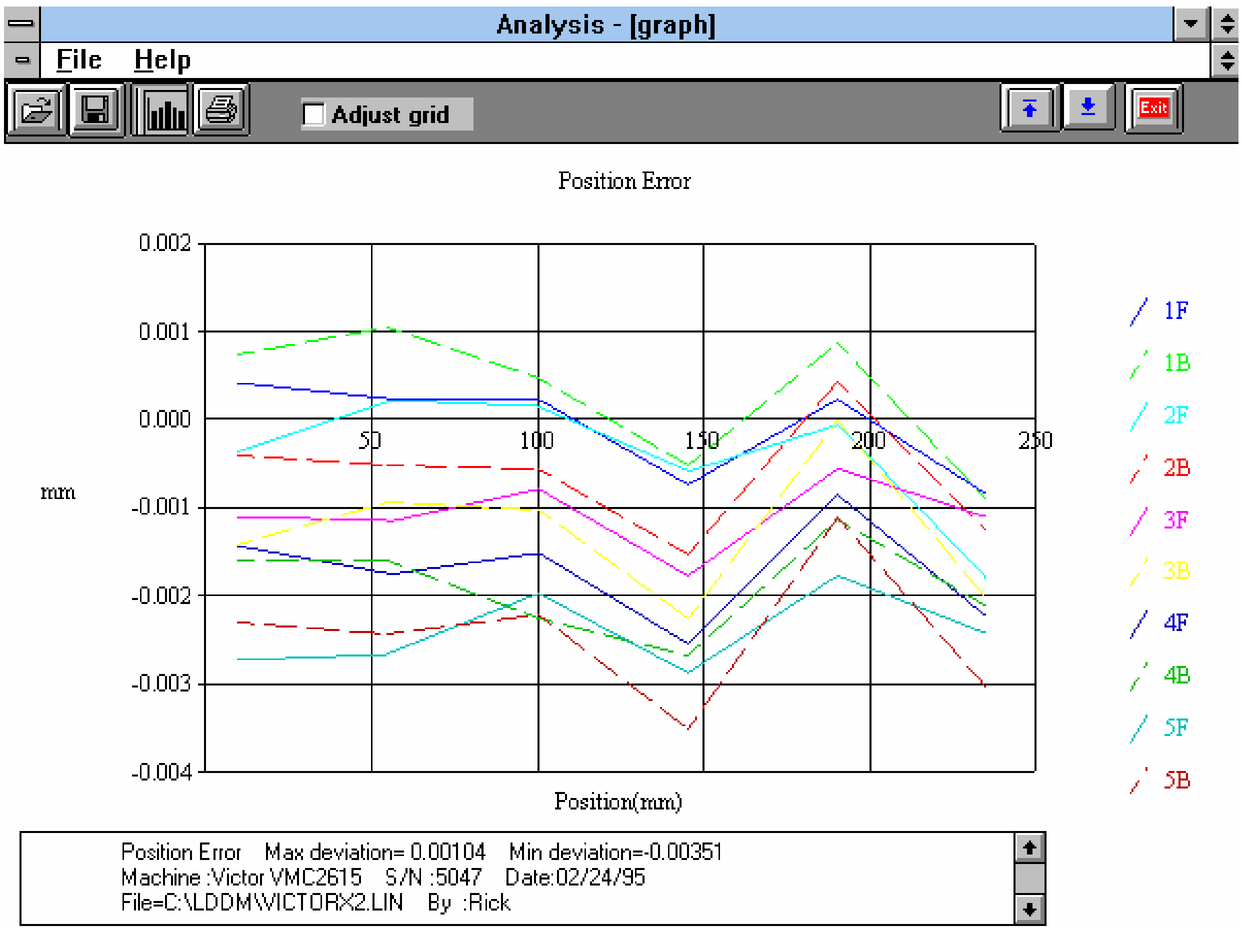


Fig. 4-7 Linear Measurement Data Plot (Individual Plots together)

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)

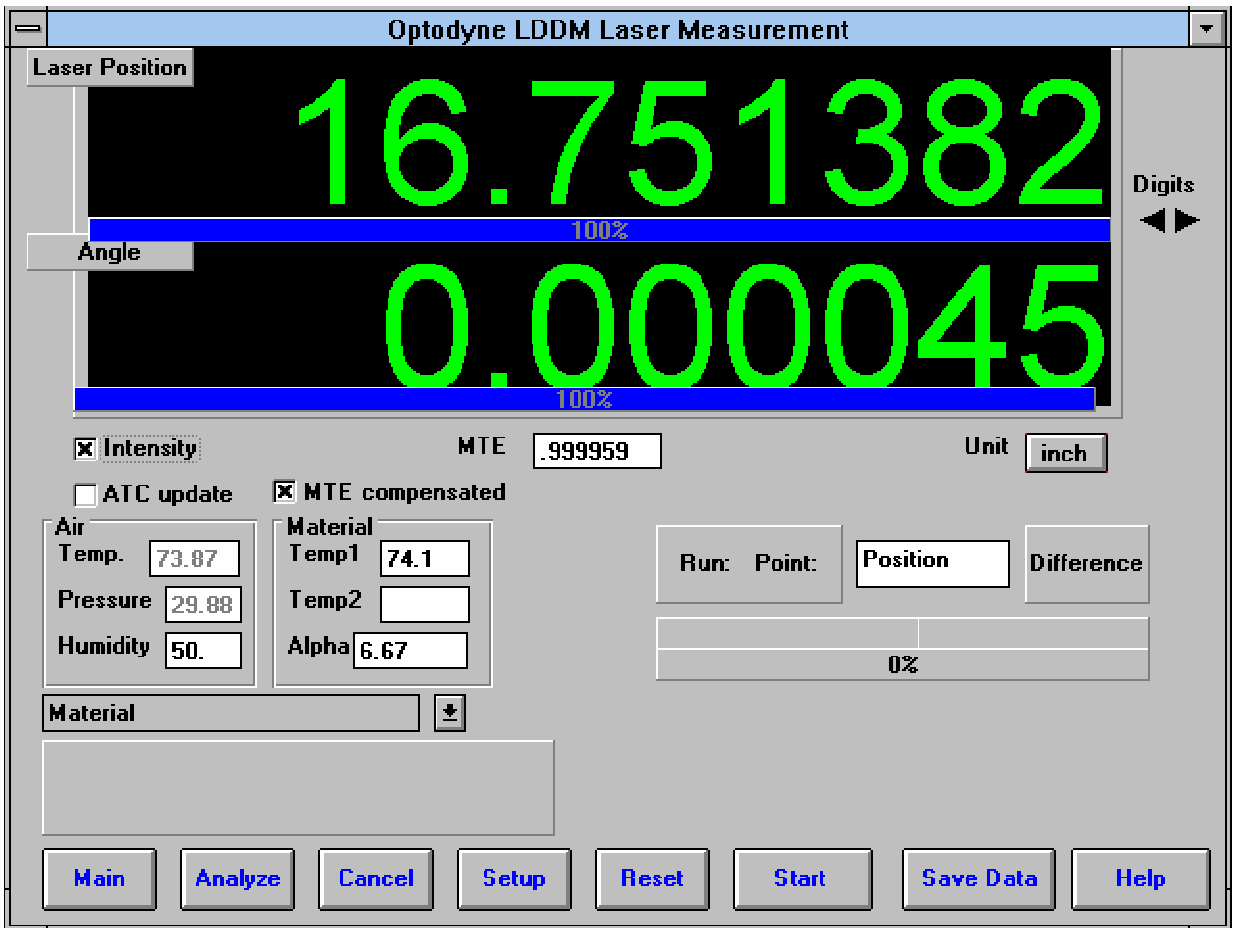


Fig. 5-1 Straightness Measurement Main Display

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.

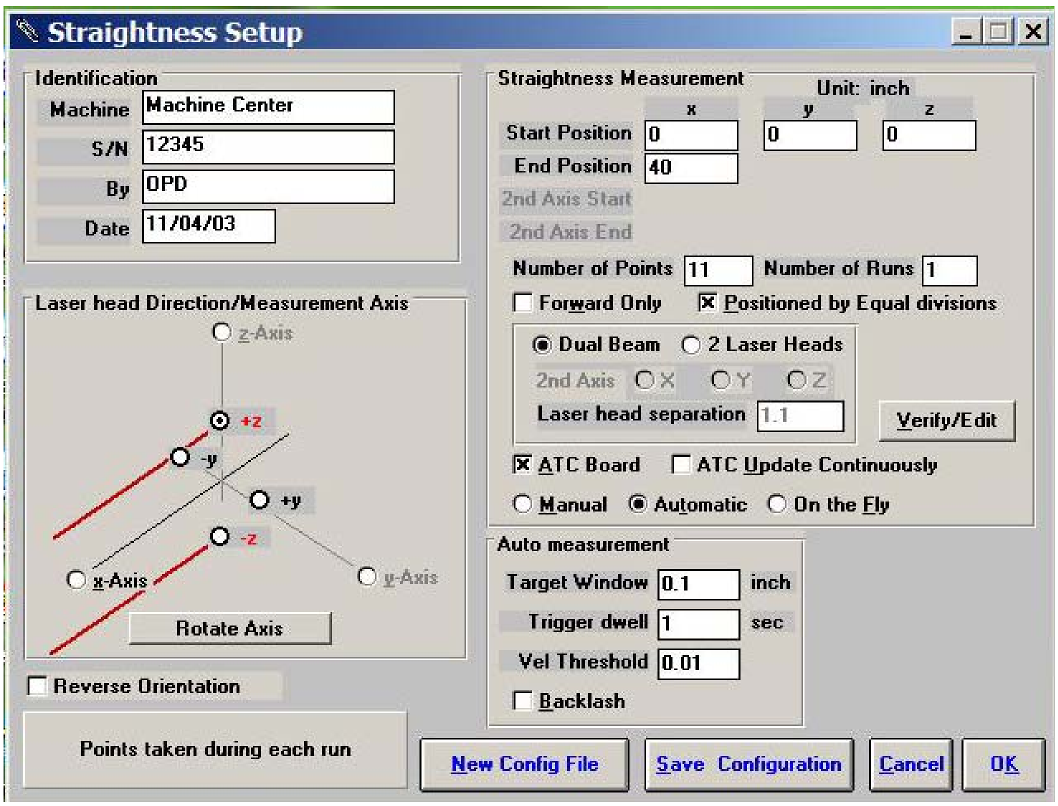


Fig. 5-2 Straightness Measurement Setup Screen

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 betaken.

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.

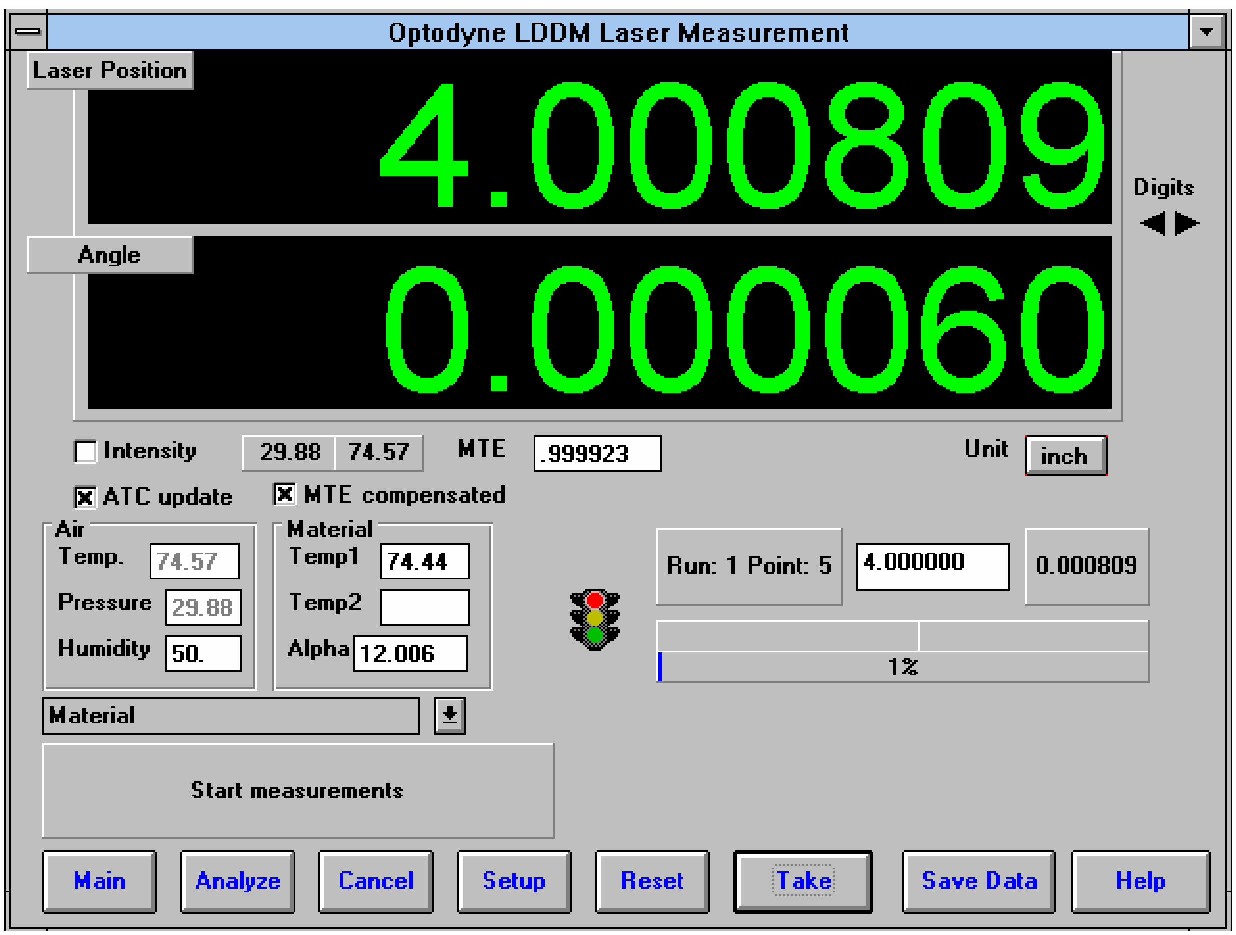


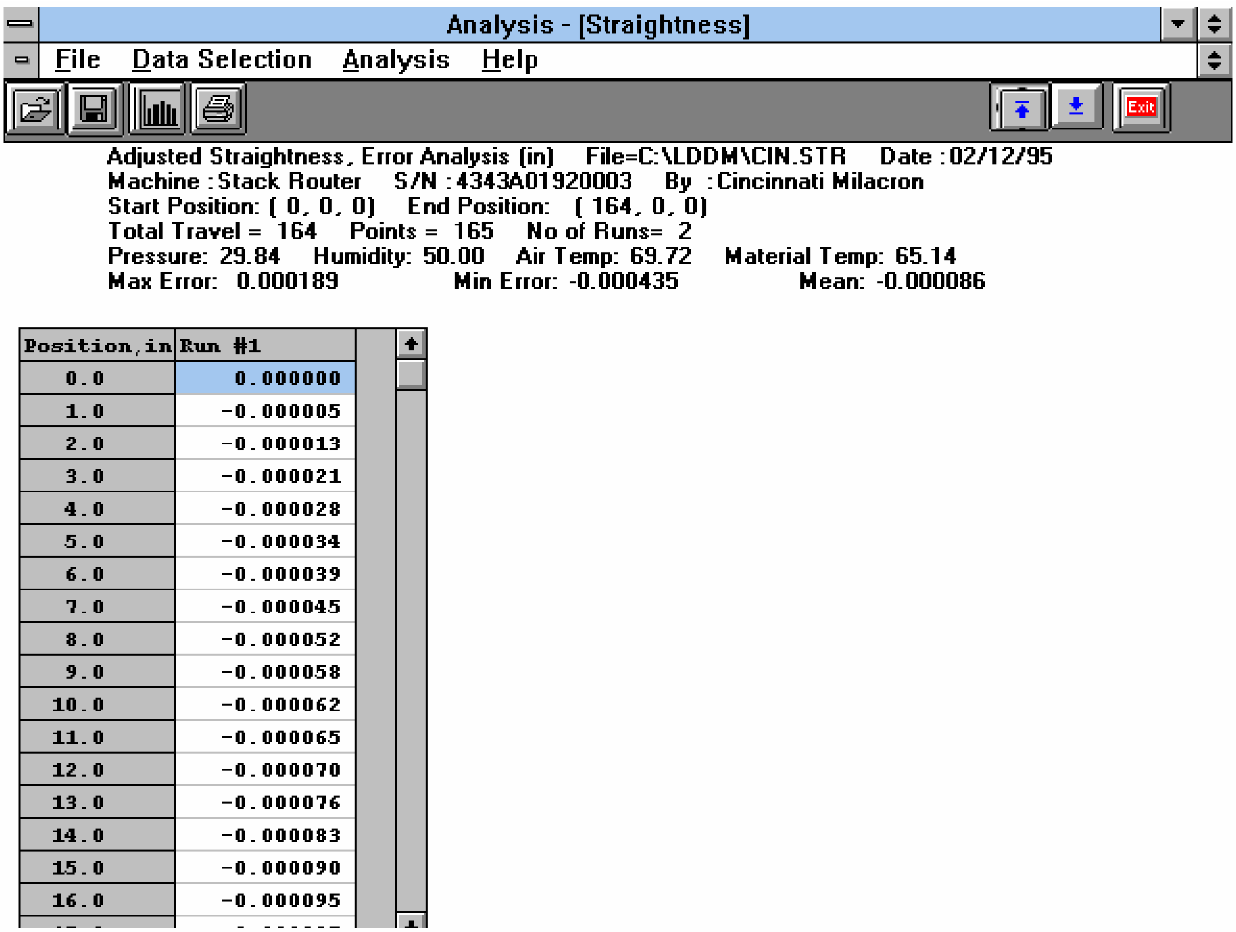
Fig. 5-3 Automatic Straightness/Linear Data Collection

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



Position, in	Run #1
0.0	0.000000
1.0	-0.000005
2.0	-0.000013
3.0	-0.000021
4.0	-0.000028
5.0	-0.000034
6.0	-0.000039
7.0	-0.000045
8.0	-0.000052
9.0	-0.000058
10.0	-0.000062
11.0	-0.000065
12.0	-0.000070
13.0	-0.000076
14.0	-0.000083
15.0	-0.000090
16.0	-0.000095

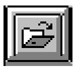
Fig. 5-4 Straightness Measurement Data Analysis Table

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.

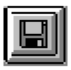
Under the **Data Selection** heading, you may choose **displacement** data, **angle** data, **straightness** data, and **adjusted straightness** data when looking at a straightness (.STR) file.

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.

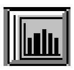
The following icons have the following function in Analysis:



Open a new data file.

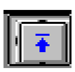


Save a data file.

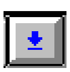


Graph a data file (After graphing, you may also change the scaling of the graph by checking X on adjust grid).

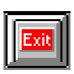
Print a data graph (for printing data tables, use the Print option under the "File" heading)



Moves to the previous screen.



Moves to the next screen.



Exits the program.

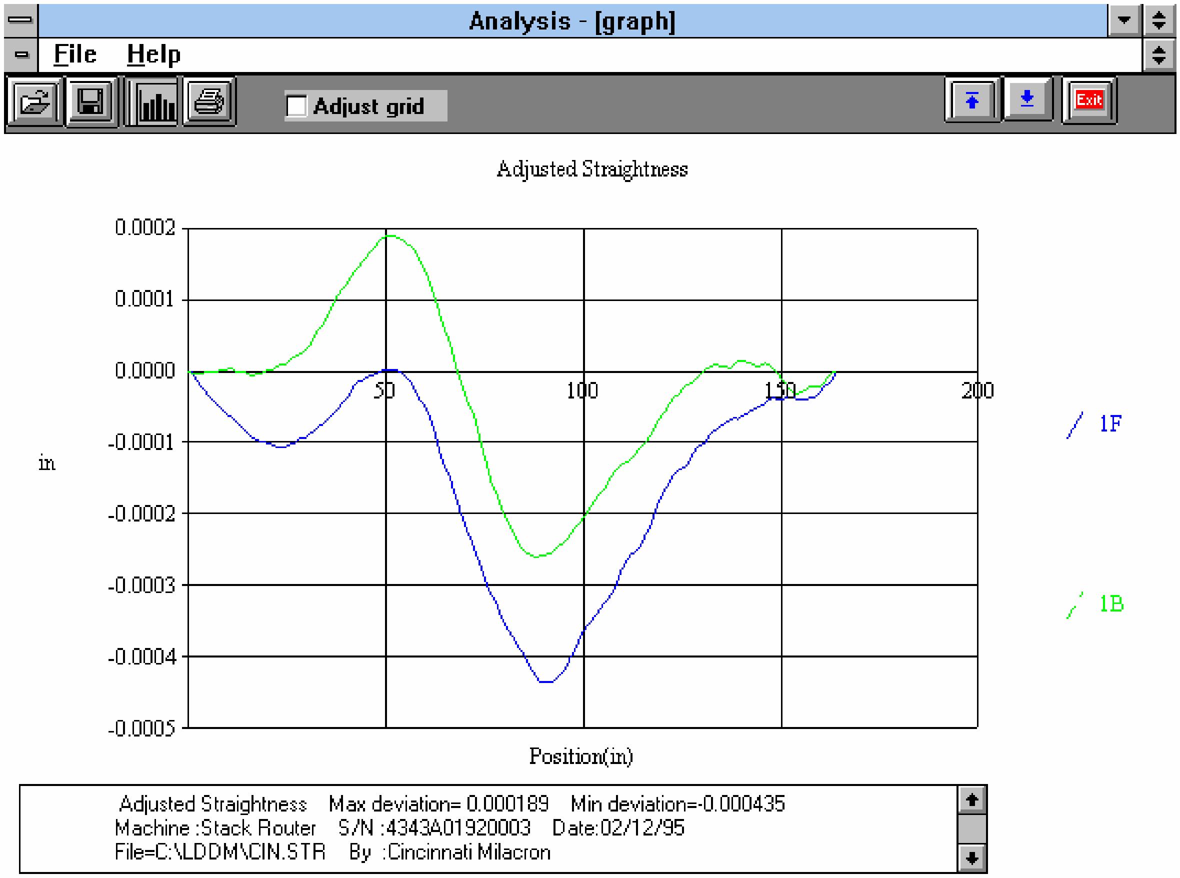


Fig. 5-5 Adjusted Straightness Measurement Data Plot

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:

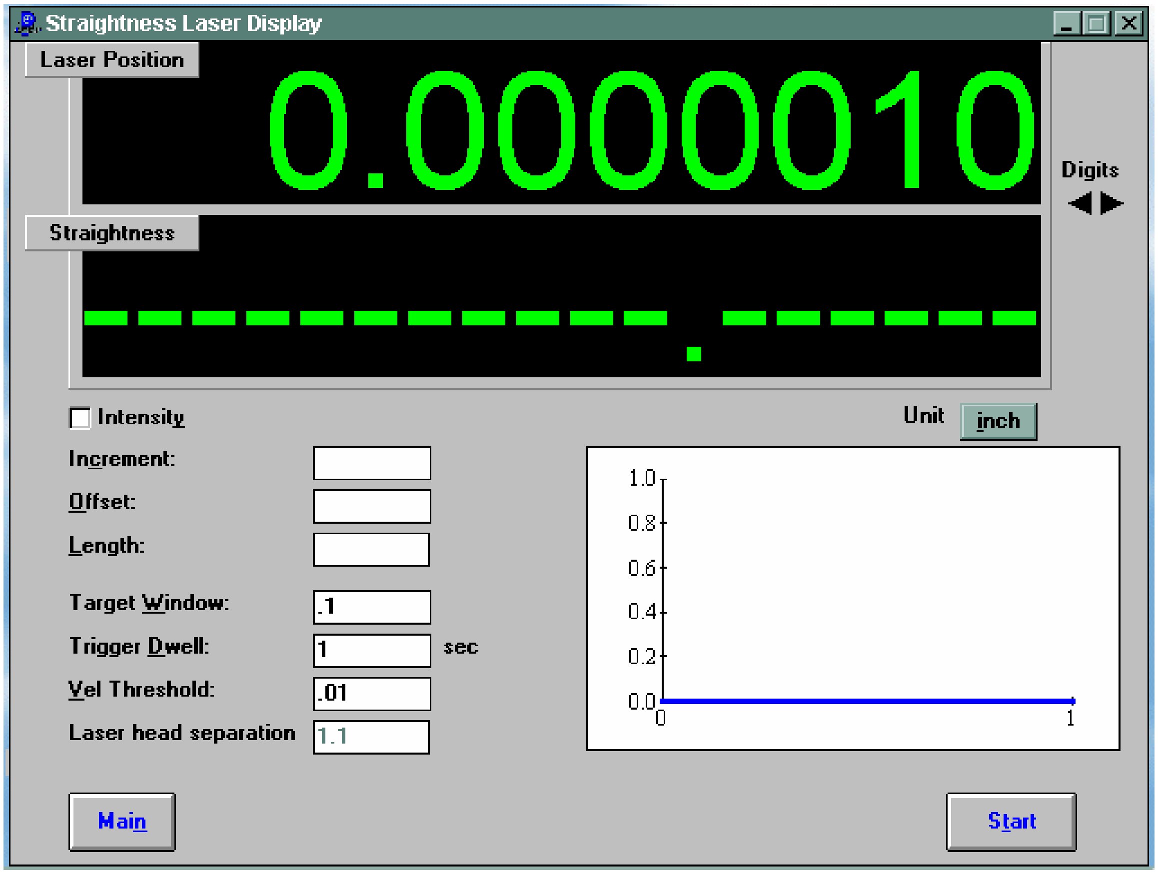


Fig. 5-6 Straightness Display Screen

The straightness displayed is calculated by integrate the measured angle times the increament 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:

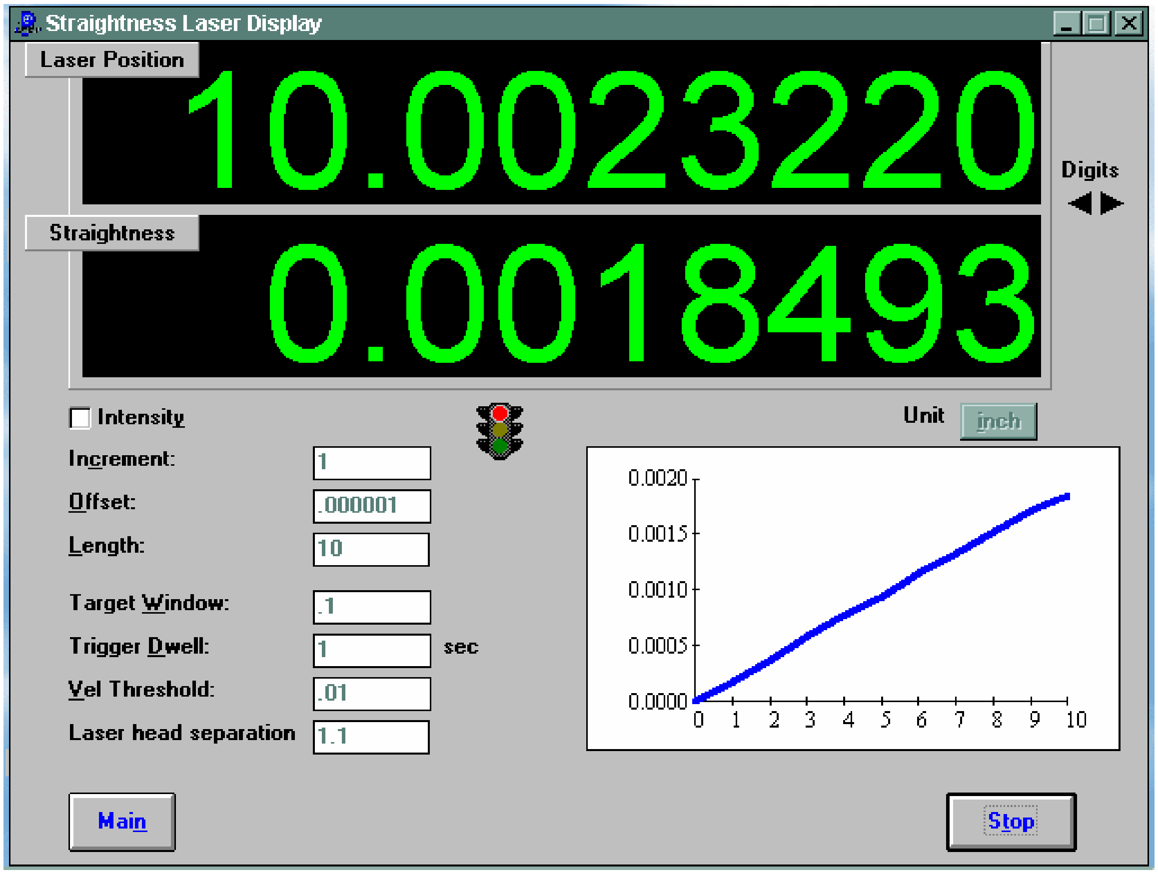


Fig. 5-7 Straightness Display Without Offset

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)

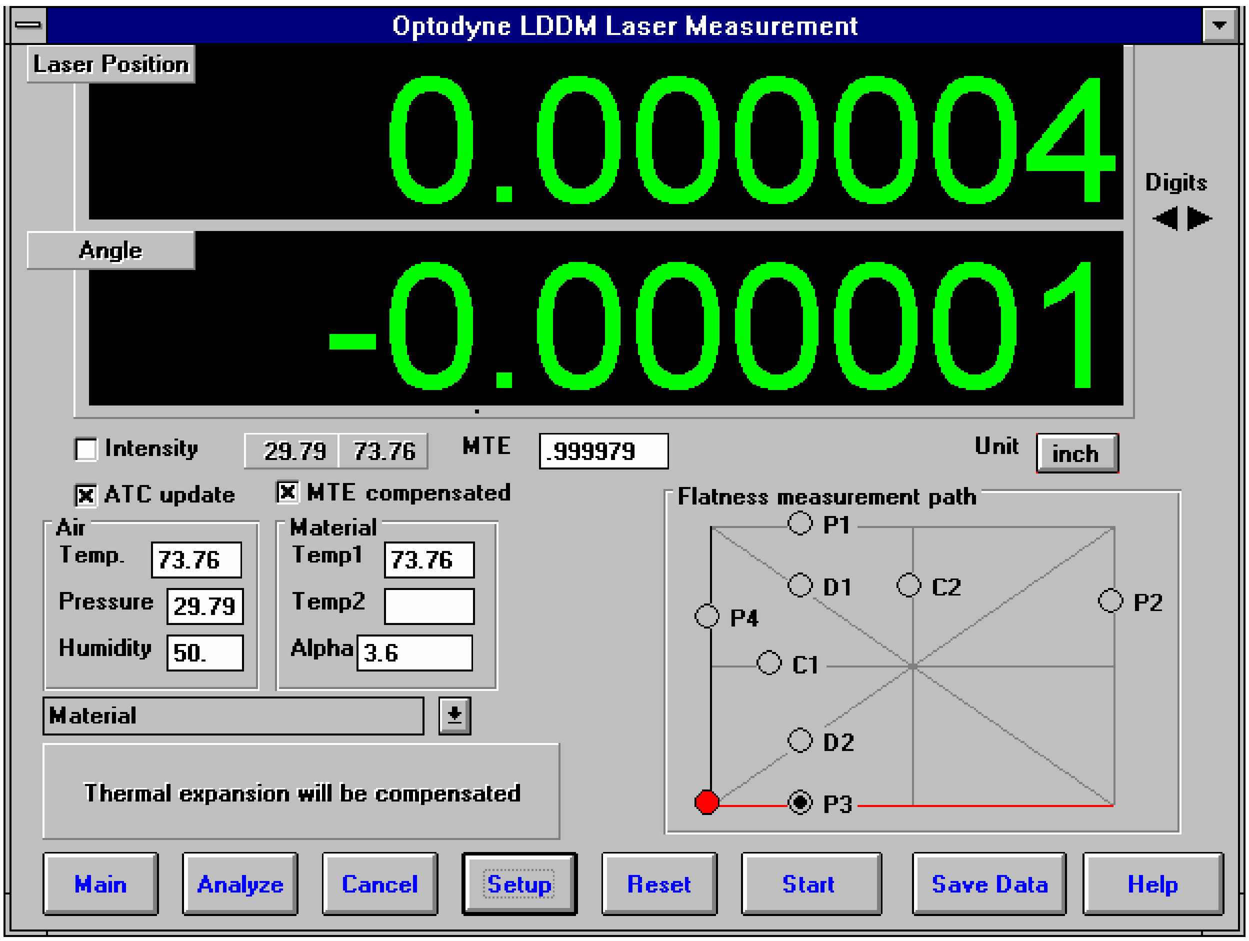


Fig. 6-1 Flatness Measurement Main Display

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 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 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.

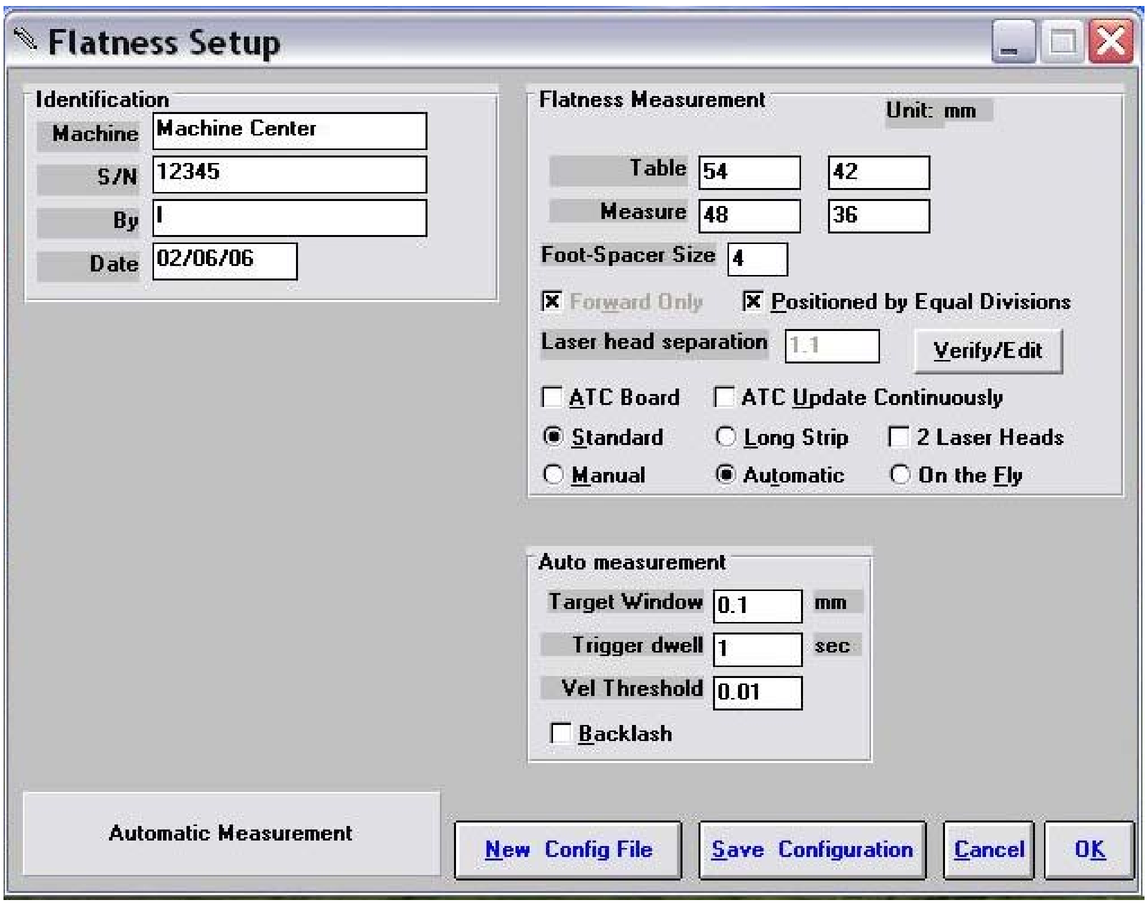


Fig. 6-2 Flatness measurement Setup Screen

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 betaken.

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.

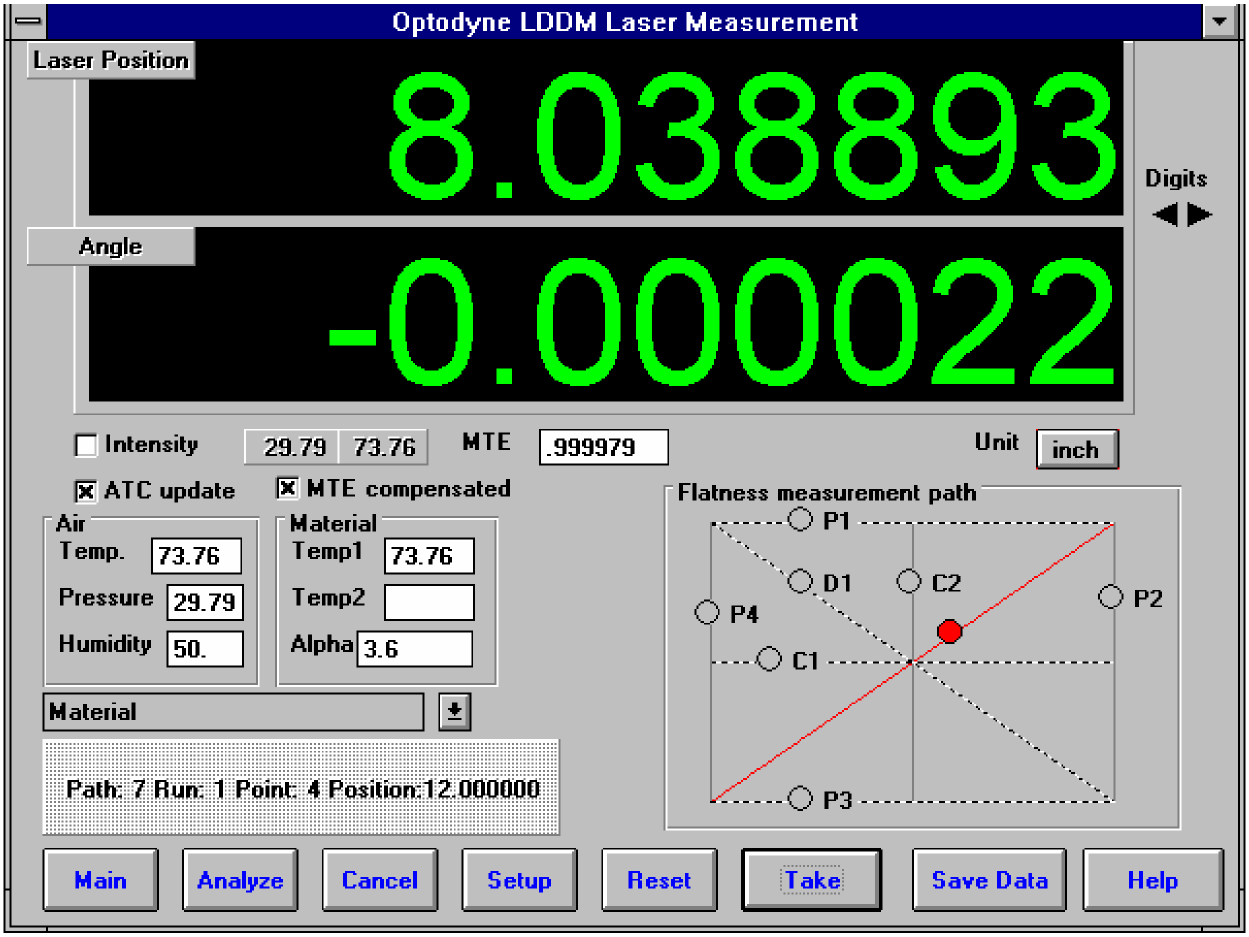


Fig. 6-3 On-The-Fly Flatness Measurement Data Collection

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.

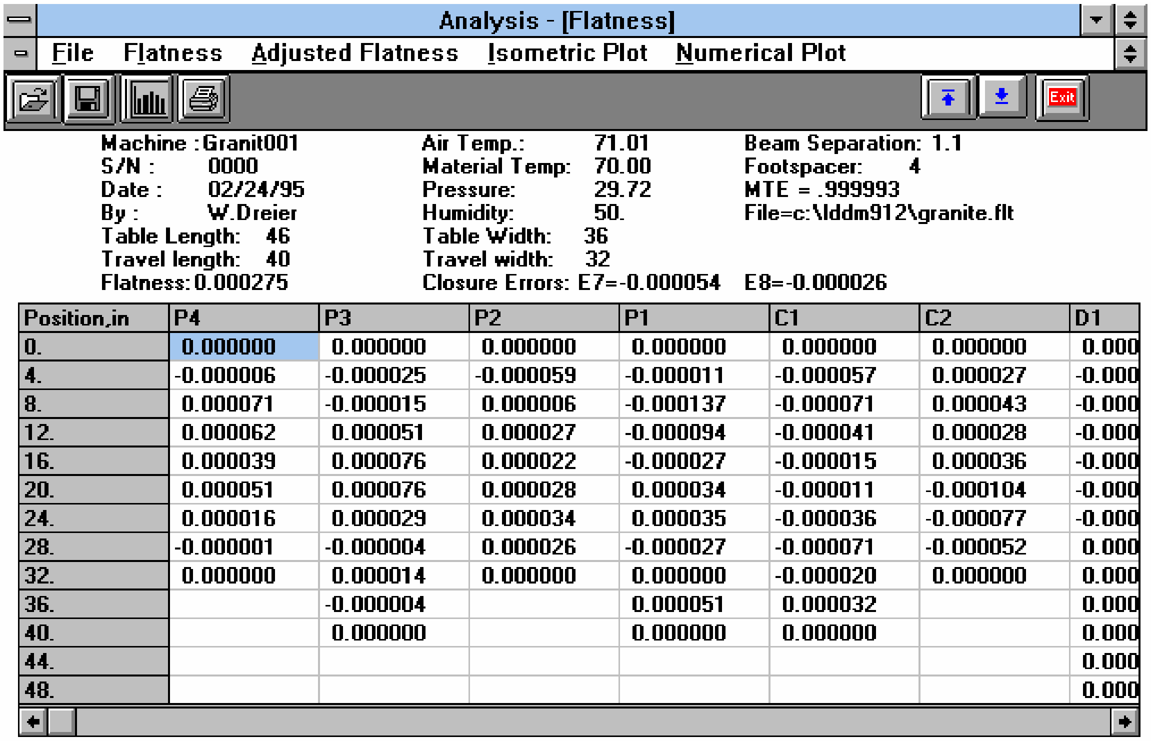
32) Click on **Setup** and make sure that the setup is the same. Hit **OK** after checking.

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)



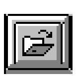
Position,in	P4	P3	P2	P1	C1	C2	D1
0.	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000
4.	-0.000006	-0.000025	-0.000059	-0.000011	-0.000057	0.000027	-0.000
8.	0.000071	-0.000015	0.000006	-0.000137	-0.000071	0.000043	-0.000
12.	0.000062	0.000051	0.000027	-0.000094	-0.000041	0.000028	-0.000
16.	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

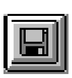
Fig. 6-4 flatness Measurement Data Table

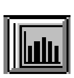
Under the **File Menu**, you can open a **new** data file, **save** a data file, set your **printer type**, set your **printer style**, or return to the **main menu**. When loading a file, choose the files with the extension of .FLT for flatness. You can only **print data** tables using the print function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

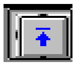
The following icons have the following function in Analysis:


Open a new data file.

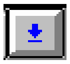

Save a data file.


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

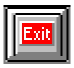
Print a data graph (for printing data tables, use the Print option under the "File" heading)



Moves to the previous screen.



Moves to the next screen.



Exits the program.

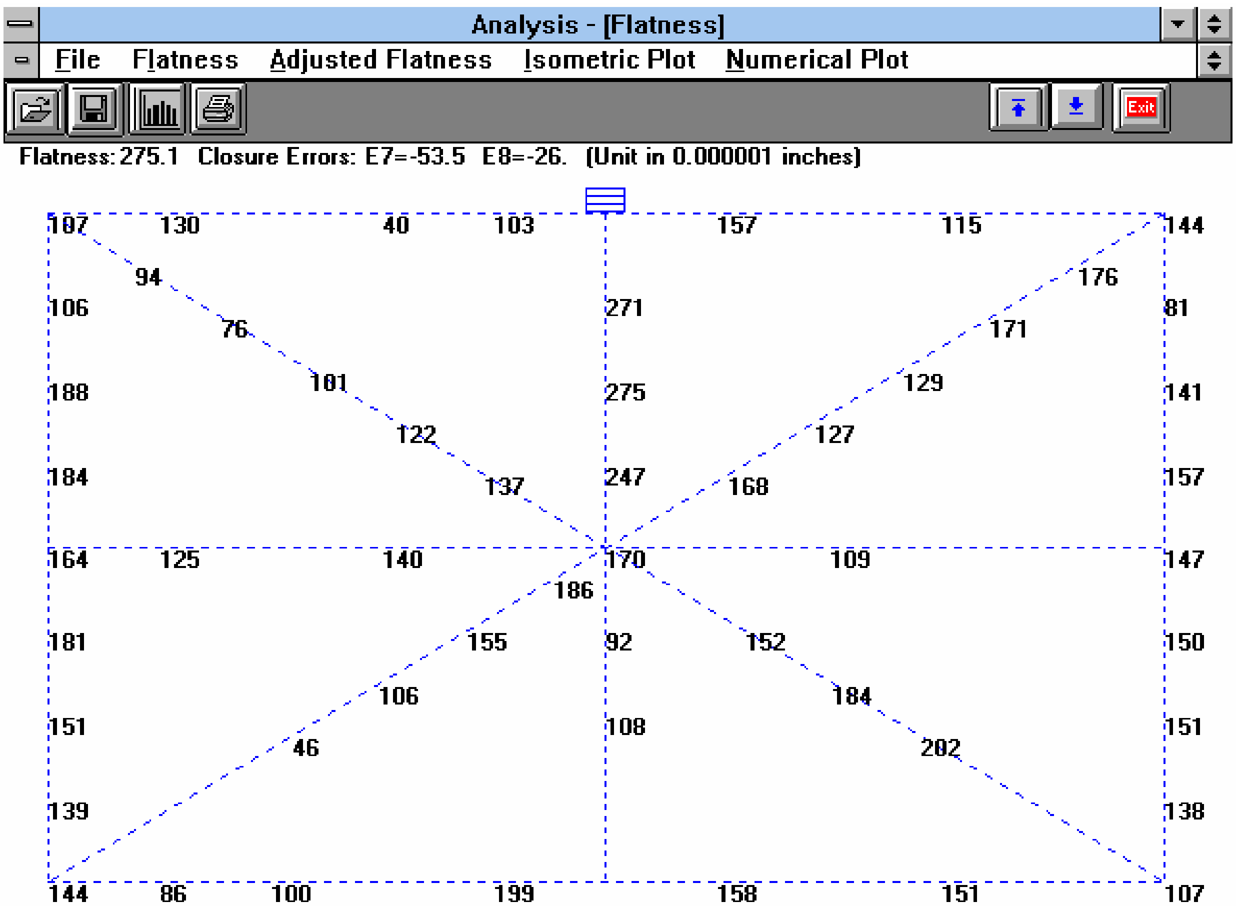


Fig. 6-5 Flatness Measurement Numerical Plot

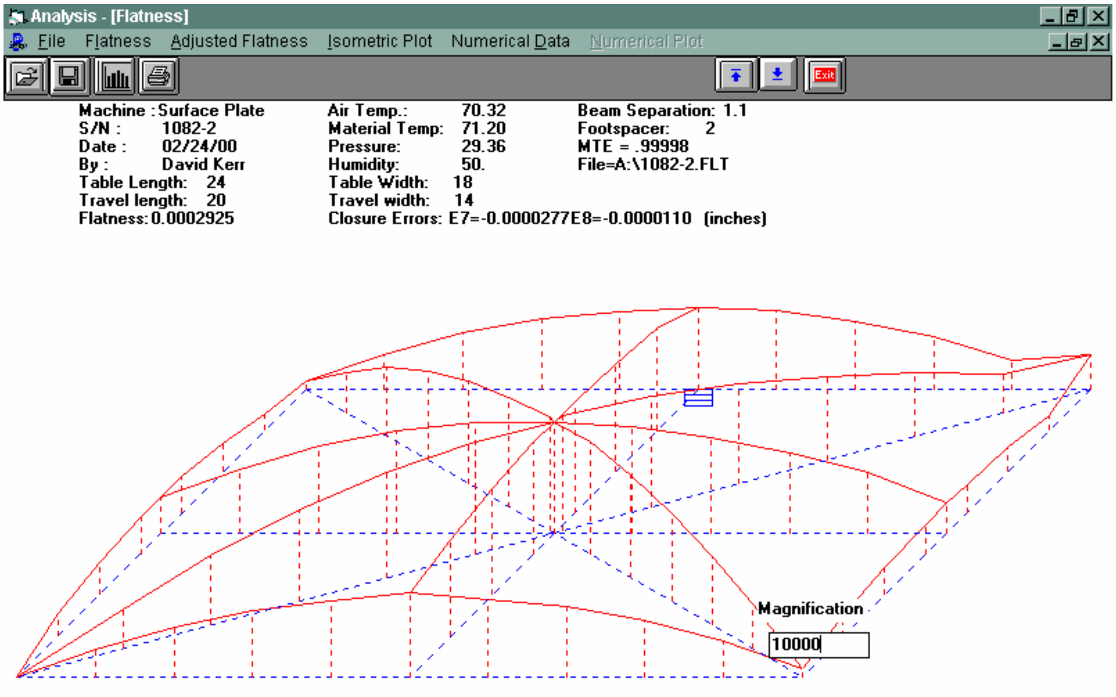


Fig. 6-6 Flatness Measurement Isometric Plot

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)

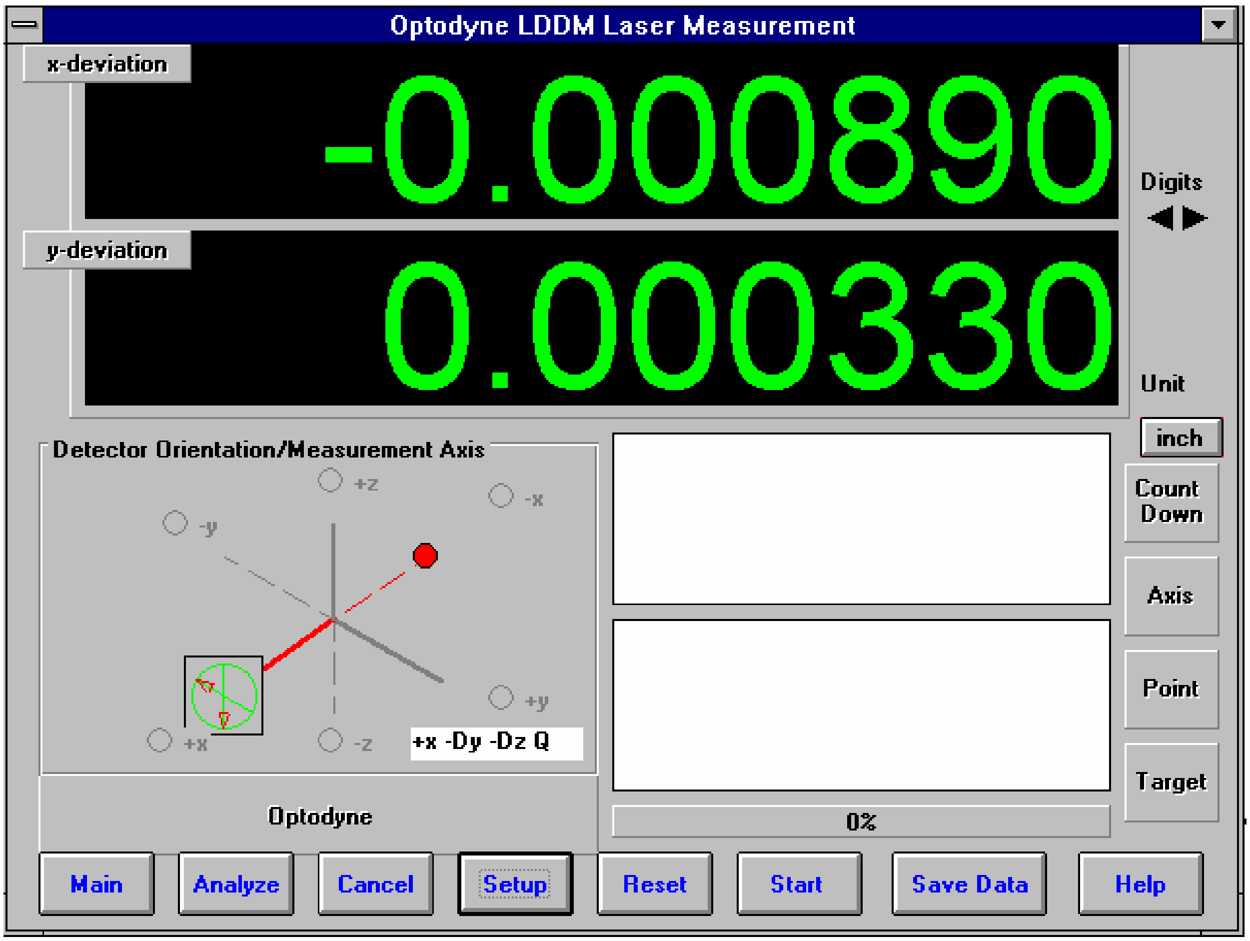


Fig. 7-1 Squareness Main display

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/Measurement 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 ±x, ±y, and ±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.

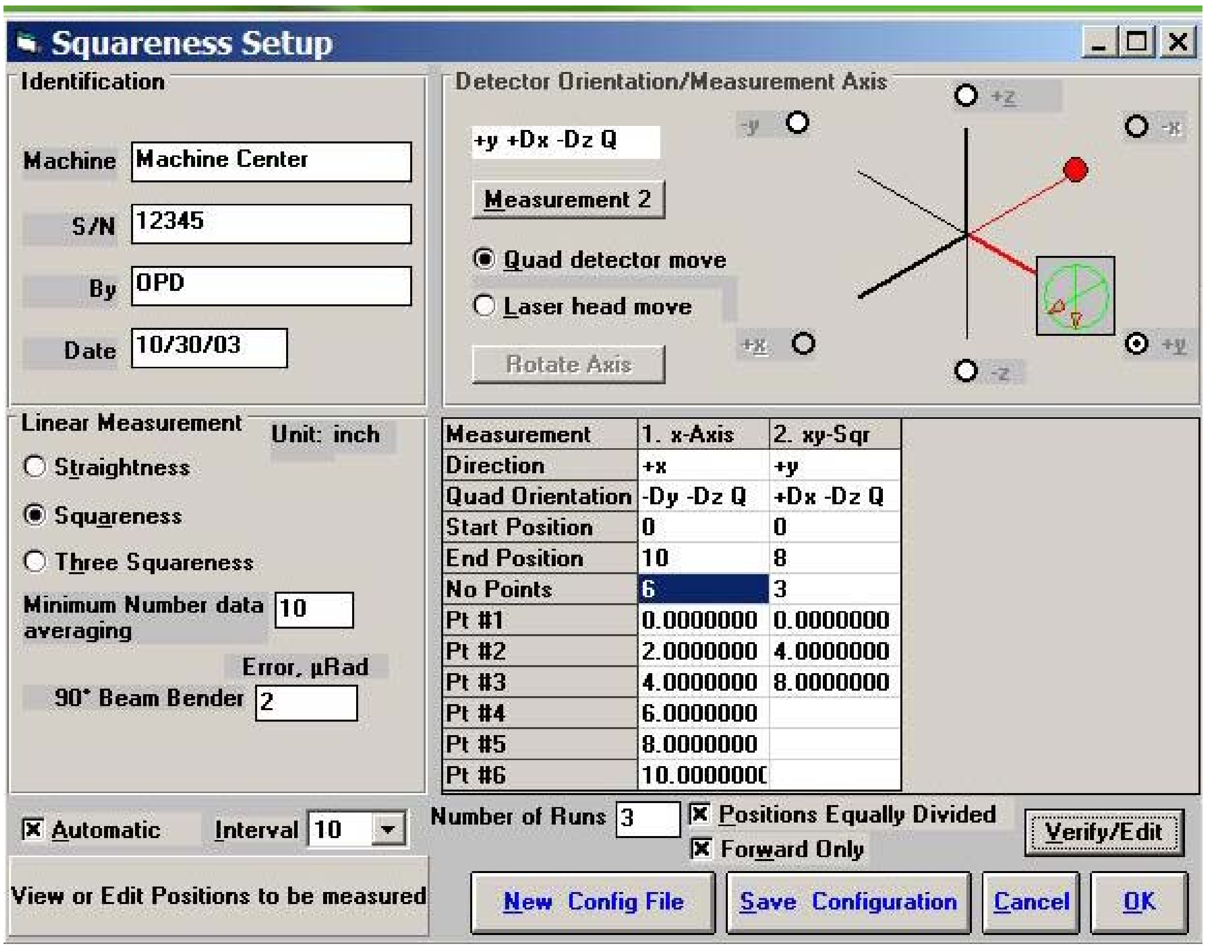


Fig. 7-2 Squareness Measurement Setuup Screen (Leg 1)

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 you 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:

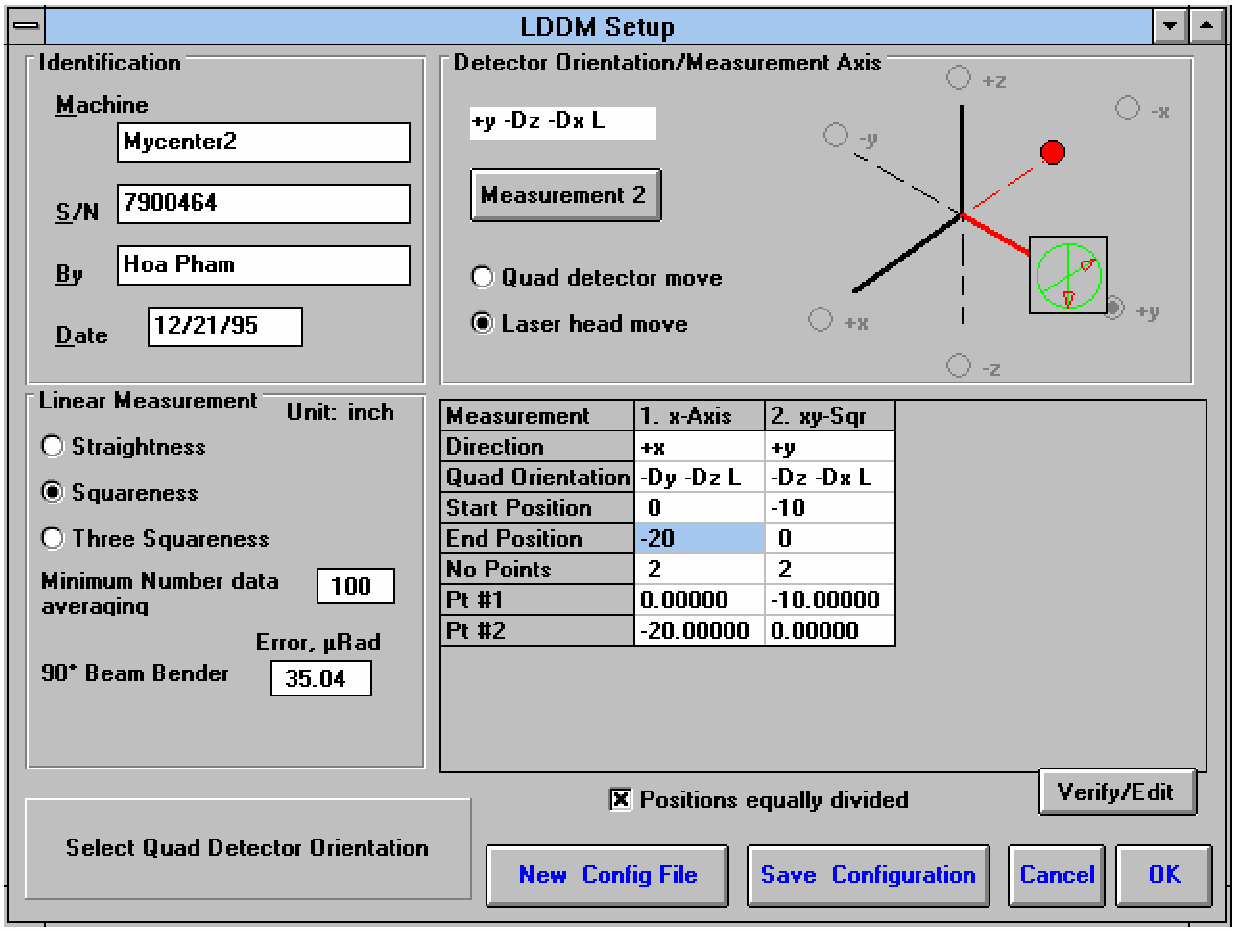


Fig. 7-3 Squareness Measurement Setup Screen (Leg 2)

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 DataPonit 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**.

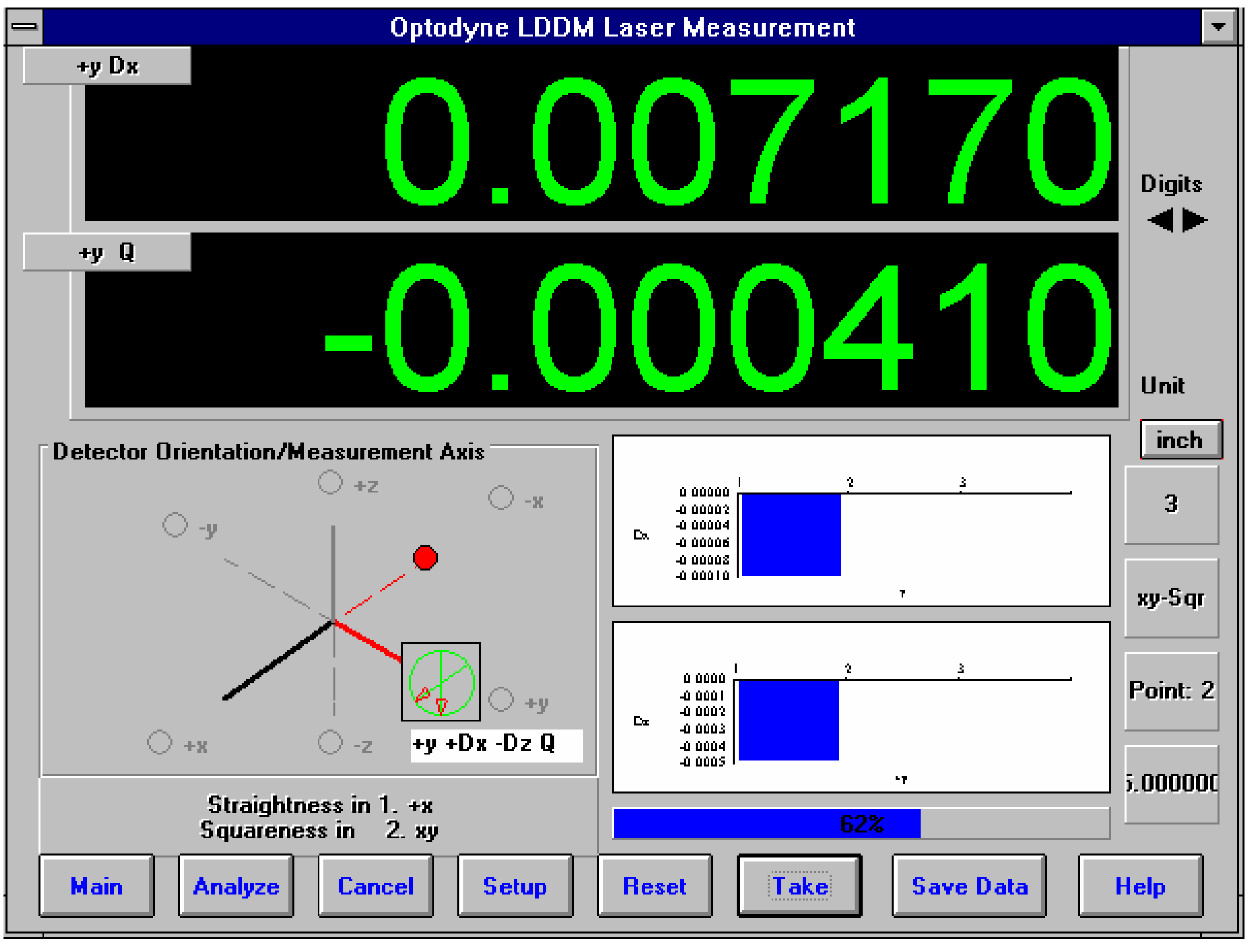


Fig. 7-4 Manual Squareness Data Collection

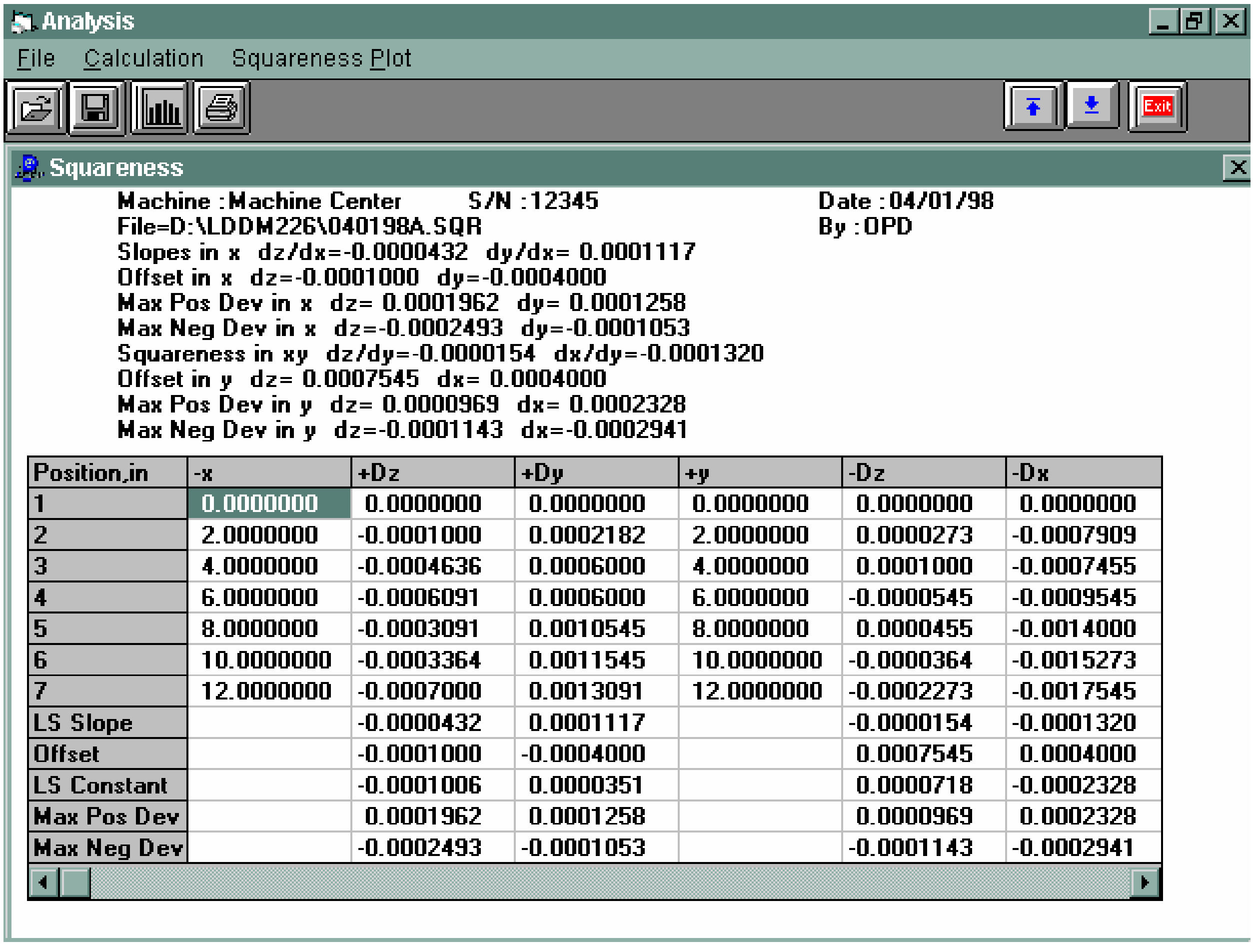
20) Setup your second axis and press the **Start Axis 2** button, repeat 19.

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)



Machine :Machine Center S/N :12345 Date :04/01/98
File=D:\LDDM226\040198A.SQR By :OPD
Slopes in x dz/dx=-0.0000432 dy/dx= 0.0001117
Offset in x dz=-0.0001000 dy=-0.0004000
Max Pos Dev in x dz= 0.0001962 dy= 0.0001258
Max Neg Dev in x dz=-0.0002493 dy=-0.0001053
Squareness in xy dz/dy=-0.0000154 dx/dy=-0.0001320
Offset in y dz= 0.0007545 dx= 0.0004000
Max Pos Dev in y dz= 0.0000969 dx= 0.0002328
Max Neg Dev in y dz=-0.0001143 dx=-0.0002941

Position,in	-x	+Dz	+Dy	+y	-Dz	-Dx
1	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
2	2.0000000	-0.0001000	0.0002182	2.0000000	0.0000273	-0.0007909
3	4.0000000	-0.0004636	0.0006000	4.0000000	0.0001000	-0.0007455
4	6.0000000	-0.0006091	0.0006000	6.0000000	-0.0000545	-0.0009545
5	8.0000000	-0.0003091	0.0010545	8.0000000	0.0000455	-0.0014000
6	10.0000000	-0.0003364	0.0011545	10.0000000	-0.0000364	-0.0015273
7	12.0000000	-0.0007000	0.0013091	12.0000000	-0.0002273	-0.0017545
LS Slope		-0.0000432	0.0001117		-0.0000154	-0.0001320
Offset		-0.0001000	-0.0004000		0.0007545	0.0004000
LS Constant		-0.0001006	0.0000351		0.0000718	-0.0002328
Max Pos Dev		0.0001962	0.0001258		0.0000969	0.0002328
Max Neg Dev		-0.0002493	-0.0001053		-0.0001143	-0.0002941

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 = 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 negtive 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.

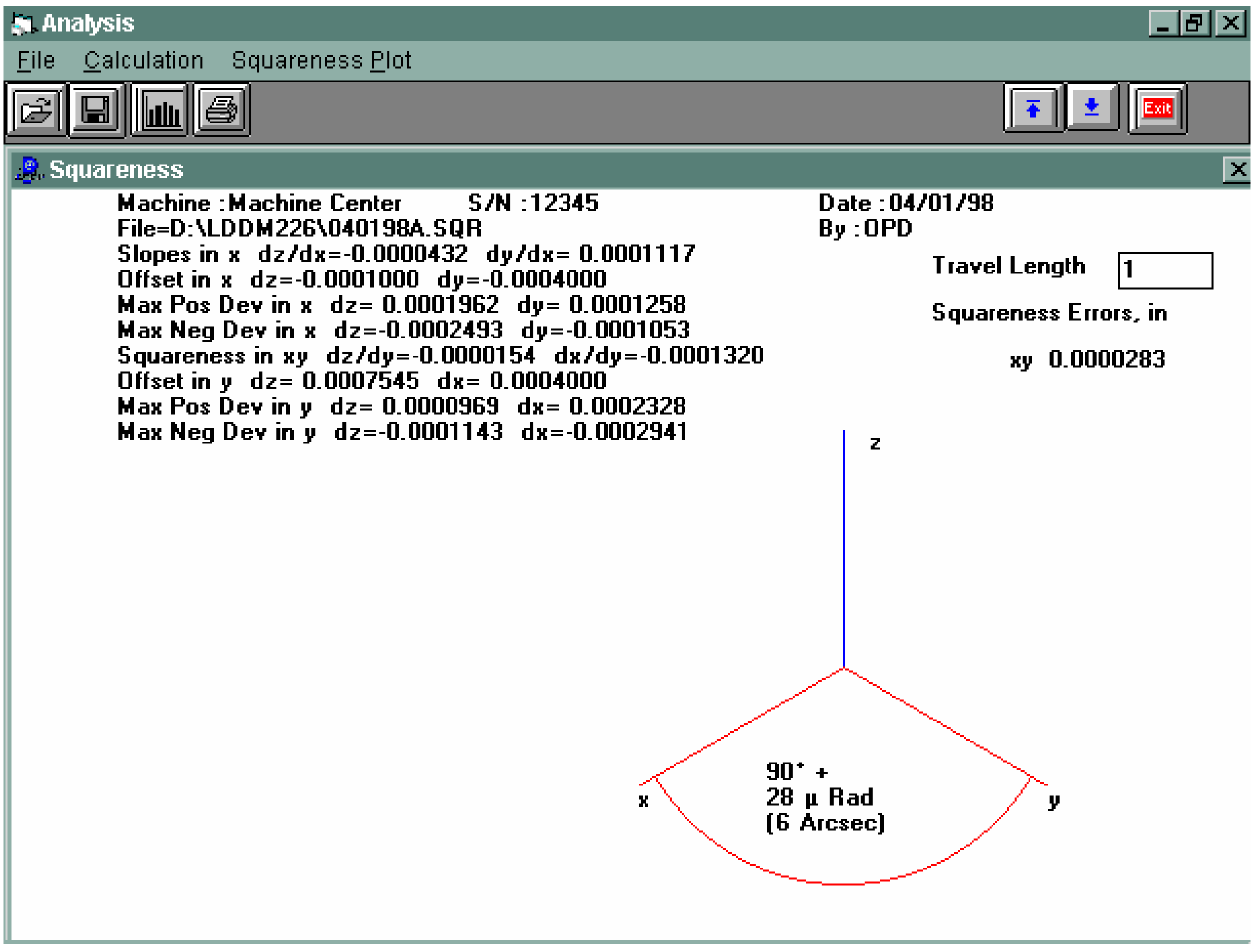


Fig. 7-6 Squareness Measurement Data Plot

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.

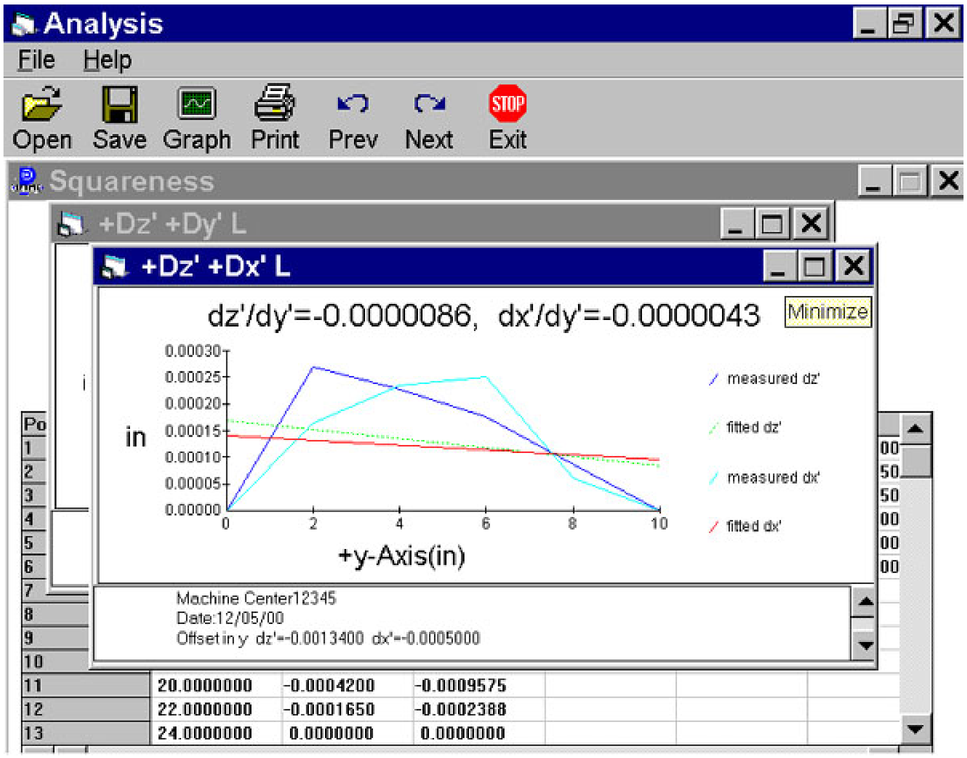


Fig. 7-7 A Plot of Adjusted Vertical and Horizontal Straightness.
The Straight Line is the Least Square Fit.

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.

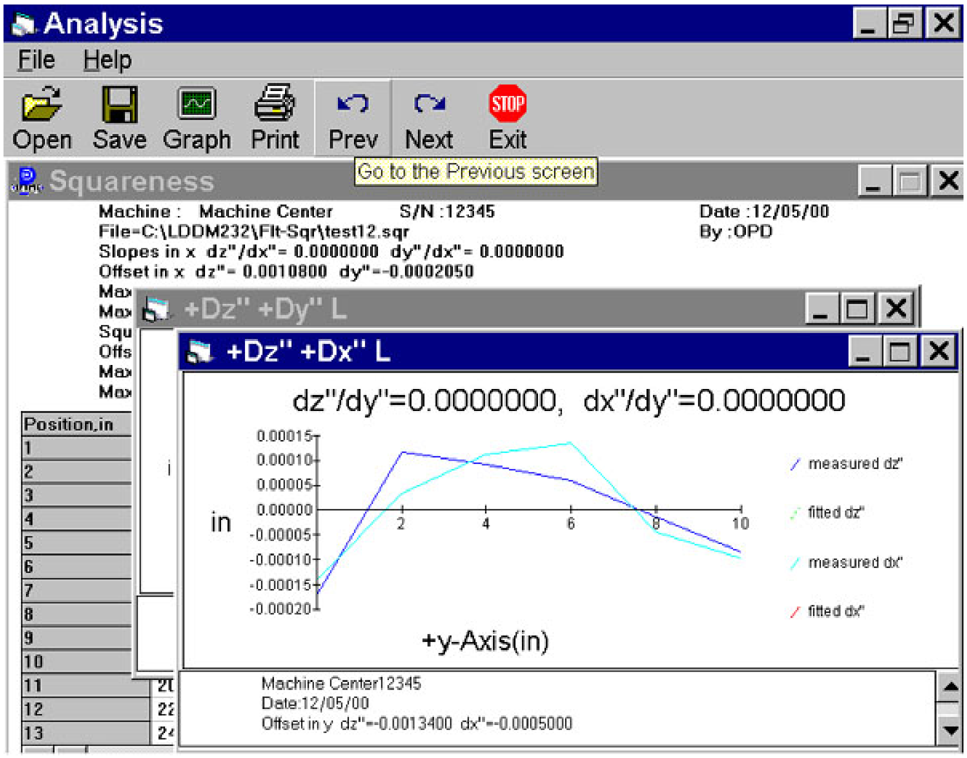
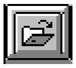
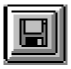
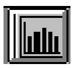


Fig. 7-8 A plot of Averaged Vertical and Horizontal Straightness. Here the Least Square Fit Line is at Zero and Parallel to the Axis of Travel.

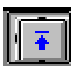
The following icons have the following function in Analysis:

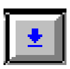

Open a new data file.

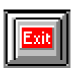

Save a data file.


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 able 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)

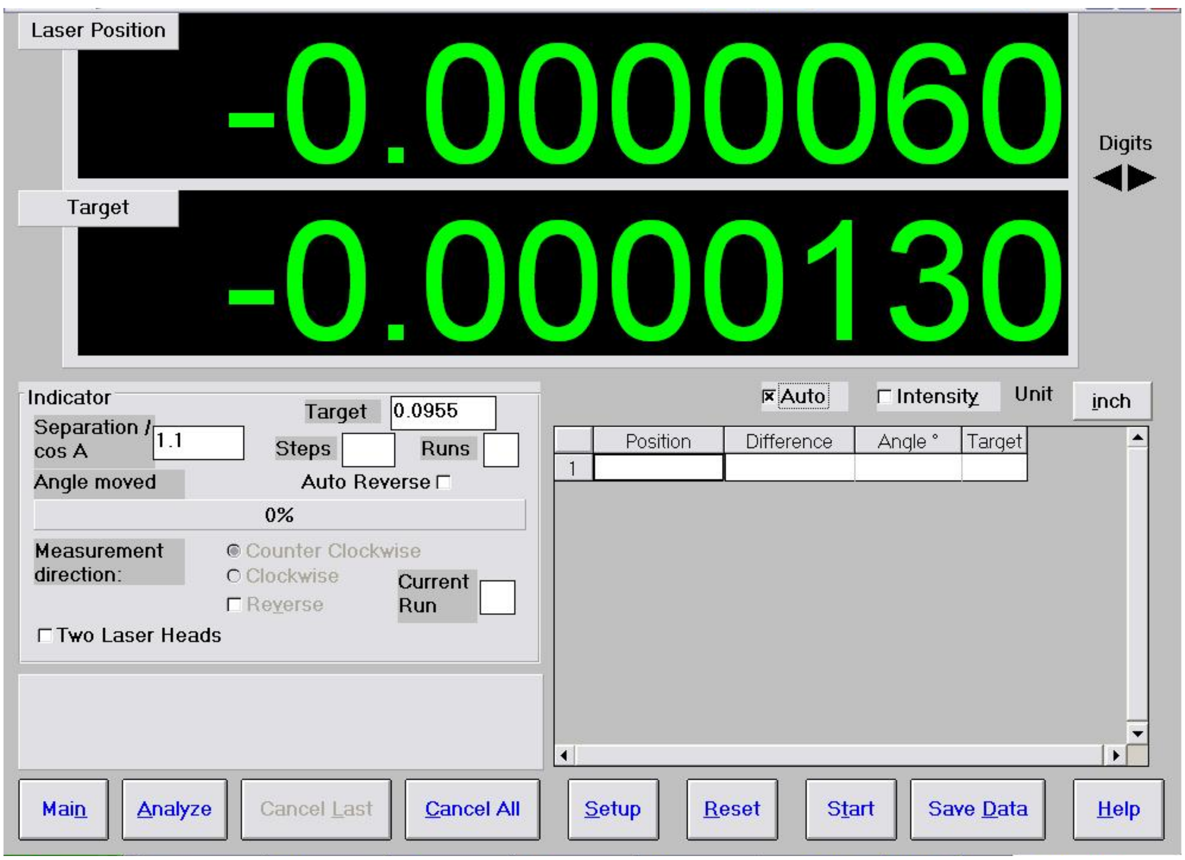


Fig. 8-1 Rotary Table Measurement Main Display

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.

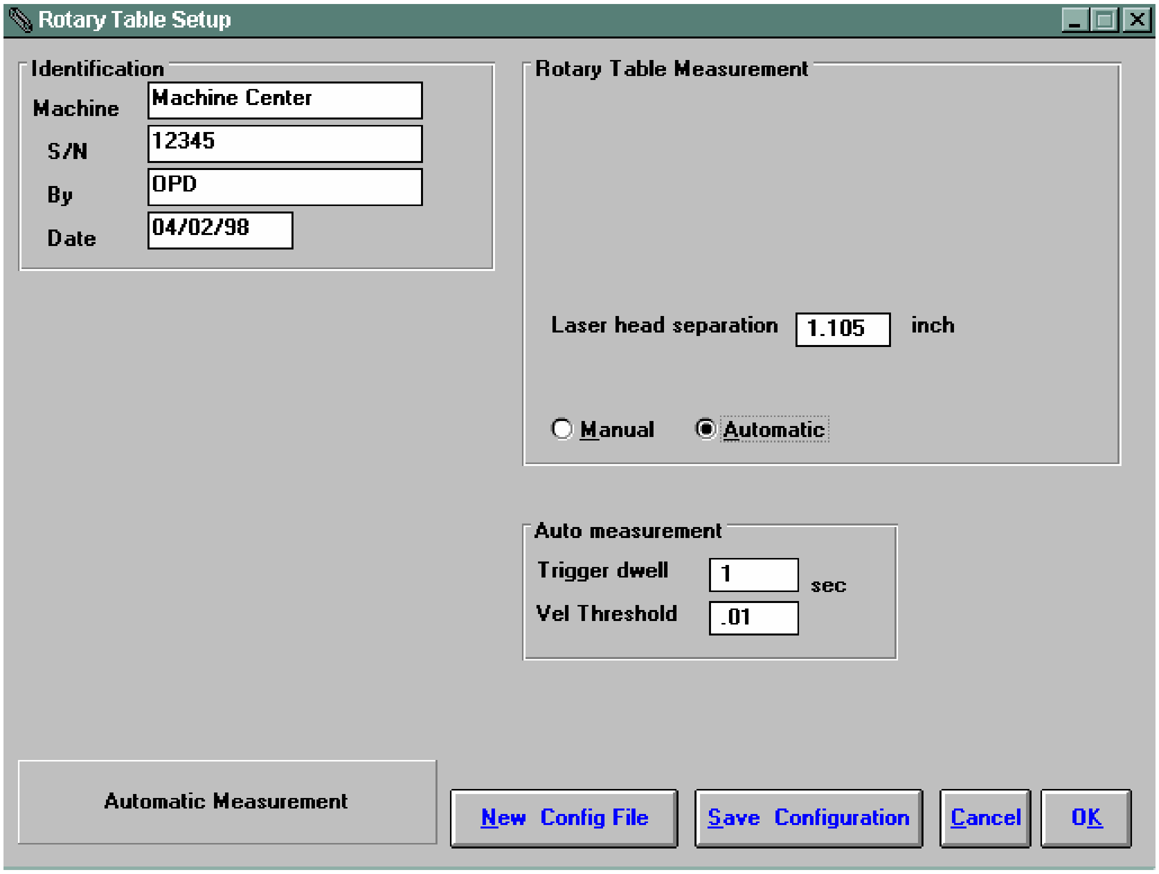


Fig. 8-2 Rotary Measurement Setup Screen

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

Analysis - [Rotary Table]

File Data Selection Analysis Help

Angle MeasurementErrors in Angle (Degree) File=D:\LDDM226\032398.ROT Date :03/23/98
Machine :Machine Center S/N :12345 By :OPD
Max Error: 0.4998779 Min Error: -0.4934731

Laser separation cos A: 1.105 Calibration ⦿ Degree ○ µRad ○ Arcsec

	Distance	Difference	Angle°	Target°
0	0.0027460	0.0002630		
32	-0.0962970	-0.1943030	-317.1036150	-317
0	0.0022230	0.0002000		
33	-0.0936590	-0.1880420	-326.9119070	-327
0	0.0010370	0.0001550		
34	-0.0953610	-0.1896660	-336.8033298	-337
0	0.0000590	0.0000890		
35	-0.0959470	-0.1892370	-346.6687518	-347
0	-0.0003140	0.0000430		
36	-0.0984950	-0.1937060	-356.7670718	-360
0	-0.0003870	-0.0000130		
37	0.0931090	0.1883870	-346.9503220	-347
0	-0.0009500	-0.0008870		
38	0.0939840	0.1903110	-336.9869943	-337
0	-0.0007900	-0.0008430		
39	0.0935770	0.1890980	-327.0897916	-327
0	-0.0008960	-0.0008010		

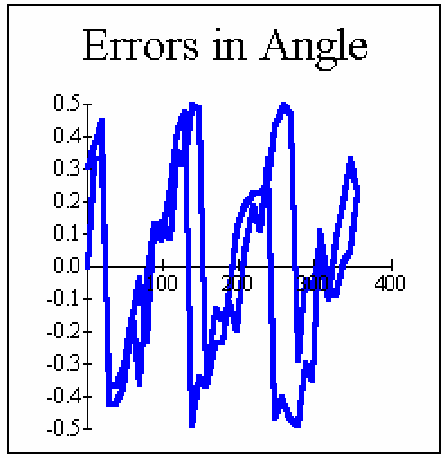
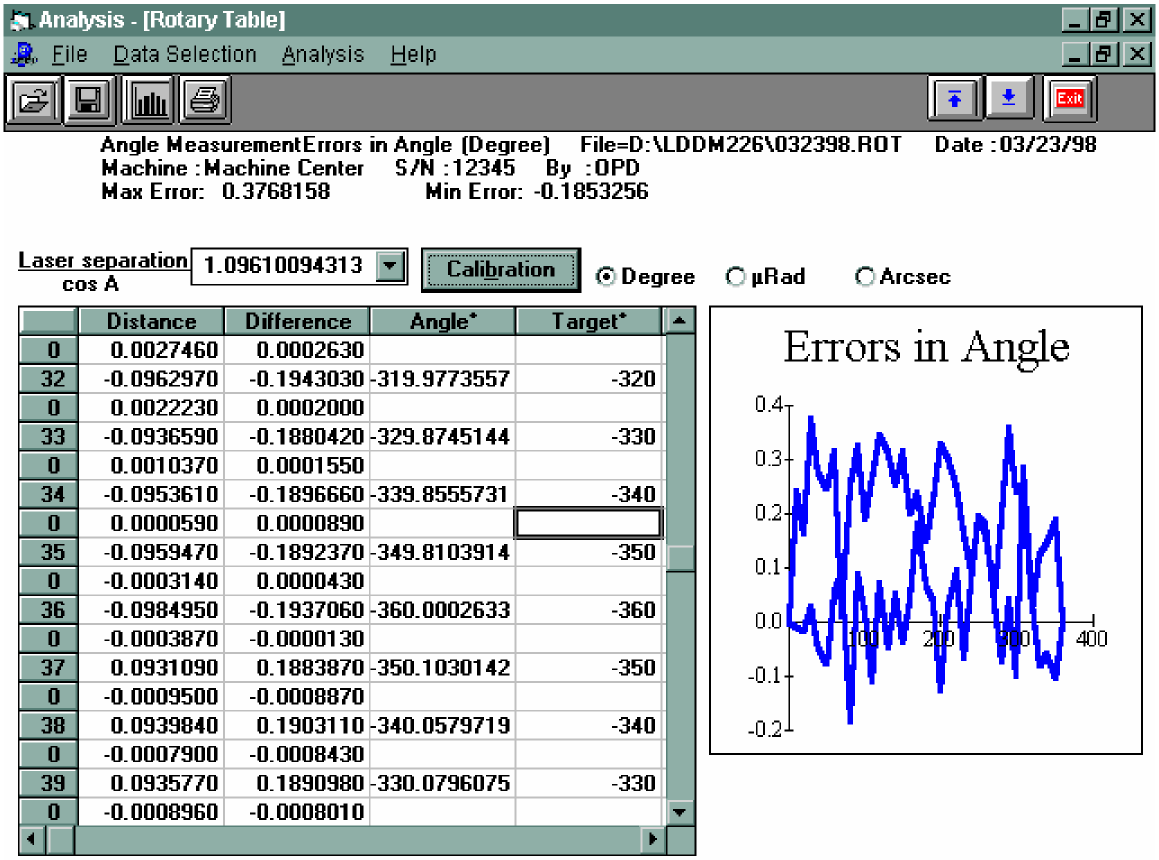


Fig. 8-3 Rotary Data Analysis Table

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 .



	Distance	Difference	Angle°	Target°
0	0.0027460	0.0002630		
32	-0.0962970	-0.1943030	-319.9773557	-320
0	0.0022230	0.0002000		
33	-0.0936590	-0.1880420	-329.8745144	-330
0	0.0010370	0.0001550		
34	-0.0953610	-0.1896660	-339.8555731	-340
0	0.0000590	0.0000890		
35	-0.0959470	-0.1892370	-349.8103914	-350
0	-0.0003140	0.0000430		
36	-0.0984950	-0.1937060	-360.0002633	-360
0	-0.0003870	-0.0000130		
37	0.0931090	0.1883870	-350.1030142	-350
0	-0.0009500	-0.0008870		
38	0.0939840	0.1903110	-340.0579719	-340
0	-0.0007900	-0.0008430		
39	0.0935770	0.1890980	-330.0796075	-330
0	-0.0008960	-0.0008010		

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:

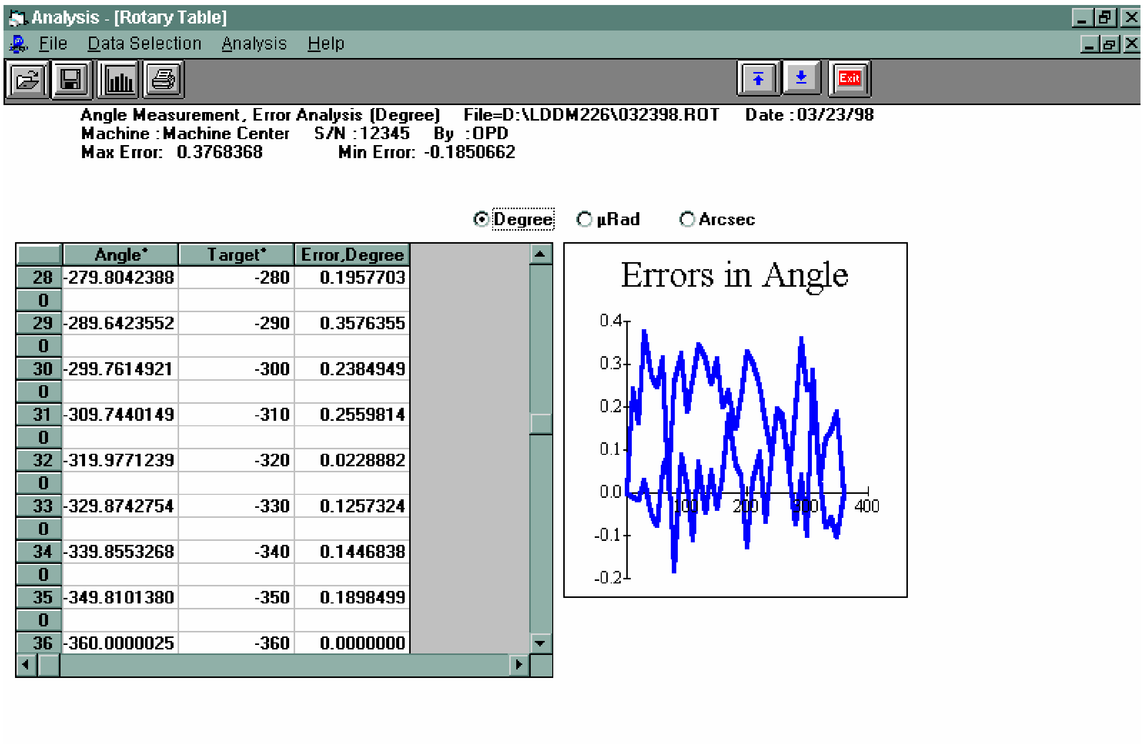


Fig. 8-5 Rotary Data Analysis Show Error table

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 .

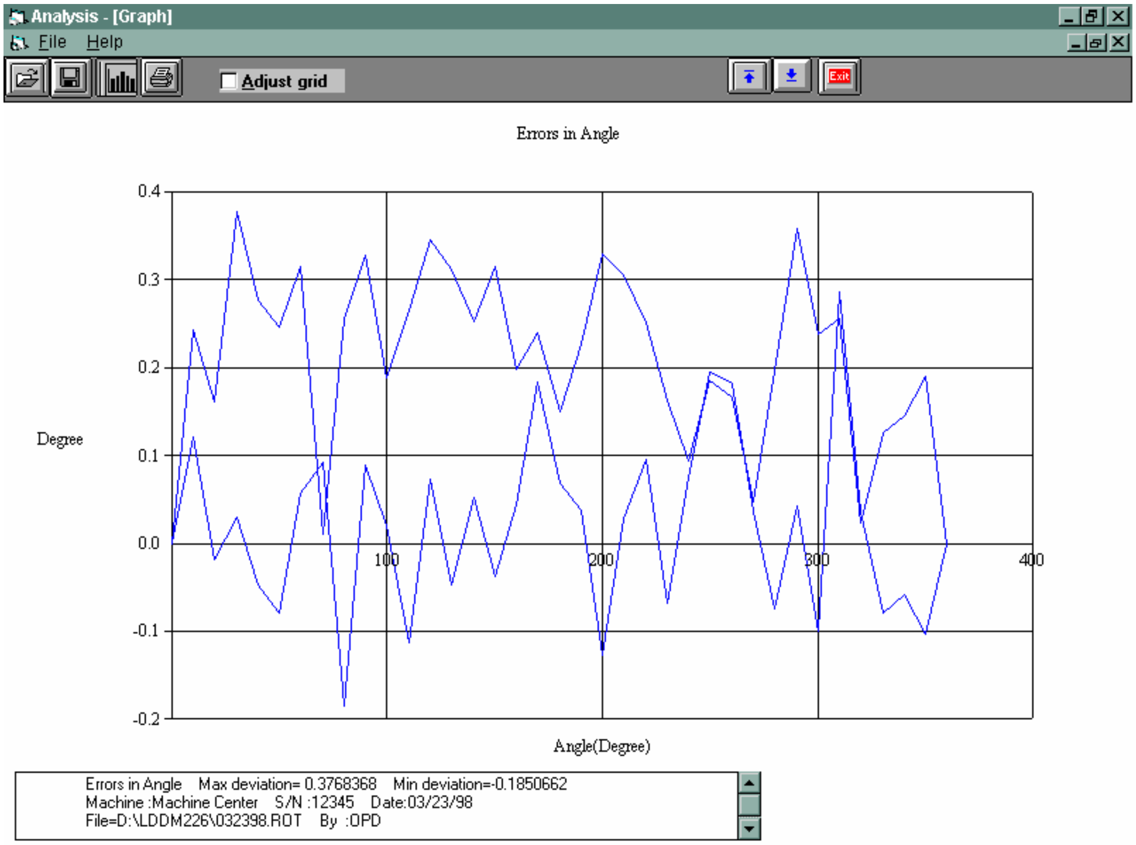


Fig. 8-6 Rotary Measurement Error Plot in Degree

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.

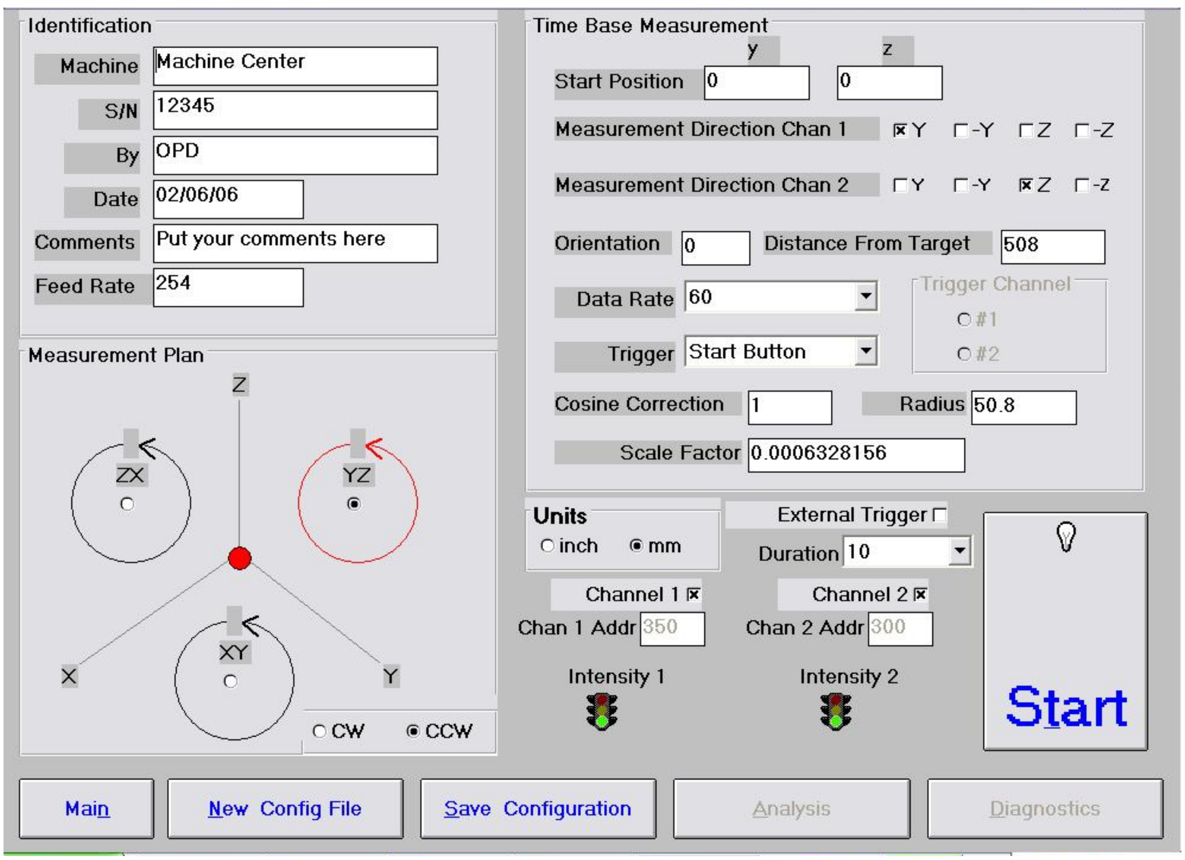


FIG. 9-1 2D TIME BASE DATA COLLECTION SCREEN

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 2cos(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.

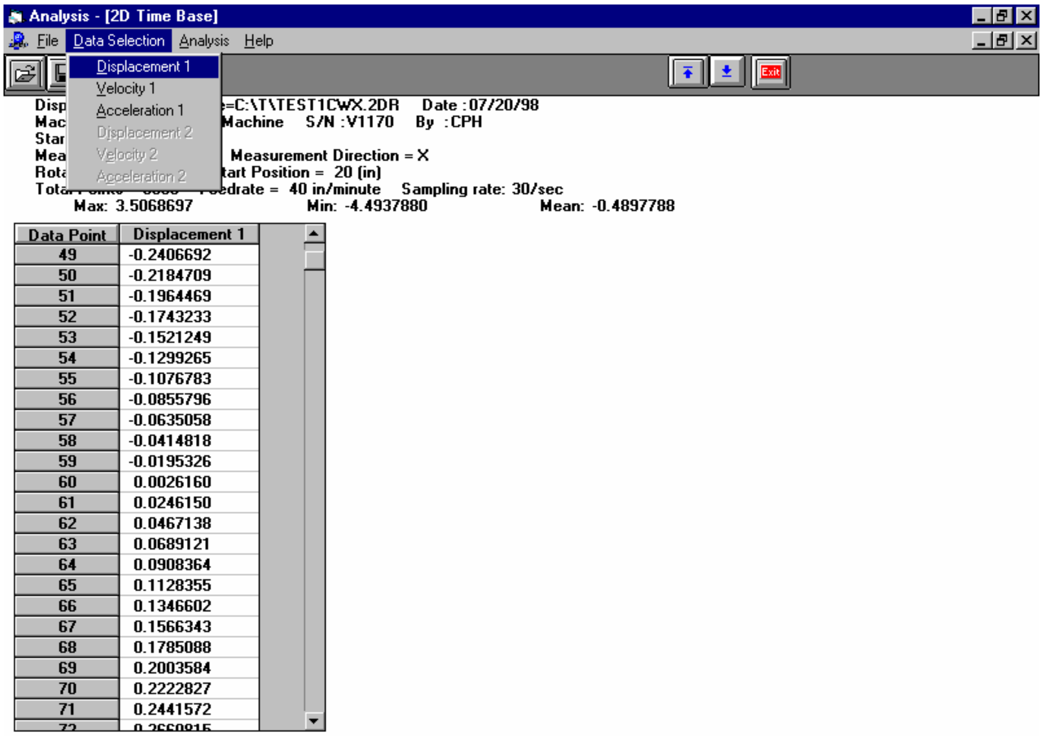


FIG.9-2 THE ANALYSIS SCREEN WITH DISPLACEMENT DATA

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

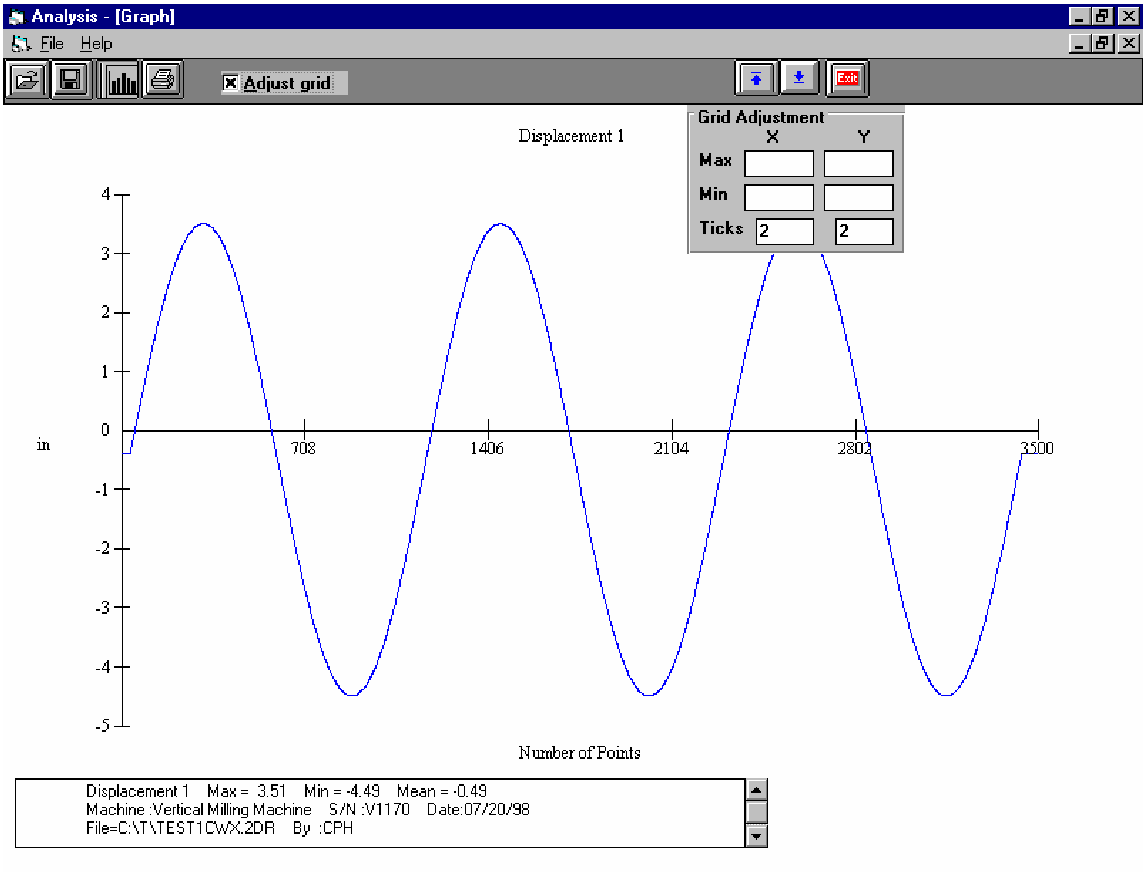


FIG. 9-3 A Typical Plot on Displacement Data

To generate a data file for polar plot, click on “file” and “save”. Select 2dd in the popup screen. Anothe 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 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. 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.

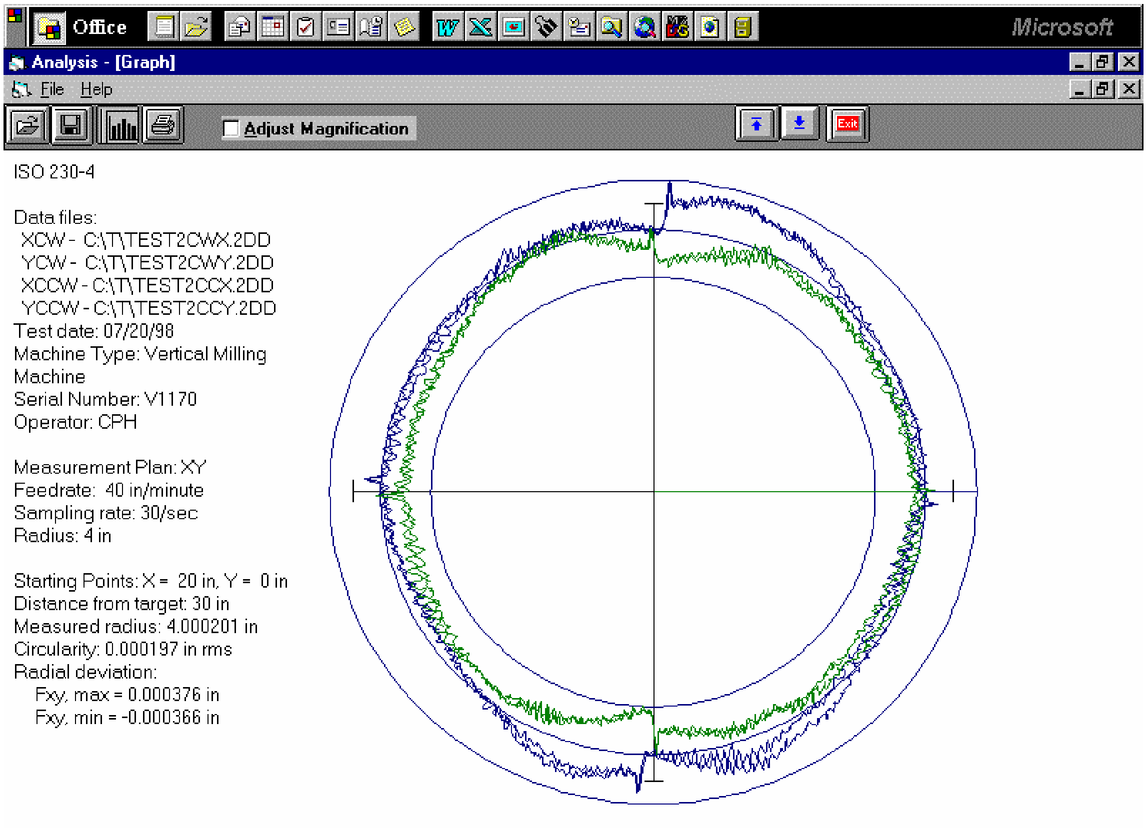


FIG. 9-4 A TYPICAL POLAR PLOT OF THE CIRCULAR PATH

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 Fxy,max and the radius of the smallest circle is the measured radius minus the Fxy,min . Or the distance between the largest circle and smallest circle is equal to Fxy,max – Fxy,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.

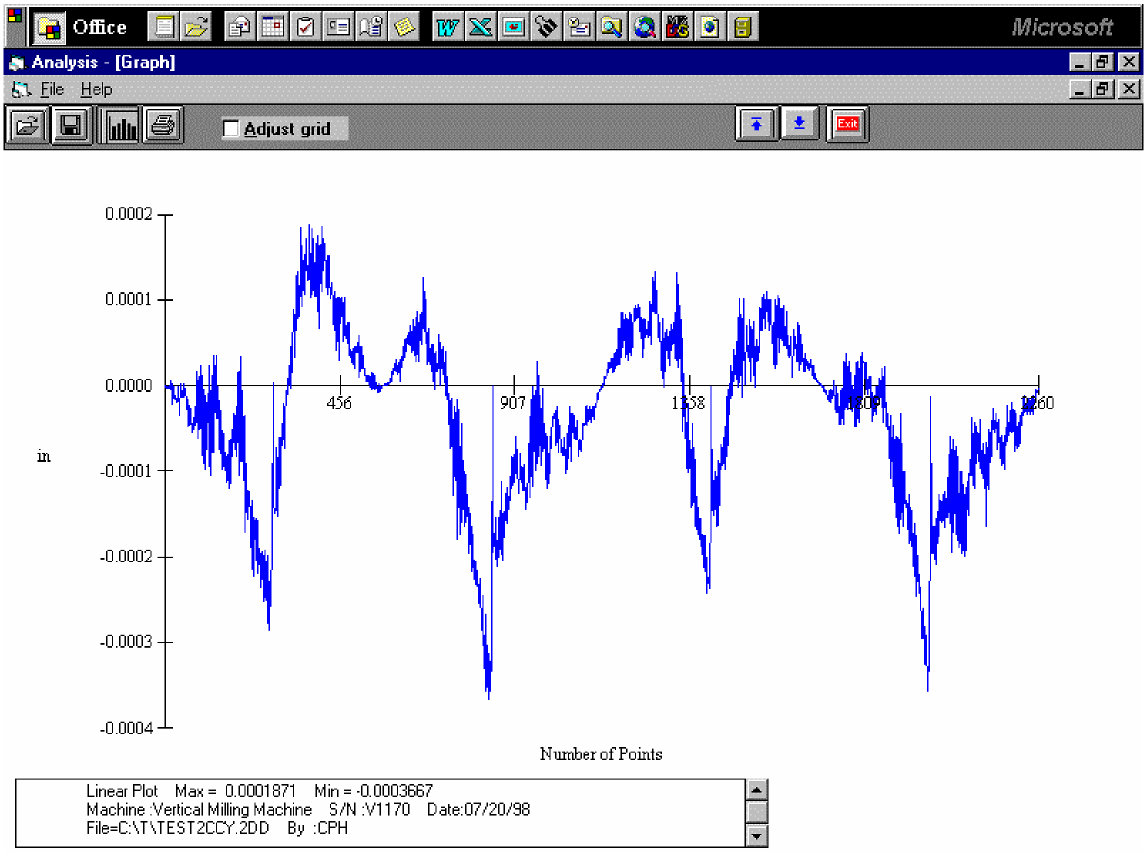


FIG. 9-5 A Typical Linear Plot of the Circuit Path

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.

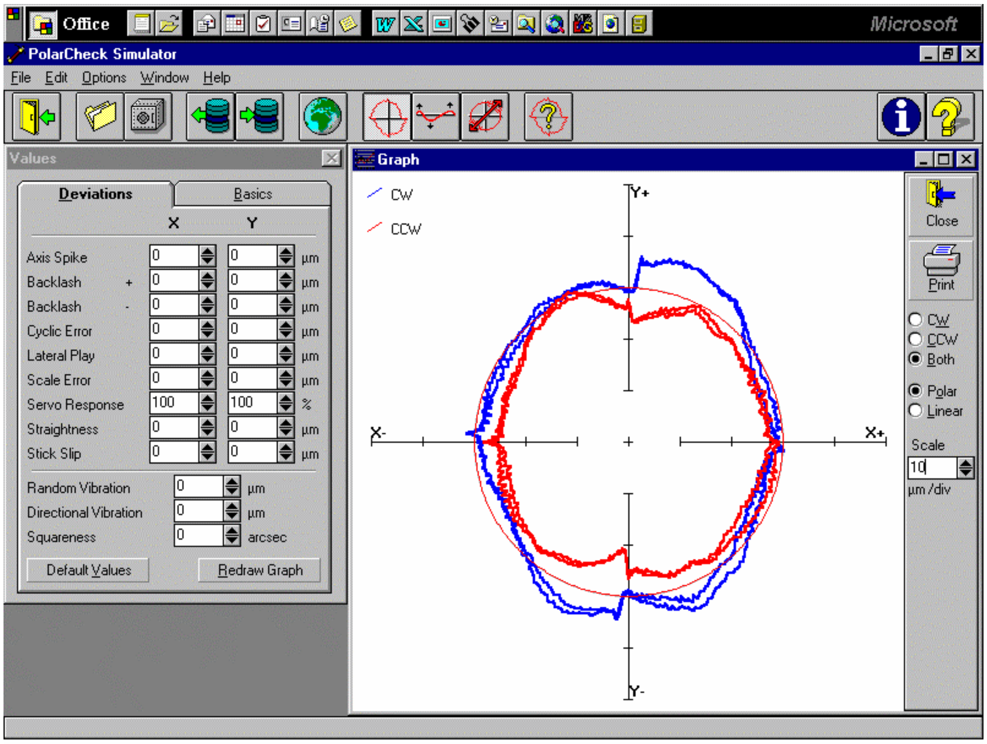


Fig. 9-6 A TYPICAL POLAR PLOT USING POLARCHECK

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.

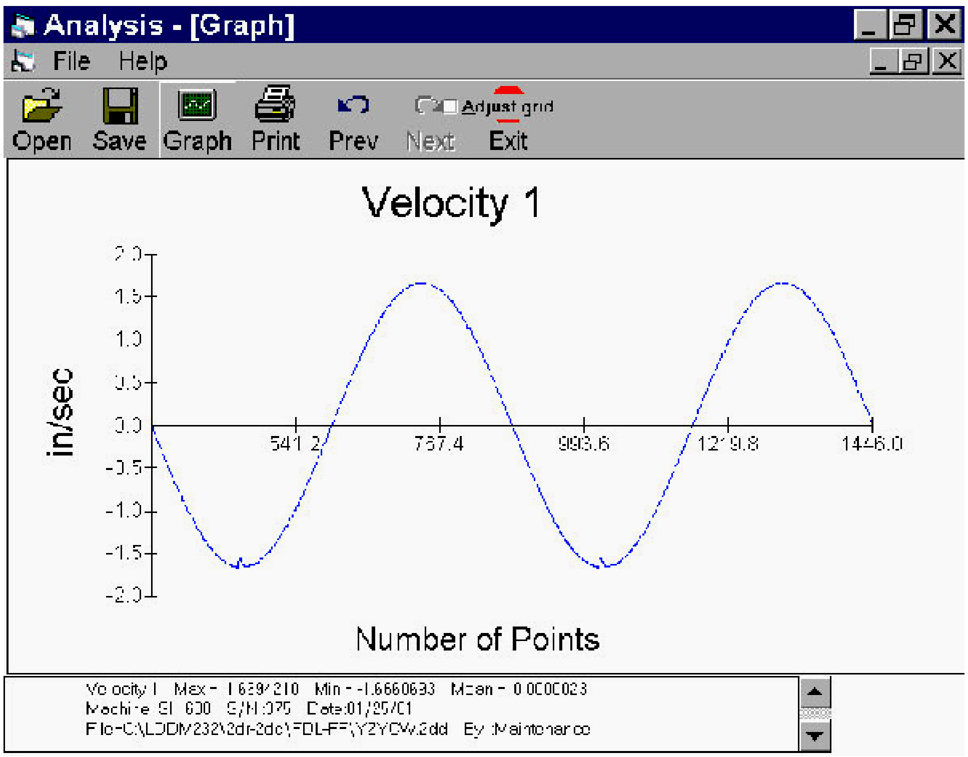


Fig. 9-7 A Plot of Velocity Profile without Feedforward. There are Notches near the Maximum Velocity in the Negative Direction.

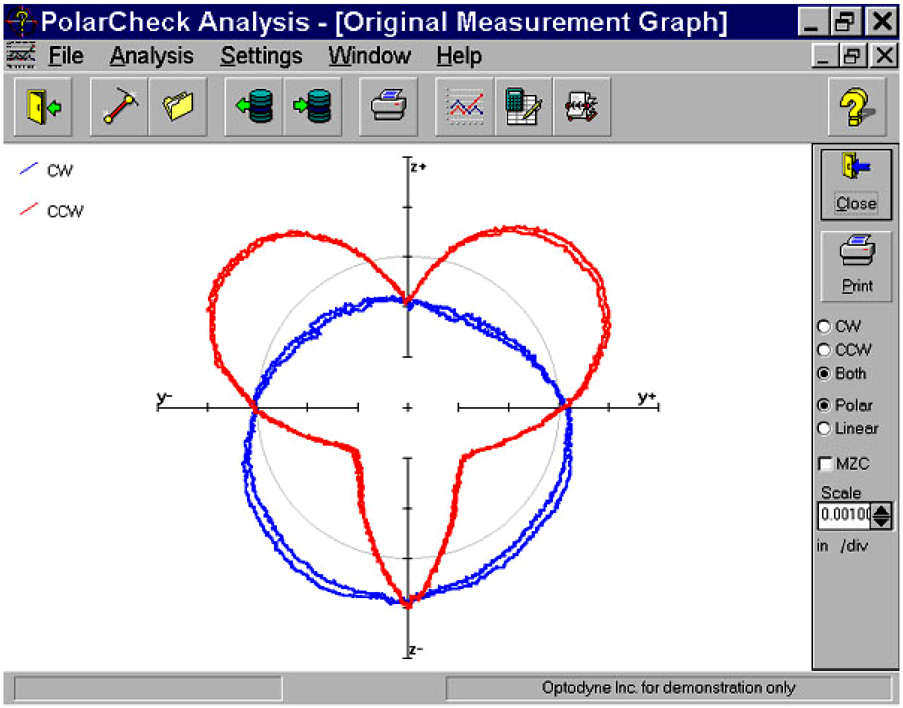


Fig. 9-8 A Polar Plot of the Circular Contouring Error without Feedforward

The large non-roundness shown in Fig. 9-8 is caused by the velocity notches. Once the feedforward function is turned-on, the velocity notchs in Fig. 9-6 are removed and the polar plot shown in Fig. 9-9. The non-roundness is reduced considerably.

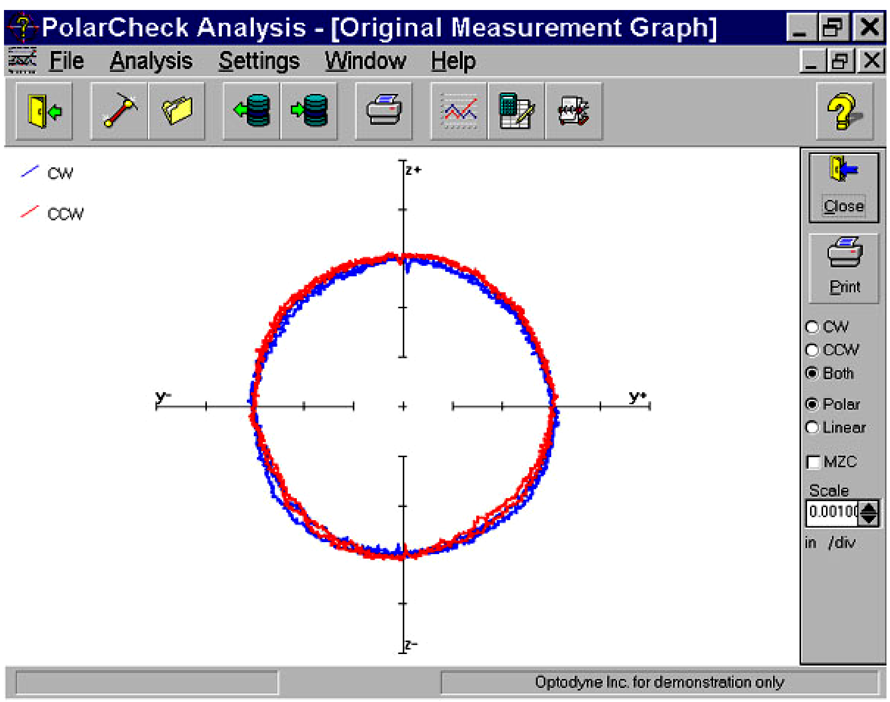


Fig. 9-9 A Polar Plot of the Circular Contouring Error with Feedforward

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,

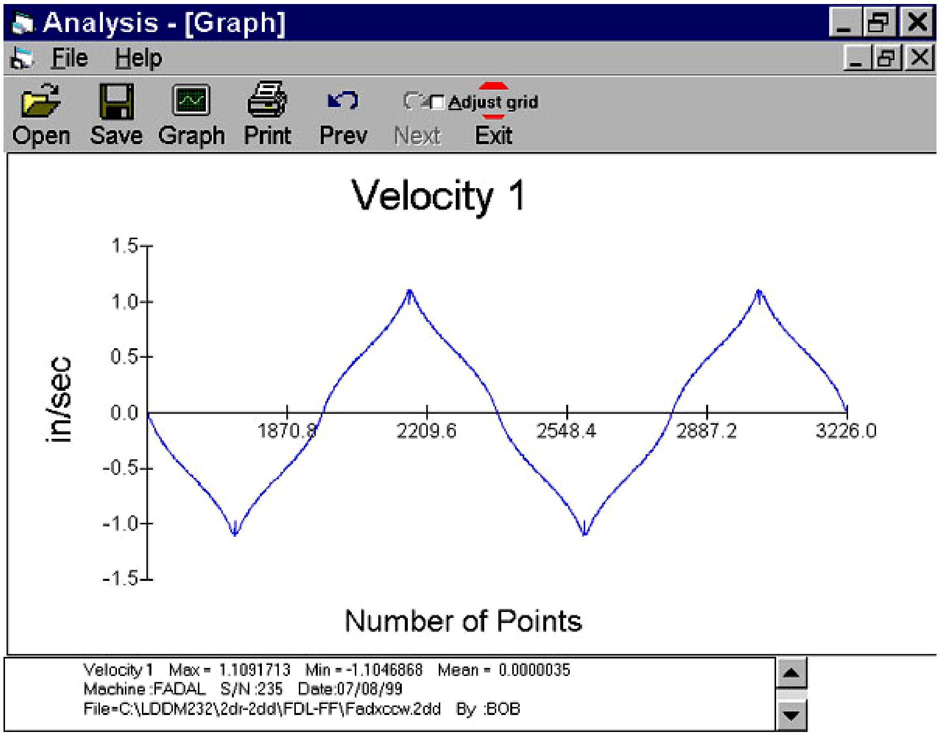


Fig. 9-10 A Plot of Velocity Profile without Velocity Feedback

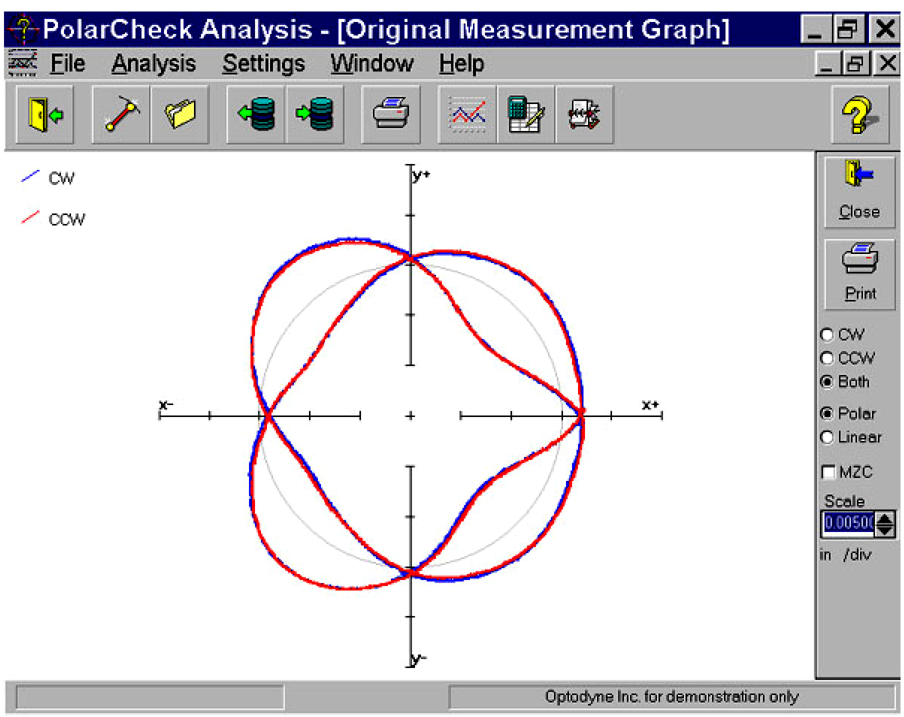


Fig. 9-11   A Polar Plot of the Circular Contouring Error without the Synchronized Data Processing

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.

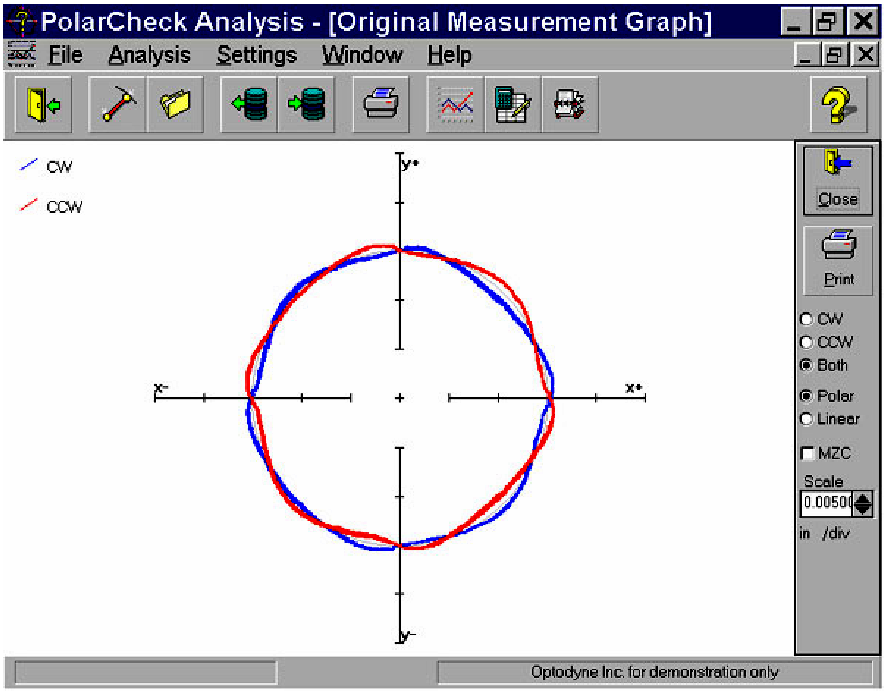


Fig. 9-12 A Polar Plot of the Circular Contouring Error
with the Synchronized Data Processing