

## 11.0 Measurement of Spindle Error Motion

### 11.1 Introduction

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 Dopplerometry. 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.

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.

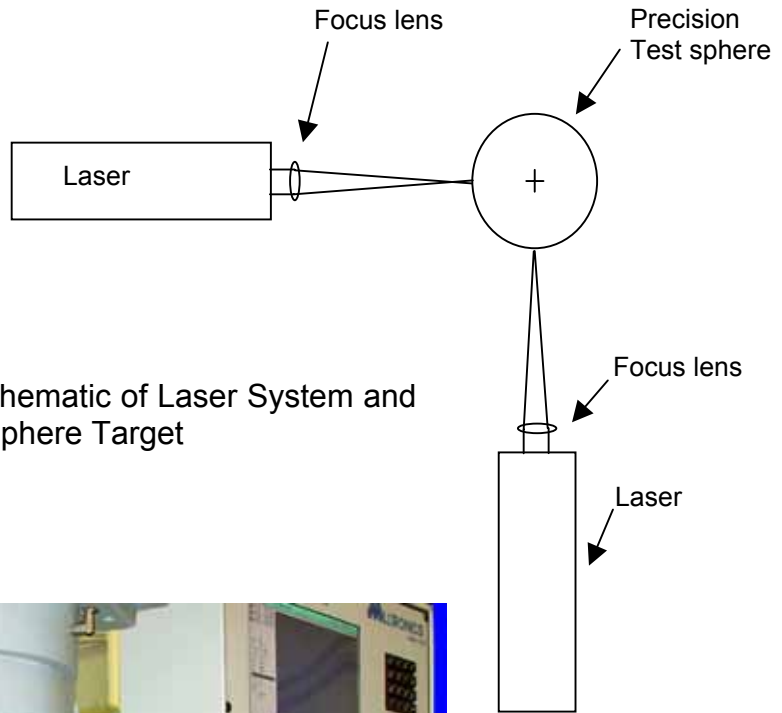


Fig.11-1 A Schematic of Laser System and the Sphere Target



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

## 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

<b><u>Accuracy:</u></b>	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.
<b><u>Resolution:</u></b>	Standard resolution is 1 μin (0.01 μm).
<b><u>Maximum Velocity:</u></b>	144 inch/sec (3600 mm/sec)
<b><u>Stand off Distance</u></b>	0.5" to 4" (10 mm to 100 mm)
<b><u>Temperature</u></b>	60°F to 90°F or (15.5°C to 32°C)

## 11.4 Basic Theory

### 11.4.1 Measurement of Spindle Offset

First point the laser in the X- or Y- direction, align the sphere to the center of rotation. Then rotate the tool holder together with the sphere tester 180 degrees. As shown in fig. 11-5, 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  $\Delta X_M$  and in Y direction is  $\Delta Y_M$ . The offset between the spindle axis of rotation and the tool center  $\Delta$  can be determined by

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

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

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

### 11.4.2 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  $\theta$  and the number of cycles  $i$ .

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

where  $r_f$  is the fundamental error motion,  $dr(\theta)$  is the residual error motion,  $dr_i(\theta)$  is the asynchronous error motion,  $\theta$  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.

$$r_f = \langle \langle r_i(\theta) \rangle_i \rangle_\theta \quad \text{Eq. 4}$$

$$dr(\theta) = \langle r_i(\theta) \rangle_i - r_f \quad \text{Eq. 5}$$

where  $\langle \rangle_i = \sum_i [ ] / N$  is the average over  $N$  cycles and  $\langle \rangle_\theta = \sum_\theta [ ] / 2\pi$  is the average over  $2\pi$  angle.

Based on the ASME B89.3.4M-1985 standard, the error motion values are defined as the followings.

Total error motion value =  $\text{Max}_{i,\theta} \{ r_i(\theta) \} - \text{Min}_{i,\theta} \{ r_i(\theta) \}$

Average error motion value =  $\text{Max}_\theta \{ r_f + dr(\theta) \} - \text{Min}_\theta \{ r_f + dr(\theta) \}$

Fundamental error motion value =  $r_f$

Residual error motion value =  $\text{Max}_\theta \{ dr(\theta) \} - \text{Min}_\theta \{ dr(\theta) \}$

Asynchronous error motion value =  $\text{Max}_\theta \{ \text{Max}_i [ r_i(\theta) ] - \text{Min}_i [ r_i(\theta) ] \}$ ,

Where  $\text{Max}_i [ ]$  is the maximum value over  $N$  cycles,  $\text{Min}_i [ ]$  is the minimum value over  $N$  cycles,  $\text{Max}_\theta \{ \}$  is the maximum value over angles  $\theta$ , and  $\text{Min}_\theta \{ \}$  is the minimum value over angles  $\theta$ .

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 tilt  $\alpha(\theta)$  can be expressed as

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

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  $Z(\theta)$ .

## 11.5 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.

## 11.6 Installation and Alignment

### 11.6.1 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.

### **11.6.2 Installation**

#### 11.6.2.1 Set up LDDM Program

See Section 7.5.2.1

#### 11.6.2.2 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.

#### 11.6.2.3 Starting LDDM Program

(See Section 7.5.2.2.)

Connect the RS232 cable, click on the LDDM icon, click on Linear ,  
On the screen for linear measurement click on Intensity.

#### 11.6.2.4 International settings

Please make sure that the “Numbers” in the “international settings” of Windows are settled with **Point as Decimal separator**, comma as thousandths separation and **Comma for Column separation**

#### 11.6.2.4 Setup Laser Head and Spherical Target

Attach the focus lens to the front of the laser head (Fig.11-3). 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.11-4. pointing the laser in the X- or Y- direction

Adjust the spindle positioning order to align the spherical surface to the focus point such that the return laser beam enters the aperture of the focus lens, and the intensity reading is maximum. Rotate the spindle and make sure the intensity reading is always maximum. Otherwise, move the spindle up or down slightly. If there are too many scratched, re-polish the sphere.

As shown in Fig. 11-4, 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.

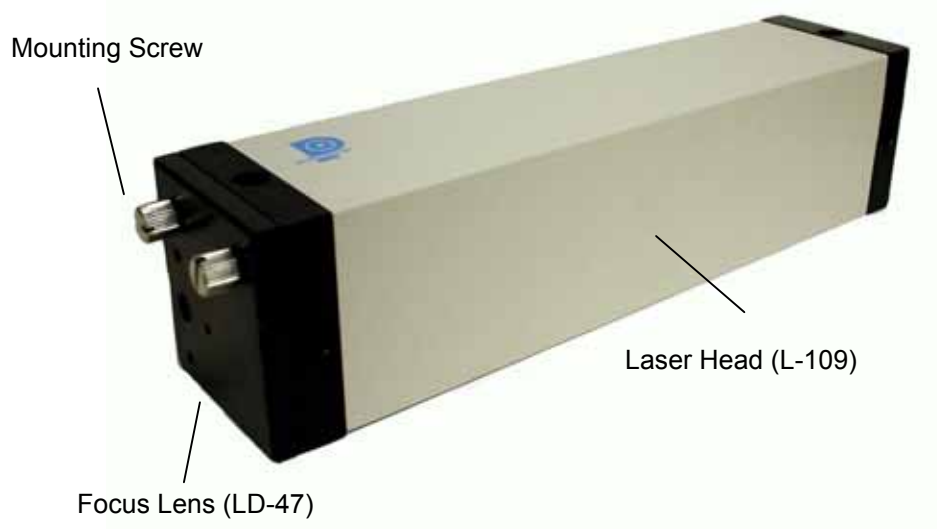


FIG. 11-3 LASER HEAD WITH FOCUS LENS



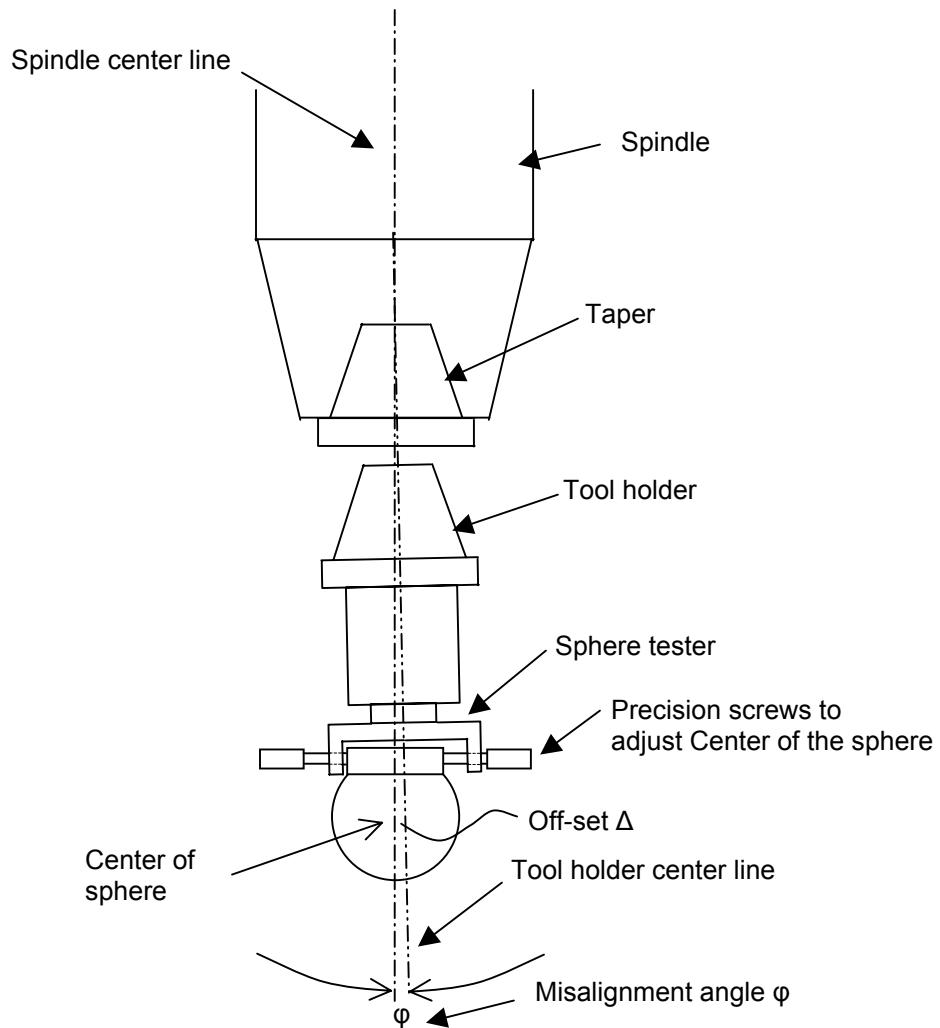


Fig. 11-4 A Schematic of the Spindle, the Tool Holder, and the Sphere Tester

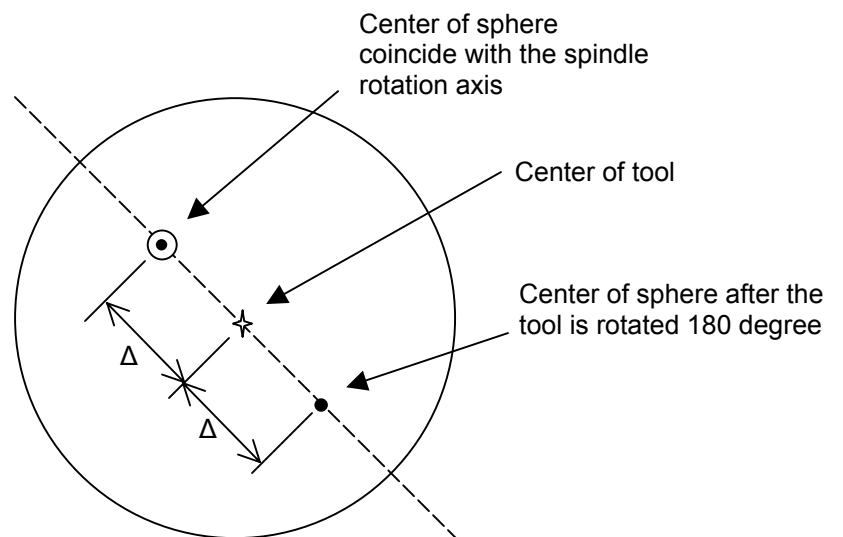


Fig. 11-5 A Schematic Illustrate the Effect of Rotating the Tool Holder by 180 Degree

### 11.6.3 Measurement of Spindle Offset

***Spindle offset is distance between the spindle axis of rotation and the tool center***

As shown in Fig. 11-4, 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. Then rotate the tool holder together with the sphere tester 180 degrees. As shown in fig. 11-5, 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  $\Delta X_M$  and in Y direction is  $\Delta Y_M$ . The offset between the spindle axis of rotation and the tool center  $\Delta$  can be determined by

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

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

The accuracy of this measurement is limited by the roundness of the sphere, typically 0.5  $\mu\text{m}$ .

### 11.6.4 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,  $\Delta X(t)$  and/or  $\Delta Y(t)$ , over several revolutions using the dynamic measurement as illustrated in section 11.7 **Taking a Dynamic Measurement.**

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

### 11.6.5 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  $\alpha(\theta)$  can be expressed as

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

#### 11.6.6 Measurement of axial error motion

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

As shown in Fig. 11-4, 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. 11-4, 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.

### 11.7 Taking a Dynamic Measurement

#### 11.7.1 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 rpm, the data rate, and the direction of measurement..

#### 11.7.2 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 notebook PC is on over the entire 360 degree rotation (Make sure the reading return to the same after a 360 degree rotation using the LDDM linear program).

#### 11.7.3 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. Enter data from 1 to 1000 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 16000 points.

For fast reference use the table below:

RPM	1	10	50	100	400	800
Minimum Data rate	1	15	60	125	500	1000
Minimum acquisition time	10min	1min	12sec	6sec	1.5sec	0.8sec

5. Trigger—start button only  
 Cosine Correction—Single pass = 1  
 Scale factor = 0.000024914 in.or 0.0000632816  
 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 16000 data points.  
           Maximum display is 6000 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 Software Description

### 11.8.1 General Description

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

### 11.8.2 2D Time Base Data Collection

See section 8.6.2

### 11.8.3 Data Analysis

See section 8.6.3

### 11.8.4 Spindle Error Motion Data Analysis

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

1. 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 of the zone to be saved for analysis.  
Return to the table and click on “File” and “Save”. Enter the starting point and the ending point. Select the starting point larger than the jumps or selecting the cycle numbers without any large jumps.  
The period or number of points per cycle will be calculated by the software A “Save Displacement Data” screen will pop up. Enter the filename and “OK”. The data will be saved in the file with extension .2DD.
5. 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.  
Click on “analysis” and “Spindle”, a “Select Axis Data Files” 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 is calculated by software and also the phase shift of 1/4 and set as default value.
6. The phase shift value should be  $\frac{1}{4}$  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 the software by using the axis 1 file and shift by 90 degree.
7. A “Set Spindle Analysis Parameters” screen will popup, as shown in Fig. 11-6. Enter the starting point number, ending point number, Make sure there is no large jump between the starting and the ending point (see above point 3) . 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  $\phi$ , CW, enter  $\phi$  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. Click on “Ok.

8. A “Select Data to Display” screen will popup, then enter the axis 2 phase shift. The default value is zero. Select the number of cycles, the table can display up to 20 cycles. and click “Ok”.  
 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. See figure 11.7 for Polar plot and Fig. 11.8 for linear plot.  
 The definition of various errors are defined in section 11.4.2

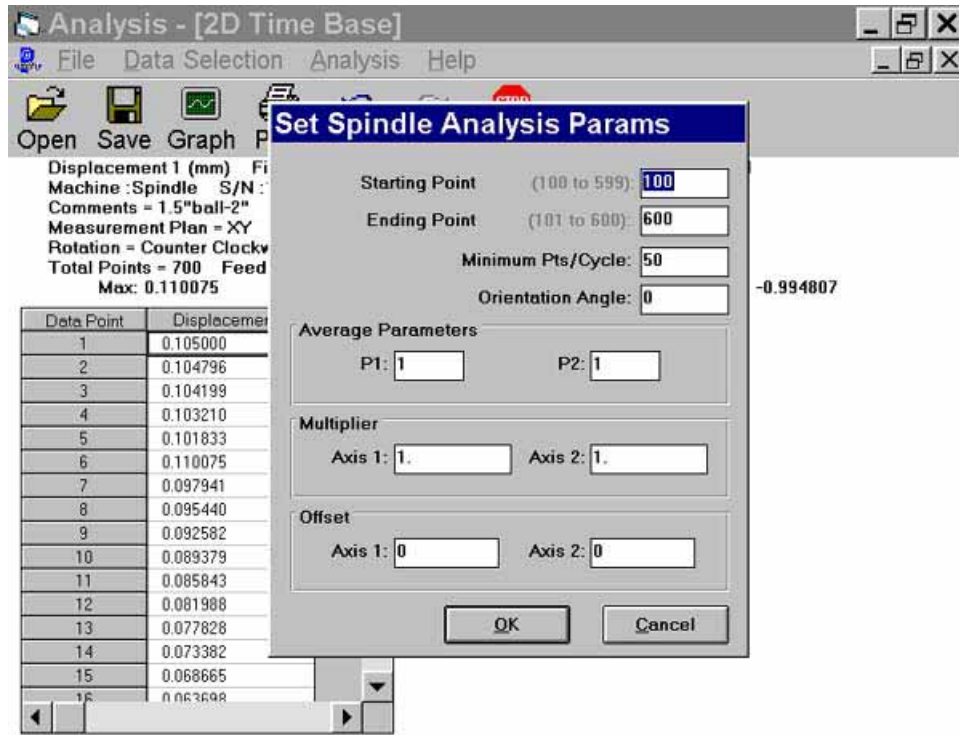


Fig. 11-6 A Popup Screen to Select the Spindle Analysis Parameters

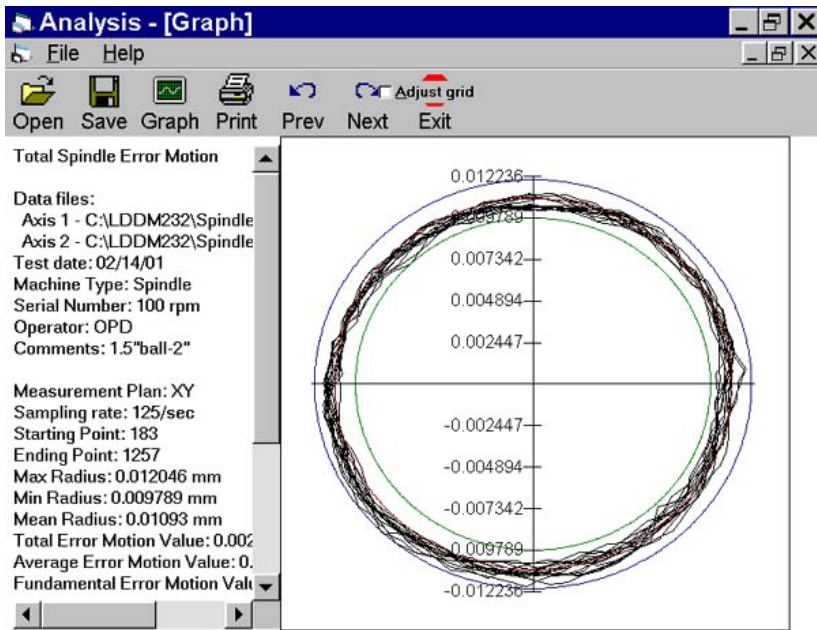


Fig. 11-7 A Polar Plot of the Spindle Error Motion

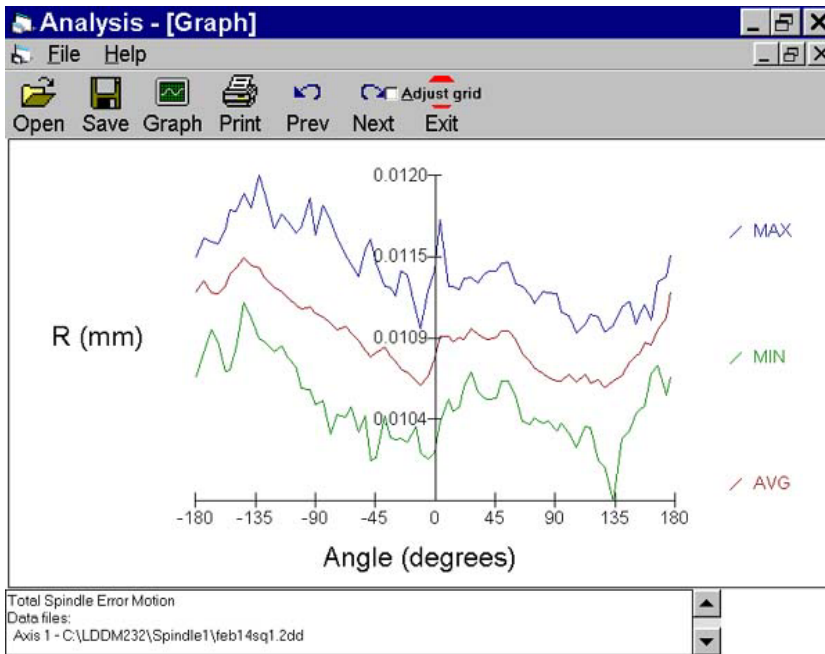


Fig. 11-8 A Linear Plot (Polar plot that is broken open and plotted from  $-180^{\circ}$  to  $180^{\circ}$  with a magnified scale for easy viewing) Amplifies the Readings Showing the Average, Maximum and Minimum Error Motion

## **11.9 Accuracy and Error Sources**

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

### 11.9.2 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.

### 11.9.3 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.