Static and Dynamic Calibration of a Haas VF-3 Vertical Machining Center

Performed by Optodyne, Inc
1180 mahalo Place,
Compton, California 90220
310-635-7481

Executive summary

The performance or the accuracy of a CNC machine tool is determined by the volumetric positioning accuracy. Recently, a new laser vector technique is developed by Optodyne for the measurement of the volumetric errors, including 3 displacement errors, 6 straightness errors, and 3 squareness errors by using a laser Doppler Displacement Meter (LDDM). Using this laser vector measurement technique the volumetric positioning errors of a Haas vertical machining center model VF-3 has been measured.

First, the displacement errors and the angular errors of all 3 axes were measured by a Laser Doppler Displacement Meter. The x-axis maximum displacement errors were +0.00045" and –0.00015", the y-axis maximum displacement errors were +0.0003" and –0.0004", and the z-axis maximum displacement errors were +0.0001" and –0.0007". The x-axis maximum pitch angle errors were 2.5 arcsec and –1.2 arcsec and yaw angle errors were 2.0 arcsec and –5.5 arcsec. The y-axis maximum pitch angle errors were 7.5 arcsec and –1.0 arcsec and yaw angle errors were 0 arcsec and –5.0 arcsec. The z-axis maximum pitch angle errors were 0.5 arcsec and –1.4 arcsec and yaw angle errors were 0 arcsec and –7.0 arcsec. These errors were relatively small as compared with similar machining centers.

Second, the laser vector method was used to measure the volumetric positioning errors including the 3 displacement errors, 6 straightness errors and 3 squareness errors. The measured volumetric positioning errors were used to compensate the tool path to further improve the positioning accuracy. The measured volumetric positioning error, or the body diagonal displacement errors without compensation was 0.0023" and with parts program compensation was 0.0009", which is an improvement of 250%.

To check the dynamic performance, the non-circular contouring accuracies were measured at various feed-rates. The contouring errors, the velocity errors, and the acceleration/deceleration errors have been measured by the non-contact laser/ballbar developed by Optodyne. The deviation in the tool path, velocity, and acceleration can be used to determine the contouring accuracy at different feed rates, and for the tuning of servo parameters.

I. Introduction

The performance or the accuracy of a CNC machine tool is determined by the volumetric positioning accuracy, which includes the linear displacement error, the straightness error, the angular error and the elastic error. A complete measurement of those errors is very complex and time consuming, for those reasons the measurement of the body diagonal displacement errors is recommended by many international standards such as ISO 230-6 and ASME B5.54 [1] for a fast check of the volumetric performance. This is because the body diagonal displacement measurement is sensitive to all of the error components. However, if the errors exceed the specification, there is not enough information for the identification of the error sources and for their compensation.

Recently, a new laser vector technique [2,3] is developed by Optodyne for the measurement of the volumetric errors, including 3 displacement errors, 6 straightness errors, and 3 squareness errors by using a laser Doppler Displacement Meter (LDDM). Using this laser vector measurement technique the volumetric positioning errors of a Haas vertical machining center model VF-3, shown in Fig 1, has been measured.

The machine working volume is 40 in by 20 in by 20 in. The laser calibration system is a Laser Doppler Displacement Meter (LDDM), Optodyne model MCV-500. It is a newest generation laser interferometer based on Doppler effect with single aperture. The system is completed with an alignment mirror to easily steer the laser beam in the diagonal direction.

First, the displacement errors and the angular errors of x-, y- and z-axis were measured by a Laser Doppler Displacement Meter. The accuracy, repeatability and mean error were calculated based the ASME B5.57 standard [1]. Second, to determine the volumetric positioning accuracy, the laser vector method has been used to determine the 3 displacement errors, 6 straightness errors and 3 squareness errors [2]. These measured errors can be used to compensate the machine errors and achieve higher accuracy [3]. To demonstrate the effect of error compensation, based on the ASME B5.57 standard, 4 body-diagonal (shown in Fig. 2) displacement errors were measured without compensation and with parts program compensation.

To check the dynamic performance, non-circular contouring accuracy has been measured at various feed-rates. The contouring errors, the velocities, and acceleration/deceleration have been measured by the non-contact laser/ballbar developed by Optodyne [4].

The target on the moving part of the machine was a 75×100mm flat mirror. The Air temperature and pressure were measured to compensate the changes in speed of light and the machine temperature was measured to correct the machine thermal expansion. The automatic data acquisition, the error analysis and automatic generation of the compensation tables, were performed by the Optodyne LDDM Windows software version 2.50.

II. Linear displacement accuracy

The linear displacement accuracy of the 3 axes were measured 5 times bi-directionally over the working volume of 40" x 20" x 20". Fig.3a, is the x-axis displacement errors. The maximum error are +0.00045" and -0.00015". Fig. 3b and 3c are the repeatability and mean errors respectively. Fig.4a, is the y-axis displacement errors. The maximum errors are 0.0003" and -0.0004". Fig. 4b and 4c are the repeatability and mean errors respectively. Fig.5a, is the z-axis displacement The maximum errors are +0.0001" and -0.0007". Based on the ASME B5.57 standard, the repeatability, accuracy and reversal errors were calculated and shown in Table I.

III. Angular accuracy

The angular accuracy of 3 axes were measured 5 times bi-directionally. Fig 6a and 6b are pitch and yaw angular errors of x-axis. The maximum pitch angle errors are 2.5 arcsec and –1.2 arcsec. The maximum yaw angle errors are 2 arcsec and –5.5 arcsec. Similarly, Fig 7a and 7b are the angular errors of y-axis. The maximum pitch angle errors are 7.5 arcsec and –1.0 arcsec. The maximum yaw angle errors are 0 arcsec and –5.0 arcsec. Fig. 8a and 8b are pitch and yaw angular errors of z-axis. The maximum pitch angle errors are 0.5 arcsec and –1.4 arcsec. The maximum yaw angle errors are 0 arcsec and –7 arcsec.

IV. Body diagonal displacement accuracy

The 4 body-diagonal displacements measurements are recommended by the ASME B5.57 standard for a fast check of the positioning and geometrical accuracy of a machine. Briefly, similar to a laser linear displacement measurement, instead of pointing the laser beam in the axis direction, pointing the laser beam in the body diagonal direction as shown in Fig.2a. Mount a retroreflector on the spindle and move the spindle in the body diagonal direction, for example from the lower left corner (X=0 Y=0 Z=0) to the upper right corner (Xmax, Ymax, Zmax). Starting from the zero position and at each increment of the three axes, which are moved together to reach the new position along the diagonal, the displacement error is measured. The accuracy of each position along the diagonal depends on the positioning accuracy of the three axes, including the straightness errors, angular errors and squareness errors. Hence the body diagonal displacement measurement is a good method for the machine verification, but there is not enough information for the identification of the error sources.

V. Volumetric positioning accuracy by laser vector method

The new laser vector measurement method or *Sequential Diagonal Measurement Method* differs from the body diagonal displacement method because each axis is moved separately and the positioning error is collected after each single movement of the X axis, of the Y axis and than of the Z axis (see Fig. 2b). For this reason, 3 times more data is collected and also the positioning error due to each single axis movement can be separated.

As shown in Fig. 1, the laser was mounted on the machine table and using the steering mirror to aligned the laser beam parallel to the diagonal. The flat mirror was mounted on the spindle with the surface perpendicular to the laser beam. The machine was programmed to move the spindle starting from one corner to the opppsite corner by sequential x-axis, y-axis and z-axis movements.

After all of the 4 diagonals have been measured, the squareness between all 3 axes were calculated. The squareness between XY is 6.51 arcsec (0.000031 in/in), between YZ is –10.76 arcsec (-0.000052 in/in), and between XZ is 1.35 arcsec (0.000007 in/in). For each axis, the displacement errors, the vertical straightness errors and the horizontal straightness are plotted in Fig. 9, 10, and 11. Fig. 9 is the error plots for the x-axis, where LF and LB are the displacement errors in the forward and backward directions, VF and VB are the vertical straightness in the forward and backward directions, and HF and HB are the horizontal straightness in the forward and backward directions. Similarly, Fig. 10 and 11 are the error plots for the y-axis and z-axis respectively.

To verify the effect of error compensation, the body diagonal displacement errors were measured based on the ASME B5-57 standard. The measured body diagonal displacement errors without compensation are shown in Fig. 12. The maximum error is 0.0023", which is relatively small as compared to a similar machining center. The measured body diagonal displacement errors with parts program compensation are shown in Fig 13. The maximum error is reduced to 0.0009", which is an improvement of 250%.

VI. Dynamic non-circular contouring accuracy

The laser/ballbar can be used to measure the circular contouring accuracy. Reported here is the dynamic non-circular contouring accuracy measurement. The programmed tool path is a diamond shape with linear and circular interpolation and transitions from linear interpolation to circular interpolations and back. It includes half-circles, vertical and horizontal lines as shown in Fig. 14. In this tool path pattern, there are 1, linear interpolation in x-axis, y-axis, inclined 45 degrees and inclined 135 degrees, 2, sharp corners of 45 degrees, 90 degrees, 135 degrees, 3, circular interpolations of half circles along x-axis and y-axis, 4, smooth transitions from linear to circular, circular to circular, circular to linear, and 5, 90 degrees transitions from linear to circular and from circular to linear. At a low feed rate of 10 in/min, the measured tool path, velocity and acceleration are shown in Fig. 15. Here the tool path is relatively accurate and almost no velocity drop. The acceleration at corners are relatively narrow. At a higher feed rate of 100 in/min, the measured acceleration/deceleration are shown in Fig. 16. Here the tool path was rounded at corners, the velocity dropped more than 50% at corners and the acceleration at corners were much wider. Most of the errors here were due to the maximum acceleration of the driver. Some of the errors were due to the servo parameters and could be used to tune the servo parameters.

VII. Summary and conclusion

In summary, we have measured the static positioning accuracy and the dynamic contouring accuracy of a Haas vertical machining center, VF-3. The linear displacement errors and the angular errors were measured by a laser calibration system. The volumetric positioning errors, including 3 displacement errors, 6 straightness errors and 3 squareness errors were measured by the laser vector method. The laser vector method is very efficient and easy to setup. It only took 2 to 4 hours instead of 20 to 40 hours by a conventional laser interferometer. The data collection and processing are all automatic to save time and minimize errors. The measured volumetric positioning errors were very small. With volumetric error compensation, the volumetric positioning errors were reduced 250%.

Using Optodyne's Laser/Ballbar system, we have performed non-circular contouring tests. The deviation in the tool path, velocity, and acceleration at different feed rates, can be used to determine the contouring accuracy and for the tuning of servo parameters. The setup time is short, the operation is simple and the data rate is high. Because of these capabilities, the Laser/Ballbar should be an essential tool for servo system, machine tool, and CNC manufacture, for optimizing motion-control parameters and contouring accuracy verification.

References

[1] "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, p69, 1992.

[2] C. Wang, " Laser Vector measurement Technique for the determination and compensation of volumetric positioning errors. Part I: Basic theory", Review of Scientific Instruments, Vol. 71, No 10, pp 3933-3937, October 2000.

[3] J. Jenecko, B. Griffin and C. Wang, "Laser Vector Measurement Technique for the determination and compensation of volumetric positioning errors. Part II: Experimental verification", Review of Scientific Instruments, Vol. 71, No. 10, pp.3938-3941, October 2000.

[4] C. Wang and B. Griffin, "A noncontact laser technique for circular contouring accuracy measurement", Review of Scientific Instruments, Vol. 72, No. 2, February 2001.

List of Tables

Figure caption

1. A photo of the Haas vertical machining center and the sequential diagonal measurement setup with the laser on the table and the flat mirror on the spindle.
2. Schematics of the laser vector measurement. (a) Body diagonal directions, and (b) Sequential steps of the movement.
3. Linear displacement errors of X-axis, (a) 5 bi-directional runs, (b) bi-directional repeatability, and (c) mean errors.
4. Linear displacement errors of Y-axis, (a) 5 bi-directional runs, (b) bi-directional repeatability, and (c) mean errors.
5. Linear displacement errors of Z-axis, (a) 5 bi-directional runs, (b) bi-directional repeatability, and (c) mean errors.
6. X-axis Angular errors, (a) pitch angle errors and (b) yaw angle errors.
7. Y-axis Angular errors, (a) pitch angle errors and (b) yaw angle errors.
8. Z-axis Angular errors, (a) pitch angle errors and (b) yaw angle errors.
9. X-axis positioning errors measured by the vector method, the top curve is the displacement error, the middle curve is the vertical straightness error and the lower curve is the horizontal straightness error.
10. Y-axis positioning errors measured by the vector method, the top curve is the displacement error, the middle curve is the vertical straightness error and the lower curve is the horizontal straightness error.
11. Z-axis positioning errors measured by the vector method, the top curve is the displacement error, the middle curve is the vertical straightness error and the lower curve is the horizontal straightness error.
12. The measured 4 body-diagonal displacement errors without compensation.
13. The measured 4 body-diagonal displacement errors with parts program compensation.
14. A diamond shape tool path with half-circles, 45 degrees and 135 degrees lines, a vertical and horizontal lines.
15. A diamond shape (shown in Fig. 14) tool path, velocity and acceleration measured in the x-direction. The feed rate was 10 in/min. The top trace is the displacement (in), the middle trace is the velocity (in/sec) and bottom trace is the acceleration in/sec/sec).
16. Same as in Fig. 15, except the feed rate was 100 in/min.

Table I, Linear displacement errors of X, Y and Z-axis based on the ASME B5.57 standard

```
X-axis displacement errors, ASME B5.57 standard
Reversal value, B= 0.000022 (at point=0)
Mean reversal value, <B>= -0.000150
Range mean bi-directional positional deviation, M= 0.000343
Systematic deviation of positioning, E=
                    0.000293  (0.000186, -0.000107)  (Forward),
                    0.000461  (0.000399, -0.000062)  (Backward),
                    0.000506  (0.000399, -0.000107)  (Bi-directional).
Repeatability of positioning, R=
                    0.000201  (at point=14)          (Forward),
                    0.000210  (at point=12)          (Backward),
                    0.000460  (at point=19)          (Bi-directional).
Accuracy, A=
                    0.000458  (0.000266, -0.000192)  (Forward),
                    0.000637  (0.000489, -0.000149)  (Backward),
                    0.000681  (0.000489, -0.000192)  (Bi-directional).

Y-axis displacement errors, ASME B5.57 standard
Reversal value, B= 0.000000 (at point=10)
Mean reversal value, <B>= -0.000264
Range mean bi-directional positional deviation, M= 0.000434
Systematic deviation of positioning, E=
                    0.000535  (0.000188, -0.000347)  (Forward),
                    0.000332  (0.000231, -0.000101)  (Backward),
                    0.000578  (0.000231, -0.000347)  (Bi-directional).
Repeatability of positioning, R=
                    0.000428  (at point=0)           (Forward),
                    0.000612  (at point=5)           (Backward),
                    0.000747  (at point=1)           (Bi-directional).
Accuracy, A=
                    0.000817  (0.000402, -0.000415)  (Forward),
                    0.000739  (0.000333, -0.000407)  (Backward),
                    0.000817  (0.000402, -0.000415)  (Bi-directional).

Z-axis displacement errors, ASME B5.57 standard
Reversal value, B=  0.000000 (at point=10)
Mean reversal value, <B>= =0.000255
Range mean bi-directional positional deviation, M= 0.000725
Systematic deviation of positioning, E=
                    0.000792  (0.000060, -0.000732)  (Forward),
                    0.000731  (0.000074, -0.000658)  (Backward),
                    0.000806  (0.000074, -0.000732)  (Bi-directional).
Repeatability of positioning, R=
                    0.000146  (at point=0)           (Forward),
                    0.000133  (at point=8)           (Backward),
                    0.000562  (at point=9)           (Bi-directional).
Accuracy, A=
                    0.000896  (0.000133, -0.000763)  (Forward),
                    0.000820  (0.000103, -0.000717)  (Backward),
                    0.000896  (0.000133, -0.000763)  (Bi-directional).
```

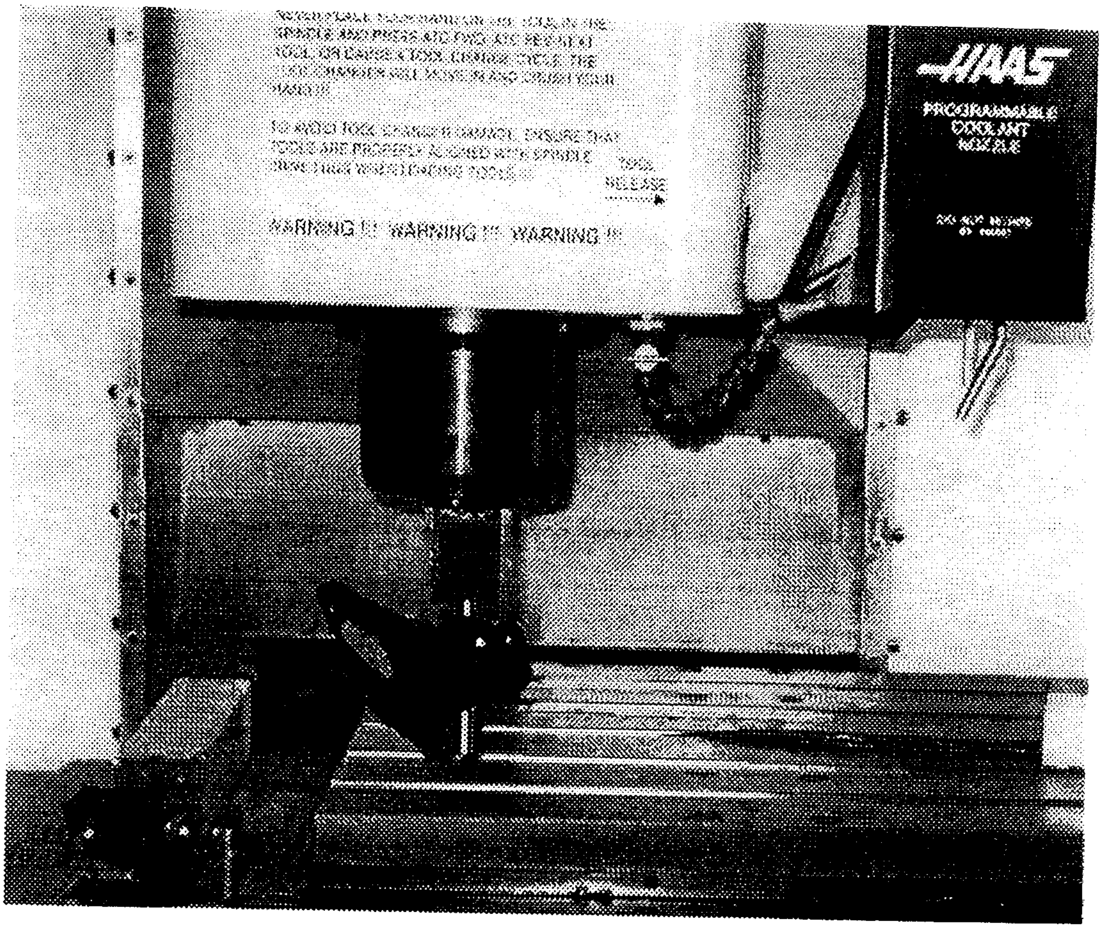
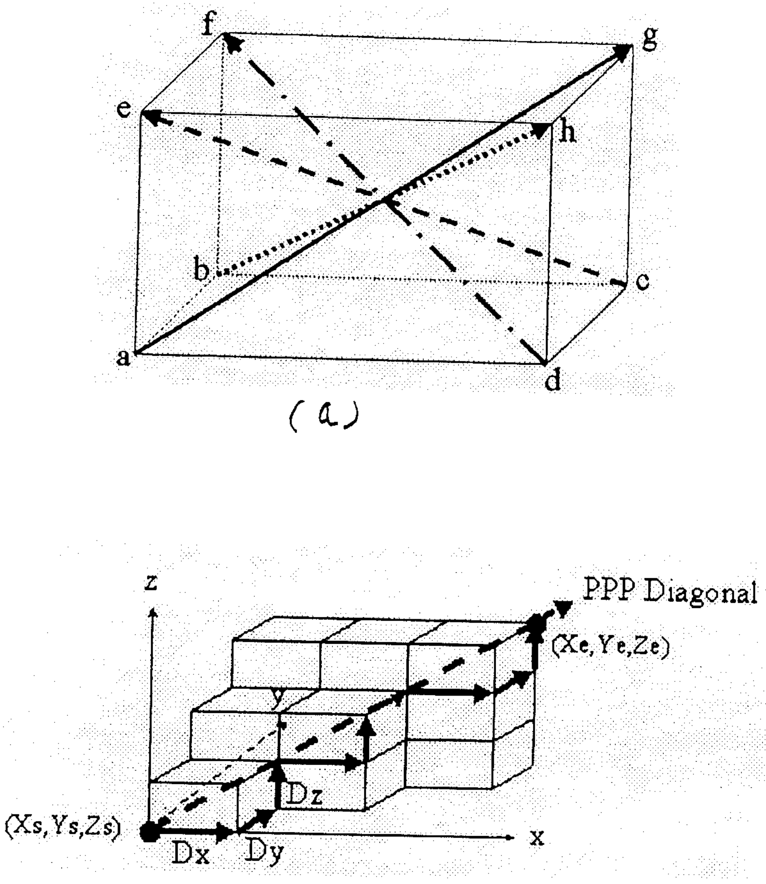


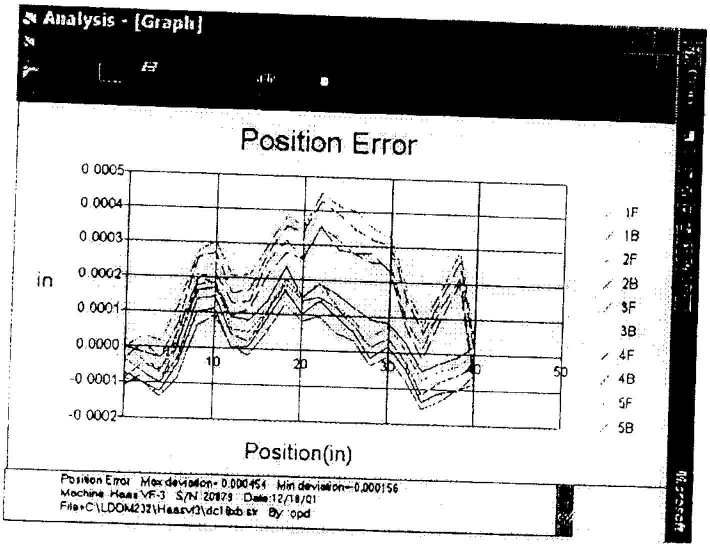
Fig. 1,
A photo of the Haas vertical machining center and the sequential diagonal measurement setup with the laser on the table and the flat-mirror on the spindle.



(a)

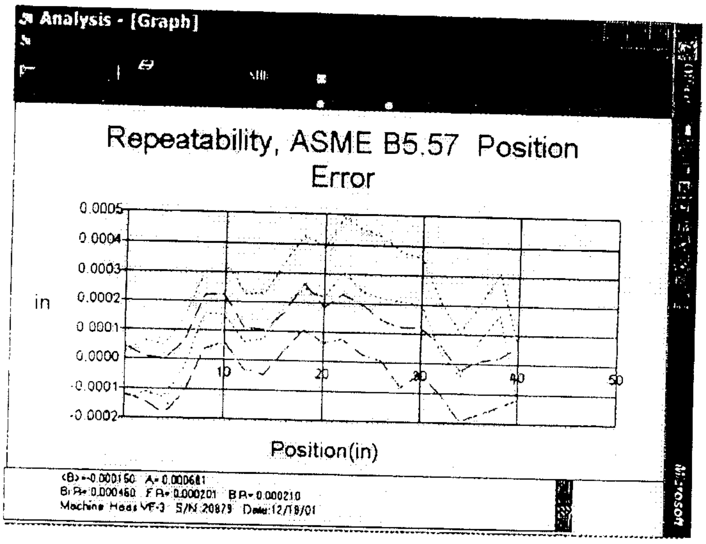
(b)

Fig. 2, Schematics of the laser vector measurement. (a) Body diagonal directions, and (b) Sequential steps of the movement.



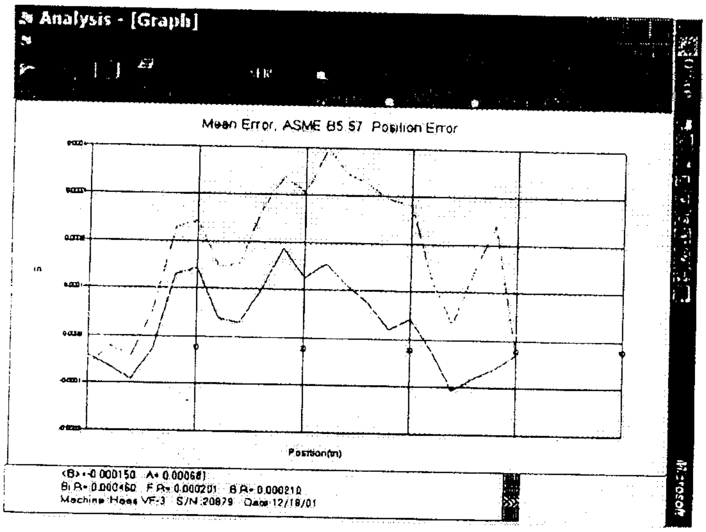
Position Error Max deviation= 0.000454 Min deviation=-0.000156
Machine Haas VF-3 S/N 20879 Date:12/18/01
File=C:\LDOM232\Haasvf3\dc18xb.sr By :opd

Fig 3a,
Linear displacement
errors of X-axis,
5 bi-directional runs.



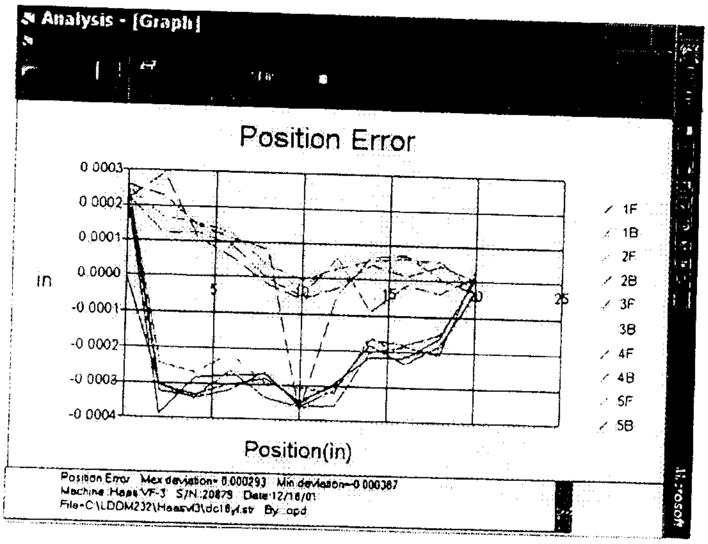
<B>=-0.000150 A=0.000681
Bi R= 0.000460 F R= 0.000201 B R= 0.000210
Machine Haas VF-3 S/N 20879 Date:12/18/01

Fig 3b,
Linear displacement errors
of X-axis,
bi-directional repeatability.



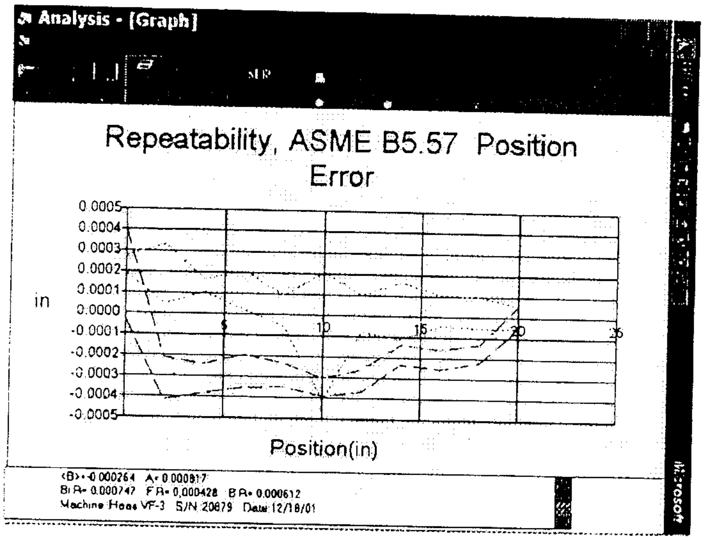
<B>=-0.000150 A=0.000681
Bi R= 0.000460 F R= 0.000201 B R= 0.000210
Machine Haas VF-3 S/N 20879 Date 12/18/01

Fig 3c,
Linear displacement
errors of X-axis,
mean errors.



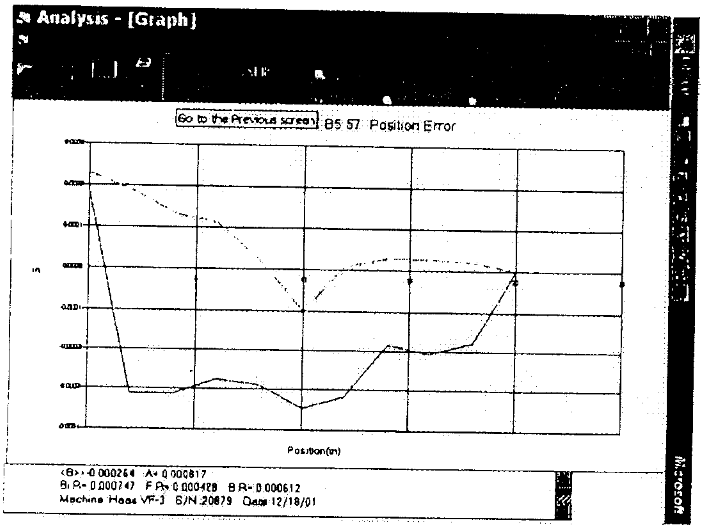
```
Position Error   Max deviation= 0.000293   Min deviation=-0.000387
Machine :Haas VF-3   S/N :20879   Date:12/18/01
File=C:\LDDM232\Haasv3\dc18y.str   By: opd
```

Fig.4a,
Linear displacement
errors of Y-axis,
5 bi-directional runs.



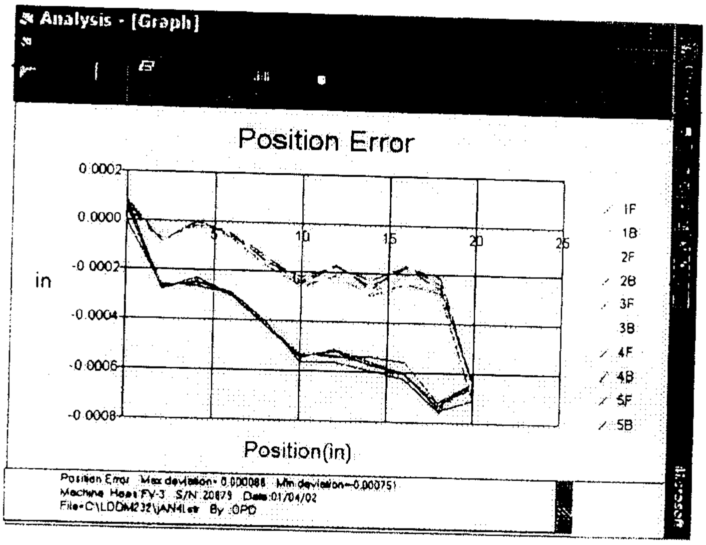
```
<B>=-0.000264   A= 0.000817
Bi R= 0.000747   F R= 0,000428   B R= 0.000612
Machine Haas VF-3   S/N 20879   Date 12/18/01
```

Fig.4b,
Linear displacement errors
of Y-axis,
bi-directional repeatability.



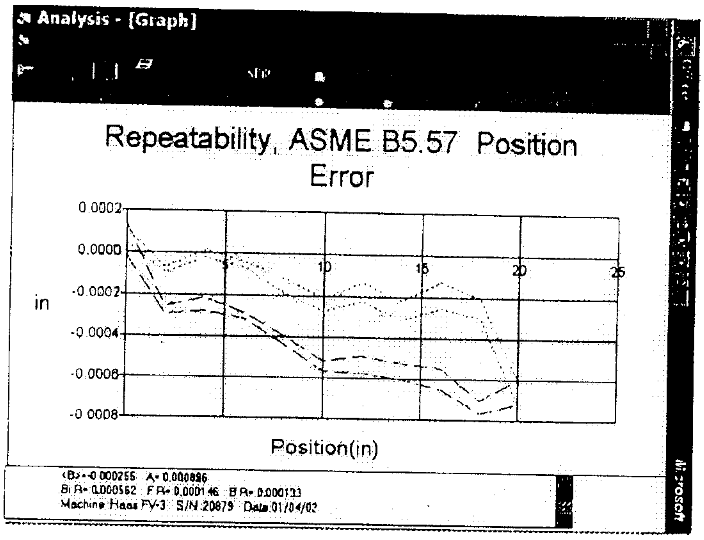
```
<B>=-0.000264   A= 0.000817
Bi R= 0.000747   F R= 0.000428   B R= 0.000612
Machine Haas VF-3   S/N 20879   Date 12/18/01
```

Fig.4c,
Linear displacement
errors of Y-axis,
mean errors.



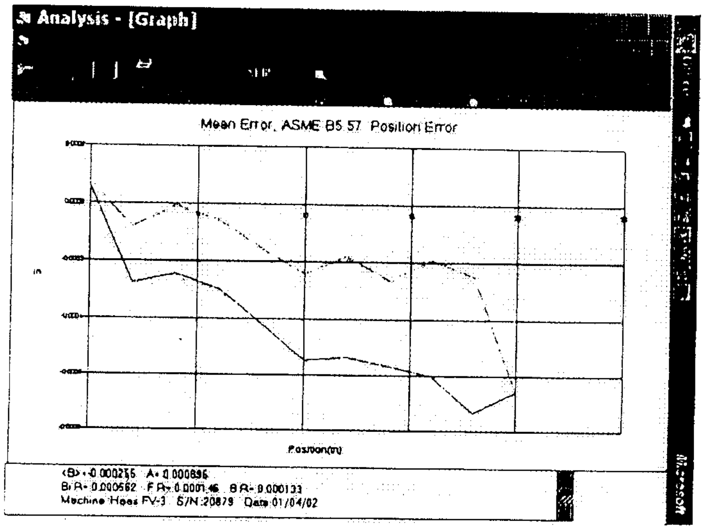
Position Error Max deviation = 0.000088 Min deviation = -0.000751
Machine Haas FV-3 S/N 20879 Date 01/04/02
File = C:\LDDM232\JAN4L.str By :OPD

Fig 5a,
Linear displacement
errors of Z-axis,
5 bi-directional runs.



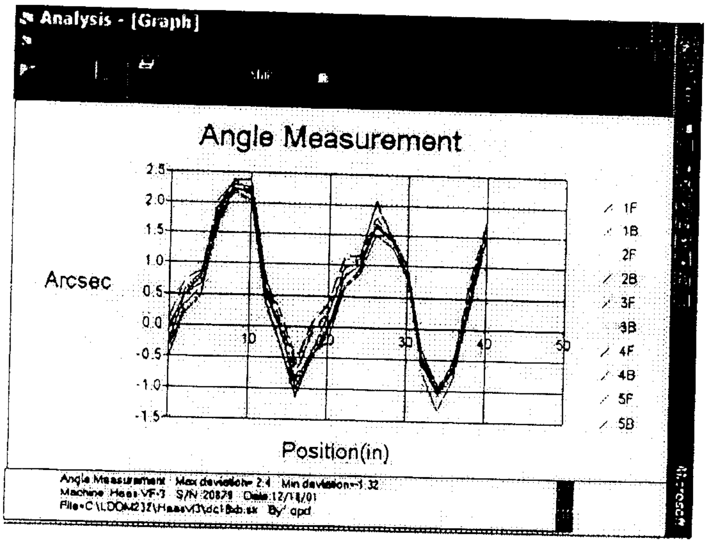
<B> = -0.000255 A = 0.000896
Bi R = 0.000562 F R = 0.000146 B R = 0.000133
Machine Haas FV-3 S/N 20879 Date 01/04/02

Fig 5b,
Linear displacement errors
of Z-axis,
bi-directional repeatability.



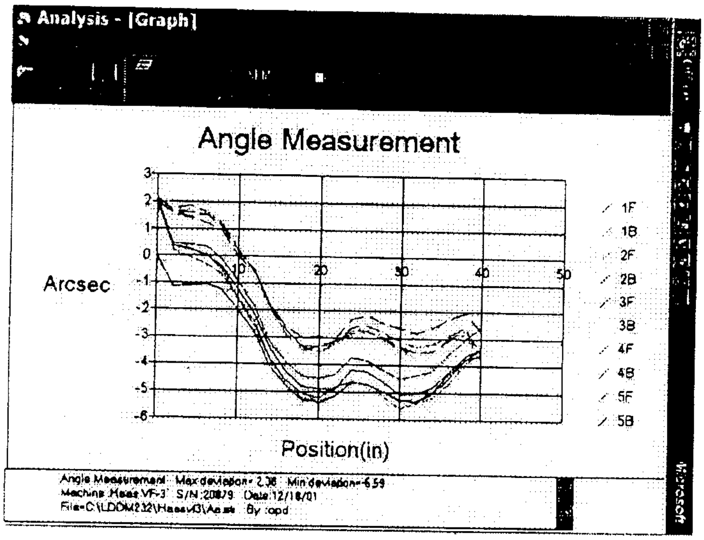
<B> = -0.000255 A = 0.000896
Bi R = 0.000562 F R = 0.000146 B R = 0.000133
Machine Haas FV-3 S/N 20879 Date 01/04/02

Fig 5c,
Linear displacement
errors of Z-axis,
mean errors.



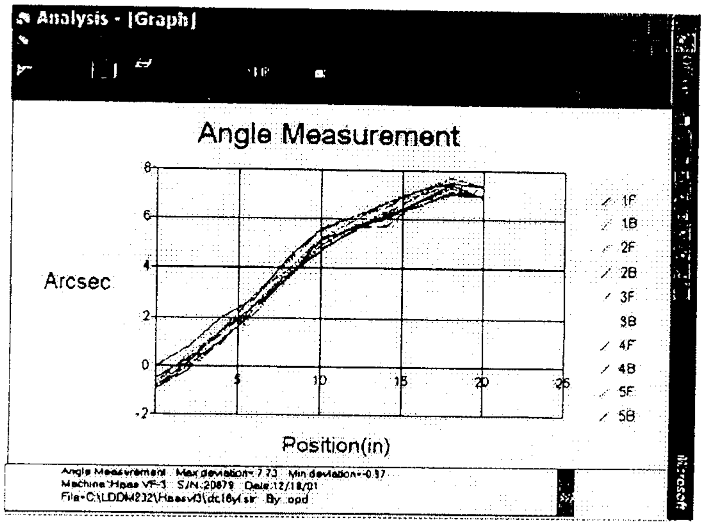
Angle Measurement Max deviation= 2.4 Min deviation=-1.32
Machine Haas VF-3 S/N 20879 Date:12/18/01
File=C:\LDDM232\HaasVf3\dc18xb.sk By' opd

Fig 6a,
X-axis pitch.



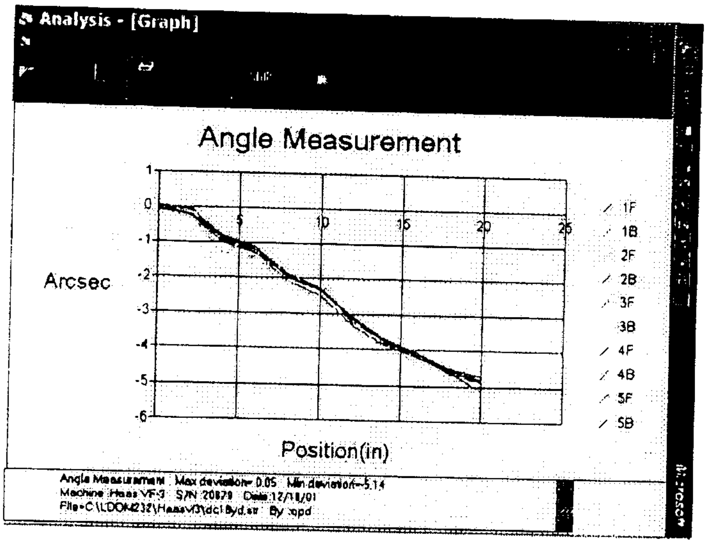
Angle Measurement Max deviation= 2.38 Min deviation=-6.59
Machine Haas VF-3 S/N 20879 Date 12/18/01
File=C:\LDDM232\HaasVf3\Ae.sk By :opd

Fig 6b,
X-axis yaw angular errors.



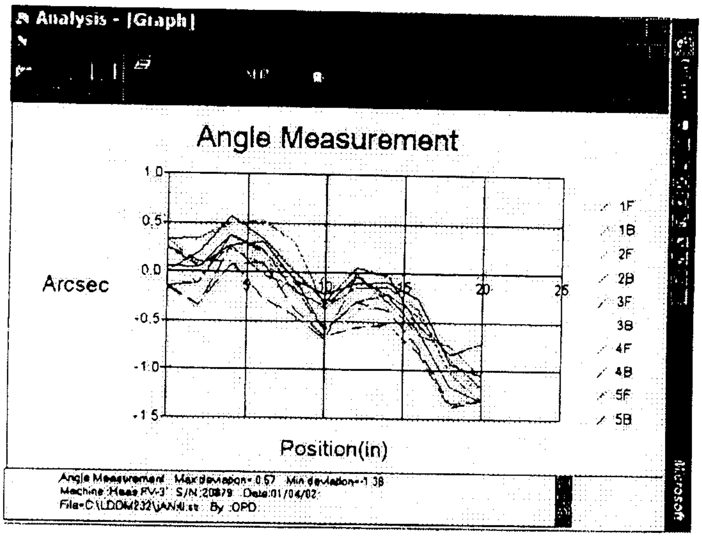
Angle Measurement Max deviation= 7.73 Min deviation=-0.37
Machine Haas VF-3 S/N 20879 Date 12/18/01
File=C:\LDDM232\HaasVf3\dc18yl.sir By :opd

Fig 7a,
Y-axis pitch angular errors.



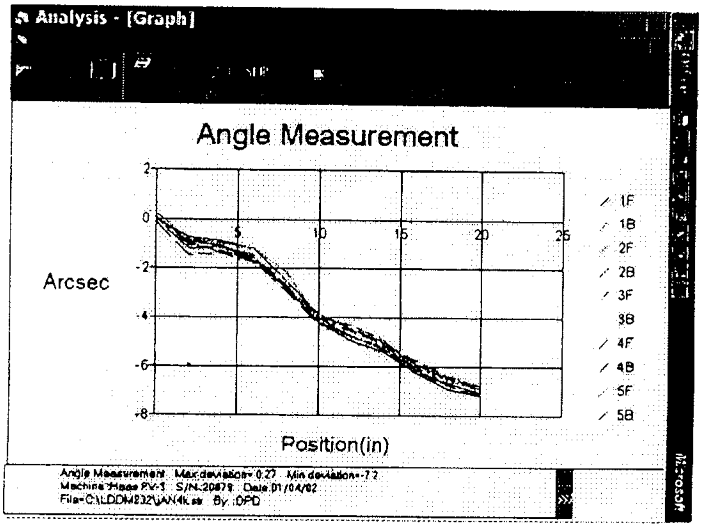
Angle Measurement Max deviation= 0.05 Min deviation=-5.14
Machine :Haas VF-3 S/N 20879 Date:12/18/01
File=C:\LDDM232\HaasVf3\dc18yd.str By :opd

Fig 7b,
Y-axis yaw angular errors.



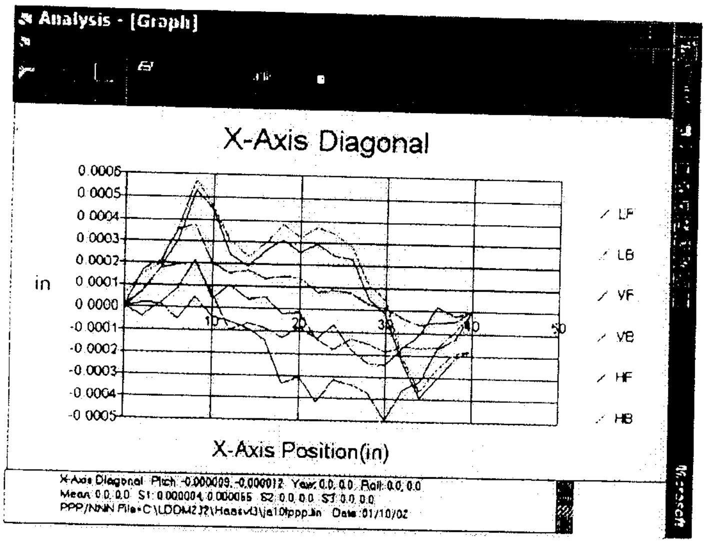
Angle Measurement Max deviation= 0.57 Min deviation=-1.38
Machine :Haas PV-3 S/N :20879 Date:01/04/02
File=C:\LDDM232\JAN4l.str By :OPD

Fig 8a,
Z-axis pitch angular errors.



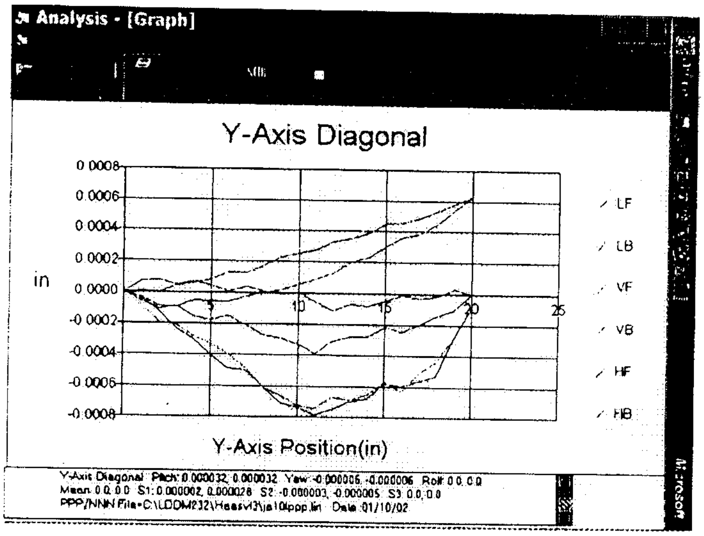
Angle Measurement Max deviation= 0.27 Min deviation=-7.2
Machine :Haas PV-3 S/N :20879 Date:01/04/02
File=C:\LDDM232\JAN4k.str By :OPD

Fig 8b,
Z-axis yaw angular errors



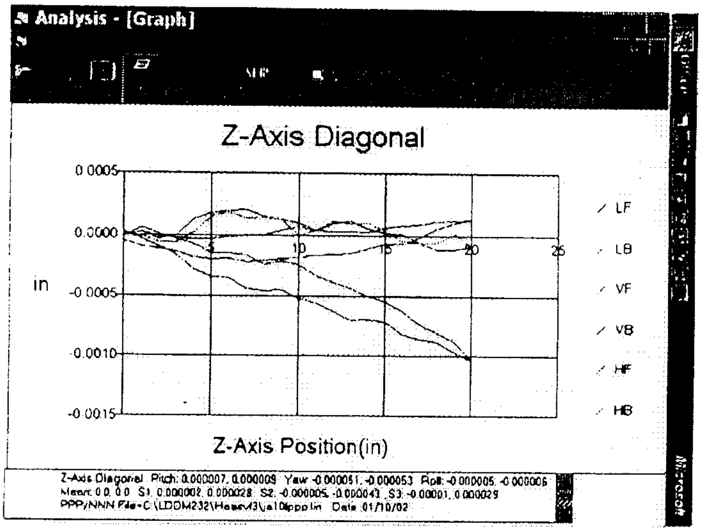
```
X-Axis Diagonal  Pitch -0.000009,-0.000012  Yaw 0.0, 0.0  Roll 0.0, 0.0
Mean 0.0, 0.0  S1 0.000004, 0.000065  S2 0.0, 0.0  S3 0.0, 0.0
PPP/NNN File=C:\LDDM232\Haasv13\ja10fppp.lin  Date:01/10/02
```

Fig 9,
X-axis positioning errors measured by the vector method. The top curve is the displacement errors, the middle & lower curves are the vertical and horizontal straightness errors respectively.



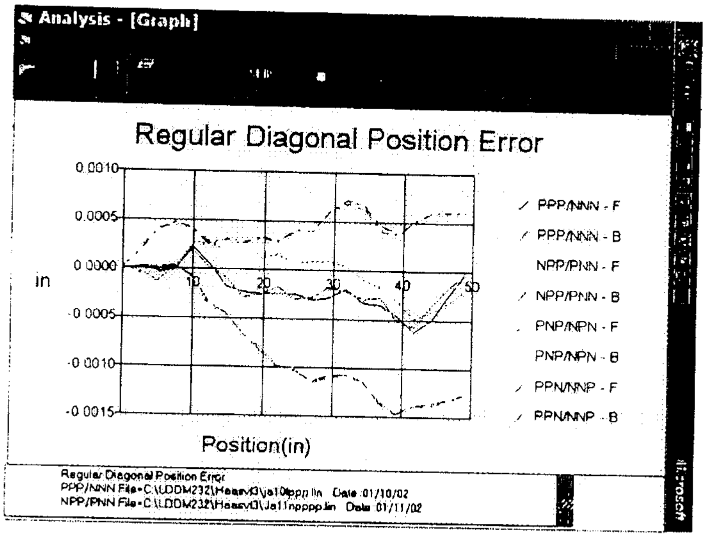
```
Y-Axis Diagonal  Pitch: 0.000032, 0.000032  Yaw -0.000006, -0.000006  Roll 0.0, 0.0
Mean 0.0, 0.0  S1: 0.000002, 0.000028  S2 -0.000003, -0.000005  S3 0.0, 0.0
PPP/NNN File=C:\LDDM232\Haasv13\ja10lppp.lin  Date 01/10/02
```

Fig 10,
Y-axis positioning errors measured by the vector method. The top curve is the displacement errors, the middle & lower curves are the vertical and horizontal straightness errors respectively.



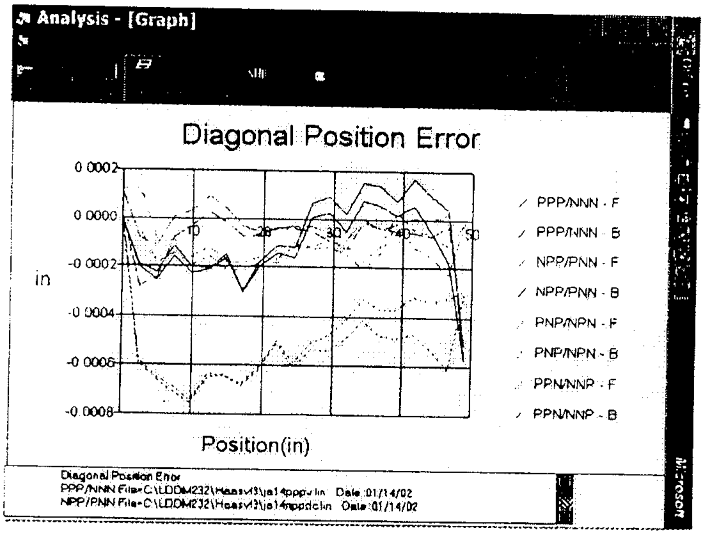
```
Z-Axis Diagonal  Pitch: 0.000007, 0.000009  Yaw -0.000051, -0.000053  Roll: -0.000005, -0.000006
Mean 0.0, 0.0  S1 0.000002, 0.000028  S2 -0.000005, -0.000043  S3 -0.00001, 0.000029
PPP/NNN File=C:\LDDM232\Haasv13\ja10fppp.lin  Date 01/10/02
```

Fig 11,
Z-axis positioning errors measured by the vector method. The top curve is the displacement errors, the middle & lower curves are the vertical and horizontal straightness errors respectively.



Regular Diagonal Position Error
PPP/NNN File=C:\LDDM232\Haasv3\ja10pppp.lin Date:01/10/02
NPP/PNN File=C:\LDDM232\Haasv3\Ja11npppp.lin Date:01/11/02

Fig 12,
The measured body diagonal displacement errors without compensation.



Diagonal Position Error
PPP/NNN File=C:\LDDM232\Haasv3\ja14pppv.lin Date:01/14/02
NPP/PNN File=C:\LDDM232\Haasv3\ja14nppdc.lin Date:01/14/02

Fig 13,
The measured body diagonal displacement errors with part program compensation.

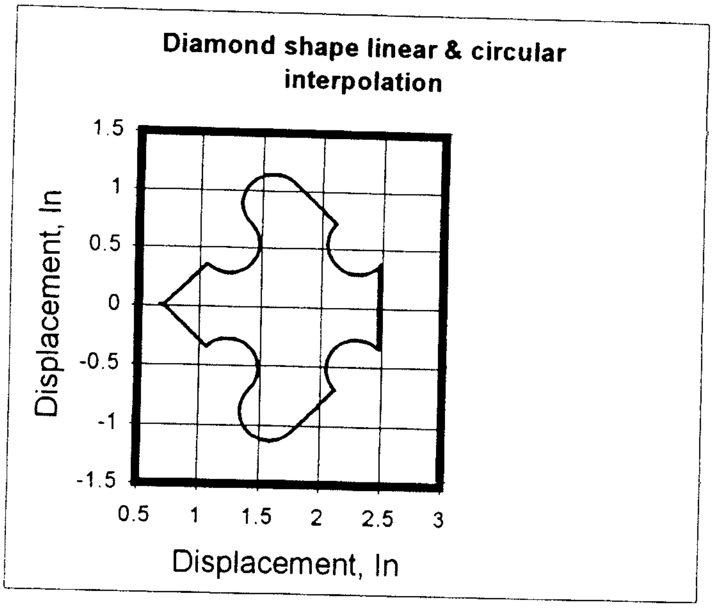


Fig. 14,
A diamond shape tool path with half-circles, 45 degrees and 135 degrees lines, [illegible] vertical and horizontal lines.

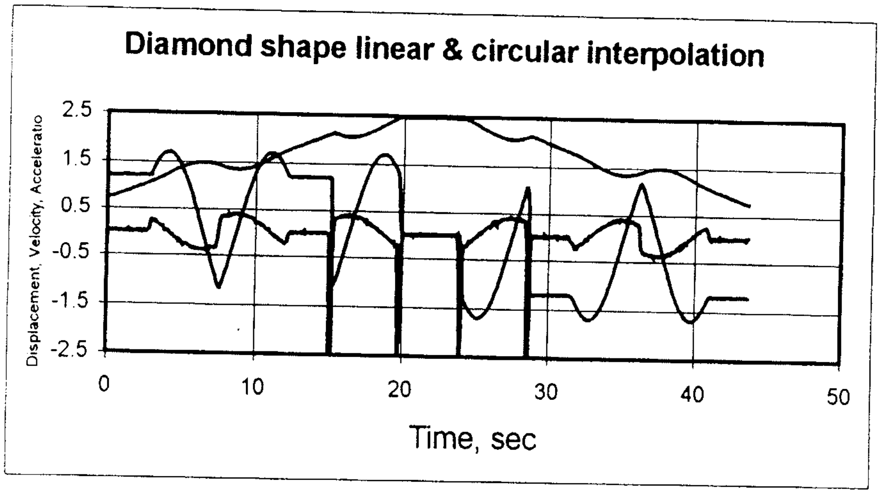


Fig. 15,
A diamond shape (shown in Fig. 14) tool path, velocity and acceleration measured in the X-direction. The top trace is the displacement (in), the middle trace is the velocity (in/sec) and the bottom trace is the acceleration (in/sec^2).

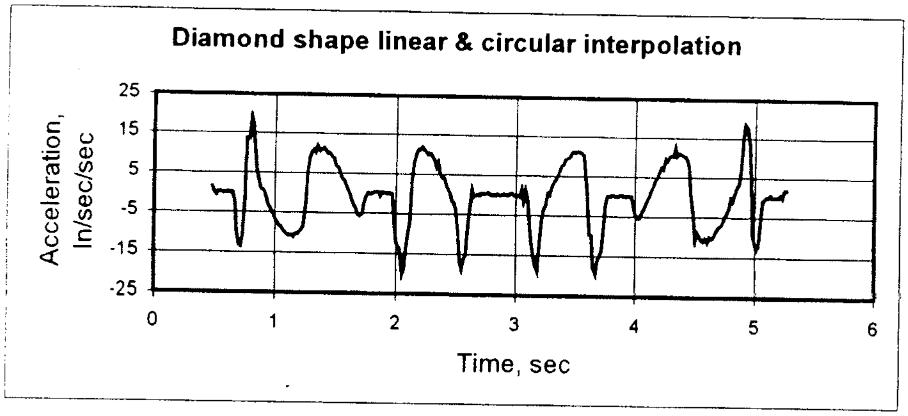


Fig. 16,
The acceleration/deceleration measured in the X-direction. Same as the bottom trace of Fig. 15, except the feed rate was 100 in/min.