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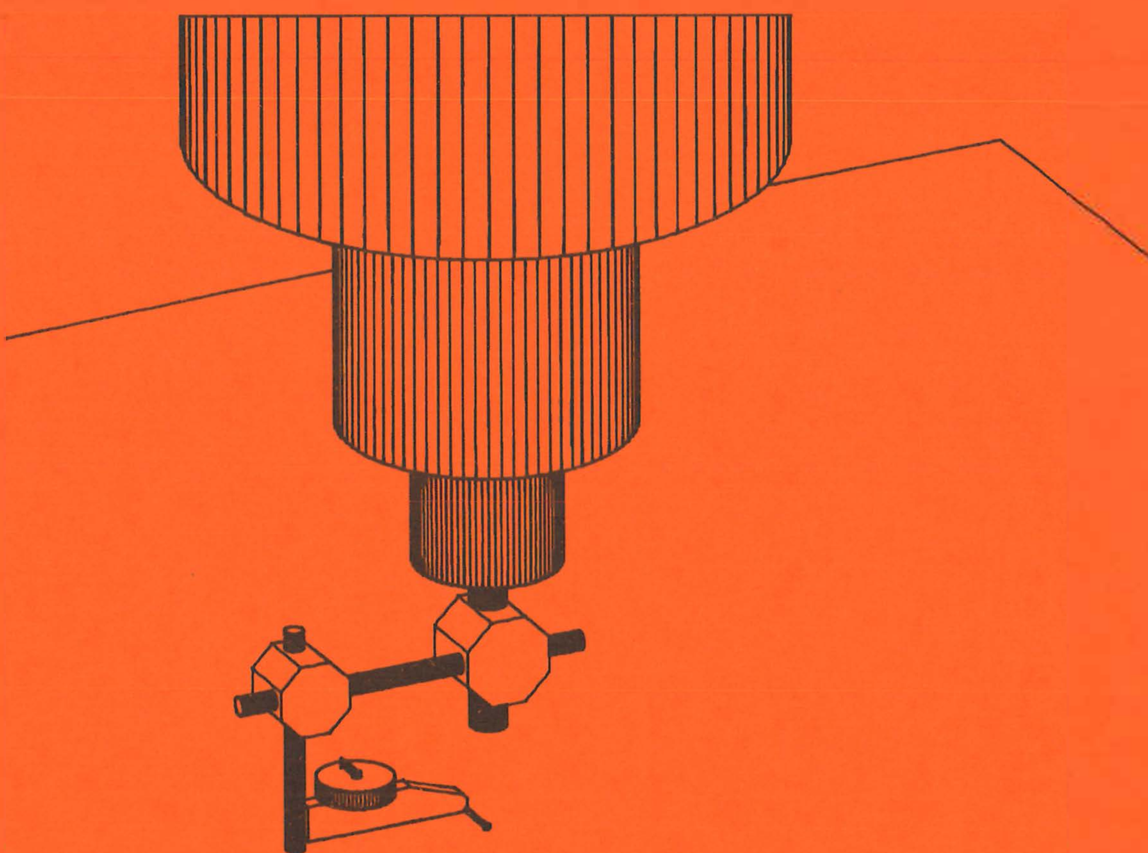
CNC Router Evaluation Procedures

Edward L. Adams
Everette D. Rast
Neal D. Bennett



Abstract

The lack of procedures for evaluating computer numerically controlled (CNC) routers makes it difficult for the buyers and sellers of these machines to communicate when trying to determine the best machine for a given production situation. This report provides procedures to evaluate specific machine capabilities as related to production situations. By using the procedures, both the buyers and the sellers will know how the evaluations were made and what the results mean.

The Authors

EDWARD L. ADAMS is a forest products technologist with the Northeastern Forest Experiment Station's Forestry Sciences Laboratory at Princeton, West Virginia. He received a B.S. degree in forest management and an M.S. degree in forest mensuration at West Virginia University. He worked for the USDA Forest Service in Oregon from 1960 to 1963 and joined the Northeastern Station in 1968. He retired in January 1995.

EVERETTE D. RAST is a forest products technologist with the Northeastern Forest Experiment Station's Forestry Sciences Laboratory at Princeton, West Virginia. He received a B.S. degree in forestry from the University of Missouri in 1960 and an M.S. degree in agricultural economics from The Ohio State University in 1970. He joined the USDA Forest Service in 1960 as a forester on the Mendocino National Forest and transferred to the Northeastern Forest Experiment Station, Delaware, Ohio, in 1966. From 1966 to 1987, he was with the log and tree grade project and then the management and utilization alternatives for nonindustrial private forests. In 1987 he was transferred to the Advanced Hardwood Processing and Technical Resource Center.

NEAL D. BENNETT is a general engineer with the Northeastern Forest Experiment Station's Forestry Sciences Laboratory at Princeton, West Virginia. He received a B.S. degree in biology from Concord College, Athens, West Virginia, in 1983 and an A.S. degree in mechanical engineering from Bluefield State College, Bluefield, West Virginia, in 1992. He joined the USDA Forest Service in 1988.

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USDA FOREST SERVICE
5 RADNOR CORP CTR STE 200
PO BOX 6775
RADNOR PA 19087-8775

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Introduction

Managers of furniture and cabinet manufacturing plants have the difficult task of purchasing the best computer numerical controlled (CNC) machines for particular situations. They need machines that will not only perform present tasks but also possible future tasks. Much of the information needed to compare machines is not available in the sales literature. And, because procedures are not available for evaluating the machines, managers find it difficult to communicate with machine dealers in their search for the best machine for the job.

Machine dealers also are concerned about this problem. If a dealer sells a brand "A" CNC router and it does not meet a plant manager's needs, that manager is going to be upset. And, he will probably tell others about his dissatisfaction with the machine. The negative advertising produced by this situation may cause potential buyers to avoid brand "A" when that machine may be exactly what their production situation requires. Thus, both the seller and potential buyers of the brand "A" machine lose.

This paper provides procedures for evaluating CNC routers that can be used to help solve the communication problem between buyers and sellers. By using the procedures, these individuals can, in effect, speak the same language as they try to match machines to production situations. It is not necessary to use all of the procedures when evaluating a router. Only those needed to provide information that is critical to the production situation need to be used. For example, if tool positioning accuracy is only critical in the **Z**-axis, the only procedures needed are those that measure the ability of the router to position the tool in this axis. The procedures for the **X**-axis and the **Y**-axis are not necessary. Also, the procedures do not include recommended tolerances. These values will depend on the individual production situations and must be determined by the machine user.

It should be emphasized that we are not attempting to set evaluation standards for the industry. The purpose of this paper is to provide an objective means for the buyers and sellers of CNC routers to discuss needs in terms of accuracy, repeatability, and suitability for particular production situations. However, if the secondary processing industry decides to develop standards in the future, the procedures presented in this paper could provide a good base to start from.

Following are discussions of the possible uses, the evaluation methods, and the sample results for each evaluation procedure. The procedures are divided into three categories: (1) basic evaluations, (2) spindle/table travel evaluations, and (3) machining evaluations.

List of Abbreviations

CNC	-	computer numerically controlled
CPM	-	cycles per minute
deg	-	degrees of angular measurement
E	-	volts
F	-	Fahrenheit
FLP	-	full load power (kilowatts) requirement of an electric motor
G&M code	-	more or less standard computer code for controlling computer numerically controlled equipment
hp	-	horsepower
Hz	-	hertz (one cycle per second)
I	-	electric current in amperes
IPM	-	inches per minute
kW	-	1000 watts
MDF	-	medium density fiberboard
min	-	minutes of angular measurement
mm	-	millimeters
PC	-	microcomputer
pf	-	power factor (electric motors)
RPM	-	revolutions per minute
sec	-	seconds of angular measurement
TGP	-	turned-ground-polished
thou	-	thousandths of an inch

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1.0 Basic Evaluations

1.1 Spindle

1.1.1 Steady-state Temperature and Power

Purpose—This procedure determines the steady-state temperature of the lower spindle bearing housing, and the steady-state power (kW) required with the spindle running at maximum RPM's. Because it is difficult to measure the bearing temperature directly, a representative temperature is obtained by taping a thermocouple to the spindle housing as near as possible to the lower bearing. This steady-state condition must be reached for some of the other procedures.

Recommended equipment:

- Turned-ground-polished (TGP) rod that is 0.75 inch in diameter and 3 inches long. If the spindle will not accept a 0.75-inch-diameter tool shank, use a TGP rod with a diameter that matches the largest tool shank that the spindle will accept.

- Digital power analyzer that measures to 0.01 kW and will handle the frequency (HZ) range of the current being sent to the spindle. It also must handle both three- and four-wire, three-phase power connections. And, it should have an accuracy of ± 0.5 percent of the full range from 20 Hz to 5 kHz.

- Hand-held digital thermometer with thermocouple that will measure to 0.1 °F. The thermometer should have an accuracy of at least 0.1 percent of the reading.

Method—With the thermometer thermocouple and power analyzer attached to the spindle, the temperature and power (kW) requirements are recorded every 10 minutes until the temperature reaches a steady state. The following steps describe the procedure:

Step 1
: Mount the TGP rod into the spindle collet/chuck.

Step 2
: Tape the thermocouple to the spindle housing as near as possible to the lower spindle bearing.

Step 3
: Connect the power analyzer to the power leads of the spindle motor. In making the connection, use a three-phase, three-wire or three-phase, four-wire hookup per the requirements of the spindle motor. This connection also must be made between the spindle motor and any transistor inverter used to control the speed (RPM) of the motor. Figure 1.1 shows a typical hookup.

Step 4
: Record both the temperature and power every 10 minutes. The temperature is measured to 0.1 °F and the power measured to 0.01 kW. These values are recorded until the temperature, rounded to the nearest degree, does not change for two consecutive 10-minute periods. At that point, the spindle is considered to be at steady state.

Results—Figure 1.2 shows sample results for this procedure.

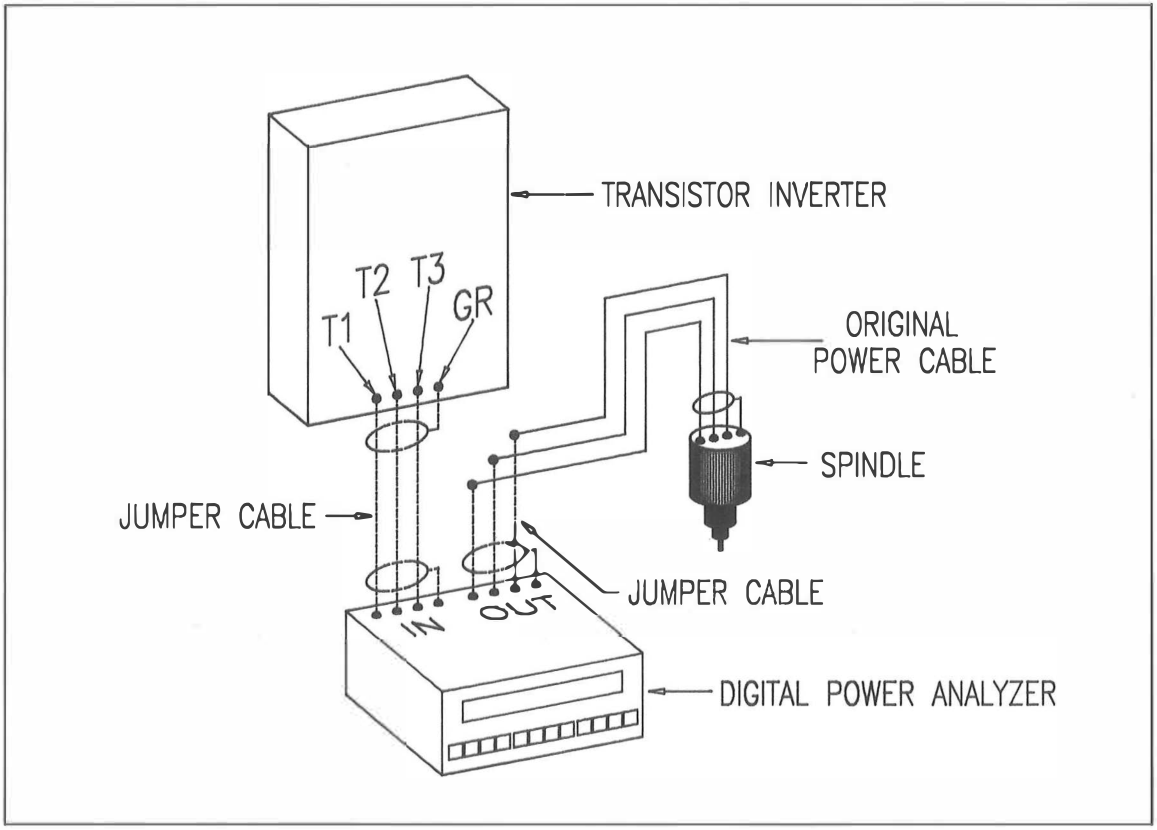


Figure 1.1—Power analyzer hookup for spindle warm-up procedure.

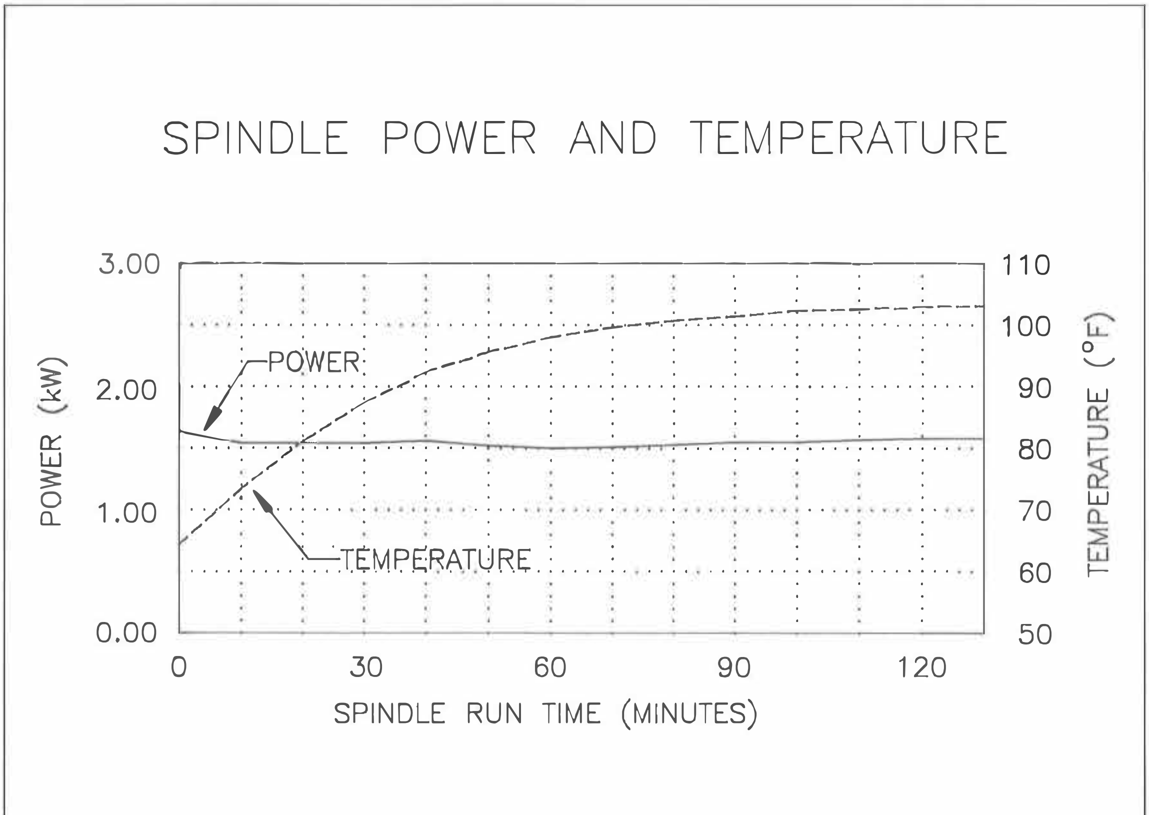


Figure 1.2—Temperature and power resulting from warm-up procedure.

1.1.2 RPM Accuracy

Purpose—This procedure evaluates the accuracy of the router controller and/or transistor inverter to set the RPM's of the spindle motor. Because the surface quality of the cut depends on the RPM of the tool, along with other factors such as tool vibration, part vibration, and sharpness of the tool, it is important that the spindle runs at the set RPM's.

Recommended equipment:

- Turned-ground-polished (TGP) rod that is 0.75 inch in diameter and 3 inches long. If the spindle will not accept a 0.75-inch-diameter tool shank, use a TGP rod with a diameter that matches the largest tool shank that the spindle will accept.
- Hand-held digital phototachometer with a range covering the maximum RPM of the router to be evaluated (accuracy ± 1 RPM).
- Reflective paint.

Method—Before beginning this evaluation, the spindle must be run until the steady-state temperature and power (kW) requirements are reached as discussed in procedure 1.1.1. After spindle warm-up, use the following steps. During the warm-up period, the voltage to the spindle motor should be checked for abnormal level and fluctuations. Abnormal voltage can affect the results from this procedure.

Step 1
Mount the TGP rod in the router spindle.

Step 2
Using reflective paint, paint a 1/2-inch square patch on the side of the TGP rod. The coat of paint should be as thin as possible to minimize its effect on spindle vibration that can be caused if the spindle is out-of-balance.

Step 3
Select a set of target RPM's covering the range of RPM's provided by the spindle motor.

Step 4
Set the router to run at each target RPM by manually adjusting the power cycles per second (Hz) on the transistor inverter or by programming the router controller. At each target RPM, measure and record the actual value to the nearest RPM.

Results—For the study router, the results were:

Spindle RPM	
Target	Actual
3,000	3,001
6,000	6,003
9,000	8,995
12,000	12,009
15,000	14,997
18,000	17,987

1.1.3 Tool Centering Ability

Purpose—This procedure determines the ability of the spindle collet/chuck to properly center a tool. The router accuracy depends on this ability. Also, if the tools are not centered to reasonable tolerances, vibrations can damage bearings.

Recommended equipment:

- A 3-inch-long TGP rod for each shank diameter collet/chuck to be used in the router.
- Dial gauge that has graduations of 0.0001 inch, reading of 0-4-0, and range of 0.008 inch with an accuracy of at least 0.00008 inch over the full range.

- Hardware to mount the dial gauge.

Method—Before beginning this evaluation, the spindle must be run until the steady-state temperature and power (kW) requirements are reached as discussed in procedure 1.1.1. After spindle warm-up, use one of the following procedures to measure the total runout of the TGP rod. The first set of procedures is for spindles with collet and nut mechanisms for mounting tools. The second set is for spindles with collet, nut, and quick-release mechanisms for mounting tools. The third set is for spindles with hydraulic chuck and quick-release mechanisms for mounting tools.

- Collet and Nut

Step 1

Insert a 3-inch-long TGP rod into the collet and make sure that it reaches the full depth of the collet. Insert the collet and rod into the router shank and tighten the collet nut as recommended by the router manufacturer.

Step 2

Mount the dial gauge to the table and position the gauge anvil (contact point) at a point tangent to the side of the TGP rod as shown in Figure 1.3. Then measure and record the total runout to the nearest 0.0001 inch on the TGP rod at a distance of 1-1/4 inches from the collet while turning the spindle by hand.

Step 3

Loosen the collet nut until the collet is forced out of the router shank. Rotate the collet 1/10 of a turn relative to the shank. Retighten the spindle nut. Measure and record total runout as discussed in Step 2.

Step 4

Repeat Step 3 until total runout has been measured and recorded 10 times. Then determine the minimum, maximum, and average total runout.

Step 5

Repeat Steps 1 through 4 for each collet size to be used in the spindle.

Results—For the study router, the results of this evaluation were:

Spindle Runout (Thou)		
(Collet & Nut) 3/4-Inch		
Minimum	Maximum	Average
0.1	0.5	0.4

- Quick-Release Chuck (w/Collet and Collet Nut)

Step 1

Insert a 3-inch-long TGP rod into the collet and make sure that it reaches the full depth of the collet. Insert the collet and rod into the quick-change chuck and tighten the collet nut as recommended by the router manufacturer.

Step 2

Using a felt-tipped pen, place positioning marks around the router shank at 90° intervals. Write the degrees of rotation by each mark (that is, 0, 90, 180, 270). Then place a mark on the quick-change chuck so that it can be aligned with the marks on the router shank.

Step 3

Insert the quick-change chuck into the router shank with the mark on the chuck aligned with the 0° mark on the shank. With a dial gauge mounted on the router table, measure

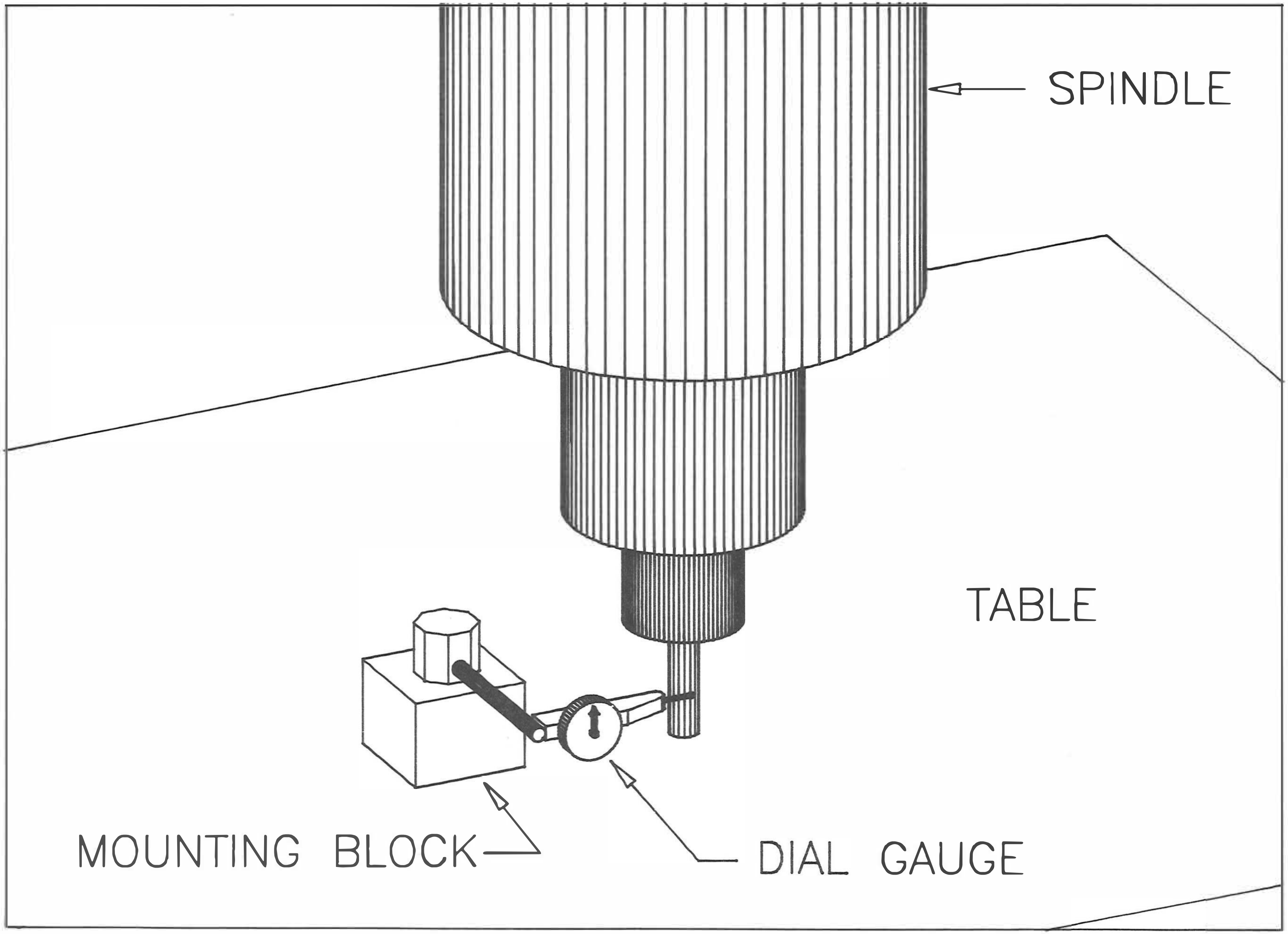


Figure 1.3—Equipment setup for measuring spindle runout.

and record the total runout to the nearest 0.0001 inch on the TGP rod at a distance of 1-1/4 inches from the collet while turning the spindle by hand.

Step 4
Remove the quick-change chuck and loosen the collet nut until the collet is forced out of the chuck. Rotate the collet one-tenth of a turn relative to the shank. Retighten the spindle nut.

Step 5
Repeat Steps 3 and 4 until the total runout has been measured and recorded 10 times with the chuck mark aligned with the 0° mark on the shank.

Step 6
Repeat Steps 4 and 5 with the mark on the chuck aligned with the 90°, 180°, and 270° marks on the spindle shank. Then determine the minimum, maximum, and average total runout.

Step 7
Repeat this entire procedure for each collet size to be used in the spindle.

Results—For the study router, the results of this evaluation were:

Spindle Runout (Thou) (Quick-Release Chuck - W/Collet & Nut) 3/4-Inch		
Minimum	Maximum	Average
0.3	0.5	0.4

- Quick-Release Chuck (Hydraulic)

Step 1
Install a 3-inch long TGP rod into the hydraulic chuck making sure that it is fully seated.

Step 2
Using a felt-tipped pen, place positioning marks around the router shank at 90° intervals. Write the degrees of rotation by each mark (that is, 0, 90, 180, 270). Then place a mark on the hydraulic chuck so that it can be aligned with the marks on the router shank.

Step 3
Insert the hydraulic chuck into the router shank with the mark on the chuck aligned with the 0° mark on the shank. With a dial gauge mounted on the router table, measure and record the total runout to the nearest 0.0001 inch on the TGP rod at a distance of 1-1/4 inches from the collet while turning the spindle by hand.

Step 4
Repeat Step 3 with the mark on the chuck aligned with the 90°, 180°, and 270° marks on the spindle shank. Then determine the minimum, maximum, and average runout.

Step 5
Repeat this entire procedure for each different size hydraulic chuck to be used on the router.

Results—For the study router, the results of this evaluation were:

Spindle Runout (Thou) (Quick-Release Chuck - Hydraulic) 3/4-Inch		
Minimum	Maximum	Average
0.0	0.2	0.1

1.1.4 Trueness of Rotation

Purpose—This procedure evaluates the trueness of rotation of the spindle about the Z-axis. This will indicate the ability of the spindle to drill holes or produce machined surfaces that are perpendicular to the X-axis and Y-axis of the router table.

Recommended equipment:

- Turned-ground-polished (TGP) rod that is 0.5 inch in diameter and 4 inches long.
- Bar or rod approximately 8 inches long with connector that can be attached to the TGP rod at 90°.
- Dial gauge that has graduations of 0.0005 inch, reading of 0-15-0, and range of 0.030 inch with an accuracy of at least 0.0004 inch over the full range.

Method—Before beginning this evaluation, the spindle must be run until the steady-state temperature and power (kW) requirements are reached as discussed in procedure 1.1.1. After spindle warm-up, use the following steps.

Step 1
Locate and mark points A, B, and C on the router table as shown in Figure 1.4. Point A is centered in the Y-axis and one-quarter of the distance from the -X end of the table. Point B is located in the center of the table. Point C is centered in the Y-axis and one-quarter of the distance from the +X end of the table.

Step 2
Install a 0.5-inch TGP rod into the spindle chuck with the rod extending 2 inches below the collet.

Step 3
Attach a crossbar or rod perpendicular to the TGP rod 1 inch below the collet/chuck and lower the spindle until the face of the collet/chuck is 2.25 inches above the table (Fig. 1.4). This positions the spindle at approximately the normal cutting height.

Step 4
Attach a dial gauge to the crossbar or rod so that the anvil (contact point) of the gauge is 6 inches from the center line of the TGP rod and lowered so that it gives a reading on the table (Fig. 1.4). Notice that the anvil of the dial gauge is positioned at 45°. If the anvil is not geared to allow this, it will be necessary to apply a correction factor to the readings obtained.

Step 5
Raise the spindle and position it so that the end of the TGP rod is directly above point A on the spindle table. Lower the spindle until the dial gauge registers near its mid-measurement range. Rotate the spindle shaft by hand until the dial gauge is at the -X position and adjust the gauge to read "0". Then rotate the spindle shaft by hand to the +X position and record the ± dial gauge reading to the nearest 0.001 inch at the new position. Next, rotate the spindle shaft by hand until the dial gauge is at the -Y position and adjust the gauge to read "0". Then rotate the spindle shaft by hand to the +Y position and record the ± dial gauge reading to the nearest 0.001 inch at the new position.

Step 6
Repeat Step 5 for points B and C as located in Step 1.

Results—Using the recorded deviations, calculate the tilt angles (degree, minutes, seconds) and errors (thou/inch) for the trueness of rotation axis of the spindle in both the X-axis and the Y-axis for all three points on the table.

To calculate the tilt angle, use the following equation:

TILT ANGLE = ARCTAN (GAUGE READING / 12)

The tilt angle is then converted to degrees, minutes, and seconds.

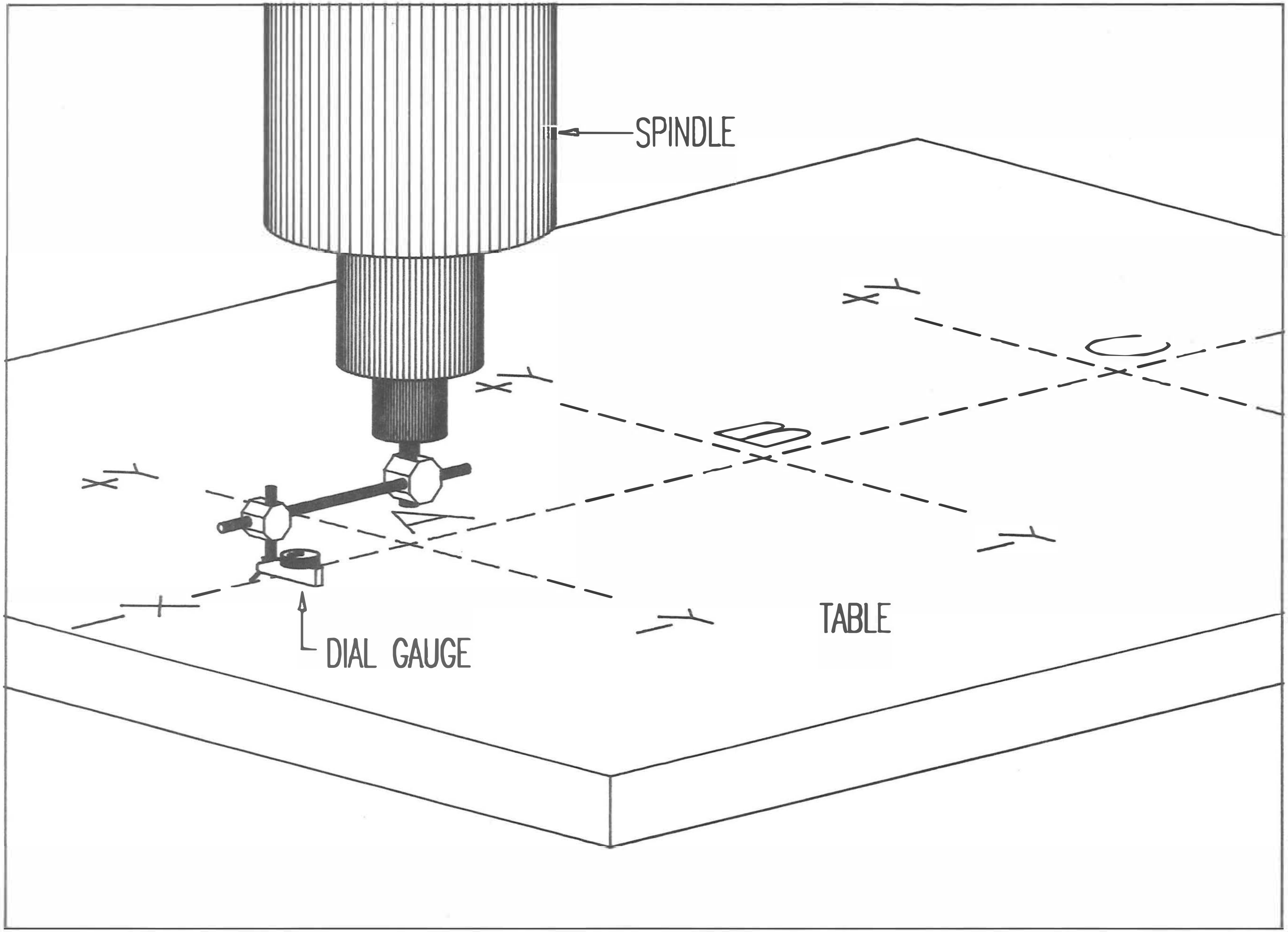


Figure 1.4—Data collection points and equipment setup for measuring spindle trueness of rotation.

The errors in trueness of rotation are calculated by dividing the deviations by 12 inches, which represent the distance between the two measurement points in each axis. The resulting error values are presented as thou/inch.

For the study router, the deviations in dial gauge readings along with the resulting tilt angles and errors were:

Spindle Trueness of Rotation				
Table Position	Trueness Axis	Deviation (Inches)	Tilt Angle (Deg.,Min.,Sec.)	Error (Thou/Inch)
A	X	- 0.015	- 00 04'18"	- 1.2
	Y	0.005	00 01'26"	0.4
B	X	- 0.009	- 00 02'35"	- 0.7
	Y	0.008	00 02'18"	0.7
C	X	- 0.012	- 00 03'26"	- 1.0
	Y	0.003	00 00'52"	0.2

Positive deviations, tilt angles, and errors indicate that the top of the spindle rotational axis is tilted toward the positive end of the X-axis or Y-axis. Conversely, negative deviations, tilt angles, and errors indicate that the top of the spindle rotational axis is tilted toward the negative end of the X-axis or Y-axis.

1.1.5 Cutting Power

Purpose—This procedure evaluates the ability of the spindle to satisfactorily machine selected materials using specified tool sizes and configurations. The prospective buyer of the machine specifies the: (1) type of materials (MDF, plywood, oak, and so on), (2) depth and width of the cuts to be made, and (3) sizes and configurations of the tools to be used. This procedure will assure that the router spindle has the power required to meet the buyer's needs. If this procedure indicates that the available power (kW) is marginally adequate, a larger spindle motor or different milling procedure should be considered.

Recommended equipment:

- Balanced tool(s) of the specified size and configuration.
- 24-inch by 36-inch panel(s) of specified materials to be processed.
- Digital power analyzer that will handle the frequency (Hz) range of the current being sent to the spindle. It also must handle three-phase, three-wire or three-phase, four-wire requirements of the spindle motor. And, it must have an accuracy of ± 0.5 percent of the full range from 20 Hz to 5 kHz.
- Digital thermometer with thermocouple that can be taped to the spindle housing. The thermometer must have an accuracy of at least 0.1 percent of the reading.

Method—This evaluation compares the power (kW) required to make the designated cuts to the full load power (kW) requirements of the spindle motor.

Step 1

Using the data from the spindle motor name plate, determine the full load power requirement for the motor by using the following equation:

$$kW = (1.73 \times I \times E \times pf) / 1000$$

Where:
kW = Full Load Kilowatts
I = Current
E = Voltage
pf = Power Factor

Step 2

Using procedure 1.1.1, warm up the spindle to its steady-state temperature and power (kW) condition.

Step 3

Turn off the spindle motor and remove the TGP rod. Then, mount a tool of the designated size and configuration in the spindle. Check the tool runout to assure that it does not exceed the manufacturer's specification.

Step 4

Make the desired cuts in the material to be processed. Record the average and maximum power required to make these cuts. When processing solid wood, generally the power requirements will be higher when the tool is traveling in the direction of the grain.

Step 5

Repeat Steps 1 through 4 for each tool size/configuration and material designated for evaluation.

Results—For this evaluation, cuts were made in MDF board with both a 1/2-inch diameter straight double-flute bit and a 1-inch diameter straight double-flute bit. With each bit, the cuts were full bit width and full depth in the 3/4-inch MDF board. The procedure started by cutting a large square and then cutting progressively smaller squares until 900 inches of cut had been made with each bit. For both cuts, the spindle speed was 18,000 RPM and the feed speed was 315 IPM. The results for this procedure were:

Full Load Power (15-hp Perske Spindle Motor)

FLP = (1.73 X 38 X 230 X 0.77) / 1000 = 11.64 kW

Required Spindle Power		
Bit Diameter	Average Kilowatts	Maximum Kilowatts
1/2-inch	2.48	2.60
1-inch	4.86	5.37

Comparing the maximum power required to make the test cuts to the spindle's full load power shows that the 15-hp spindle motor was more than adequate for making the required cuts with both bits.

1.1.6 Base Vibration Spectrum

Purpose—This procedure uses a vibration analyzer to provide a base frequency spectrum graph of the spindle vibrations resulting from rotational balance imperfections and bearings. This information can be used to detect major problems with the rotational balance and bearings of the spindle. The spectrum graph also can be compared to future spectrum graphs to evaluate the condition of the spindle bearings after the router has been in use for a period of time. This test is performed without a collet or chuck assembly attached to the spindle shank.

Recommended equipment:

- A vibration analyzer equivalent to Computational Systems Incorporated's Model 2110 Machinery Analyzer or Palomar Technology's Microlog Model 6210.

Method—With the thermocouple and power analyzer attached to the spindle as discussed in procedure 1.1.1., the spindle is operated until the steady-state temperature and power (kW) requirements are reached. After spindle warm-up, use the following steps.

Step 1

Remove the spindle collet or chuck assembly.

Step 2

Run the spindle motor at maximum RPM's.

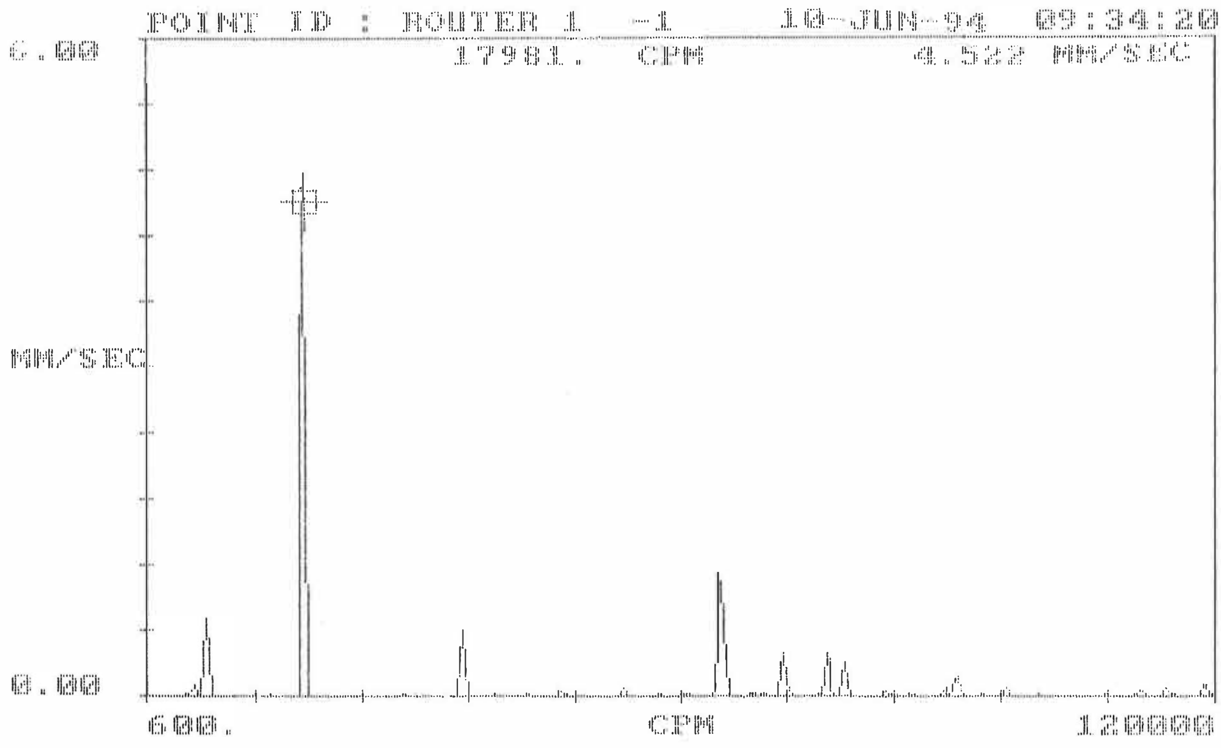
Step 3

Using a vibration analyzer, develop a graph of the vibration spectrum (peak mm/second) covering 300 cycles per minute (CPM) to 120,000 CPM. The measurement is to be taken as near as possible to the lower spindle bearing. Before developing the spectrum graph, determine the position of maximum vibration by taking measurements every 45° around the lower spindle housing. This and all future vibration measurements should be taken at this point of maximum vibration.

Results—Figure 1.5 shows an example of a vibration spectrum graph for a router spindle motor.

```
POINT # 10   ROUTER 1   -1
  [  ,   ]

SIGNAL STATUS              : OK
LAST MEASUREMENT ON        : 10-JUN-94   09:34:20
RPM READING                : 18000.
LOAD                       :   100.
OVERALL =4.91      MM/SEC PEAK DIG
SPECTRUM=4.89      MM/SEC PEAK DIG
```



FREQUENCY	DATA	FREQUENCY	DATA	FREQUENCY	DATA	FREQUENCY	DATA
5949.	0.1097	53946.	0.1054	76878.	0.4186	91362.	0.2131
7208.	0.7193	60673.	.04786	78862.	0.3274	96836.	.09252
17981.	4.522	64922.	1.265	83280.	.06893	112016	.06998
35978.	0.6146	70030.	.05764	86640.	.04949	114720	.09848
46688.	.07905	71922.	0.4134	89866.	.09091	118946	0.1353

Figure 1.5—Frequency spectrum of spindle vibration.

1.2 Drill

1.2.1 RPM Accuracy

Purpose—This procedure evaluates RPM accuracy of the drill motor. Because the quality of the hole edges depends to some extent on the correct RPM of the drill motor, the drill should run at the rated RPM.

Recommended equipment:

- Turned-ground-polished (TGP) rod that is 0.5 inch in diameter and 4 inches long. If the drill collet/chuck will not take a 0.5-inch tool, use a TGP rod of the maximum diameter acceptable to the collet/chuck.
- Hand-held digital phototachometer with a range covering the maximum RPM of the drill (accuracy ± 1 RPM).
- Reflective paint.

Method—Before beginning this evaluation, run the drill through approximately 20 drilling cycles to assure that the drill bearings are fully lubricated. Once this is done, use the following steps.

Step 1
Paint a 1/2-inch square patch of the reflective paint on the collet/chuck. The coat of paint should be as thin as possible to minimize the effect on drill vibration that can be caused if the drill is out-of-balance.

Step 2
With the drill motor running, measure and record the RPM's with the hand-held phototachometer.

Results—For the study router, the results of this evaluation were:

Drill RPM	
Target	Actual
1200	1065

1.2.2 Tool Centering Ability

Purpose—This procedure determines the centering ability of the drill chuck by measuring the total runout of a TGP rod mounted in the chuck. Excessive runout can affect the smoothness and diameter of the holes to be drilled.

Recommended equipment:

- A turned-ground-polished (TGP) rod that is 0.5 inch in diameter and 6 inches long. If the drill collet/chuck will not take a 0.5-inch tool, use a TGP rod of the maximum diameter acceptable to the collet/chuck.
- Dial gauge that has graduations of 0.0001 inch, reading of 0-4-0, and range of 0.008 inch with an accuracy of at least 0.00008 inch over the full range.
- Hardware to mount the dial gauge to the router table.

Method—Before beginning this evaluation, run the drill through at least 20 cycles to assure that the drill bearings are fully lubricated. At that point, use the following steps.

Step 1
Mount the TGP rod securely in the drill chuck.

Step 2
Mount the dial gauge to the table and position the gauge anvil (contact point) at a point tangent to the side of the TGP rod and 3 inches below the collet/chuck as shown in Figure 1.6.

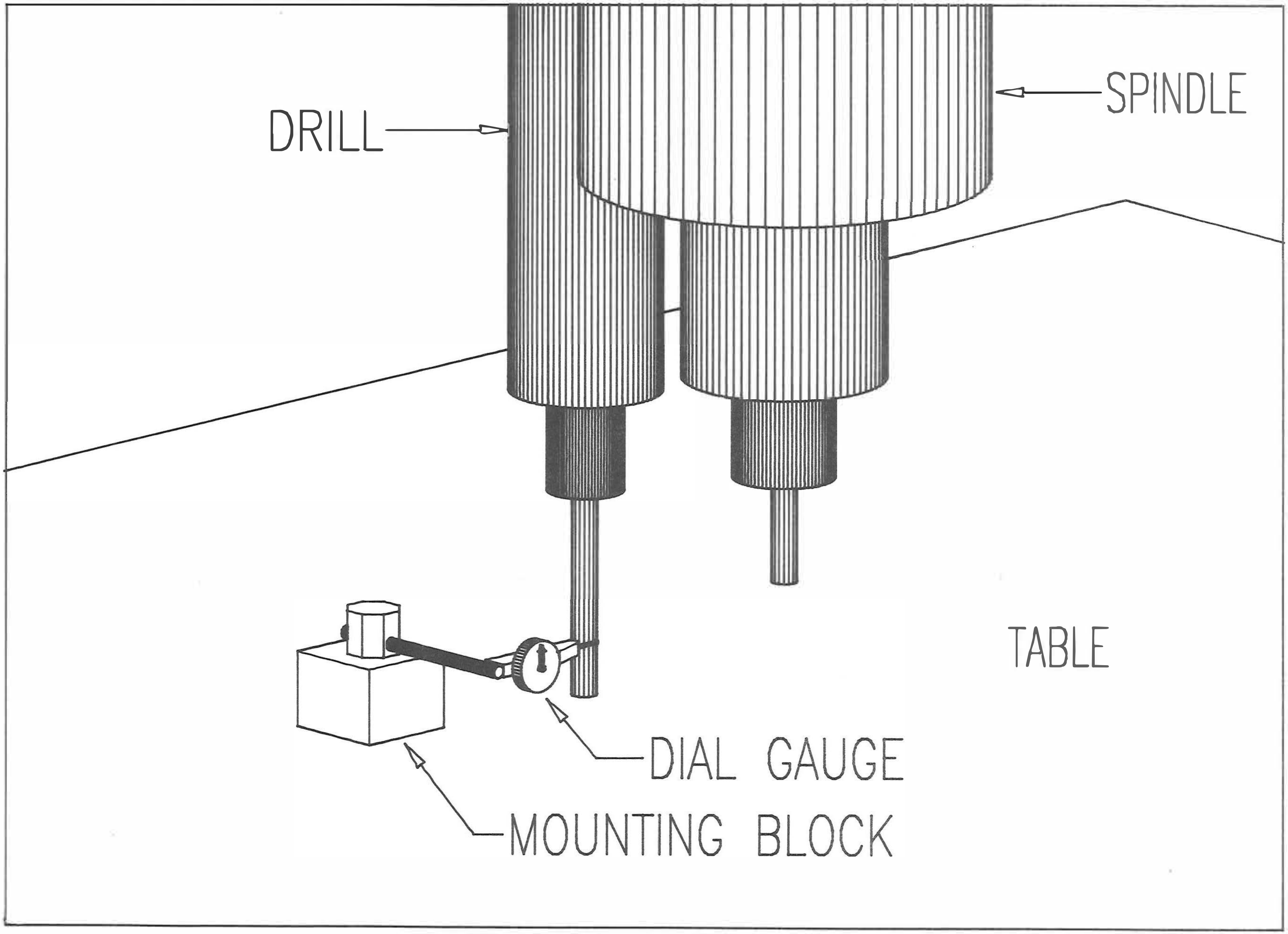


Figure 1.6—Equipment setup for drill runout.

Step 3

Turning the drill chuck by hand, observe and record the total runout of the TGP rod to the nearest 0.0001 inch.

Step 4

Loosen, reposition the TGP rod, and retighten the drill chuck.

Step 5

Repeat Steps 3 and 4 to obtain 10 total runout values. Then determine the minimum, maximum, and average total runout.

Results—For the study router, the results of this evaluation were:

Drill Runout (Thou)		
Minimum	Maximum	Average
0.7	1.2	0.9

1.2.3 Trueness Of Rotation

Purpose—This procedure evaluates the trueness of rotation of the drill about its rotational axis. This will indicate the ability of the drill to machine holes that are perpendicular to the surface of the material to be machined.

Recommended equipment:

- Turned-ground-polished (TGP) rod that is 0.5 inch in diameter and 6 inches long. If the drill collet/chuck will not take a 0.5-inch tool, use a TGP rod of the maximum diameter acceptable for the collet/chuck.
- Bar or rod approximately 8 inches long with connector that can be attached to the TGP rod at 90°.
- A dial gauge that can be attached to the above bar or rod. The dial gauge should have graduations of 0.0005 inch, reading of 0-15-0, and range of 0.030 inch with an accuracy of at least 0.0004 inch over the full range.

Method—Before beginning this evaluation, the drill should be run through approximately 20 drilling cycles to assure that the drill bearings are fully lubricated. At that point, use the following steps.

Step 1

Locate and mark points A, B, and C on the router table as indicated in Figure 1.7.

Step 2

Install the 0.5-inch TGP rod into the drill collet/chuck.

Step 3

Attach a crossbar or rod perpendicular to the TGP rod 3 inches below the collet/chuck (Fig. 1.7).

Step 4

Attach a dial gauge to the crossbar or rod and lower so that the anvil (contact point) of the gauge is 6 inches from the center line of the TGP rod (Fig. 1.7). Notice that the anvil of the dial gauge is positioned at 45°. If the anvil is not geared to allow this, it will be necessary to apply a correction factor to the readings obtained.

Step 5

Position the drill until the end of the rod is above the table at point A. Lower the drill until the dial gauge registers near its mid-measurement range. Rotate the drill shaft by hand until the dial gauge is at the -X position and adjust the gauge to read "0". Then rotate the drill shaft by hand to the +X position and record the ± dial gauge reading to the nearest 0.001 inch at the new position. Next, rotate the drill shaft by hand until the

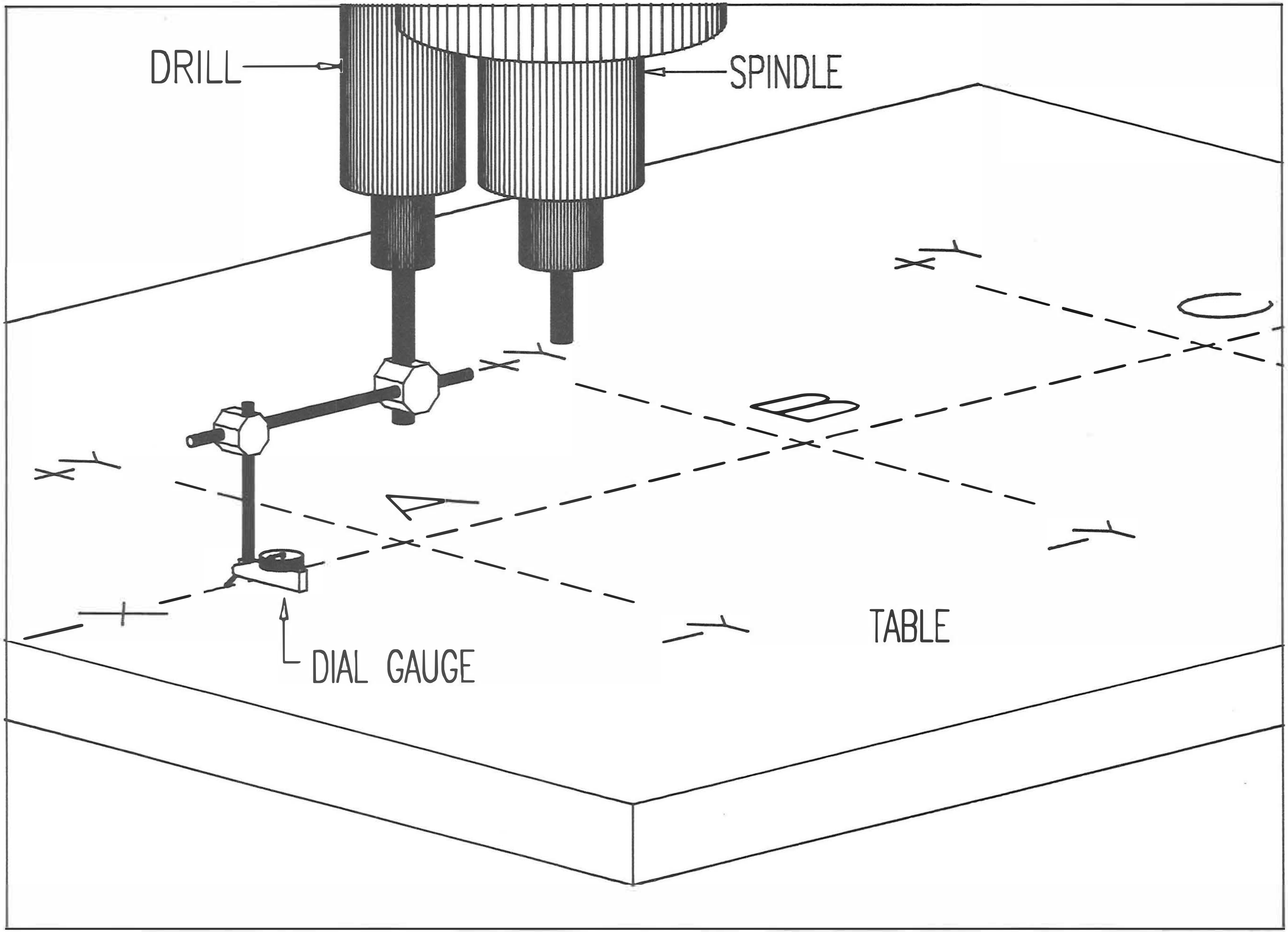


Figure 1.7—Data collection points and equipment setup for measuring drill trueness of rotation.

dial gauge is at the -Y position and adjust the gauge to read “0”. Then rotate the drill shaft by hand to the +Y position and record the ± dial gauge reading to the nearest 0.001 inch at the new position.

Step 6

Repeat Step 5 for points B and C as located in Step 1.

Results—Using the recorded deviations, calculate the tilt angles (degree/minute/seconds) and errors (thou/inch) for the trueness of rotation axis of the drill in both the X-axis and the Y-axis for all three points on the table.

To calculate the tilt angle, use the following equation:

TILT ANGLE = ARCTAN (GAUGE READING / 12)

The tilt angle is then converted to degrees, minutes, and seconds. The errors in trueness of rotation are calculated by dividing the deviations by 12 inches, which represent the distance between the two measurement points in each axis. The resulting error values are presented in thou/inch.

For the study router, the deviations in dial gauge readings along with resulting tilt angles and errors were:

	Drill Trueness of Rotation			
Table Position	Trueness Axis	Deviation (Inches)	Tilt Angle (Deg.,Min.,Sec.)	Error (Thou/Inch)
A	X	- 0.028	- 00 08'01"	- 2.3
	Y	- 0.003	- 00 00'52"	- 0.2
B	X	- 0.027	- 00 07'44"	- 2.2
	Y	0.001	00 00'17"	0.1
C	X	- 0.027	- 00 07'44"	- 2.2
	Y	- 0.006	- 00 01'43"	- 0.5

A positive deviation and tilt angle indicate that the top of the spindle rotational axis is tilted toward the positive end of the X-axis or Y-axis. Conversely, negative deviations, tilt angles, and errors indicate that the top of spindle rotational axis is tilted toward the negative end of the X-axis or Y-axis.

1.3 Router Table

1.3.1 Table Flatness

Purpose—This procedure uses a laser interferometer system to determine the flatness of the router table. Table flatness is important when machining in axes other than the X and Y. This includes the drilling of holes as well as the machining of surfaces. However, this lack of flatness might not be a problem if the spindle is used to grind the table top to provide a consistent table to spindle distance.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring angular (pitch and yaw) deviations. The optics include an angular interferometer, angular reflector, and two flatness turning mirrors. It is also necessary to have a flatness base with foot spacing that will miss the grooves in the table. Flatness measurements do not require environmental compensations for air temperature, barometric pressure, and relative humidity. And, it is not necessary to make adjustments for the thermal expansion of the scale material, which in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10)[1] by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and plot the table flatness. Although the PC and software are not necessary, they greatly facilitate data collection and plotting for this procedure.

Method—If the router has a vacuum table, insert screws into each vacuum port in the table and apply vacuum for this procedure. At that point, use the following steps.

Step 1
Lay out the lines for a Moody flatness test on the router table as shown in Figure 1.8.

Step 2
Set up the laser system as instructed in the system user's manual for a Moody flatness procedure. Figure 1.8 also shows a typical setup for this procedure.

Step 3
Collect the required data.

Step 4
If the maximum closure error is greater than 0.5 thou, repeat Steps 1 and 2 until an acceptable error is achieved.

Results—Figure 1.9 is a graphic plot of the table flatness along with the total range in elevation between the high and low point of the table and the two Moody closure errors. The first closure error represents the mismatch of elevations at the intersection of the diagonal lines AE and GC (Fig. 1.8). The second closure error represents the mismatch of elevations at the intersection of lines HD and FB (Fig. 1.8). The maximum closure errors should be less than 0.5 thou. Figure 1.10 shows the actual deviations along the Moody measurement lines.

1.3.2 Spindle to Table Distance Variation

Purpose—This procedure uses a dial gauge to determine the spindle to table distance variations of a router. This variation is important when machining accuracy in the **Z**-axis is critical.

Recommended equipment:

- Dial gauge that has graduations of 0.0005 inch, reading of 0-15-0, and range of 0.030 inch with an accuracy of at least 0.0004 inch over the full range.

- Hardware for mounting the dial gauge that will fit into the collet and allow the gauge to be mounted so that the ball of the anvil is centered at the point of spindle rotation.

Method—Before beginning this evaluation, insert screws into each vacuum port in the table and apply vacuum. At that point, use the following steps.

Step 1
Insert the dial gauge hardware into the collet and tighten the spindle nut. Rotate the anvil (contact point) of the dial gauge down at a 45° angle. Then, mount the dial gauge so that the ball of the anvil is centered at the point of spindle rotation. In other words, when the spindle is turned by hand, the ball remains at the same point in the **XY**-plane. Figure 1.11 shows this setup.

[1]1989. Laser interferometer system—PC10 user manual. Renishaw Transducer Systems Limited. Printed in the United Kingdom by S.A.C.Technographic Ltd.

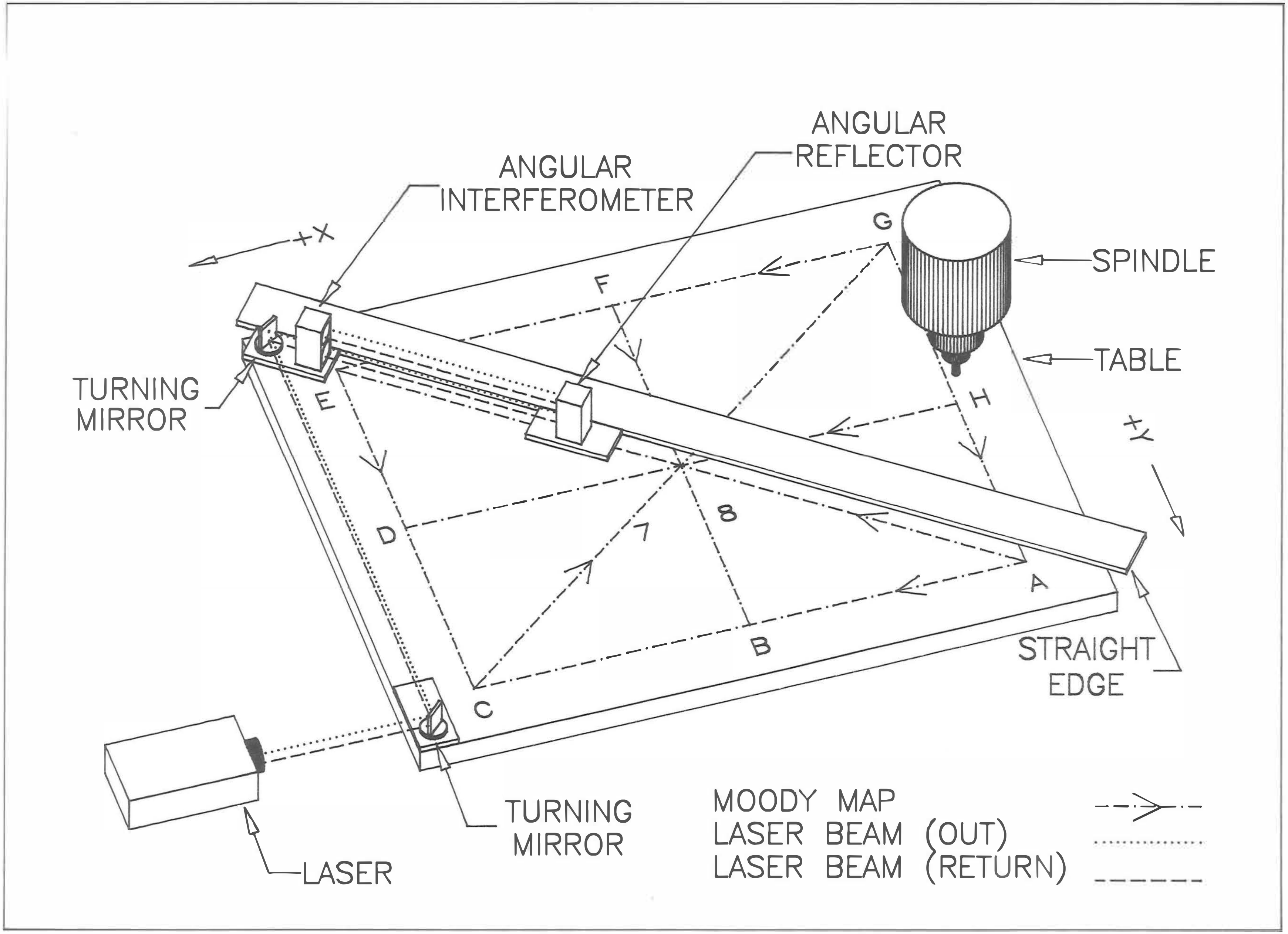


Figure 1.8—Data collection lines and a typical laser setup for a Moody flatness test.

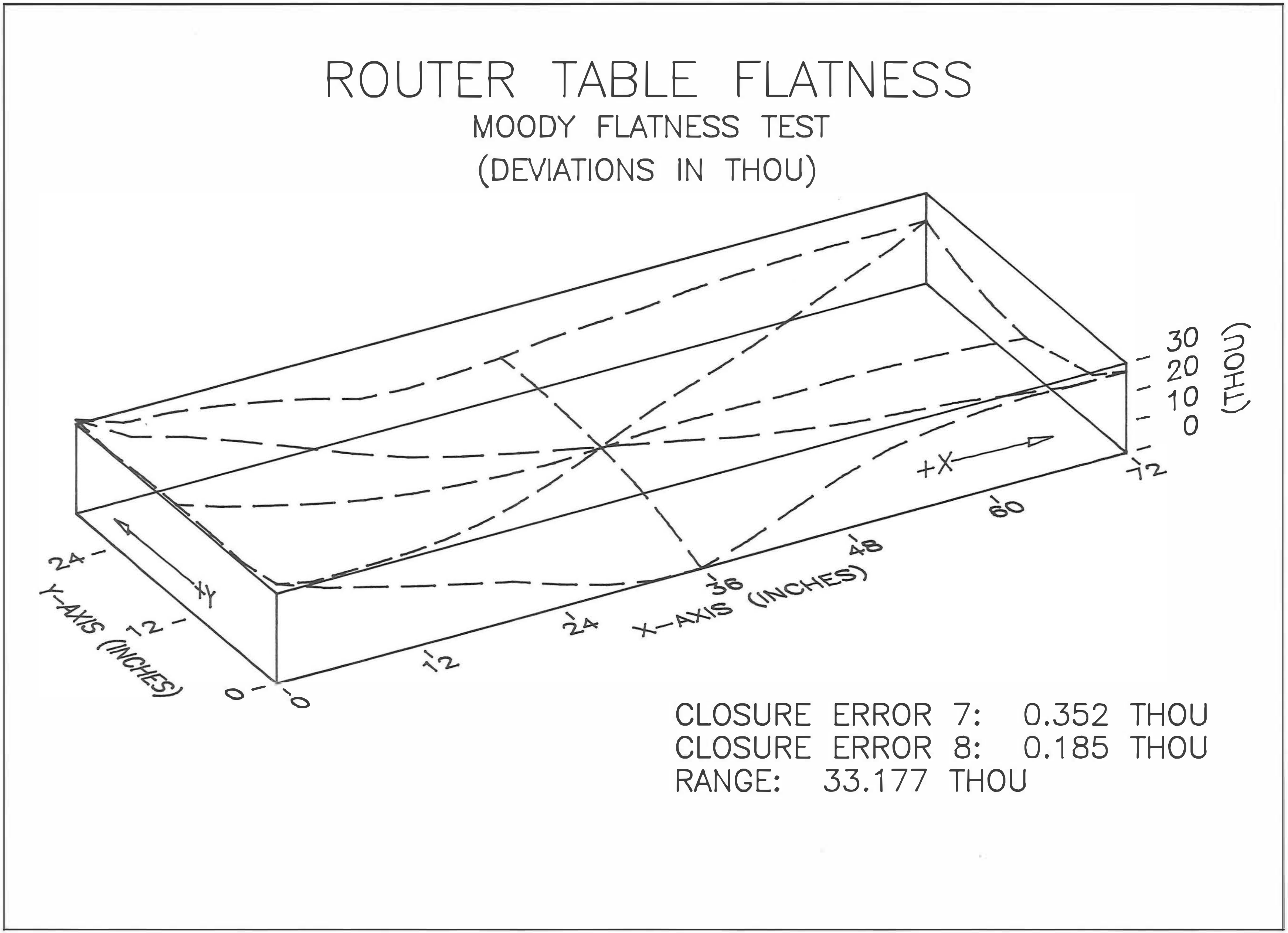


Figure 1.9—Graph showing router table deviations as determined by a Moody flatness test.

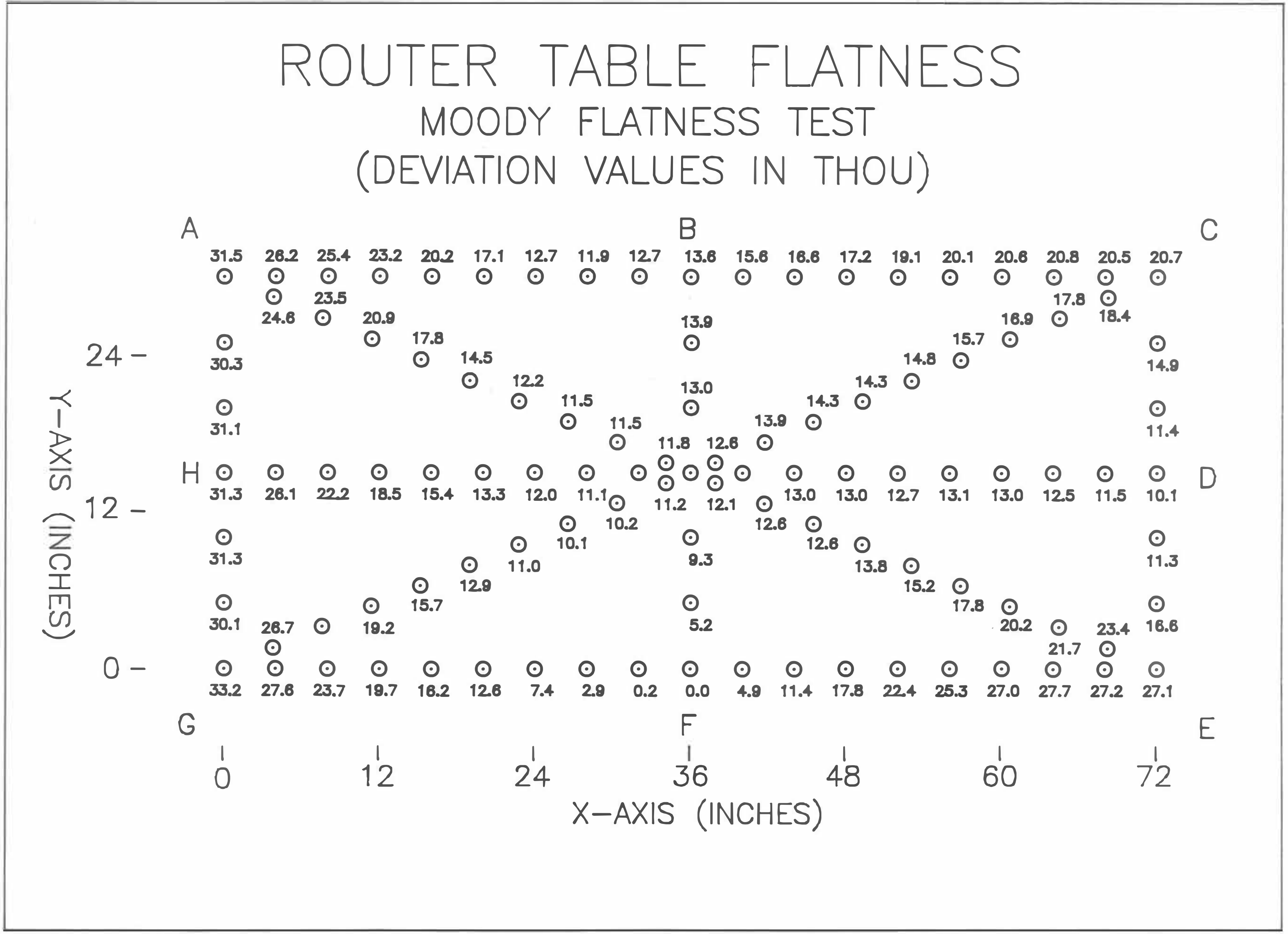


Figure 1.10—Actual table deviations as determined by a Moody flatness test.

Step 2

Using a felt-tipped marker, lay out a system of equally spaced dots on the table. Space the dots 6 inches apart and center in both the X-axis and Y-axis. The rows and columns should be numbered as shown in Figure 1.12. If slots in the table will not allow the 6-inch spacing of the measurement points, use spacing as near as possible to 6 inches.

Step 3

Move the spindle so that the dial gauge anvil is directly over point (0,0) and lower it until the dial gauge needle is at the mid-point of its scale. Rotate the dial gauge face so that it provides a reading of "0".

Step 4

Without raising the spindle, move the spindle/table to the various points as located in Step 2 and record the ± dial gauge readings to the nearest 0.001 inch. Before moving the spindle to each point, rotate it by hand if necessary to assure that the dial gauge anvil is drawn to the point without jamming into the grooves of the table.

Step 5

If the dial gauge is not constructed to allow true readings to be taken with the anvil set at 45°, apply a correction factor to the readings obtained in the above step. The manufacturer or distributor of the gauge can provide this correction factor.

Results—The resulting variations in distances between the spindle and table are then presented as either a graph (Fig. 1.13) or a table (Fig. 1.14).

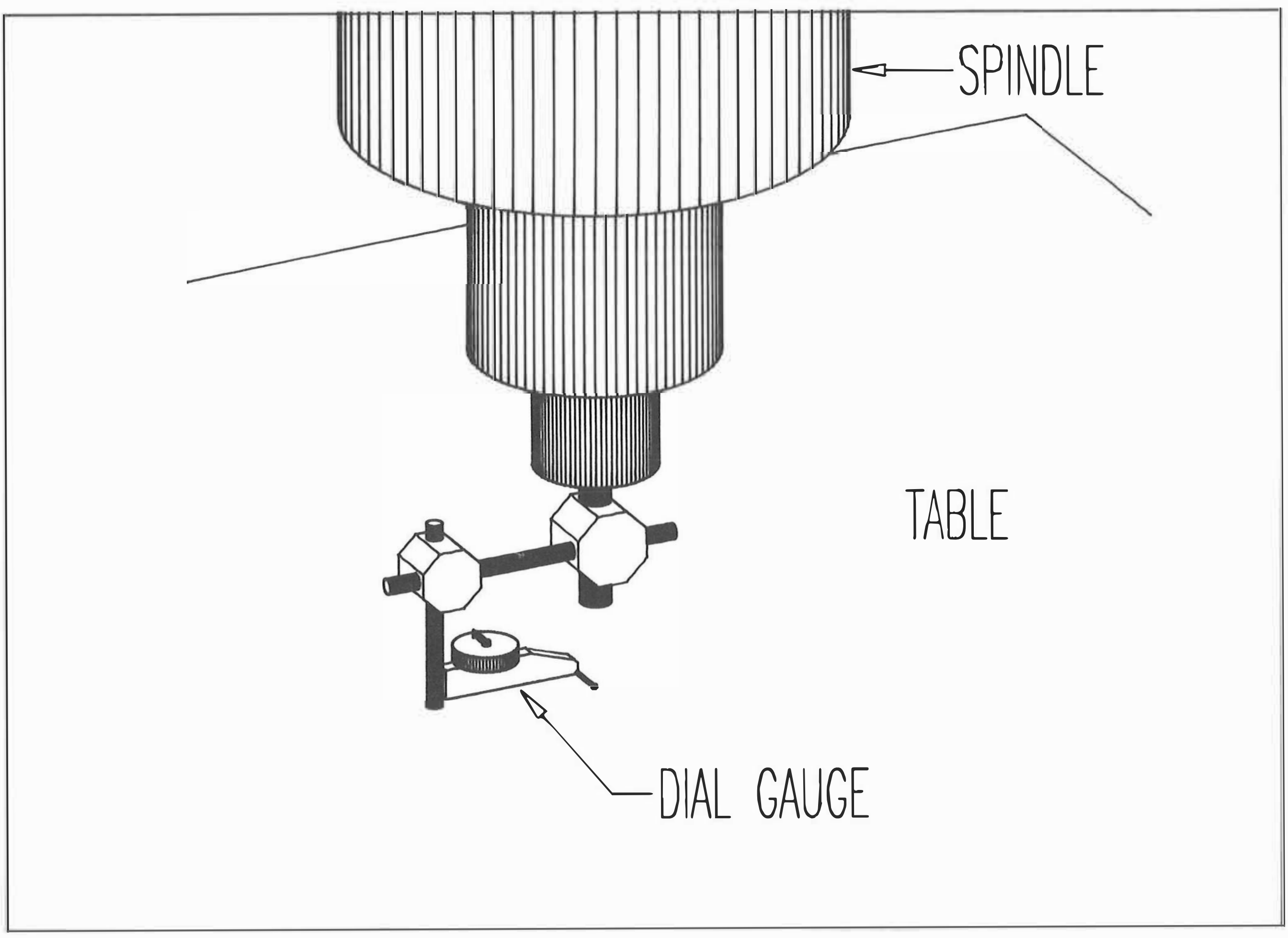


Figure 1.11—Equipment setup for measuring spindle to table distance variations.

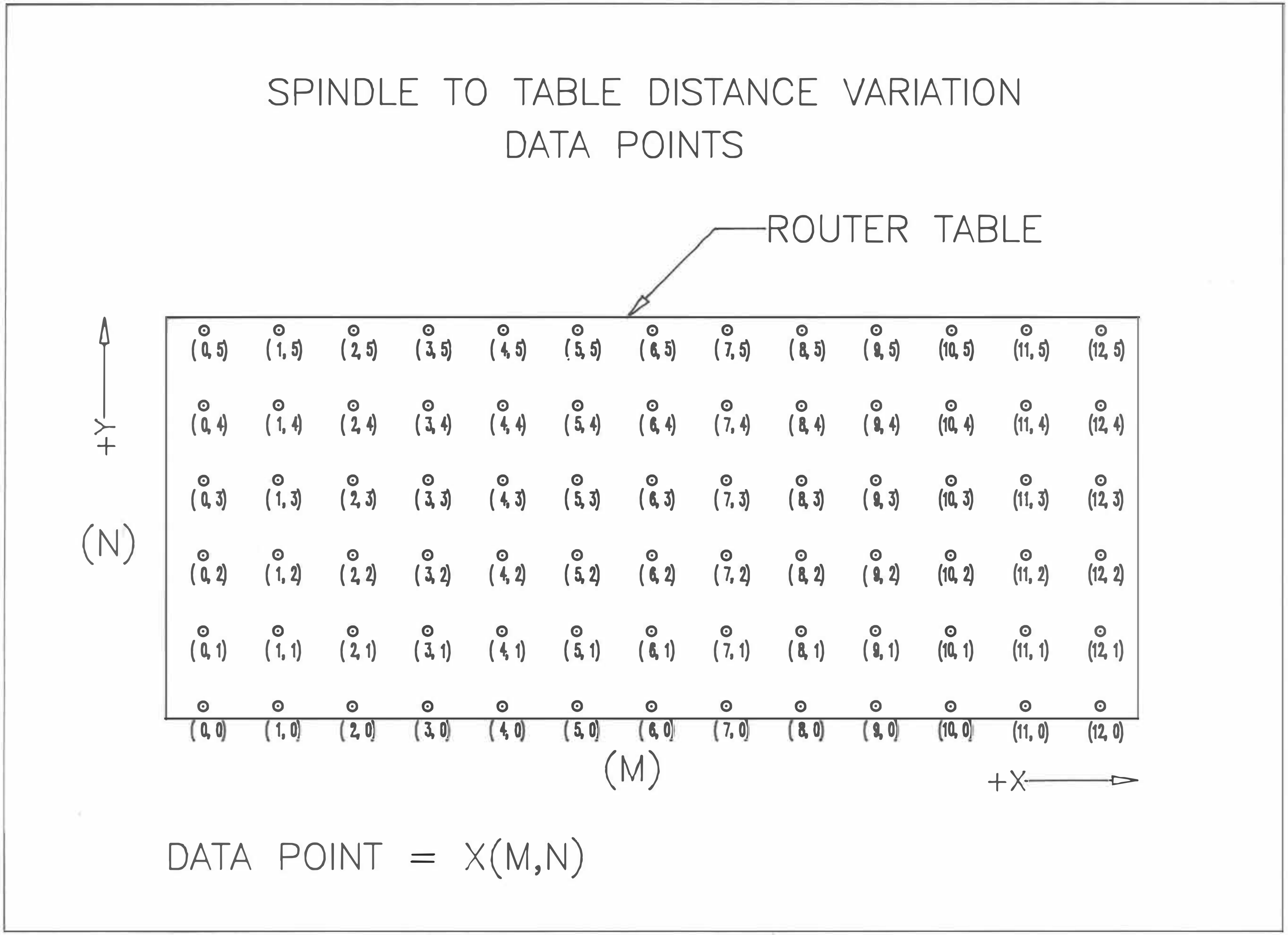


Figure 1.12—Data point layout for measuring spindle to table distance variations.

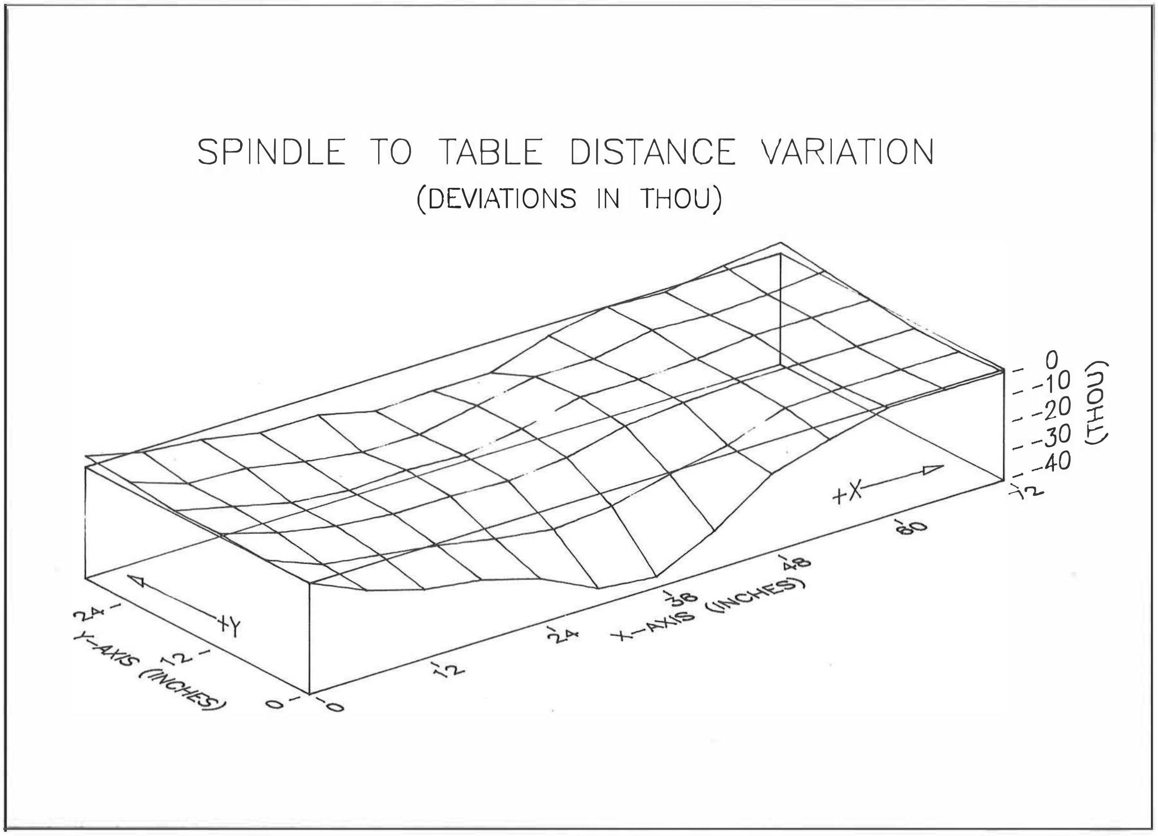


Figure 1.13—Graph showing spindle to table distance variations.

SPINDLE TO TABLE DISTANCE VARIATION

(DEVIATION VALUES IN THOU)

+Y (N)

(+4.0)	(−1.0)	(−3.0)	(−7.0)	(−7.0)	(−12.0)	(−11.0)	(−7.0)	(−4.0)	(0.0)	(−1.0)	(+2.0)	(+4.0)
(+3.0)	(−4.0)	(−5.0)	(−9.0)	(−12.0)	(−12.0)	(−8.0)	(−4.0)	(−4.0)	(0.0)	(−1.0)	(0.0)	(+2.0)
(+1.0)	(−4.0)	(−9.0)	(−11.0)	(−10.0)	(−11.0)	(−8.0)	(−3.0)	(−3.0)	(−2.0)	(0.0)	(0.0)	(0.0)
(+1.0)	(−5.0)	(−10.0)	(−11.0)	(−11.0)	(−12.0)	(−10.0)	(−5.0)	(−3.0)	(−2.0)	(−2.0)	(−2.0)	(−2.0)
(0.0)	(−8.0)	(−11.0)	)−14.0)	(−18.0)	(−21.0)	(−19.0)	(−14.0)	(−10.0)	(−3.0)	(−2.0)	(−2.0)	(−2.0)
(0.0)	(−9.0)	(−15.0)	(−18.0)	(−24.0)	(−34.0)	(−38.0)	(−28.0)	(−12.0)	(−6.0)	(−1.0)	(−1.0)	(−1.0)

(M)

+X

Figure 1.14—Actual spindle to table distance variations.

1.3.3 Tool/Table Deflection from Cutting Side Pressures

Purpose—This procedure determines the tool deflection that occurs if 75 pounds of side pressure is applied between the tool and the table. The 75 pounds represents the side pressures that can occur as the tool cuts material. Factors that might contribute to these deflections include: (1) spindle bearings and shaft play, (2) spindle mounting hardware, (3) spindle way shafts and bushings, (4) spindle ball screw assembly, (5) table way shafts and bushings, and (6) table ball screw assembly. These deflections can produce unsatisfactory cutting accuracy if they are too great.

Recommended equipment:

- Turned ground polished (TGP) rod at least 0.5 inch in diameter.
- Tension scale with a capacity of at least 75 pounds.
- Hydraulic cylinder and hydraulic hand pump.
- Mounting hardware for mounting hydraulic cylinder to router table.
- A dial gauge that can be mounted to the router table. The dial gauge should have graduations of 0.0005 inch, readings of 0-15-0, and range of 0.030 inch with an accuracy of at least 0.0004 inch over the full range.

Method—Before beginning this evaluation, the spindle must be run until the steady-state temperature and power (kW) requirements are reached as discussed in Procedure 1.1.1. The router table and spindle must be exercised in all axes at least 20 cycles. At that point, use the following steps.

Step 1
Mount the TGP rod into the collet/chuck. Then, with the dial gauge mounted on the table, position the anvil (contact point) 1.25 inches below the collet and tanget to the TGP rod as shown in Figure 1.15.

Step 2
Assemble the scales, hydraulic cylinder, and cylinder hardware as shown in Figure 1.15. Then, hook the cylinder hardware over the -X end of the table and apply 75 pounds of pressure in the -X direction on the TGP rod at approximately 1.25 inches from the face of the collet.

Step 3
Record the deflection of the TGP rod as shown on the dial gauge.

Step 4
Repeat the above steps for the +X, -Y, and +Y directions.

Results—The total deflections for study router were:

Tool to Table	
Pressure Direction	Deflection (Thou)
+X	0.8
-X	0.8
+Y	0.2
-Y	0.2

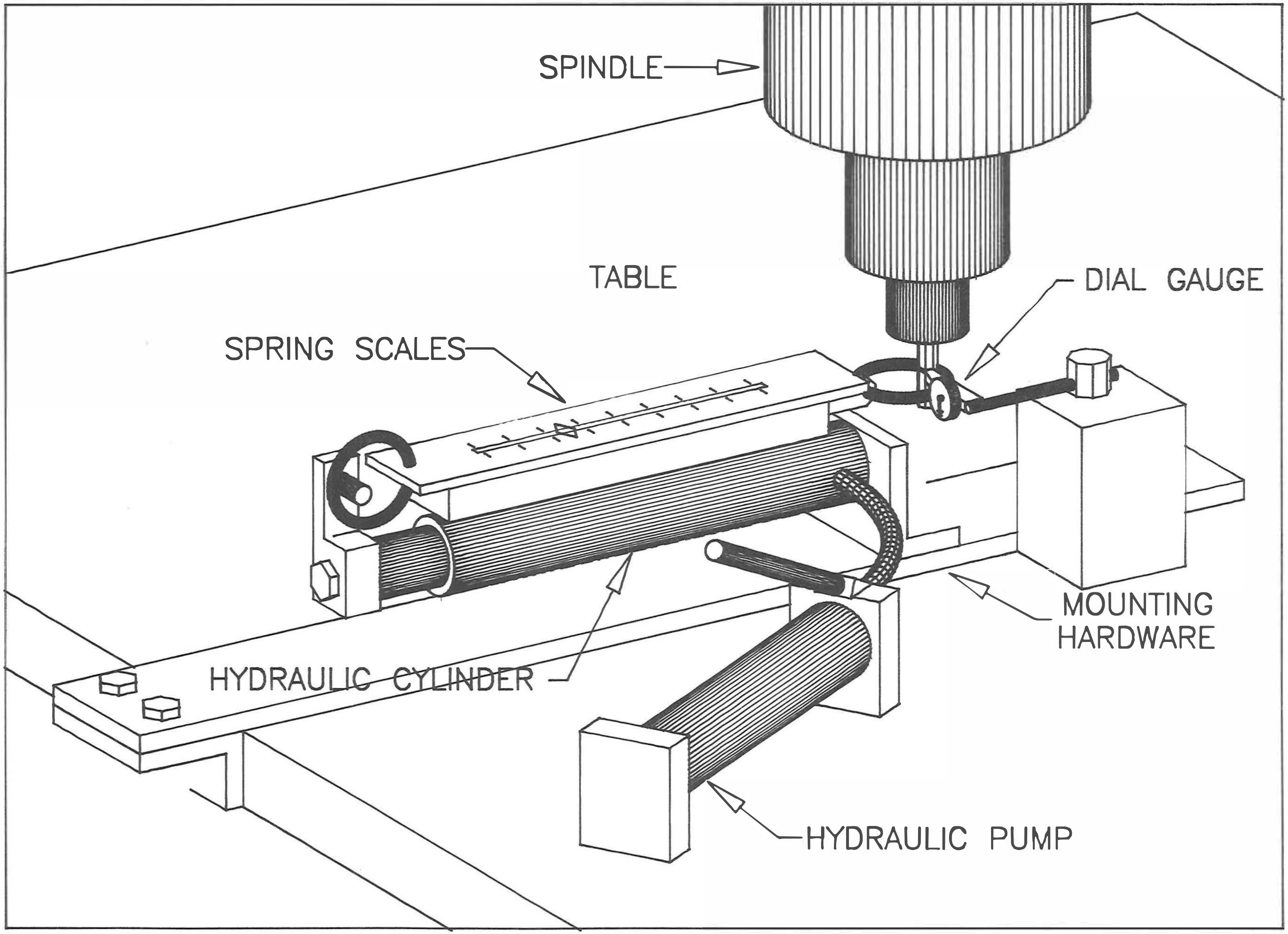


Figure 1.15—Equipment setup for measuring tool/table deflections resulting from cutting side pressures.

2.0 Spindle/table Travel Evaluations

2.1 Positioning Accuracy

2.1.1 X-axis Positioning

Purpose—This procedure determines the ability of the router to accurately position a tool in the X-axis in response to the machine controller and its program. Router construction affects positioning, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the ability of the router's servo motor and ball screw to respond to the instructions from the controller.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring linear displacement. The optics include a beam splitter and two linear reflectors plus the hardware required for mounting them. The system must allow for environmental compensations for air temperature, barometric pressure, and relative humidity. It also should allow for adjustments to be made based on the temperature of the machine scale and the thermal expansion coefficient of the scale material. The scale in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that controls the movement in the X-axis should be exercised through at least 20 full cycles. This reduces the error in positioning that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1

The router controller is programmed to move the table/spindle in the X-axis. If the ball screw has standard threads, the controller must be programmed to move the table/ spindle 50 mm at a time. If the ball screw has metric threads, the controller must be programmed to move 2 inches at a time. With this movement, the ball screw will not be in the same rotational position for each position measurement of the table/spindle. The table/spindle must travel the full extent of the X-axis in 2-inch or 50-mm increments. However, provide at least 1 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the difference between the distance specified by the controller program and the distance actually moved. The program also must provide for bi-directional travel so that measurements can be taken in both the +X and -X directions. After the measurement is recorded for the last point in a given direction, move the spindle/table ahead 1 inch. Then reverse the direction of travel 1 inch to the finalpoint for the first measurement in the other direction. Examples of these programs and their subroutines, titled LINEAR POSITIONING IN X-AXIS for (STANDARD UNITS) and (METRIC UNITS), are shown in Figure A.1.1 of Appendix A.1.

Step 2

Set up the laser as instructed in the laser user's manual. Figure 2.1 shows an example of the laser optics setup. The laser is aligned down the middle of the table in the X-axis. Assure that adjustments are made in the laser measurements for air temperature, barometric pressure, relative humidity, and thermal expansion of the ball screw material.

Step 3

Measure and record the difference between the controller instructed moves and the actual moves of the table/spindle in both directions in the X-axis. Repeat this procedure for five full forward and reverse cycles.

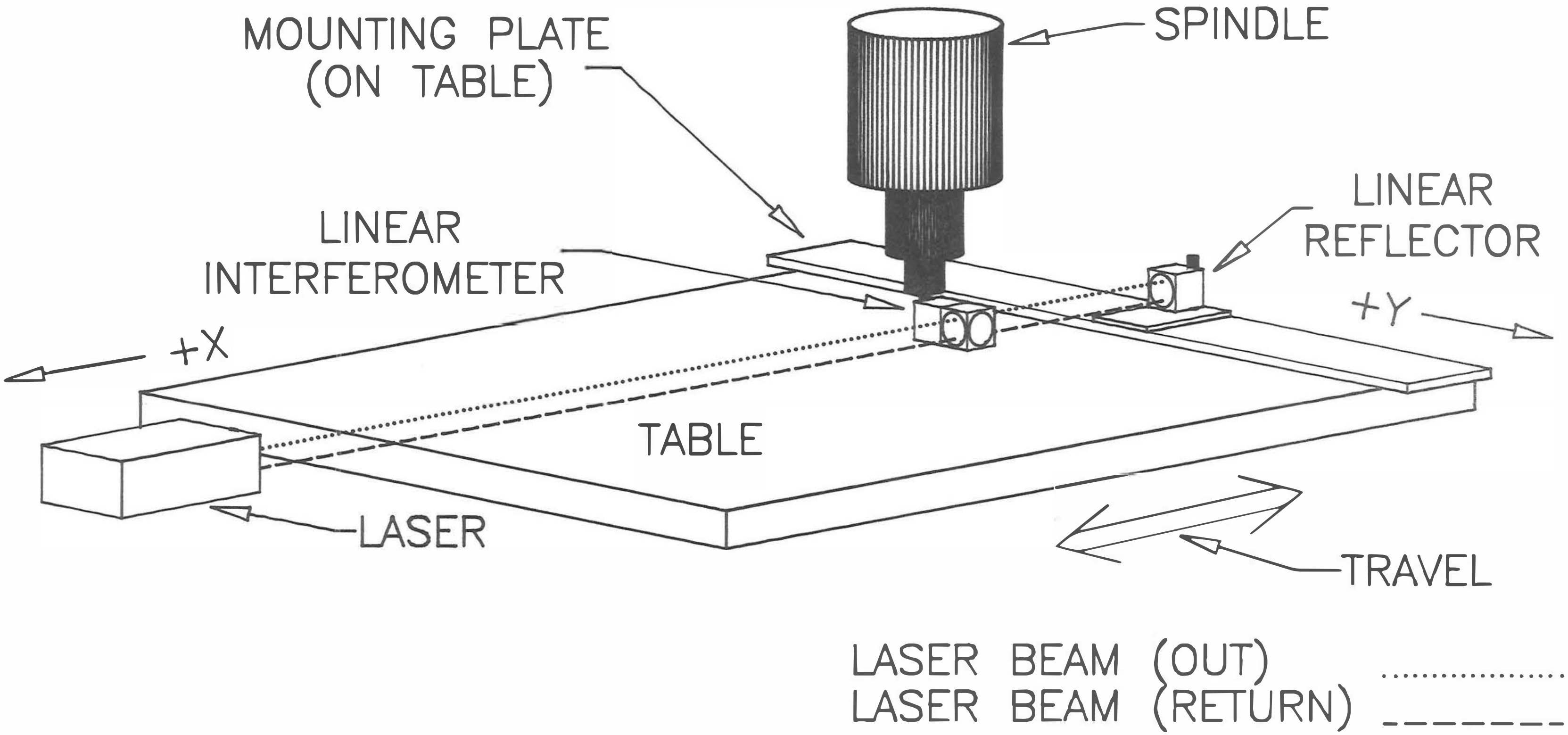


Figure 2.1—Laser setup for measuring positioning accuracy in the X-axis.

Results—Plot a graph based on the German VDI 3441 standard showing the differences between the specified positions and the actual positions of the table/spindle in both the +X and the -X directions. In collecting data, the table was moved 50 mm at a time because the ball screws had standard threads. The error in positioning also was measured in metric units. However, the software used to provide the analysis has the option of converting the data to standard units. Figure 2.2 is an example of the graph with representative statistics. The graph shows mean positional errors in both the positive and negative directions, the bi-directional mean positioning error, and the maximum "±3 sigma" repeatability bands from either direction of travel. Discussion of the data presented below the graph follows:

- Mean Reversal Error (U mean) and Maximum Reversal error (U max) are commonly referred to as 'backlash' or 'lost motion.' They are defined as the difference obtained from the mean values in both directions of travel for each target position.

- Mean Positional Scatter (Ps mean) and Maximum Positional Scatter (Ps max) represents the effect of random deviations in the positional errors at each position along the test axis. They may be regarded as a measure of the uni-directional repeatability.

- Positional Deviation (Pa) is the maximum difference in the mean positional error values of all measured points along the test axis.

- Positional Uncertainty (P) is the total deviation along the test axis and takes into account the values of positional deviation, reversal error, and positional scatter at each point.

The above definitions were taken from the RENISHAW TRANSDUCER SYSTEMS LIMITED, Laser Interferometer System PC10 User Manual.[1]

2.1.2 Y-axis Positioning

Purpose—This procedure determines the ability of the router to accurately position a tool in the Y-axis in response to the machine controller and its program. Router construction affects the positioning, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the ability of the router's servo motor and ball screw to respond to the instructions from the controller.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring linear displacement. The optics include a beam splitter and two linear reflectors plus the hardware required for mounting them. The system must allow for environmental compensations for air temperature, barometric pressure, and relative humidity. It also should allow for adjustments to be made based on the temperature of the machine scale and the thermal expansion coefficient of the scale material. The scale in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that controls the movement in the Y-axis should be exercised through at least 20 full cycles. This reduces the error in positioning that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

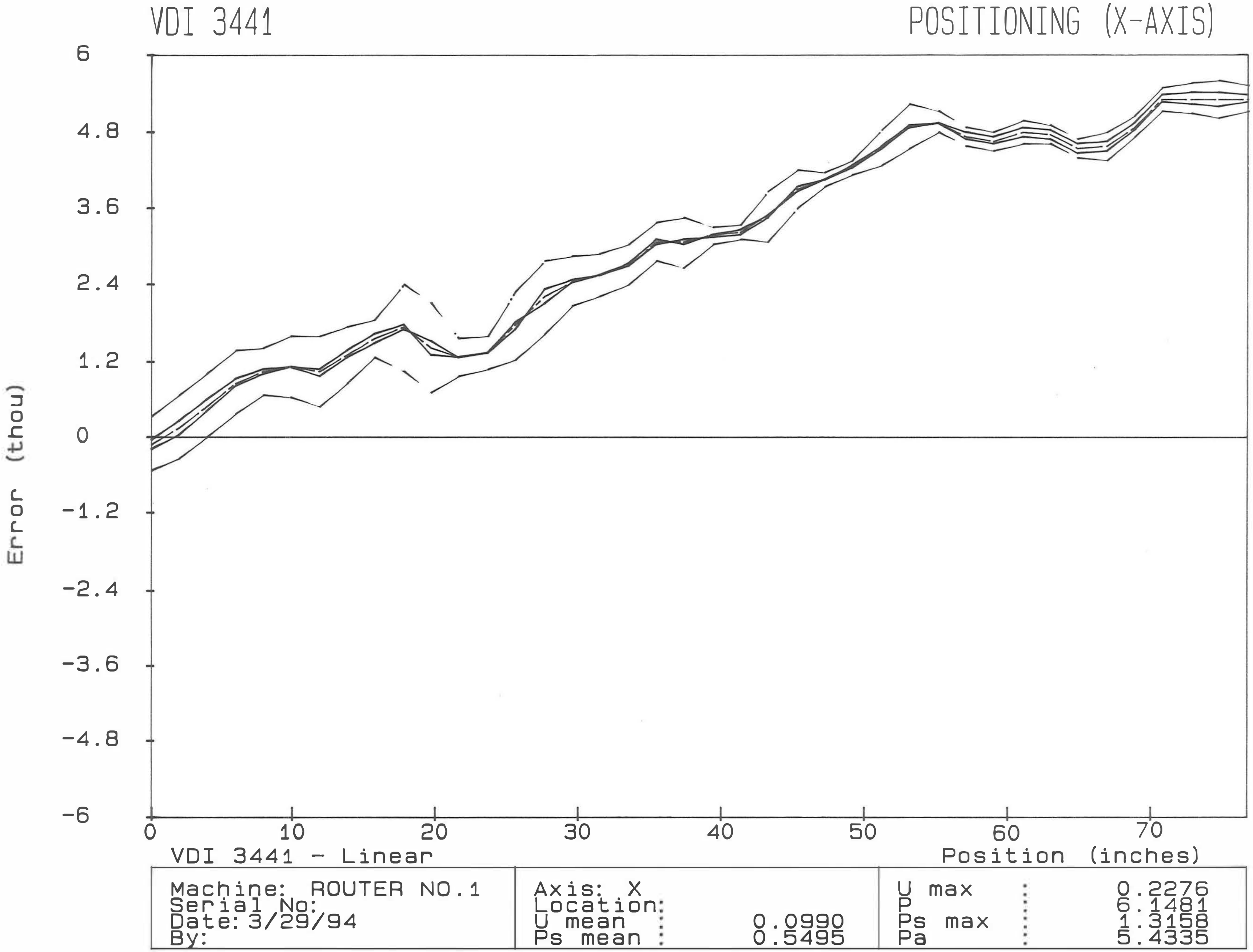


Figure 2.2—Results showing positioning accuracy in the X-axis as measured by laser system.

Step 1

The router controller is programmed to move the table/spindle in the Y-axis. If the ball screw has standard threads, the controller must be programmed to move the table/spindle 50 mm at a time. If the ball screw has metric threads, the controller must be programmed to move 2 inches at a time. With this movement, the ball screw will not be in the same rotational position for each positional measurement of the table/spindle. The table/spindle must travel the full extent of the Y-axis in 2-inch or 50-mm increments. However, provide at least 1 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the difference between the distance specified by the controller program and the distance actually moved. The program also must provide for bi-directional travel so that measurements can be taken in both the +Y and -Y directions. After the measurement is recorded for the last point in a given direction, move the spindle/table ahead 1 inch. Then reverse the direction of travel 1 inch to the final point for the first measurement in the other direction. Examples of these programs and their subroutines, titled LINEAR POSITIONING IN Y-AXIS for (STANDARD UNITS) and (METRIC UNITS), are shown in Figure A.1.1 of Appendix A.1.

Step 2

Set up the laser as instructed in the laser user's manual. Figure 2.3 shows an example of the laser optics setup. Assure that adjustments are made in the laser measurements for air temperature, barometric pressure, relative humidity, and thermal expansion of the ball screw material.

Step 3

Measure and record the difference between the controller instructed moves and the actual moves of the table/spindle in both directions in the Y-axis. Repeat this procedure for five full forward and reverse cycles.

Results—Plot a graph based on the German VDI 3441 standard showing the differences between the specified positions and the actual positions of the table/spindle travel in both the +Y and the -Y directions. In collecting data, the table was moved 50 mm at a time because the ball screws had standard threads. The error in positioning also was measured metric units. However, the software used to provide the analysis has the option of converting the data to standard units. Figure 2.4 is an example of the graph with representative statistics. The graph shows mean positional errors in both the positive and negative directions, the bi-directional mean positioning error, and the maximum "±3 sigma" repeatability bands from either direction of travel. See section 2.1.1 "X-axis Positioning" for a discussion of the data presented at the bottom of the graph.

2.1.3 Z-axis Positioning

Purpose—This procedure determines the ability of the router to accurately position a tool in the Z-axis in response to the machine controller and its program. Router construction affects positioning of which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the ability of the router's servo motor and ball screw to respond to the instructions from the controller.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring linear displacement. The optics include a beam splitter and two linear reflectors plus the hardware required for mounting them. The system must allow for environmental compensations for air temperature, barometric pressure, and relative humidity. It also should allow for adjustments to be made based on the temperature of the machine scale and the thermal expansion coefficient of the scale material. The scale in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

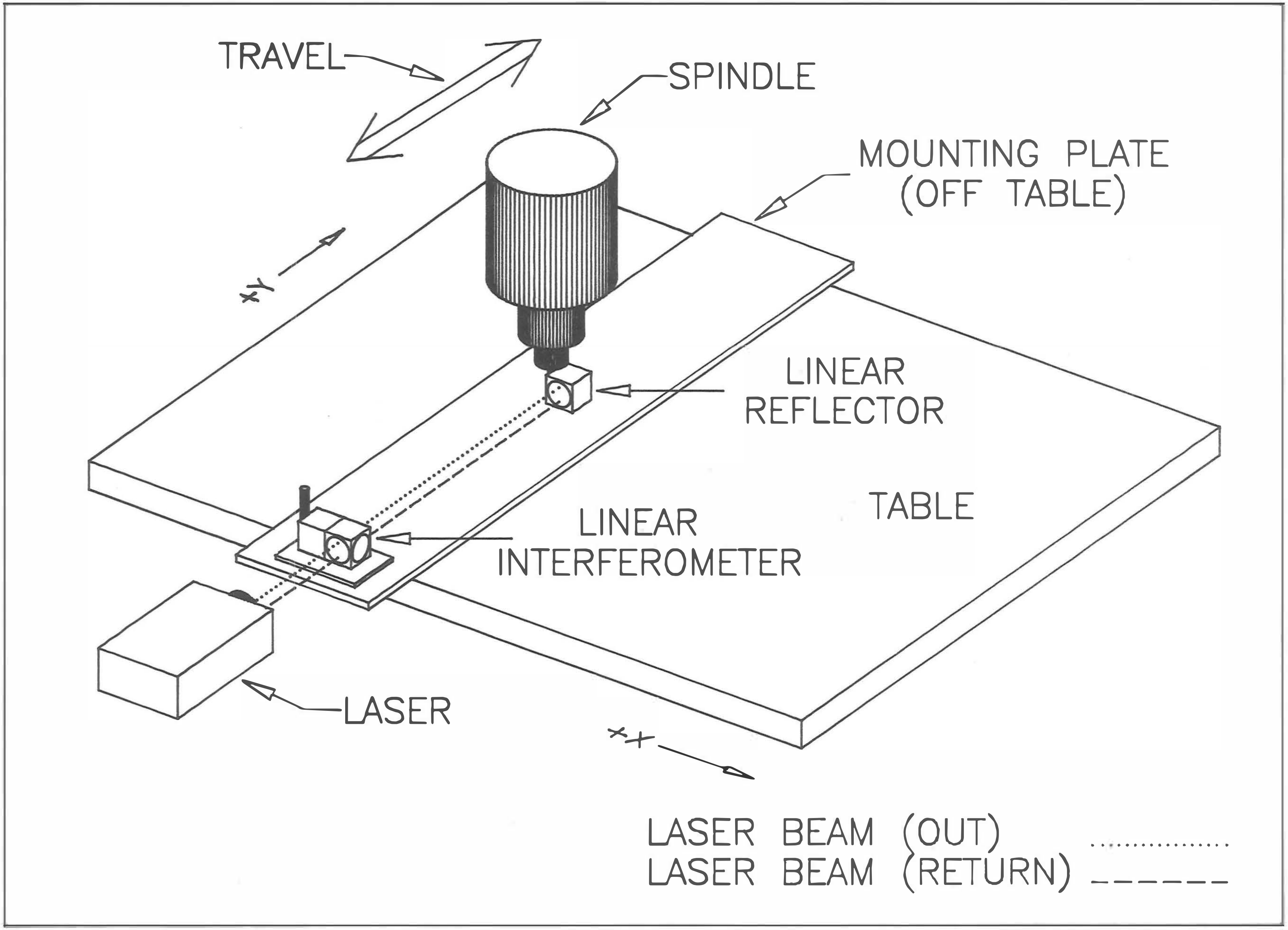
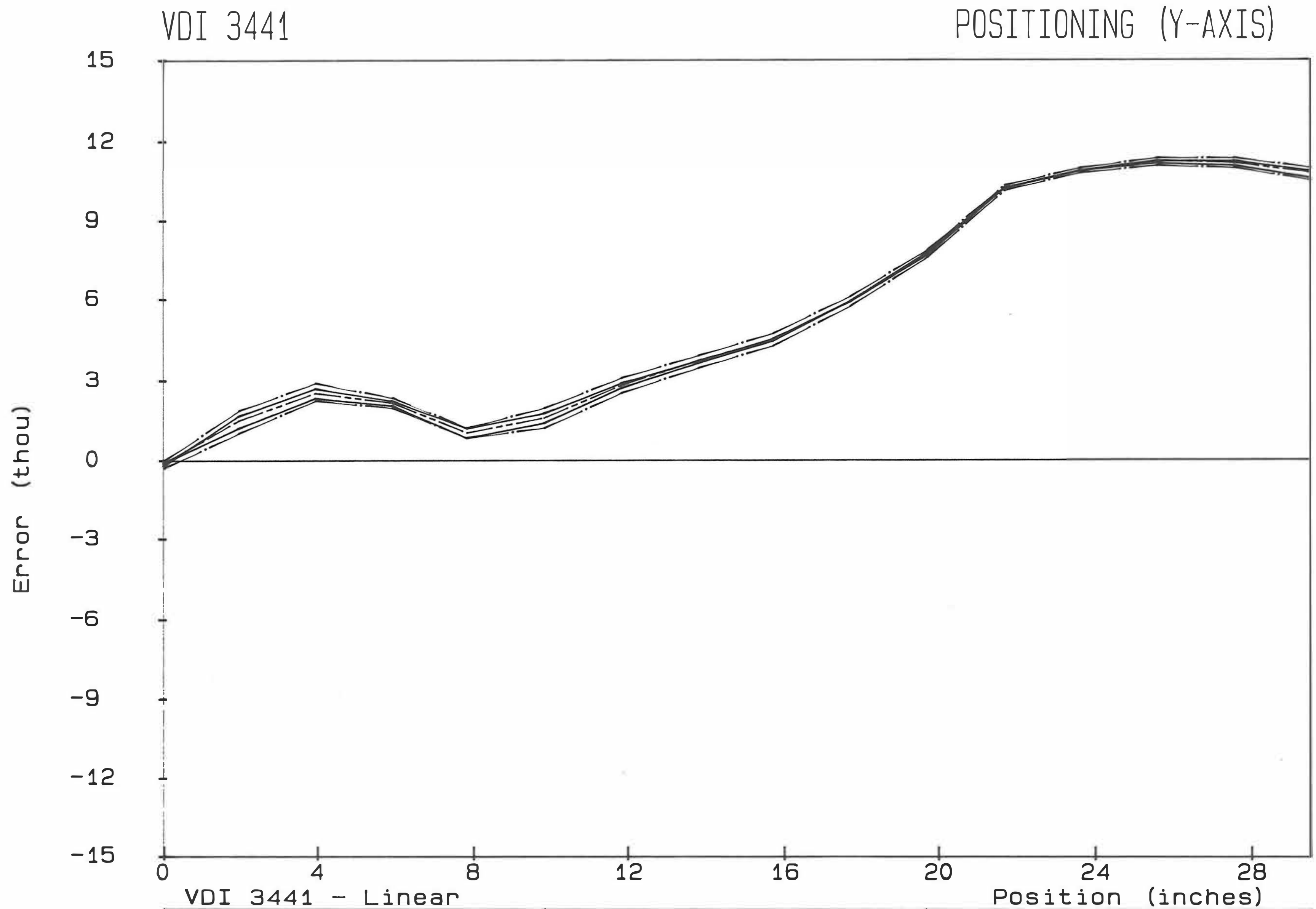


Figure 2.3—Laser setup for measuring positioning accuracy in the Y-axis.



Machine: ROUTER NO.1	Axis: Y		U max	:	0.4543
Serial No:	Location:		P	:	11.6831
Date: 3/29/94	U mean :	0.1672	Ps max	:	0.4437
By:	Ps mean :	0.2761	Pa	:	11.3362

Figure 2.4—Results showing positioning accuracy in the Y-axis as measured by laser system.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that controls the movement in the Z-axis should be exercised through at least 20 full cycles. This reduces the error in positioning that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1

The router controller is programmed to move the table/spindle in the Z-axis. If the ball screw has standard threads, the controller must be programmed to move the table/ spindle 6 mm at a time. If the ball screw has metric threads, the controller must be programmed to move 0.25 inch at a time. With this movement, the ball screw will not be in the same rotational position for each position measurement of the table/spindle. The table/spindle must travel the full extent of the Z-axis in 0.25-inch or 6 mm increments. However, provide at least 0.25 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the difference between the distance specified by the controller program and the distance actually moved. The program also must provide for bi-directional travel so that measurements can be taken in both the +Z and -Z directions. After the measurement is recorded for the last point in a given direction, move the spindle/table ahead 0.25 inch. Then reverse the direction of travel 0.25 inch to the final point for the first measurement in the other direction. Examples of these programs and their subroutines, titled LINEAR POSITIONING IN Z-AXIS for (STANDARD UNITS) and (METRIC UNITS), are shown in Figure A.1.1 of Appendix A.1.

Step 2

Set up the laser as instructed in the laser user's manual. Figure 2.5 shows an example of the laser optics setup. Assure that adjustments are made in the laser measurements for air temperature, barometric pressure, relative humidity, and thermal expansion of the ball screw material.

Step 3

Measure and record the difference between the controller instructed moves and the actual moves of the table/spindle in both directions in the Z-axis. Repeat this procedure for five full forward and reverse cycles.

Results—Plot a graph based on the German VDI 3441 standard showing the differences between the specified positions and the actual positions of the table/spindle travel in both the +Z and the -Z directions. In collecting data, the table was moved 6 mm at a time because the ball screws had standard threads. The error in positioning also was measured in metric units. However, the software used to provide the analysis has the option of converting the data to standard units. Figure 2.6 is an example of the graph with representative statistics. The graph shows mean positional errors in both the positive and negative directions, the bi-directional mean positioning error, and the maximum "±3 sigma" repeatability bands from either direction of travel. See section 2.1.1 "X-axis Positioning" for a discussion of the data presented at the bottom of the graphic plot.

2.2 Feed Rate Accuracy

2.2.1 X-axis Feed Rate Accuracy

Purpose—This procedure determines the ability of the router to provide accurate tool feed rates in the X-axis as set by the machine controller and its program. Router construction affects the feed, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the ability of the router's servo motor and ball screw to respond to the instructions from the controller.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring linear velocity. The optics (same as those used for linear displacement) include a beam splitter and two linear reflectors plus the hardware required for mounting them. The

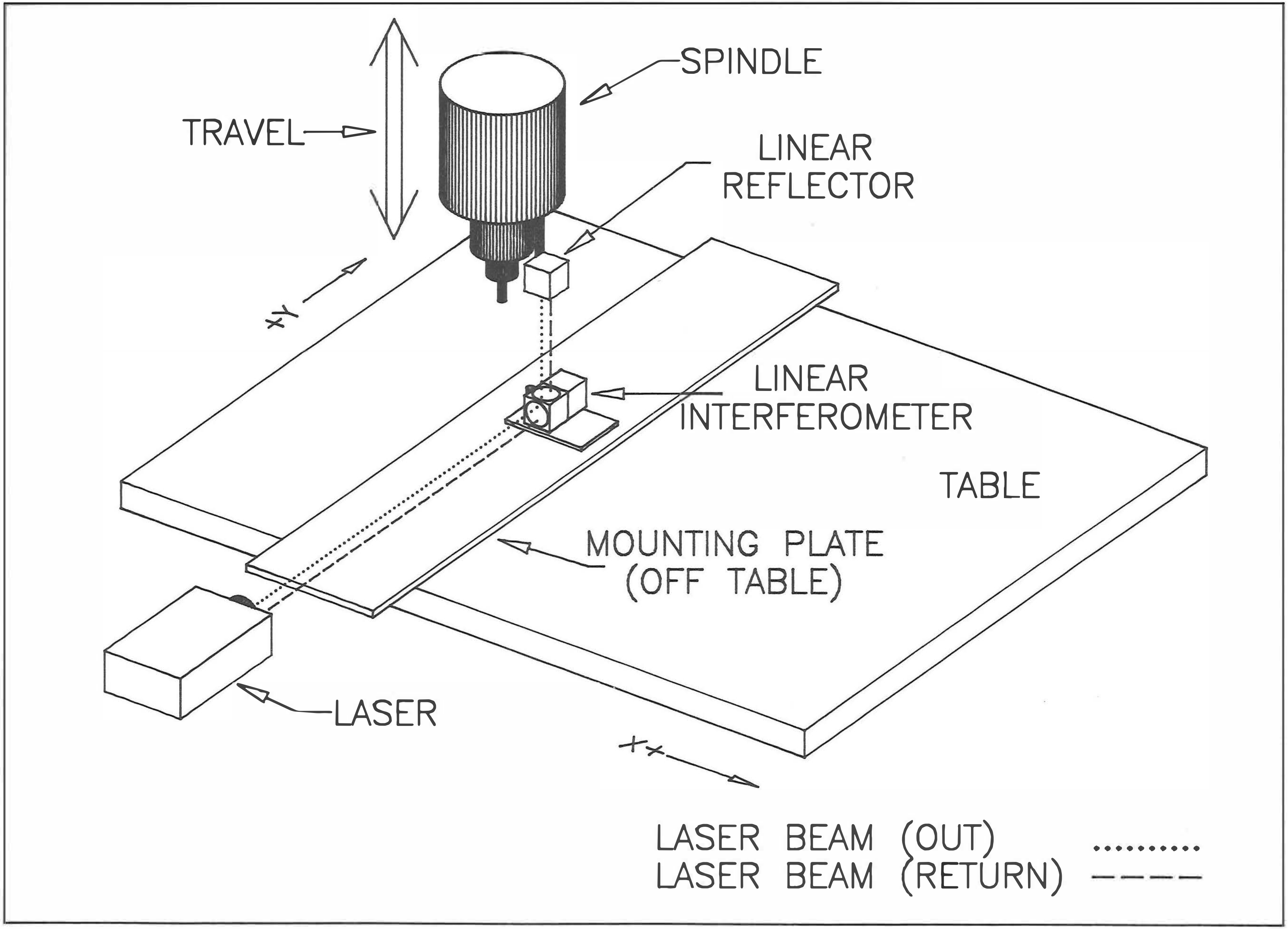


Figure 2.5—Laser setup for measuring positioning accuracy in the Z-axis.

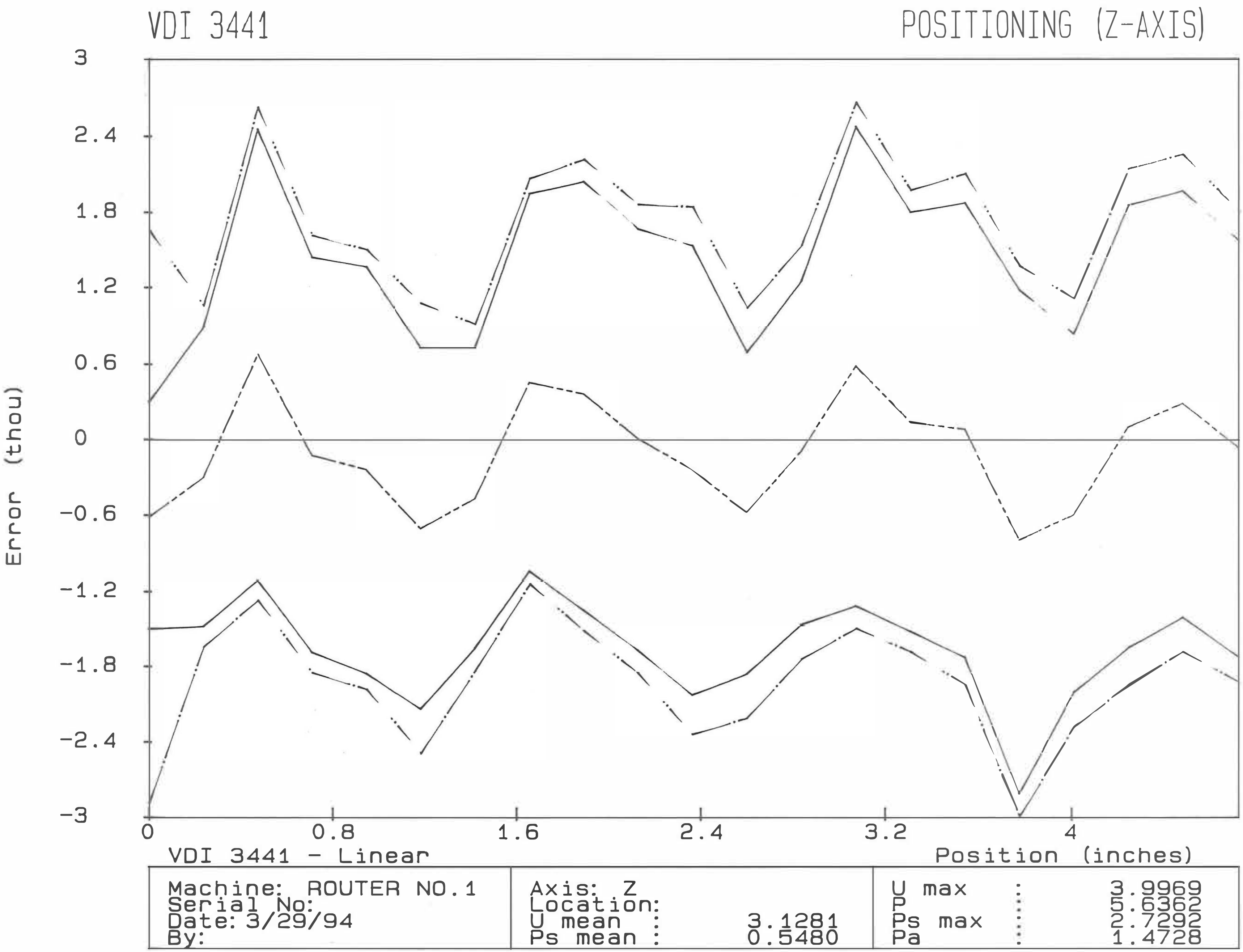


Figure 2.6—Results showing positioning accuracy in the Z-axis as measured by laser system.

system must allow for environmental compensations for air temperature, barometric pressure, and relative humidity. It also should allow for adjustments to be made based on the temperature of the machine scale and the thermal expansion coefficient of the scale material. The scale in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that controls the movement in the X-axis should be exercised through at least 20 full cycles. This is done so that measurements are not taken on a cold servo motor and ball screw. Once this is done, use the following steps.

Step 1

Develop a program for the controller that moves the table/spindle the full length of travel in the X-axis at a feed rate of 50 inches per minute and then returns to the start position. Have the program repeat this procedure for feed rate increments of 50 inches per minute (that is, 100, 150, and so on) until the maximum X-axis feed rate is reached. An example of this program and its subroutine, titled SAMPLE FEED RATE PROGRAMS (X-AXIS), is shown in Figure A.2.1 of Appendix A.2.

Step 2

Set up and align the laser as instructed in the laser user's manual. Figure 2.7 shows an example of the laser optics setup. The laser is aligned down the middle of the table in the X-axis. Assure that adjustments are made for air temperature, barometric pressure, relative humidity, and thermal expansion of the ball screw material.

Step 3

Run the controller program and record the laser measured feed rate at the midpoint of table/spindle travel for each feed rate set up in the controller program.

Result—Plot a graph of the differences between the specified feed rate and the actual feed rate of the table/spindle travel. Figure 2.8 shows an example of such a plot.

2.2.2 Y-axis Feed Rate Accuracy

Purpose—This procedure determines the ability of the router to provide accurate tool feed rates in the Y-axis as set by the machine controller and its program. Router construction affects the feed which may be as a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the ability of the router's servo motor and ball screw to respond to the instructions from the controller.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring linear velocity. The optics (same as those used for linear displacement) include a beam splitter and two linear reflectors plus the hardware required for mounting them. The system must allow for environmental compensations for air temperature, barometric pressure, and relative humidity. It also should allow for adjustments to be made based on the temperature of the machine scale and the thermal expansion coefficient of the scale material. The scale in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

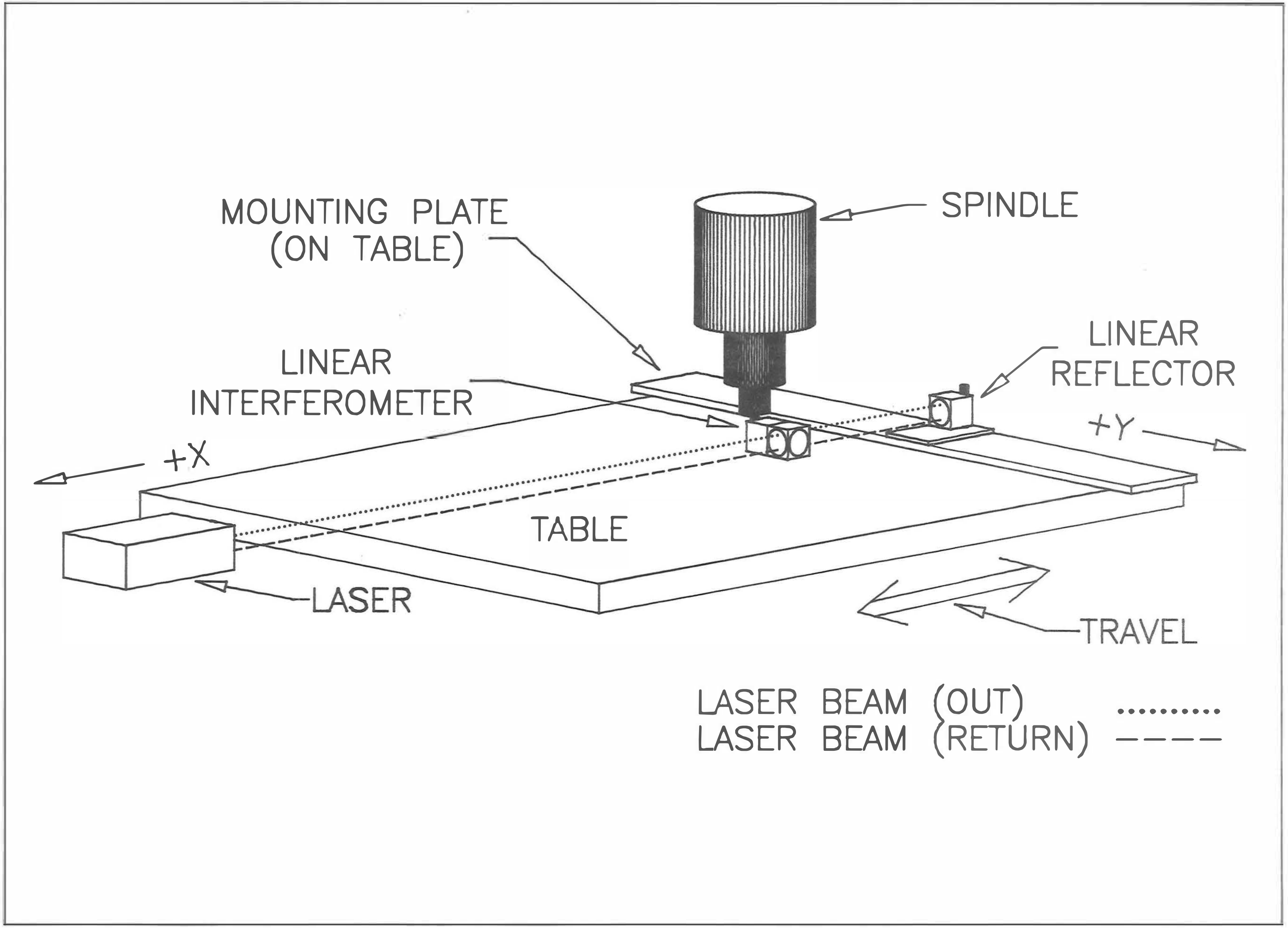


Figure 2.7—Laser setup for measuring feed rate accuracy in the X-axis.

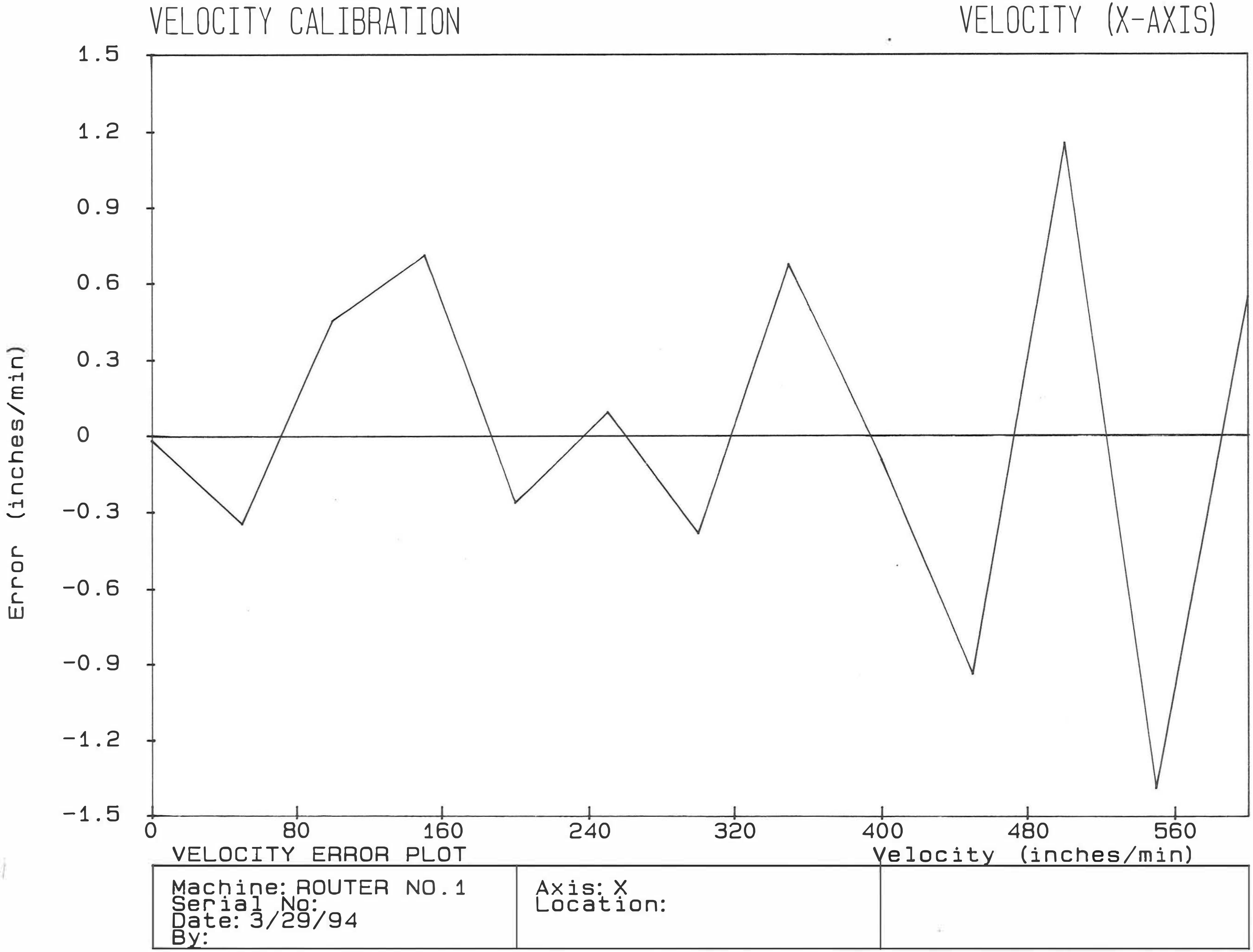


Figure 2.8—Results showing feed rate accuracy in the X-axis as measured by laser system.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that controls the movement in the Y-axis should be exercised through at least 20 full cycles. This is done so that measurements are not taken on a cold servo motor and ball screw. Once this is done, use the following steps.

Step 1
Develop a program for the controller that moves the table/spindle the full length of travel in the Y-axis at a feed rate of 50 inches per minute and then returns to the start position. Have the program repeat this procedure for feed rate increments of 50 inches per minute (that is, 100, 150, and so on) until the maximum Y-axis feed rate is reached. An example of this program and its subroutine, titled SAMPLE FEED RATE PROGRAMS (Y-AXIS), is shown in Figure A.2.1 of Appendix A.2.

Step 2
Set up and align the laser as instructed in the laser user's manual. Figure 2.9 shows an example of the laser optics setup. Assure that adjustments are made for air temperature, barometric pressure, relative humidity, and thermal expansion of the ball screw material.

Step 3
Run the controller program and record the laser measured feed rate at the midpoint of table/spindle travel for each feed rate set up in the controller program.

Results—Plot a graph of the differences between the specified feed rate and the actual feed rate of the table/spindle travel. Figure 2.10 shows an example of such a plot.

2.2.3 Z-axis Feed Rate Accuracy

Purpose—This procedure determines the ability of the router to provide accurate tool feed rates in the Z-axis as set by the machine controller and its program. Router construction affects the feed, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the ability of the router's servo motor and ball screw to respond to the instructions from the controller.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring linear velocity. The optics (same as those used for linear displacement) include a beam splitter and two linear reflectors plus the hardware required for mounting them. The system must allow for environmental compensations for air temperature, barometric pressure, and relative humidity. It also should allow for adjustments to be made based on the temperature of the machine scale and the thermal expansion coefficient of the scale material. The scale in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

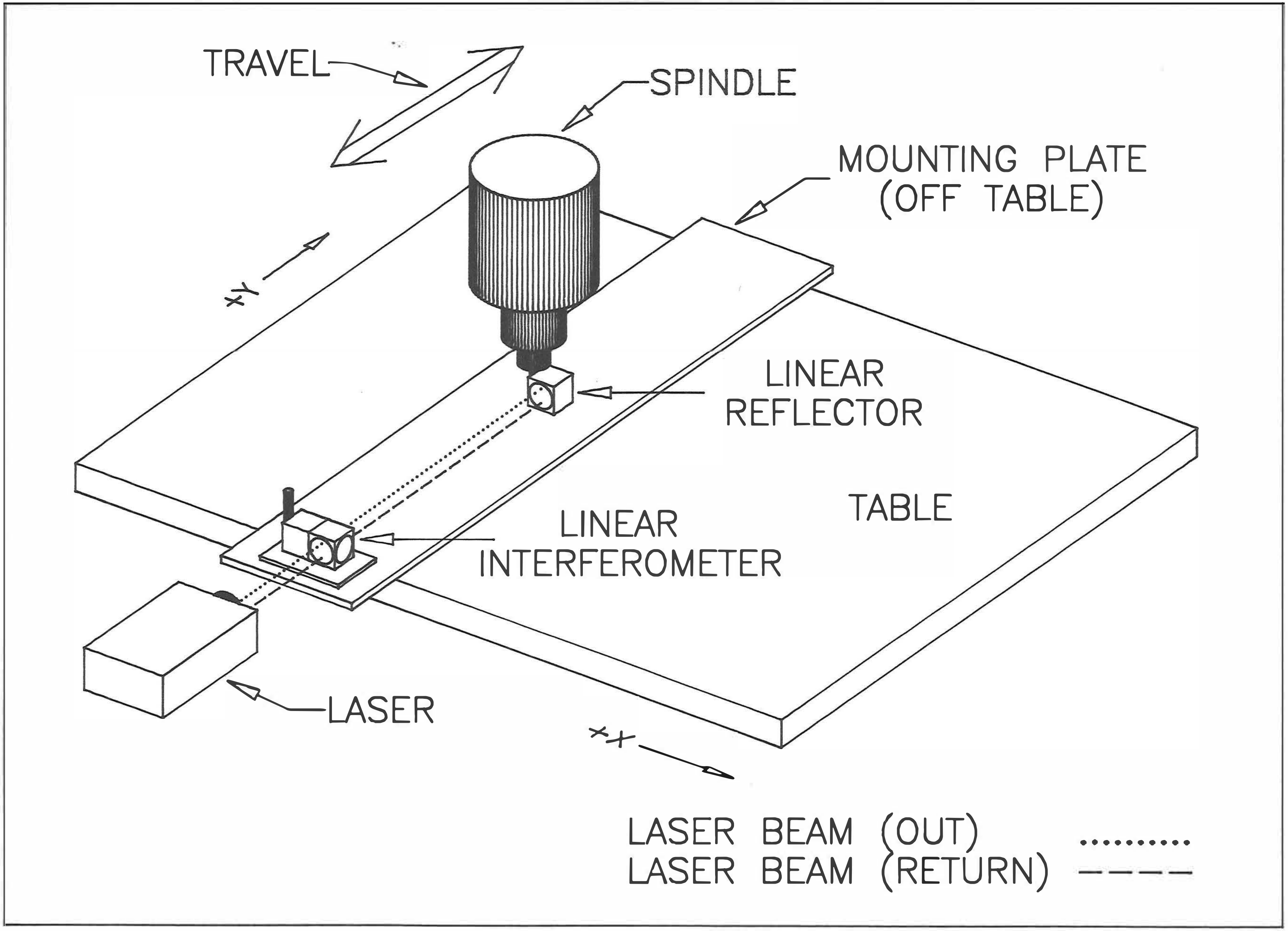


Figure 2.9—Laser setup for measuring feed rate accuracy in the Y-axis.

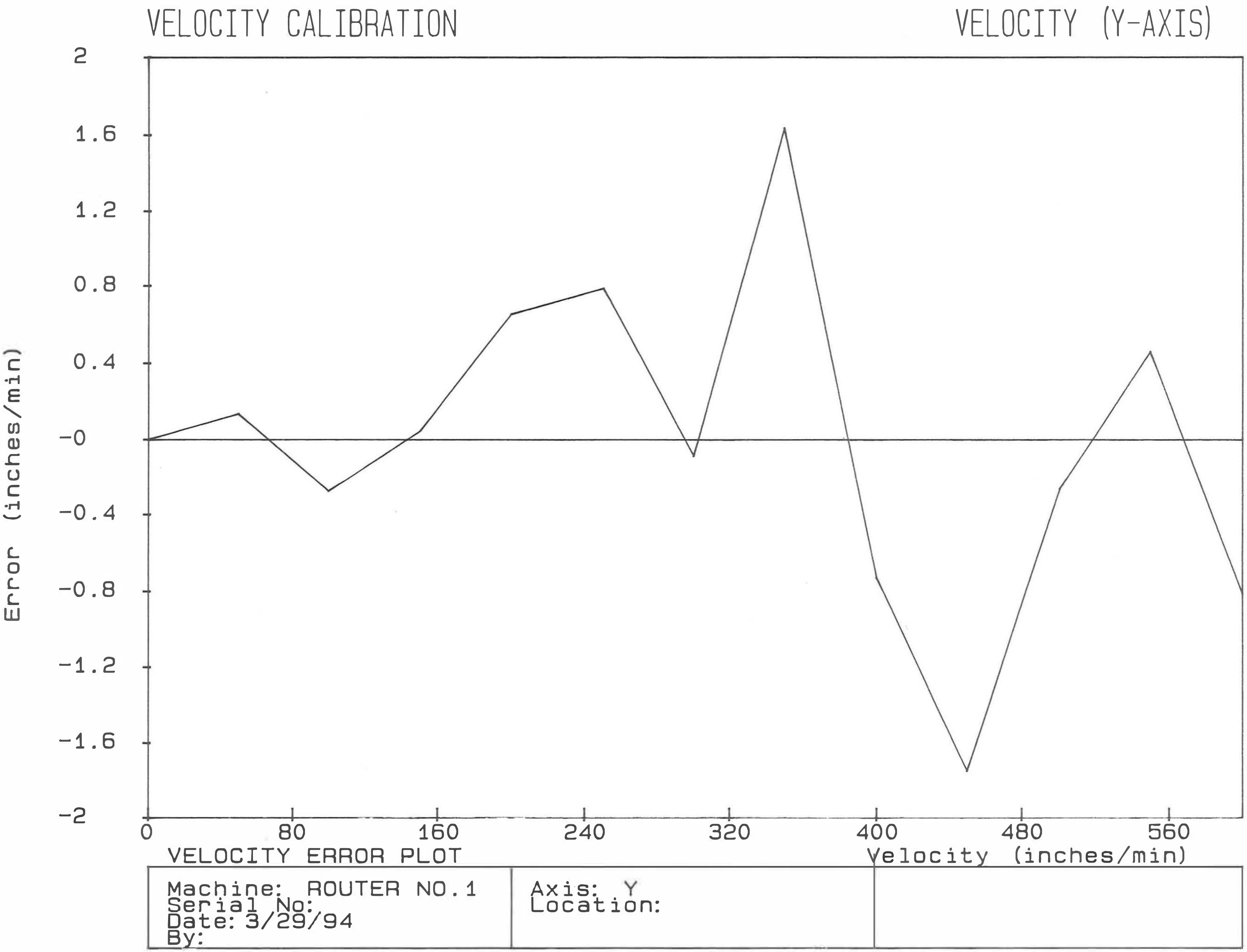


Figure 2.10—Results showing feed rate accuracy in the Y-axis as measured by laser system.

Method—Before beginning this evaluation, the servo motor and ball screw that controls the movement in the Z-axis should be exercised through at least 20 full cycles. This is done so that measurements are not taken on a cold servo motor and ball screw. Once this is done, use the following steps.

Step 1
Develop a program for the controller that moves the table/spindle the full length of travel in the Z-axis at a feed rate of 50 inches per minute and then returns to the start position. Have the program repeat this procedure for feed rate increments of 50 inches per minutes (that is, 100, 150, and so on) until the maximum Z-axis feed rate is reached. An example of this program and its subroutine, titled SAMPLE FEED RATE PROGRAMS (Z-AXIS), is shown in Figure A.2.1 of Appendix A.2.

Step 2
Set up and align the laser as instructed in the laser user's manual. Figure 2.11 shows an example of the laser optics setup. Assure that adjustments are made for air temperature, barometric pressure, relative humidity, and thermal expansion of the ball screw material.

Step 3
Run the controller program and record the laser measured feed rate at the midpoint of table/spindle travel for each feed rate set up in the controller program.

Results—Plot a graph of the differences between the specified feed rate and the actual feed rate of the table/spindle travel. Figure 2.12 shows an example of such a plot.

2.3 Straightness

2.3.1 X-axis Straightness (Horizontal & Vertical Planes)

Purpose—This procedure determines the ability of the router to move a cutting tool in a straight line when moving in both the horizontal and vertical planes of the X-axis. Router construction affects the movement, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the straightness and alignment of the ways used to guide the table/spindle.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring linear straightness. The optics include a straightness interferometer and straightness reflector plus the hardware required for mounting them. It is not necessary to make environmental compensations for air temperature, barometric pressure, and relative humidity. However, follow the recommendations of the laser manufacturer concerning air turbulence, heaters, and air fans. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that controls the movement in the X-axis should be exercised through at least 20 full cycles. This reduces the error in positioning for data collection that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

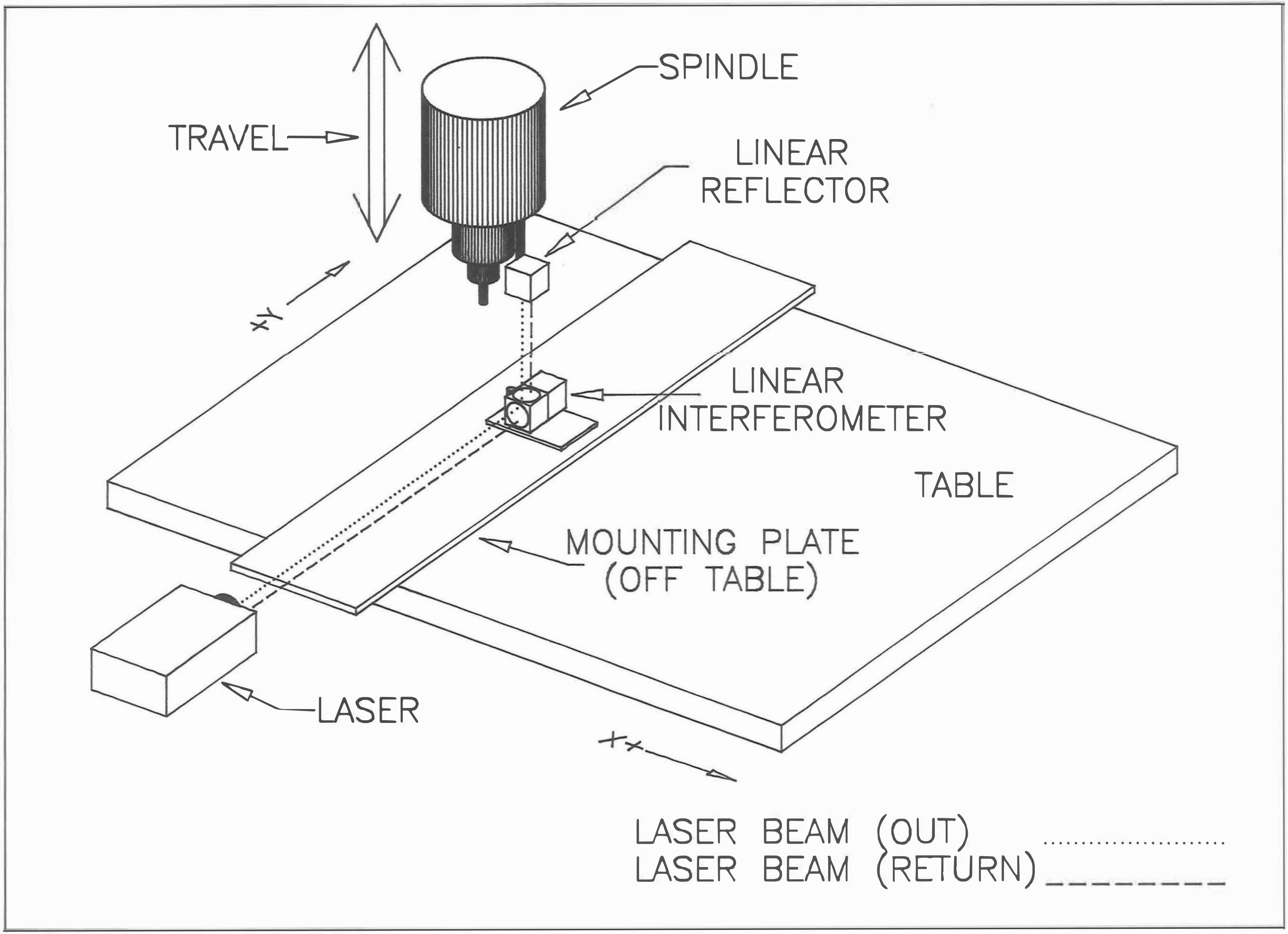


Figure 2.11—Laser setup for measuring feed rate accuracy in the Z-axis.

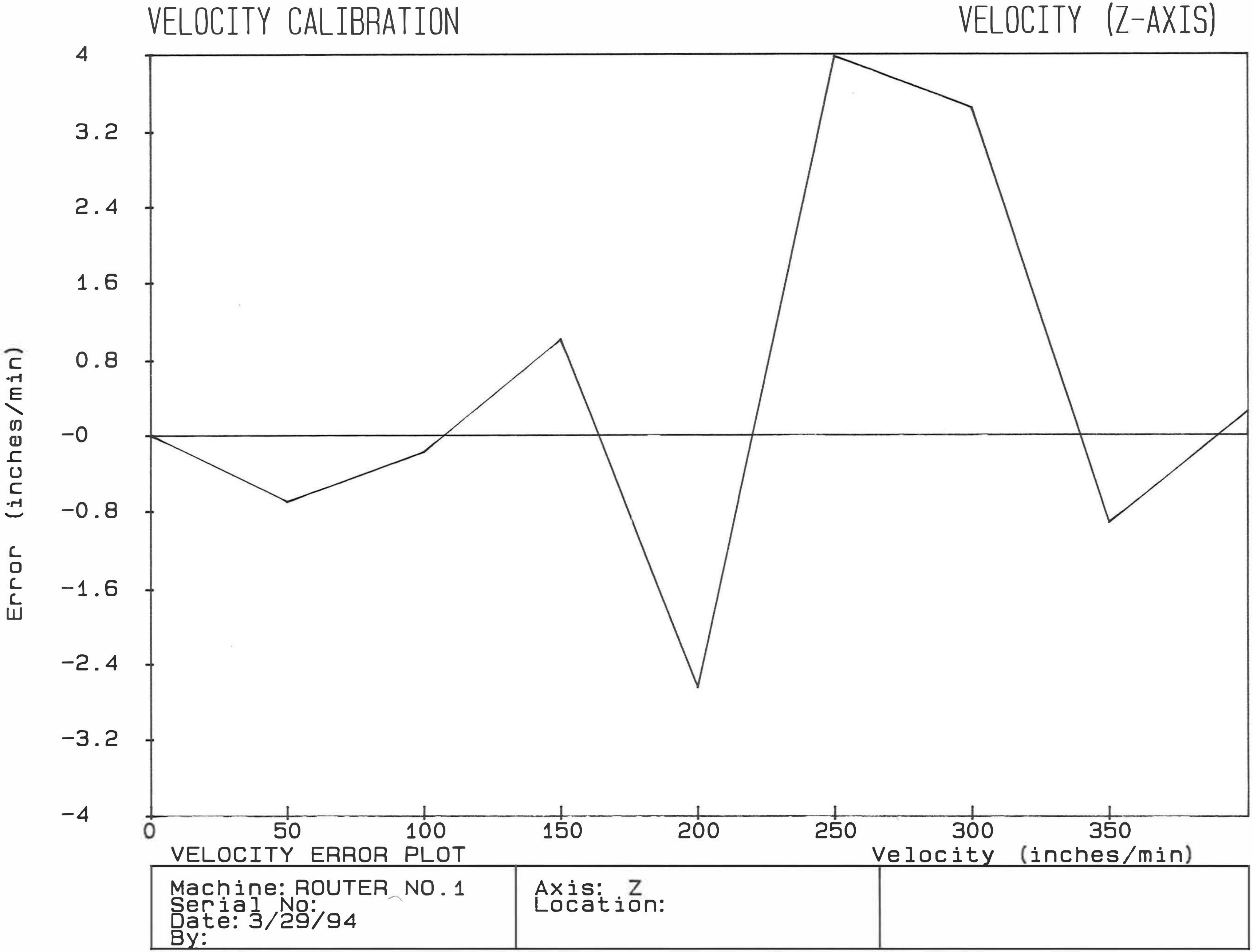


Figure 2.12—Results showing feed rate accuracy in the Z-axis as measured by laser system.

Step 1

Develop a program for the controller that moves the table/spindle the full length of the X-axis in 2-inch increments. However, provide at least 1 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the deviation in straightness of travel. The program also must provide for bi-directional travel so that measurements can be taken in both the +X and -X directions. After the measurement is recorded for the last point in a given direction, move the spindle/table ahead 1 inch. Then reverse the direction of travel 1 inch to the final point for the first measurement in the other direction. An example of this program and its subroutines, titled LINEAR POSITIONING IN X-AXIS (STANDARD UNITS), is shown in Figure A.1.1 of Appendix A.1.

Step 2

Set up and align the laser for determining straightness in the horizontal plane as shown in Figure 2.13. The laser is aligned down the middle of the table in the X-axis. Be sure to follow the instructions in the laser user's manual concerning air turbulence, heaters, and air fans.

Step 3

Measure and record the deviation in straightness of travel at the start point and at the end of each 2-inch move in both the +X and the -X directions. Repeat this procedure for five full forward and reverse cycles.

Step 4

Move the straightness interferometer to the -X end of the table as shown in Figure 2.14 and repeat Step 3.

Step 5

Repeat Steps 2, 3, and 4 with the laser set up for determining straightness of travel in the vertical plane as shown in Figures 2.15 and 2.16.

Results—Plot graphs based on the British Standard (BS 4656, Part 16) showing least-squares fits of the straightness errors in table/spindle travel for both the +X and the -X directions. These plots are provided for straightness errors in both the horizontal and vertical planes. Figures 2.17 and 2.18 show examples of the plots and representative statistics for straightness in the horizontal plane with the straightness interferometer positioned at both the +X and -X ends of the table. Figures 2.19 and 2.20 show examples of the plots and representative statistics for straightness in the vertical plane with the straightness interferometer positioned at both the +X and -X ends of the table. These outputs indicate the straightness of the ways for the entire length of travel. The first two plots show the mean straightness errors in both the positive and negative directions along with the "±3 sigma" repeatability bands. The third plot shows both the positive and negative mean straightness errors along with the combined repeatability bands. A discussion of the data presented at the bottom of the graph follows:

- Accuracy is the difference between the maximum and minimum values of the mean plus 3 standard deviations and the mean minus 3 standard deviations, respectively, regardless of travel direction.
- Uni-directional Repeatability (Uni-dir. Rep) is the maximum value of the difference between the mean plus 3 standard deviations and the mean minus 3 standard deviations at any given point, within either direction of travel.
- Bi-directional Repeatability (Bi-dir. Rep) is the maximum value of the difference between the mean plus 3 standard deviations and the mean minus 3 standard deviations at any given point, within both directions of travel. The two maximum values can be taken from different directions of travel.
- Mean Reversal Error (Mean rev) is the mean value of the differences between the mean straightness errors for the two directions of travel.

Text continues on page 53

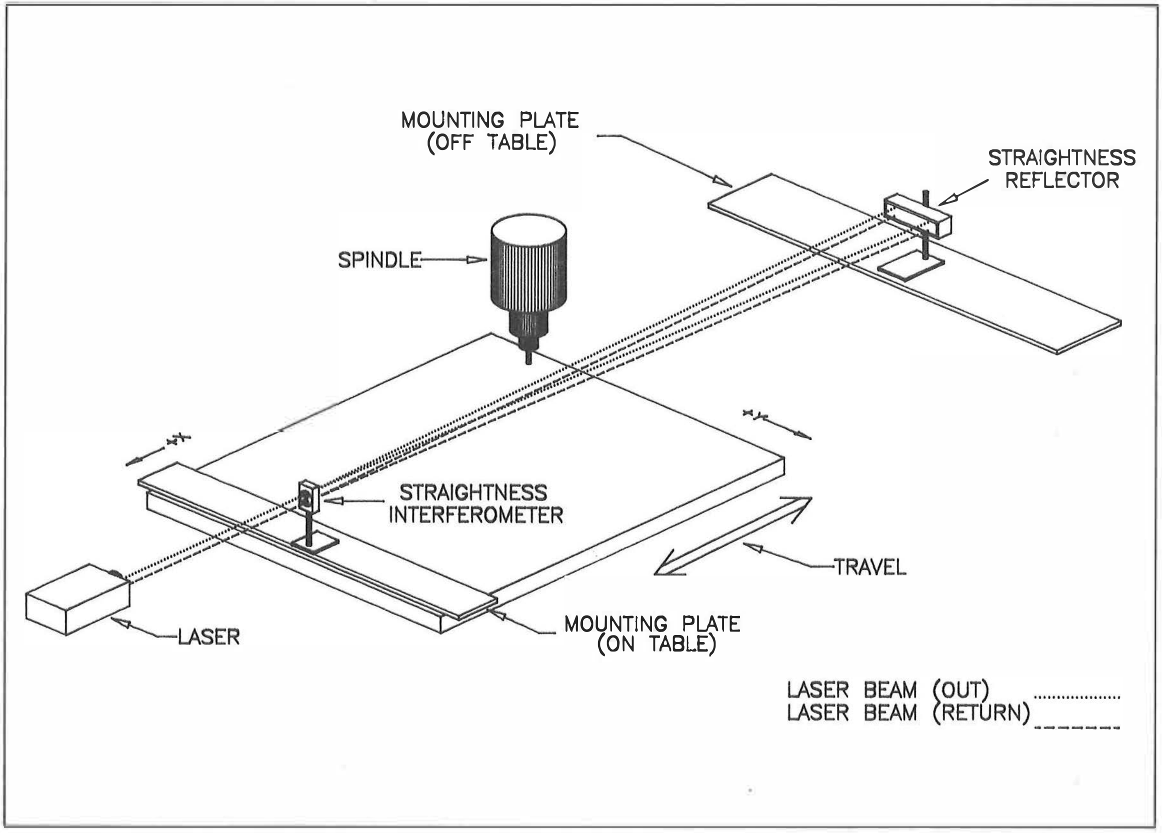


Figure 2.13—Laser setup for measuring horizontal straightness in the X-axis travel with straightness interferometer at the +X end of table.

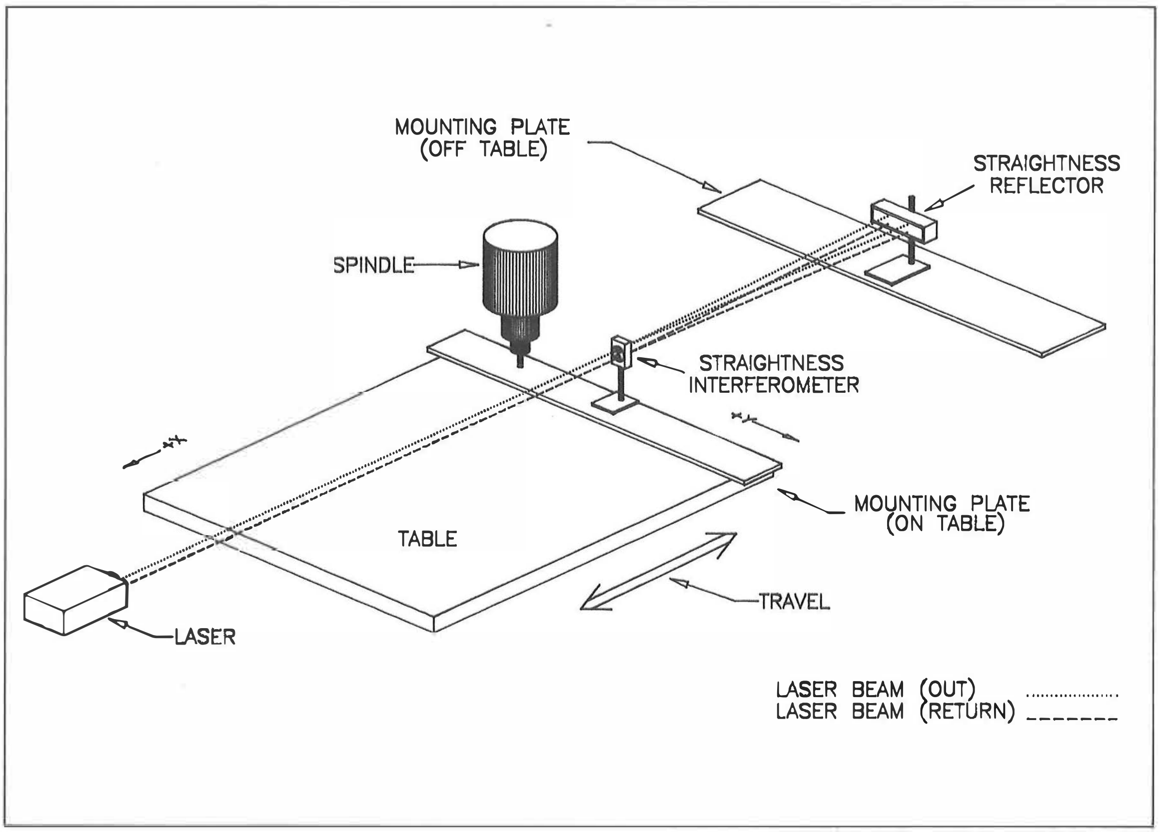


Figure 2.14—Laser setup for measuring horizontal straightness in the X-axis travel with straightness interferometer at the -X end of table.

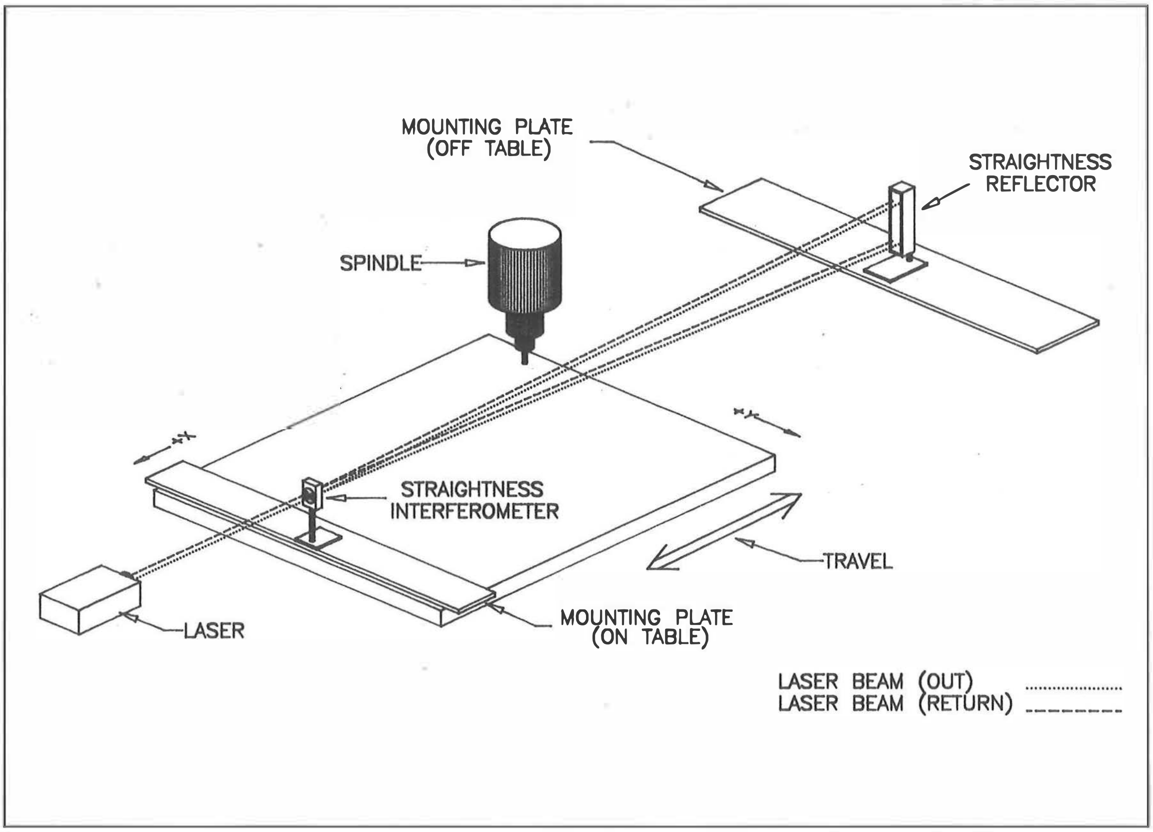


Figure 2.15—Laser setup for measuring vertical straightness in the X-axis travel with straightness interferometer at the +X end of table.

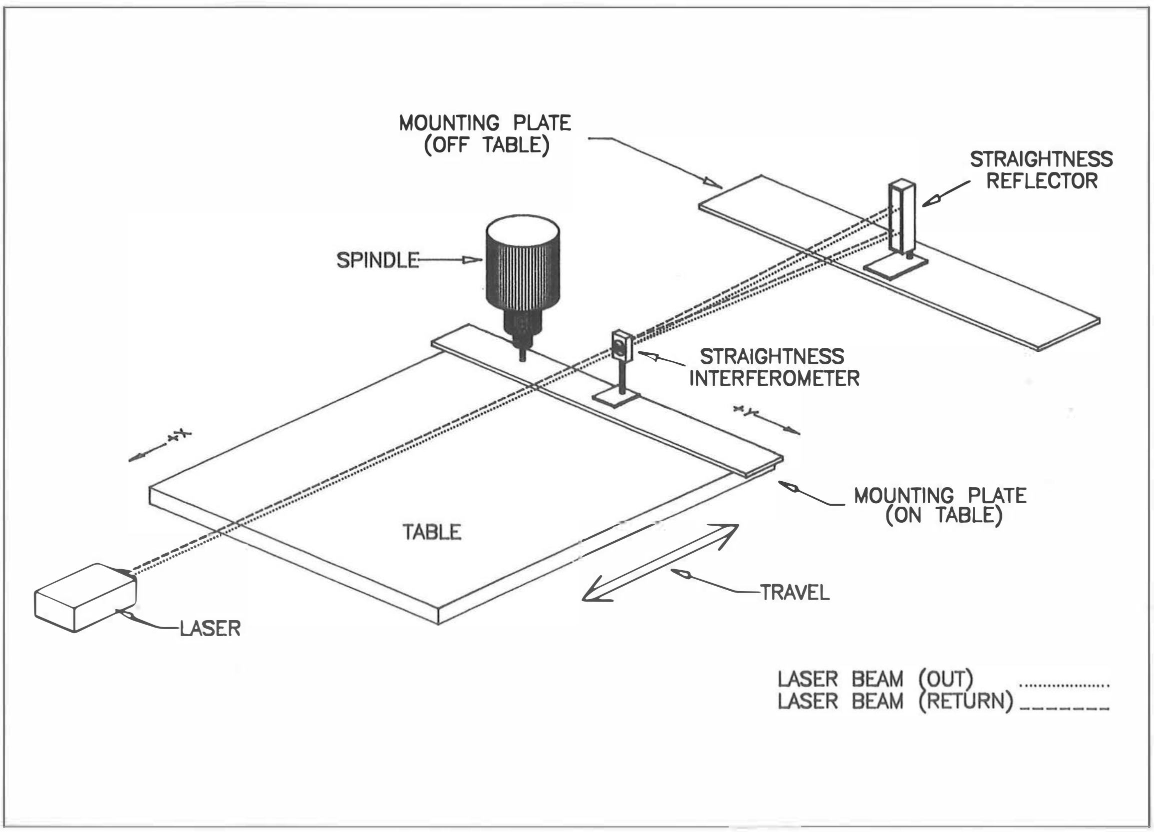
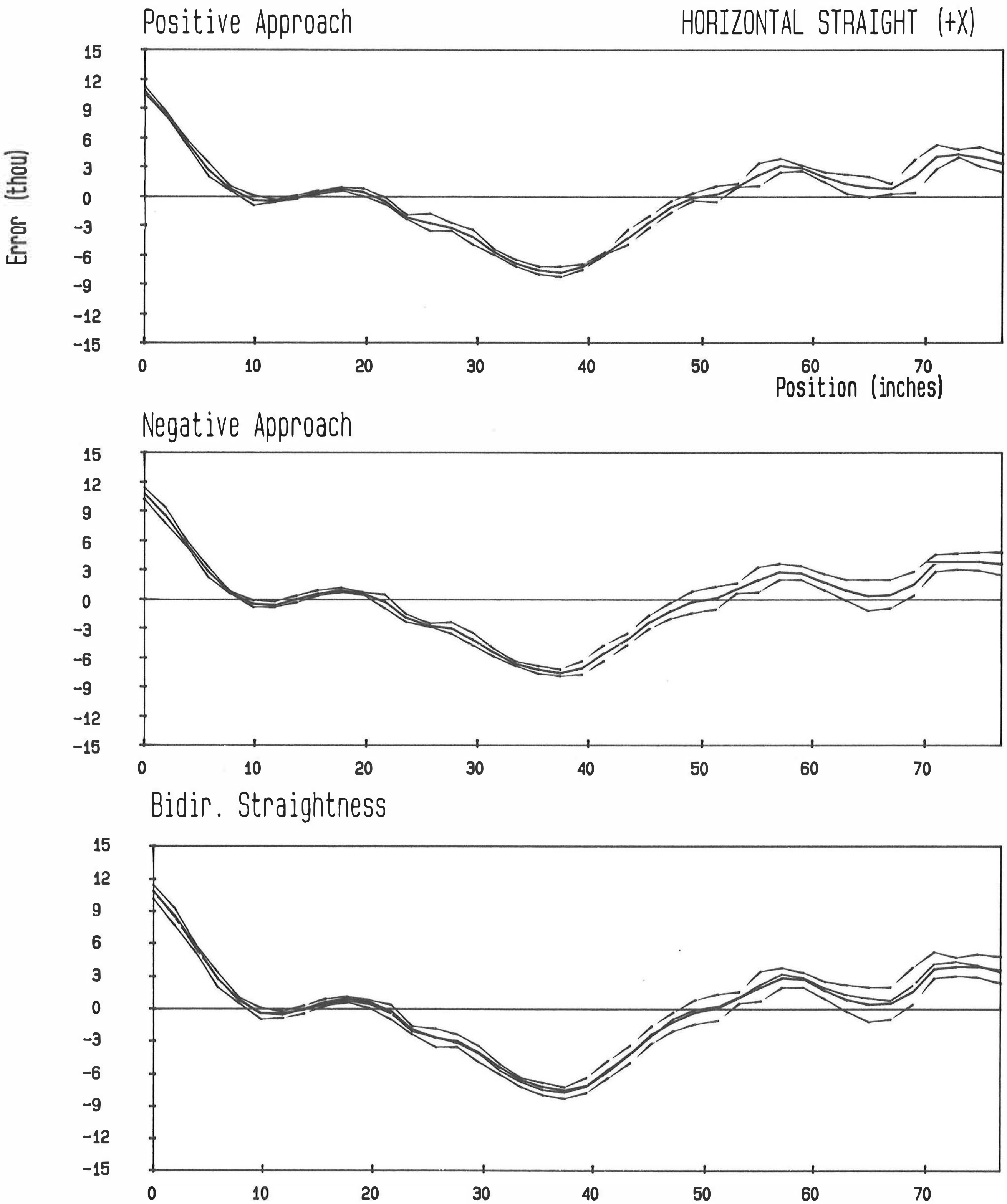
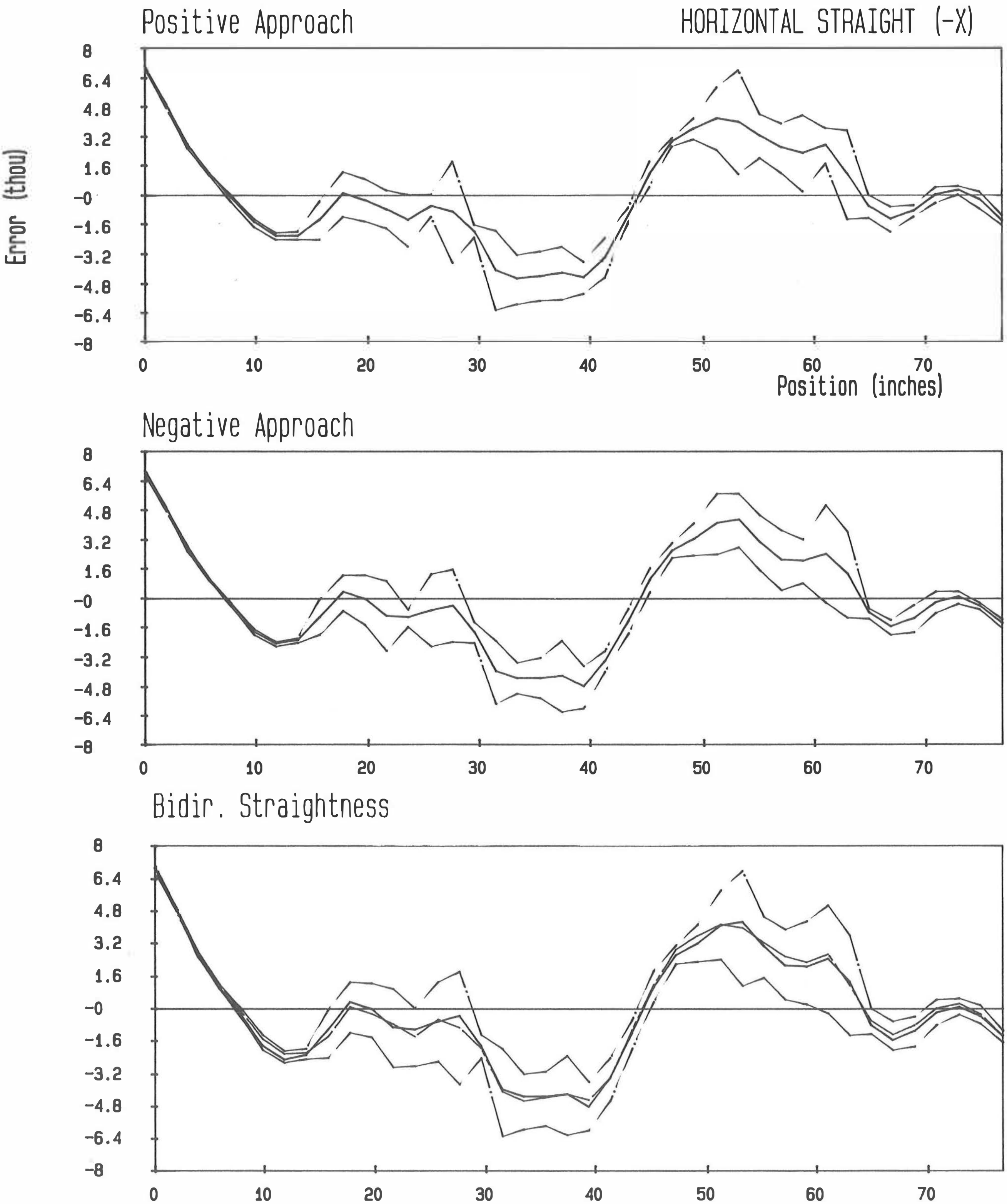


Figure 2.16—Laser setup for measuring vertical straightness in the X-axis travel with straightness interferometer at the -X end of table.



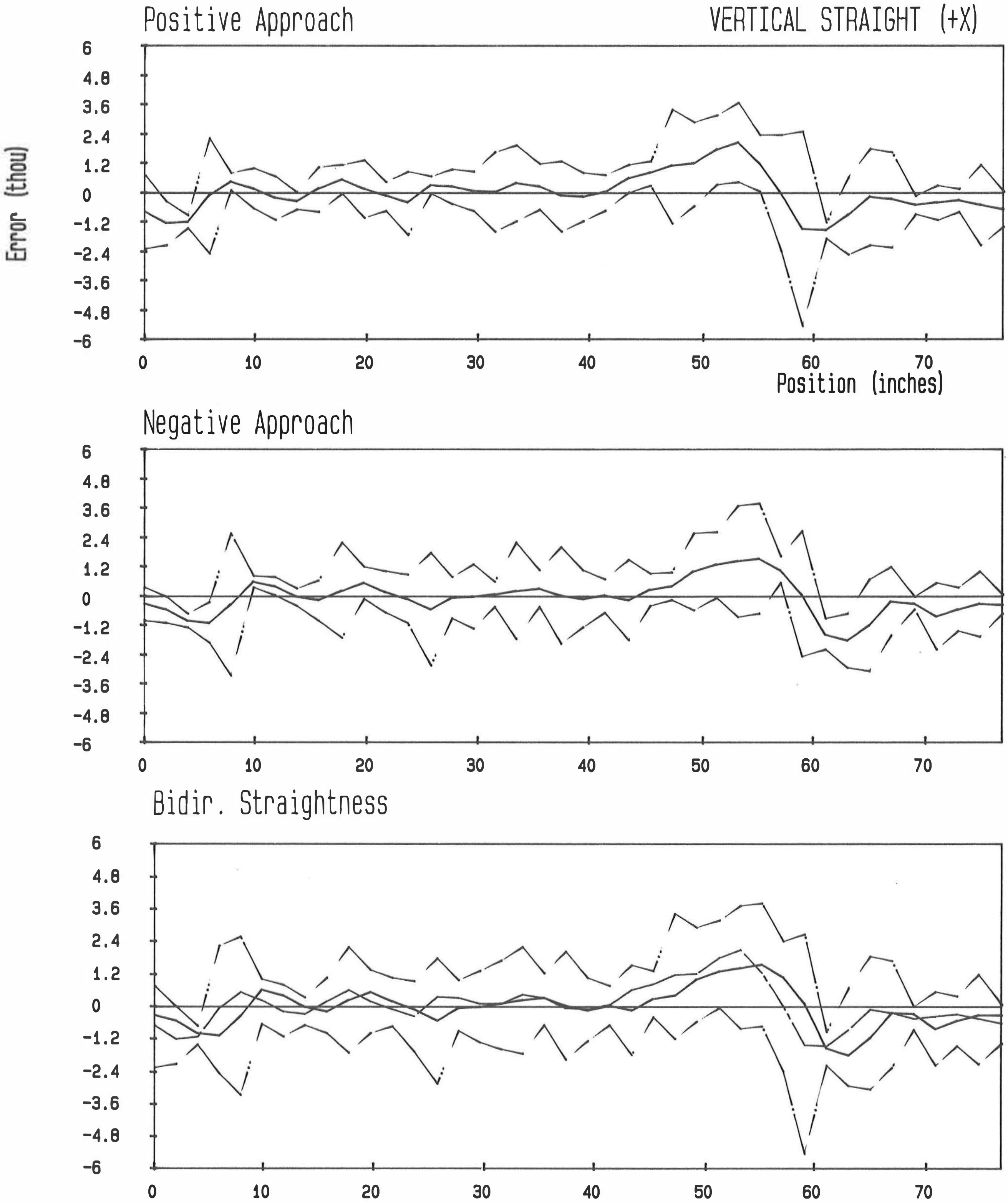
Machine: ROUTER NO.1	Axis: X	Accuracy: 19.6924
Serial No:	Location: +X END	Uni-dir. Rep: 3.4048
Date: 3/29/94	Slope: 21.48 ARCSEC	Bi-dir. Rep: 3.4099
By:	Str. Error : 18.5760	Mean rev: 0.0242

Figure 2.17—Results showing horizontal straightness in the X-axis travel with the straightness interferometer at the +X end of table.



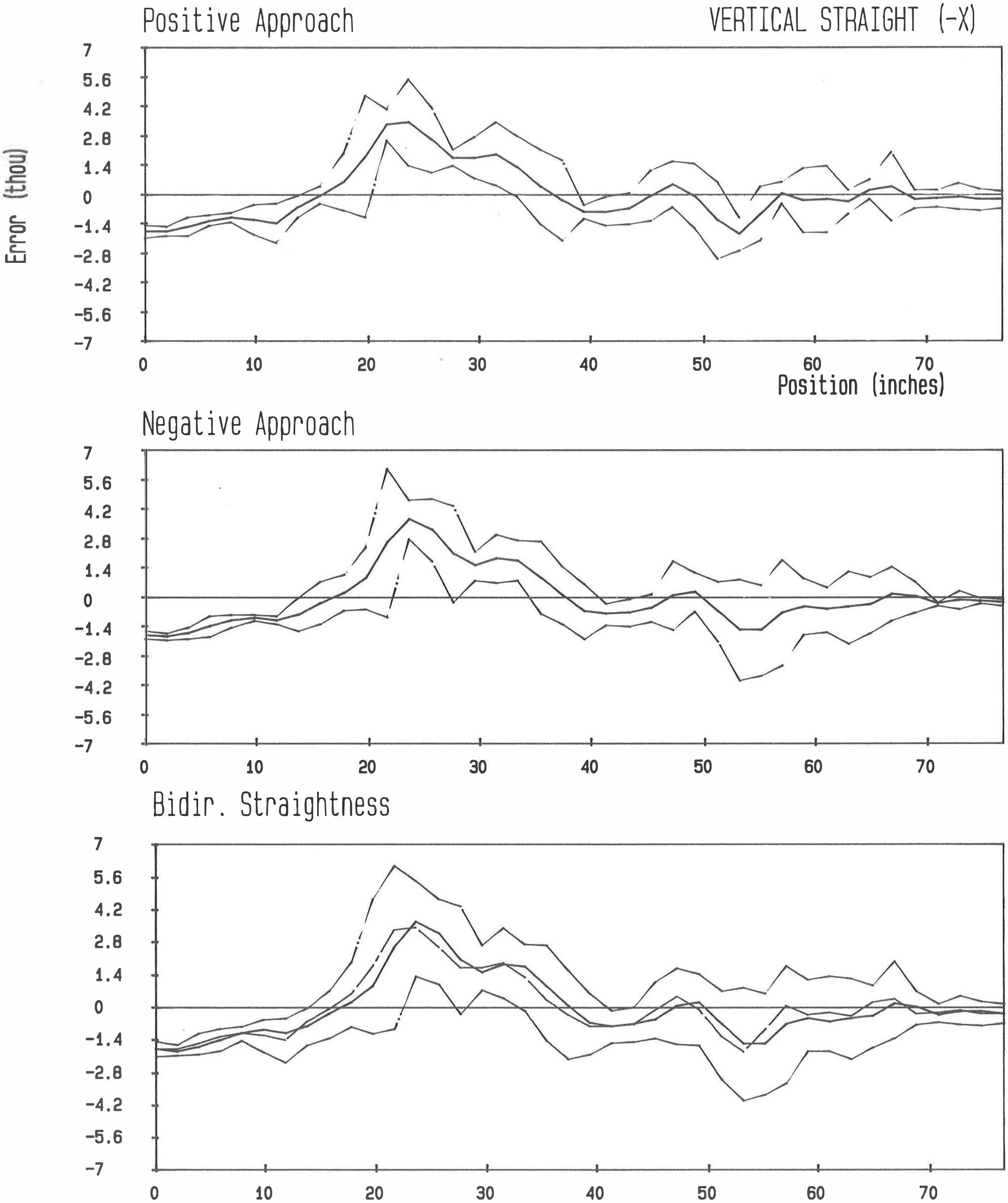
Machine: ROUTER NO.1	Axis: X	Accuracy: 13.3232
Serial No:	Location: -X END	Uni-dir. Rep: 5.6185
Date: 3/29/94	Slope: 23.95 ARCSEC	Bi-dir. Rep: 5.6185
By:	Str. Error : 11.7796	Mean rev: 0.0625

Figure 2.18—Results showing horizontal straightness in the X-axis travel with the straightness interferometer at the -X end of table.



Machine: ROUTER NO.1	Axis: X	Accuracy: 9.2451
Serial No:	Location: +X END	Uni-dir. Rep: 7.9595
Date: 3/29/94	Slope: 3.78 ARCSEC	Bi-dir. Rep: 8.0818
By:	Str. Error : 3.8898	Mean rev: 0.0573

Figure 2.19—Results showing vertical straightness in the X-axis travel with the straightness interferometer at the +X end of table.



Machine: ROUTER NO.1	Axis: X	Accuracy: 10.1034
Serial No:	Location: -X END	Uni-dir. Rep: 7.0602
Date: 3/29/94	Slope: -6.09 ARCSEC	Bi-dir. Rep: 7.0602
By:	Str. Error : 5.6144	Mean rev: 0.0481

Figure 2.20—Results showing vertical straightness in the X-axis travel with the straightness interferometer at the -X end of table.

- Slope is the misalignment angle between the laser beam used for data capture and the straightness datum as determined by the analysis.

- Straightness Error (Str. Error) is the sum of the maximum and minimum excursions of the mean straightness errors from the straightness datum defined by the analysis.

The above definitions were taken from the RENISHAW TRANSDUCER SYSTEMS LIMITED, Laser Interferometer System PC10 User Manual.[1]

2.3.2 Y-axis Straightness (Horizontal & Vertical Planes)

Purpose—This procedure determines the ability of the router to move a cutting tool in a straight line when moving in both the horizontal and vertical planes of the Y-axis. Router construction affects the movement, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the straightness and alignment of the ways used to guide the table/spindle.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring linear straightness. The optics include a straightness interferometer and straightness reflector plus the hardware required for mounting them. It is not necessary to make environmental compensations for air temperature, barometric pressure, and relative humidity. However, follow the recommendations of the laser manufacturer concerning air turbulence, heaters, and air fans. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that control the movement in the Y-axis should be exercised through at least 20 full cycles. This reduces the error in positioning for data collection that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1

Develop a program for the controller that moves the table/spindle the full length of the Y-axis in 2-inch increments. However, provide at least 1 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the deviation in straightness of travel. The program also must provide for bi-directional travel so that measurements can be taken in both the +Y and -Y directions. After the measurement is recorded for the last point in a given direction, move the spindle/table ahead 1 inch. Then reverse the direction of travel 1 inch to the final point for the first measurement in the other direction. An example of this program and its subroutines, titled LINEAR POSITIONING IN Y-AXIS (STANDARD UNITS), are shown in Figure A.1.1 of Appendix A.1.

Step 2

Set up and align the laser for determining straightness in the horizontal plane as shown in Figure 2.21. Be sure to follow the instructions in the laser user's manual concerning air turbulence, heaters, and air fans.

Step 3

Measure and record the deviation in straightness of travel at the start point and at the end of each 2-inch move in both the +Y and the -Y directions. Repeat this procedure for five full forward and reverse cycles.

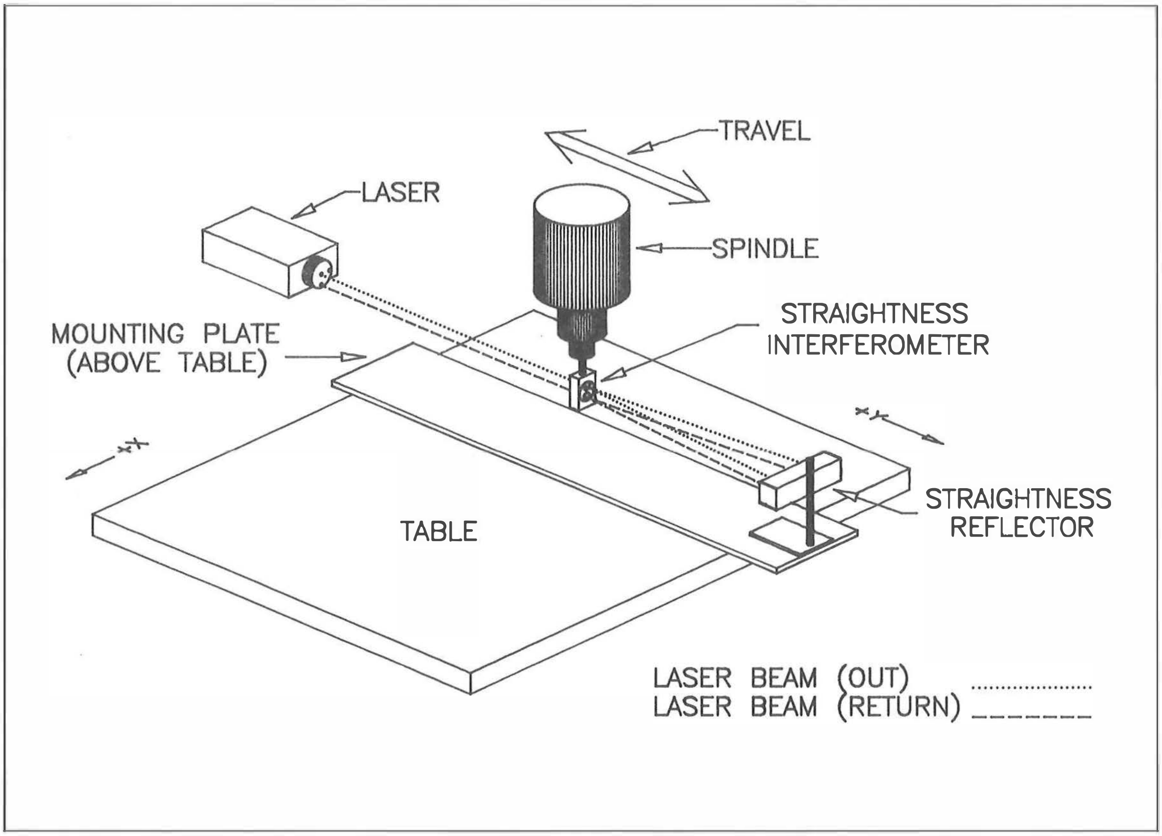


Figure 2.21—Laser setup for measuring horizontal straightness in the Y-axis travel.

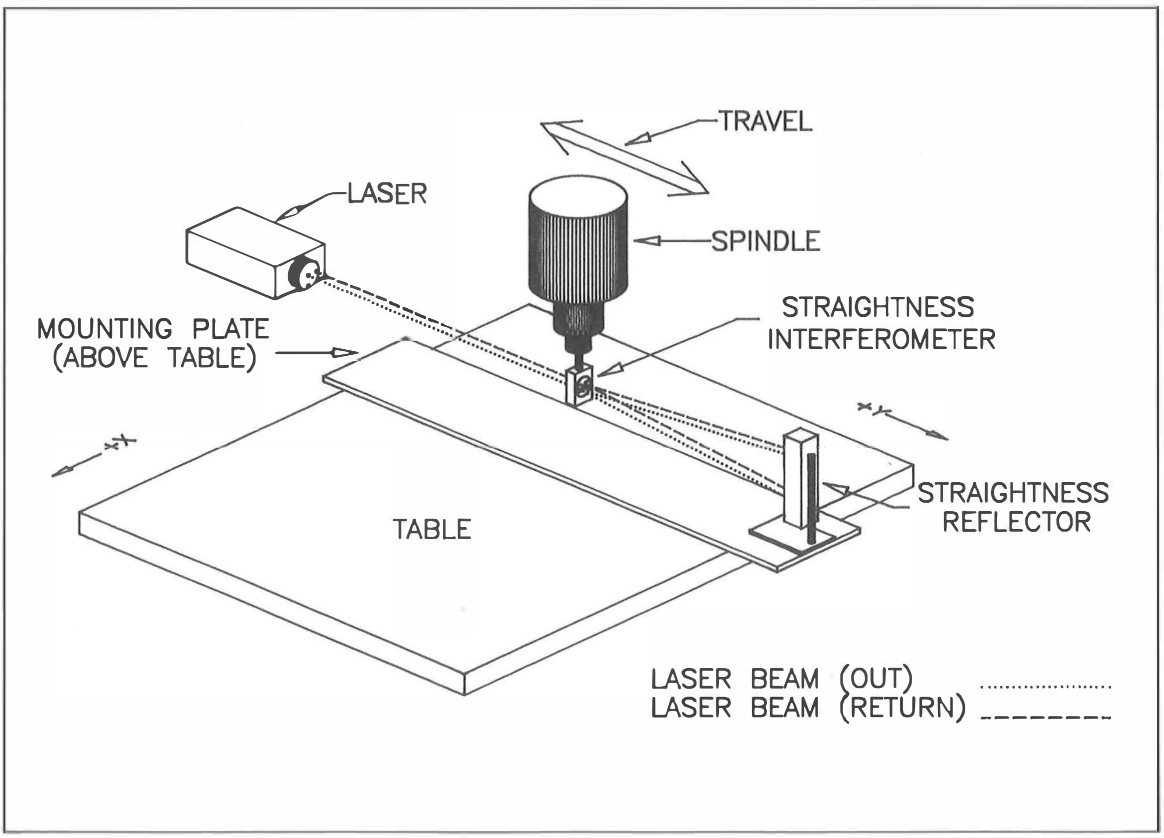
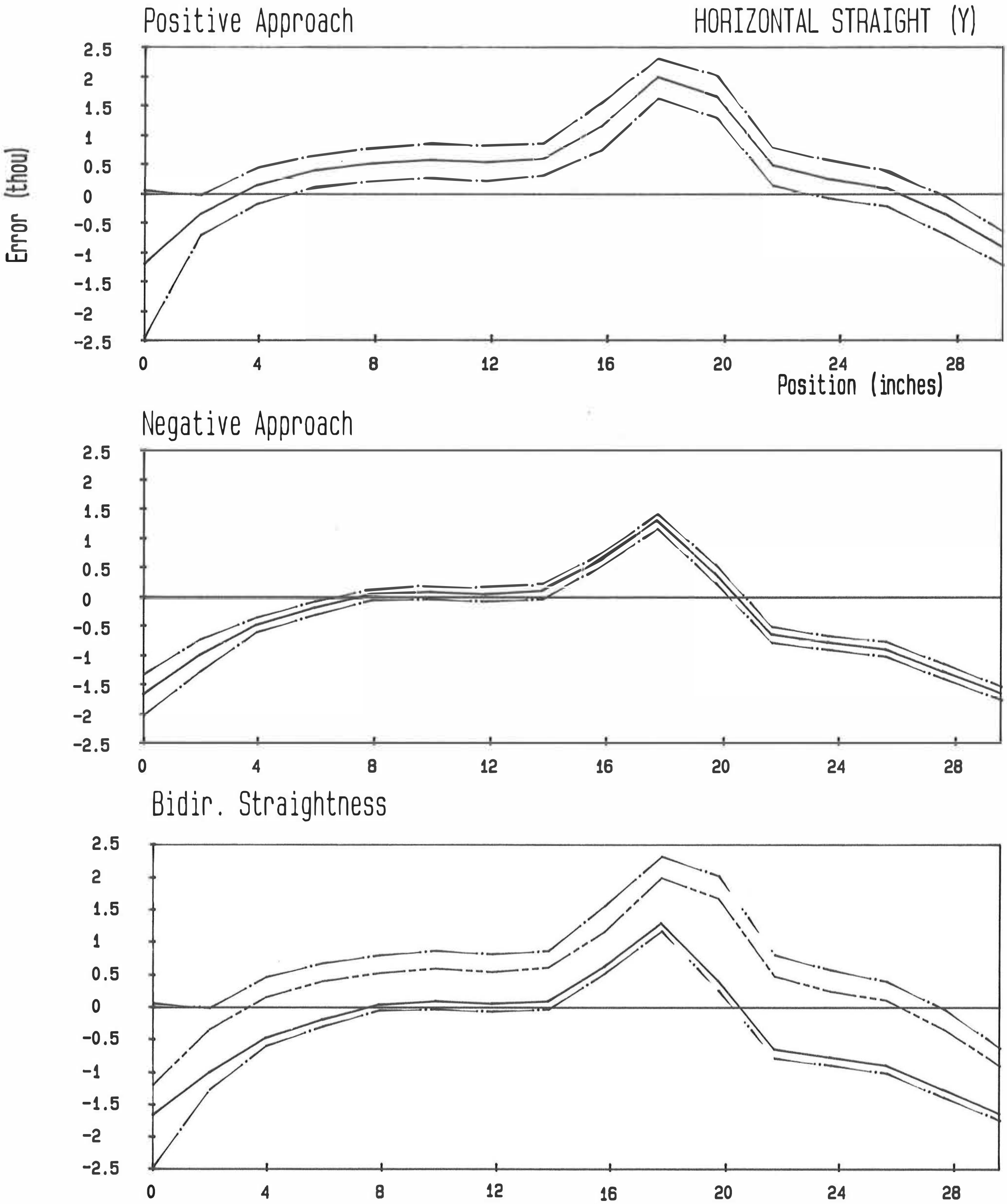
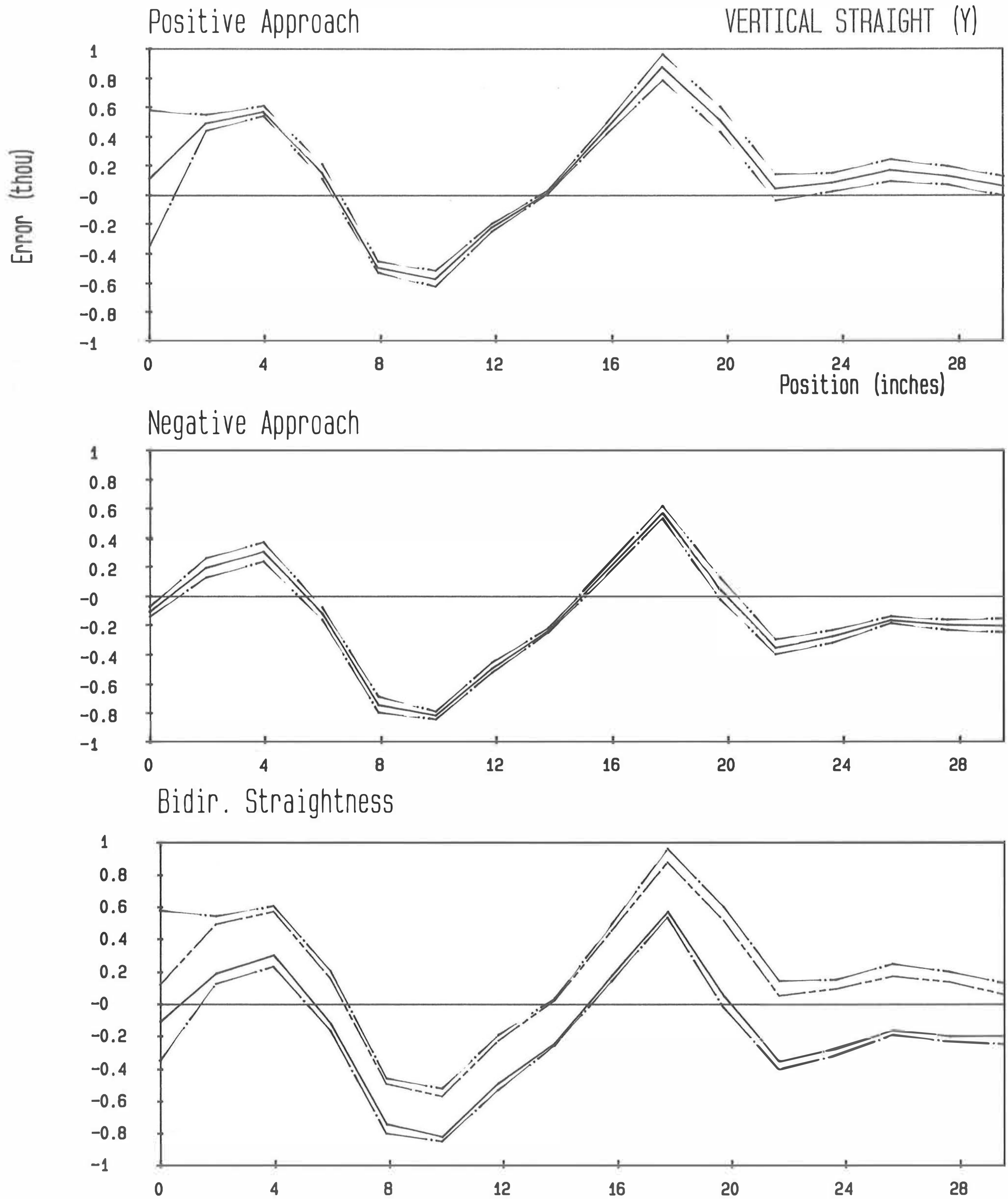


Figure 2.22—Laser setup for measuring vertical straightness in the Y-axis travel.



Machine: ROUTER NO.1	Axis: Y	Accuracy: 4.7801
Serial No:	Location:	Uni-dir. Rep: 2.5129
Date: 3/29/94	Slope: -6.15 ARCSEC	Bi-dir. Rep: 2.5129
By:	Str. Error : 3.6357	Mean rev: 0.7170

Figure 2.23—Results showing horizontal straightness in the Y-axis travel.



Machine: ROUTER NO.1	Axis: Y	Accuracy: 1.8083
Serial No:	Location:	Uni-dir. Rep: 0.9304
Date: 3/29/94	Slope: 0.93 ARCSEC	Bi-dir. Rep: 0.9304
By:	Str. Error : 1.6944	Mean rev: 0.3020

Figure 2.24—Results showing vertical straightness in the Y-axis travel.

Step 4

Repeat Steps 2 and 3 with the laser set up for determining straightness of travel in the vertical plane as shown in Figure 2.22.

Results—Plot graphs based on the British Standard (BS 4656, Part 16) showing least-squares fit of the straightness errors in table/spindle travel for both the +Y and the -Y directions. Figure 2.23 shows an example of the plot and representative statistics for straightness in the horizontal plane. Figure 2.24 shows an example of the plot and representative statistics for straightness in the vertical plane. The first two plots show the mean straightness errors in both the positive and negative directions along with the "±3 sigma" repeatability bands. The third plot shows both the positive and negative mean straightness errors along with the combined repeatability bands. See section 2.3.1 "X-axis Straightness (Horizontal & Vertical Plane)" for a discussion of the data presented at the bottom of the graph.

2.3.3 Z-axis Straightness (XZ- & YZ-Planes)

Purpose—This procedure determines the ability of the router to move a cutting tool in a straight line when moving in both the XZ-plane and YZ-plane of the Z-axis. Router construction affects the movement, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the straightness and alignment of the ways used to guide the table/spindle.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring linear straightness. The optics include a straightness interferometer, straightness reflector, vertical turning mirror, and a retroreflector plus the hardware required for mounting them. It is not necessary to make environmental compensations for air temperature, barometric pressure, and relative humidity. However, follow the recommendations of the laser manufacturer concerning air turbulence, heaters, and air fans. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning thisevaluation, the servo motor and ball screw that control the movement in the Z-axis should be exercised through at least 20 full cycles. This reduces the error in positioning for data collection that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1

Develop a program for the controller that moves the table/spindle the full length of the Z-axis in 0.25-inch increments. However, provide at least 0.25 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the deviation in straightness of travel. The program also must provide for bi-directional travel so that measurements can be taken in both the +Z and -Z directions. After the measurement is recorded for the last point in a given direction, move the spindle/table ahead 0.25 inch and then the direction of travel reversed the 0.25 inch to the final point for the first measurement in the other direction. An example of this program and its subroutines, titled LINEAR POSITIONING IN Z-AXIS (STANDARD UNITS), are shown in Figure A.1.1 of Appendix A.1.

Step 2

Set up and align the laser for determining straightness in the XZ-plane as shown in Figure 2.25. Be sure to follow the instructions in the laser user's manual concerning air turbulence, heaters, and air fans.

Step 3

Measure and record the deviation in straightness of travel at the start point and at the end of each 0.25 inch move in both the +Z and the -Z directions. Repeat this procedure for five full forward and reverse cycles.

Step 4

Repeat Steps 2 and 3 with the laser set up for determining straightness of travel in the YZ-plane as shown in Figure 2.26.

Results—Plot graphs based on the British Standard (BS 4656, Part 16) showing least-squares fits of the straightness errors in table/spindle travel in both the XZ- and YZ-planes for travel in both the +Z and the -Z directions. Figure 2.27 shows an example of the plot and representative statistics for straightness in the XZ-plane. Figure 2.28 shows an example of the plot and representative statistics for straightness in the YZ-plane. The first two plots show the mean straightness errors in both the positive and negative directions along with the "±3 sigma" repeatability bands. The third plot shows both the positive and negative mean straightness errors along with the combined repeatability bands. See section 2.3.1 "X-axis Straightness (Horizontal & Vertical Plane)" for a discussion of the data presented at the bottom of the graph.

2.4 Pitch and Yaw

2.4.1 X-axis Pitch and Yaw

Purpose—This procedure determines pitch and yaw in the router table/spindle as it moves in the X-axis. Router construction affects the movement, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the straightness and alignment of the ways used to guide the table/spindle.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring angular (pitch and yaw) deviations. The optics include an angular interferometer and angular reflector. Pitch and yaw measurements do not require environmental compensations for air temperature, barometric pressure, and relative humidity. And, it is not necessary to make adjustments for the thermal expansion of the scale material. The scale in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. However, follow the recommendations of the laser manufacturer concerning air turbulence, heaters, and air fans. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and plot the pitch and yaw information. Although the PC and software are not necessary, they greatly facilitate data collection and plotting for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that control the movement in the X-axis should be exercised through at least 20 full cycles. This reduces the error in positioning for data collection that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1

Develop a program for the controller that moves the table/spindle the full length of the X-axis in 2-inch increments. However, provide at least 1 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the pitch and yaw. This program also must provide

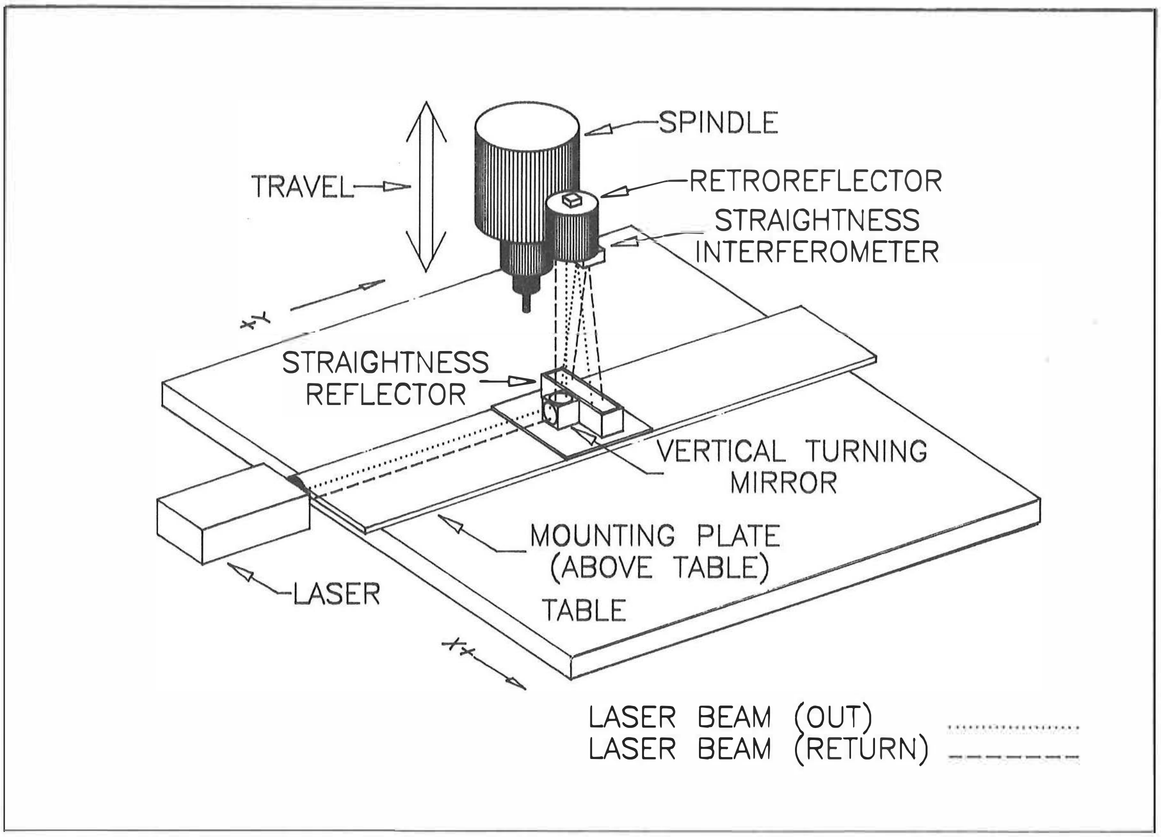


Figure 2.25—Laser setup for measuring straightness of Z-axis travel in the XZ-plane.

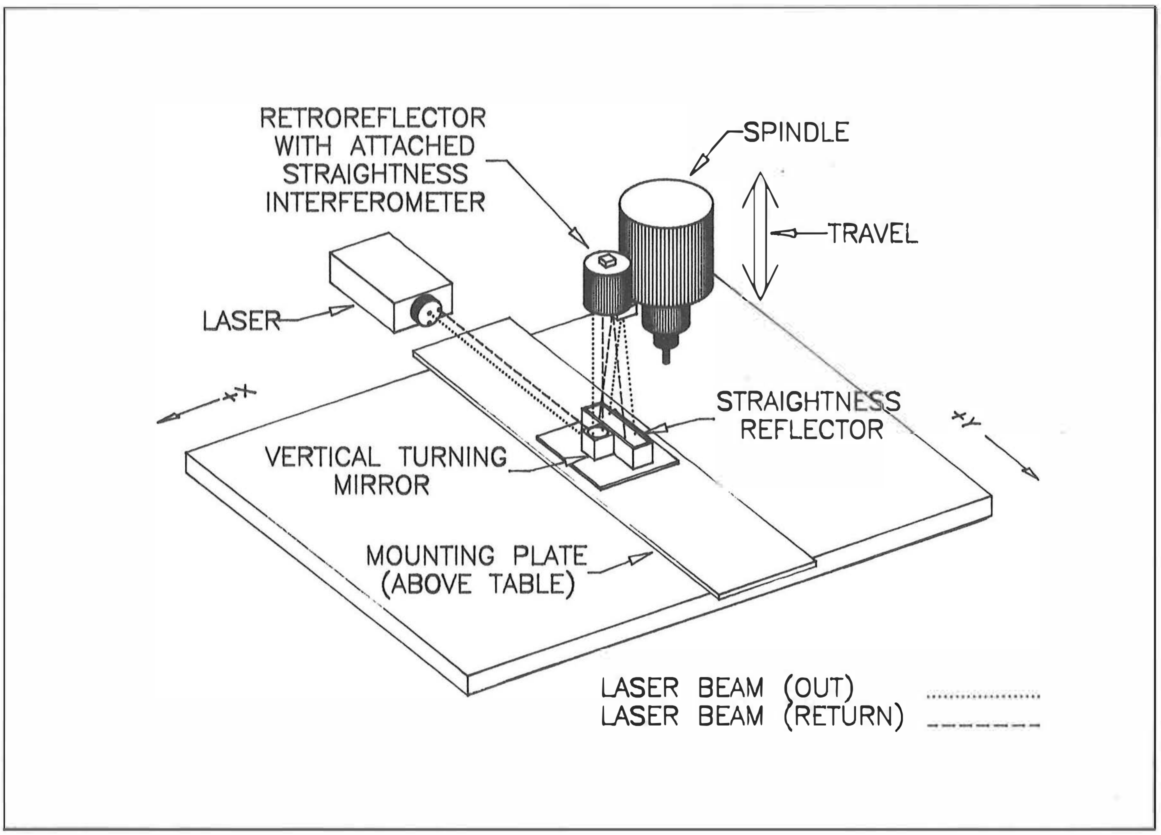


Figure 2.26—Laser setup for measuring straightness of Z-axis travel in the YZ-plane.

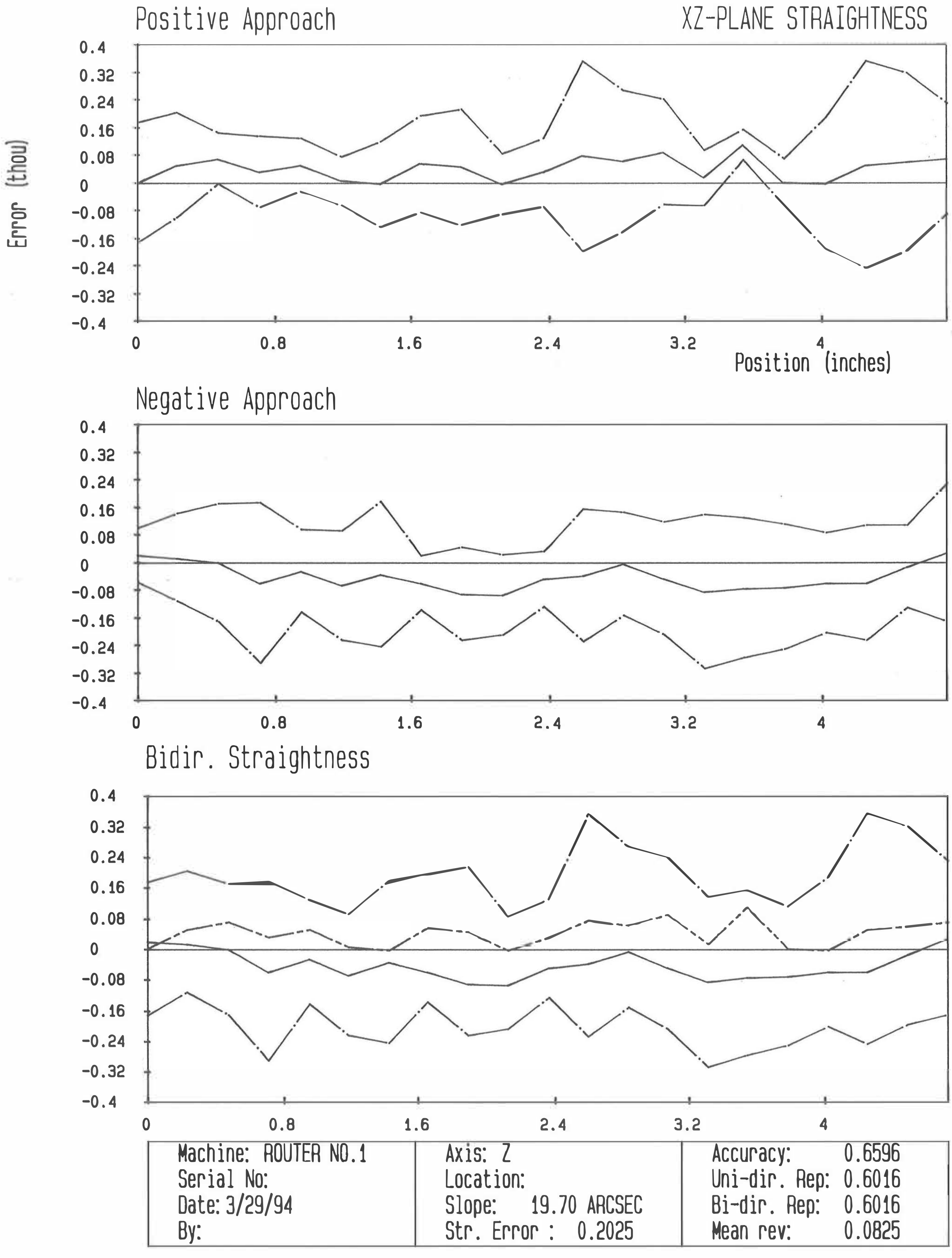
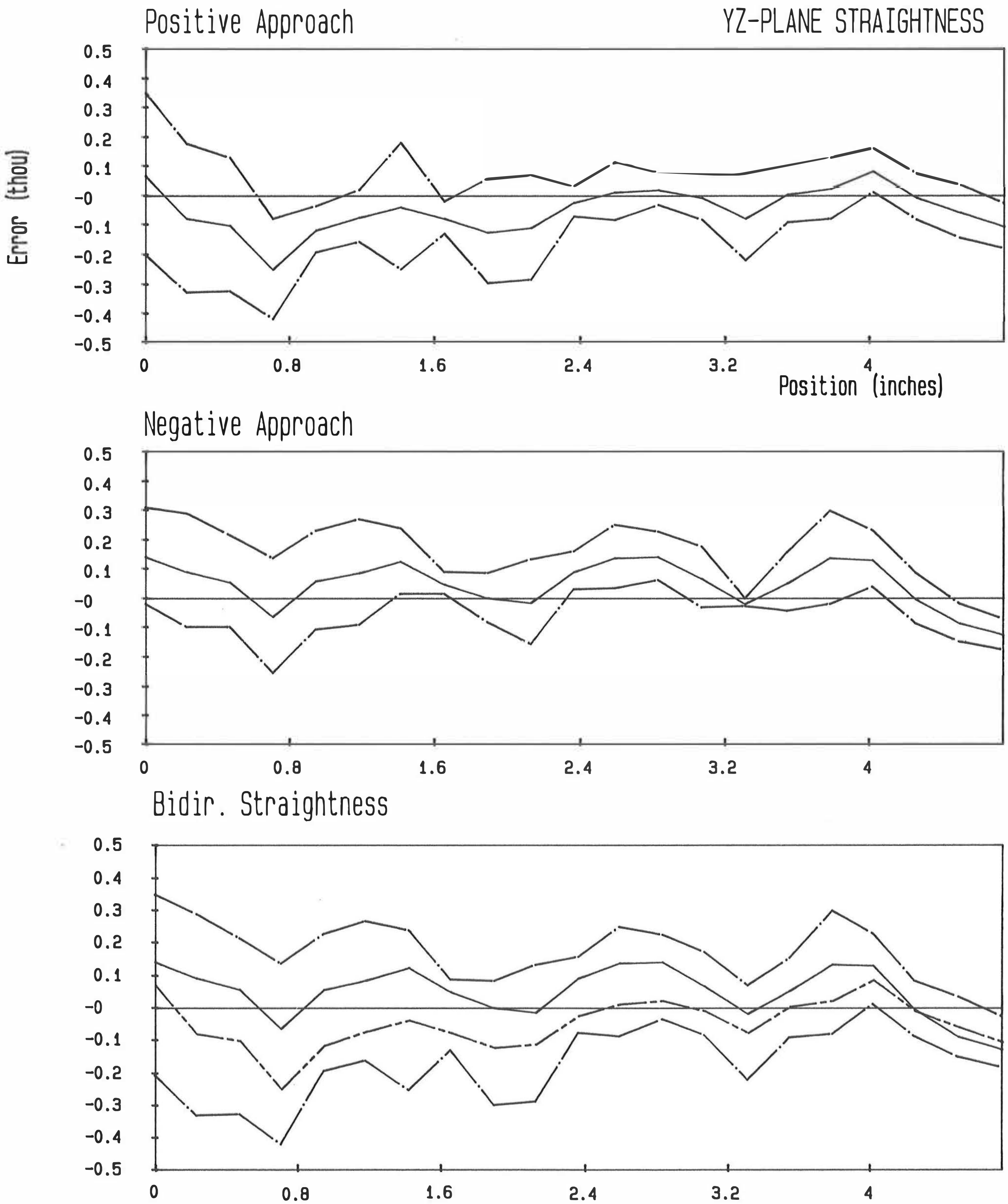


Figure 2.27—Results showing straightness of Z-axis travel in the XZ-plane.



Machine: ROUTER NO.1	Axis: Z	Accuracy: 0.7683
Serial No:	Location:	Uni-dir. Rep: 0.5554
Date: 9/29/94	Slope: 20.13 ARCSEC	Bi-dir. Rep: 0.6191
By:	Str. Error : 0.3941	Mean rev: -0.1000

Figure 2.28—Results showing straightness of Z-axis travel in the YZ-plane.

for bi-directional travel so that measurements can be taken in both the +X and -X directions. After the measurement is recorded for the last point in a given direction, move the spindle/table ahead 1 inch. Then reverse the direction of travel the 1 inch to the final point for the first measurement in the other direction. An example of this program and its subroutines, titled LINEAR POSITIONING IN X-AXIS (STANDARD UNITS), is shown in Figure A.1.1 of Appendix A.1.

Step 2
Set up and align the laser for determining pitch as shown in Figure 2.29. The laser is aligned down the middle of the table in the X-axis. Be sure to follow the instructions in the laser user's manual concerning air turbulence, heaters, and air fans.

Step 3
Measure and record the pitch at the start point and at the end of each 2-inch move in both the +X and the -X directions. Repeat this procedure for five full forward and reverse cycles.

Step 4
Repeat Steps 2 and 3 with the laser set up for determining yaw as shown in Figure 2.30.

Results—Plot graphs of the pitch as shown in Figure 2.31. Plot graphs of the yaw as shown in Figure 2.32. Both graphs are to be based on the German VDI 3441 standard. The graphs show mean angular errors in both the positive and negative directions, the bi-directional mean angular error, and the maximum "±3 sigma" repeatability bands from either direction of travel. See section 2.1.1 "X-axis Positioning" for a discussion of the statistics presented at the bottom of the graphic plot.

2.4.2 Y-axis Pitch and Yaw

Purpose—This procedure determines pitch and yaw in the router table/spindle as it moves in the Y-axis. Router construction affects the movement, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the straightness and alignment of the ways used to guide the table/spindle.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring angular (pitch and yaw) deviations. The optics include an angular interferometer and angular reflector. Pitch and yaw measurements do not require environmental compensations for air temperature, barometric pressure, and relative humidity. And, it is not necessary to make adjustments for the thermal expansion of the scale material. The scale in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. However, follow the recommendations of the laser manufacturer concerning air turbulence, heaters, and air fans. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and plot the pitch and yaw information. Although the PC and software are not necessary, they greatly facilitate data collection and plotting for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that control the movement in the Y-axis should be exercised through at least 20 full cycles. This reduces the error in positioning for data collection that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1
Develop a program for the controller that moves the table/spindle the full length of the Y-axis in 2-inch increments. However, provide at least 1 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the pitch and yaw. This program also must provide for bi-directional travel so that measurements can be taken in both the +Y and -Y directions.

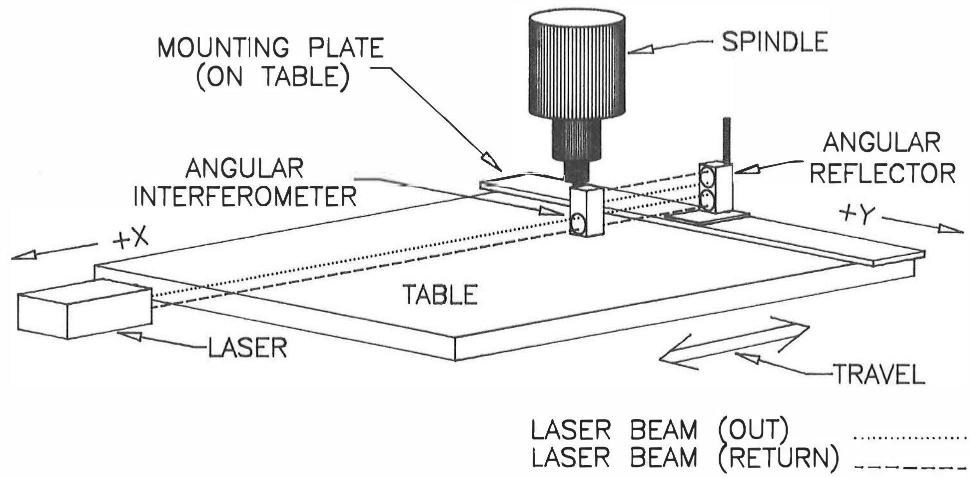


Figure 2.29—Laser setup for measuring pitch in the X-axis travel.

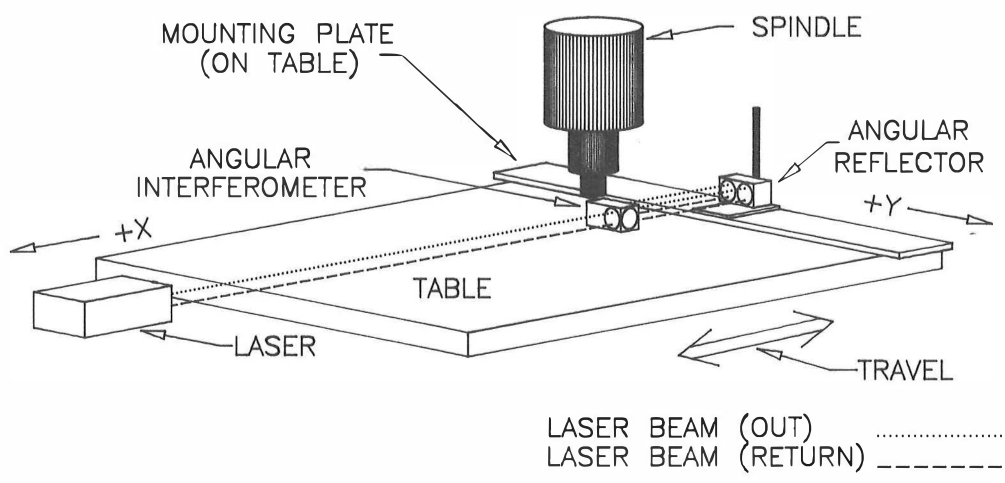


Figure 2.30—Laser setup for measuring yaw in the X-axis travel.

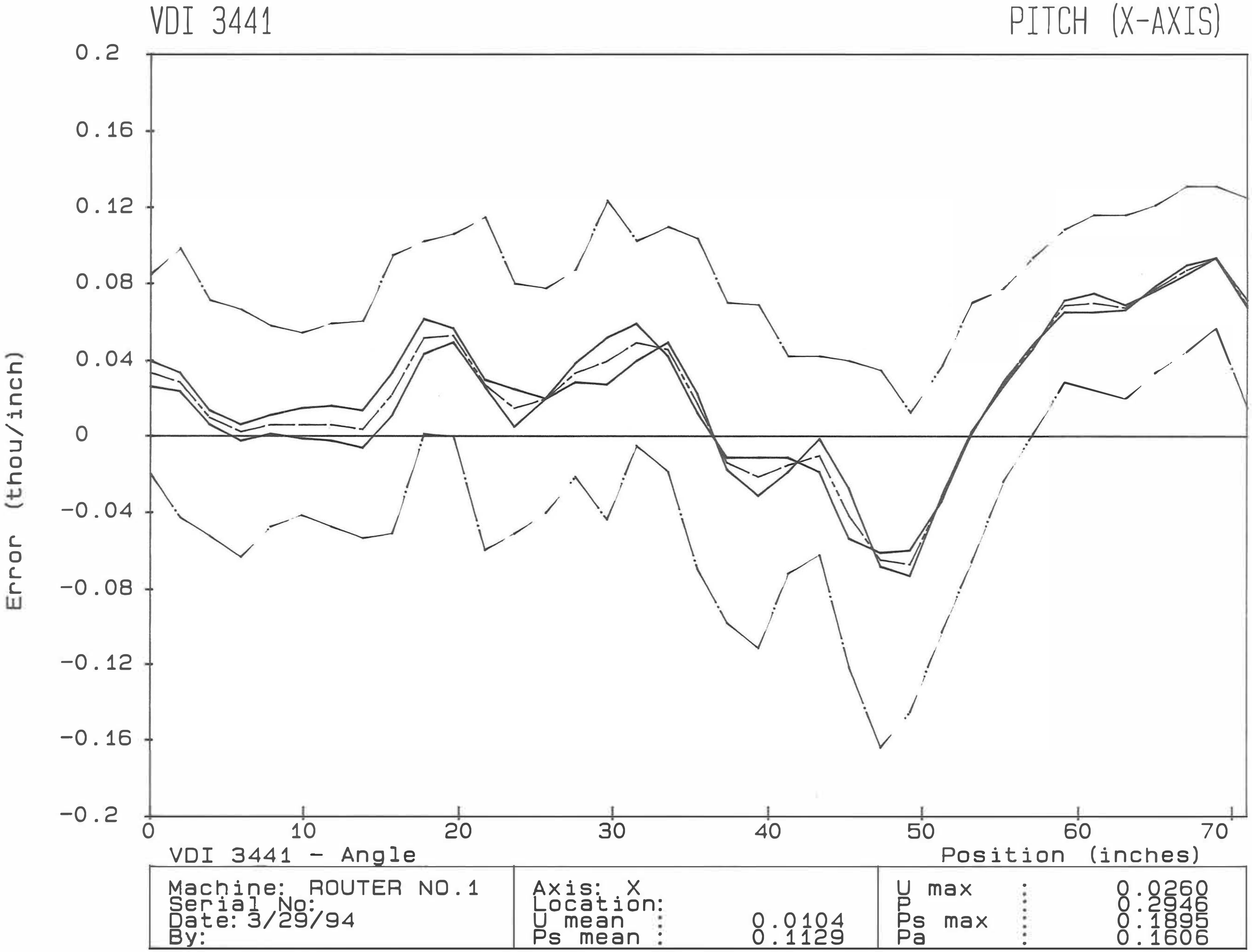
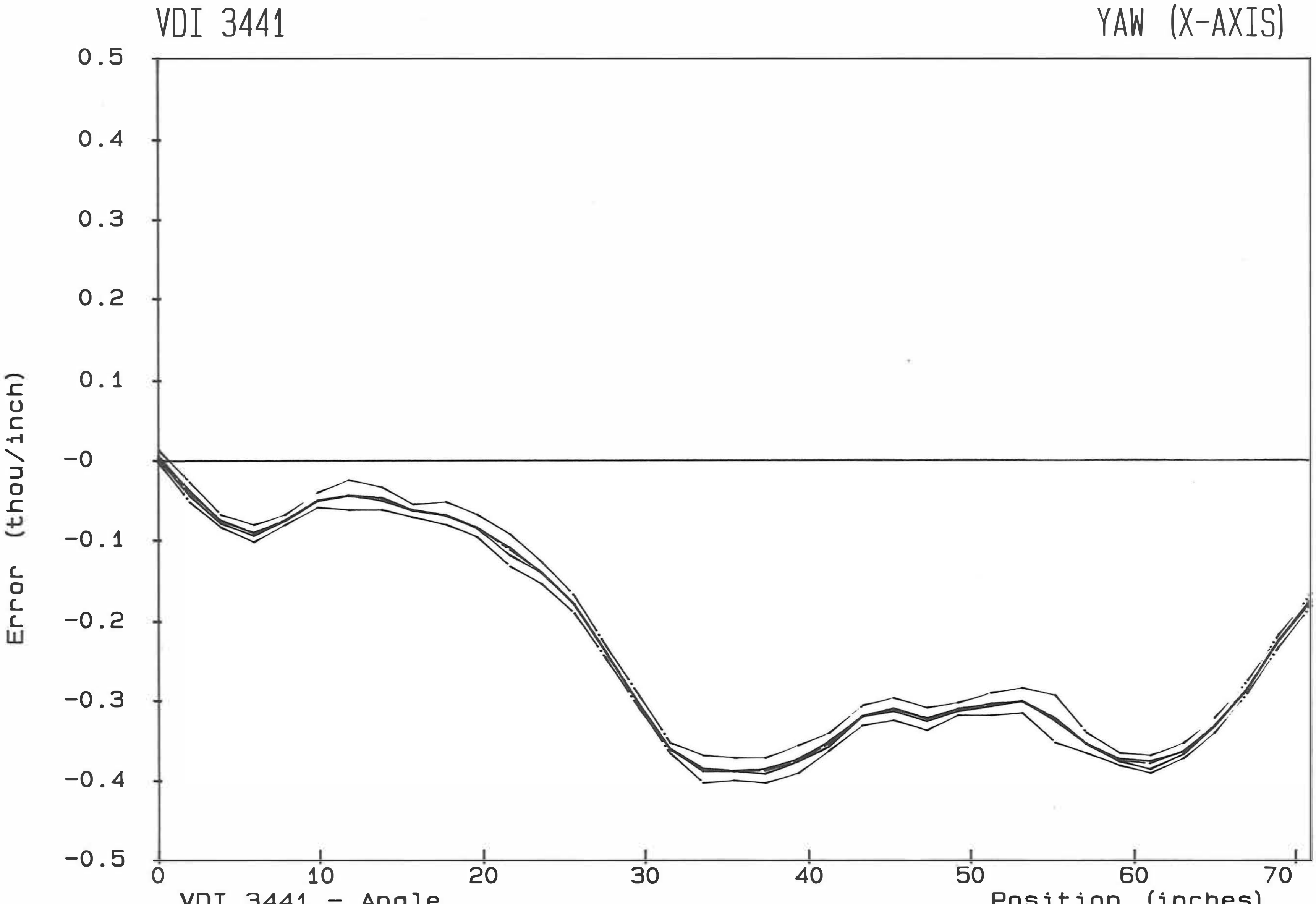


Figure 2.31—Results showing pitch in the X-axis travel.



Machine: ROUTER NO.1 Serial No: Date: 3/29/94 By:	Axis: X Location: U mean : 0.0024 Ps mean : 0.0212	U max : 0.0073 P : 0.4145 Ps max : 0.0537 Pa : 0.3907

Figure 2.32—Results showing yaw in the X-axis travel.

After the measurement is recorded for the last point in a given direction, move the spindle/table ahead 1 inch. Then reverse the direction of travel 1 inch to the final point for the first measurement in the other direction. An example of this program and its subroutines, titled LINEAR POSITIONING IN Y-AXIS (STANDARD UNITS), is shown in Figure A.1.1 of Appendix A.1.

Step 2

Set up and align the laser for determining pitch as shown in Figure 2.33. If the table moves in the Y-axis, the laser is aligned down the middle of the table in the Y-axis. Be sure to follow the instructions in the laser user's manual concerning air turbulence, heaters, and air fans.

Step 3

Measure and record the pitch at the start point and at the end of each 2-inch move in both the +Y and the -Y directions. Repeat this procedure for five full forward and reverse cycles.

Step 4

Repeat Steps 2 and 3 with the laser set up for determining yaw as shown in Figure 2.34.

Results—Plot graphs of the pitch as shown in Figure 2.35. Plot graphs of the yaw as shown in Figure 2.36. Both graphs are to be based on the German VDI 3441 standard. The graphs show mean angular errors in both the positive and negative directions, the bi-directional mean angular error, and the maximum "±3 sigma" repeatability bands from either direction of travel. See section 2.1.1 "X-axis Positioning" for a discussion of the statistics presented at the bottom of the graphic.

2.4.3 Z-axis Pitch and Yaw

Purpose—This procedure determines pitch and yaw in the router table/spindle as it moves in the Z-axis. Router construction affects the movement, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the straightness and alignment of the ways used to guide the table/spindle.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring angular (pitch and yaw) deviations. The optics include an angular interferometer and angular reflector. Pitch and yaw measurements do not require environmental compensations for air temperature, barometric pressure, and relative humidity. And, it is not necessary to make adjustments for the thermal expansion of the scale material. The scale in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. However, follow the recommendations of the laser manufacturer concerning air turbulence, heaters, and air fans. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and plot the pitch and yaw information. Although the PC and software are not necessary, they greatly facilitate data collection and plotting for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that control the movement in the Z-axis should be exercised through at least 20 full cycles. This reduces the error in positioning for data collection that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1

Develop a program for the controller that moves the table/spindle the full length of the Z-axis in 0.25-inch increments. However, provide at least 0.25 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the pitch and yaw. This program also must provide for bi-directional travel so that measurements can be taken in both the +Z and -Z

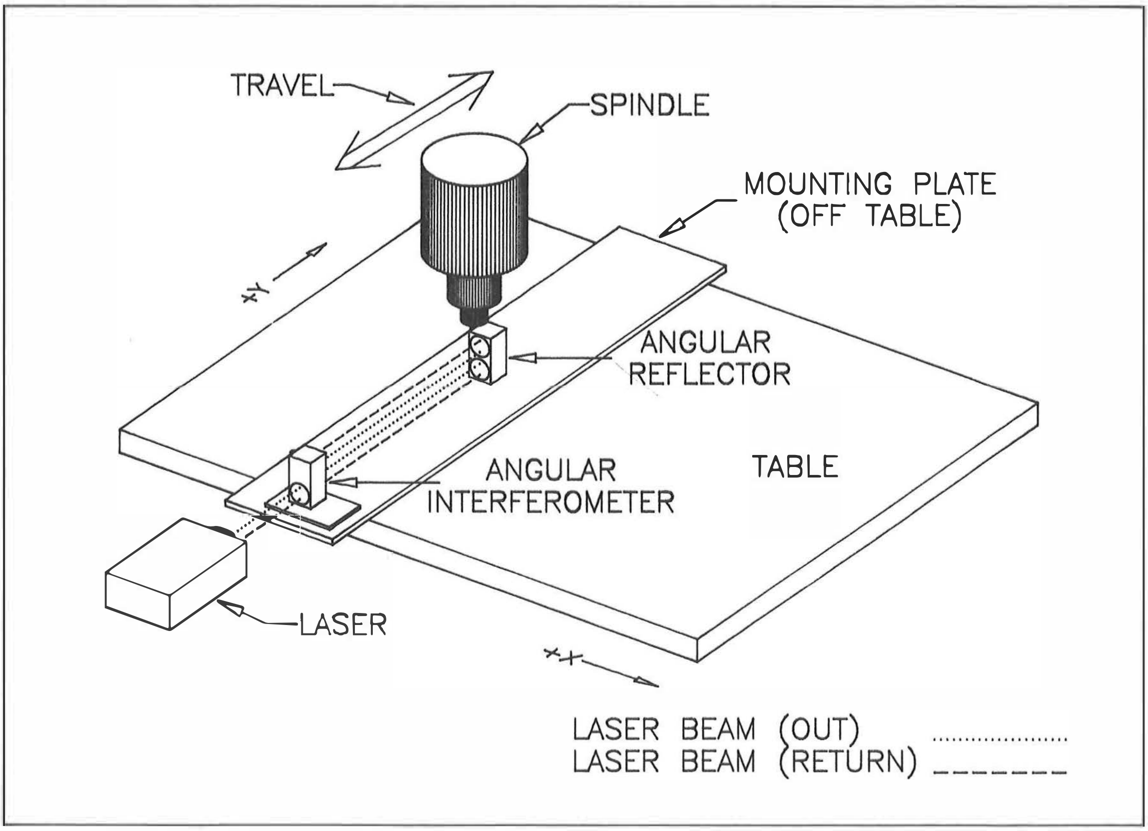


Figure 2.33—Laser setup for measuring pitch in the Y-axis travel.

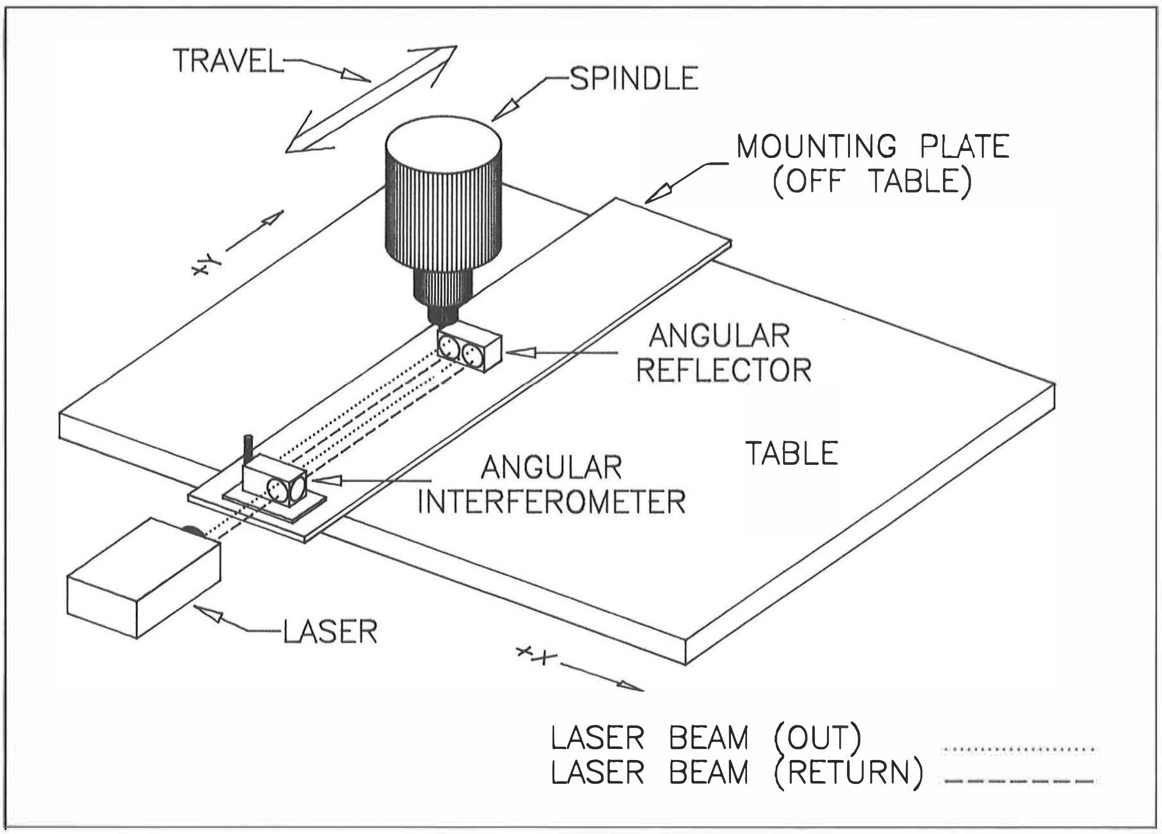


Figure 2.34—Laser setup for measuring yaw in the Y-axis travel.

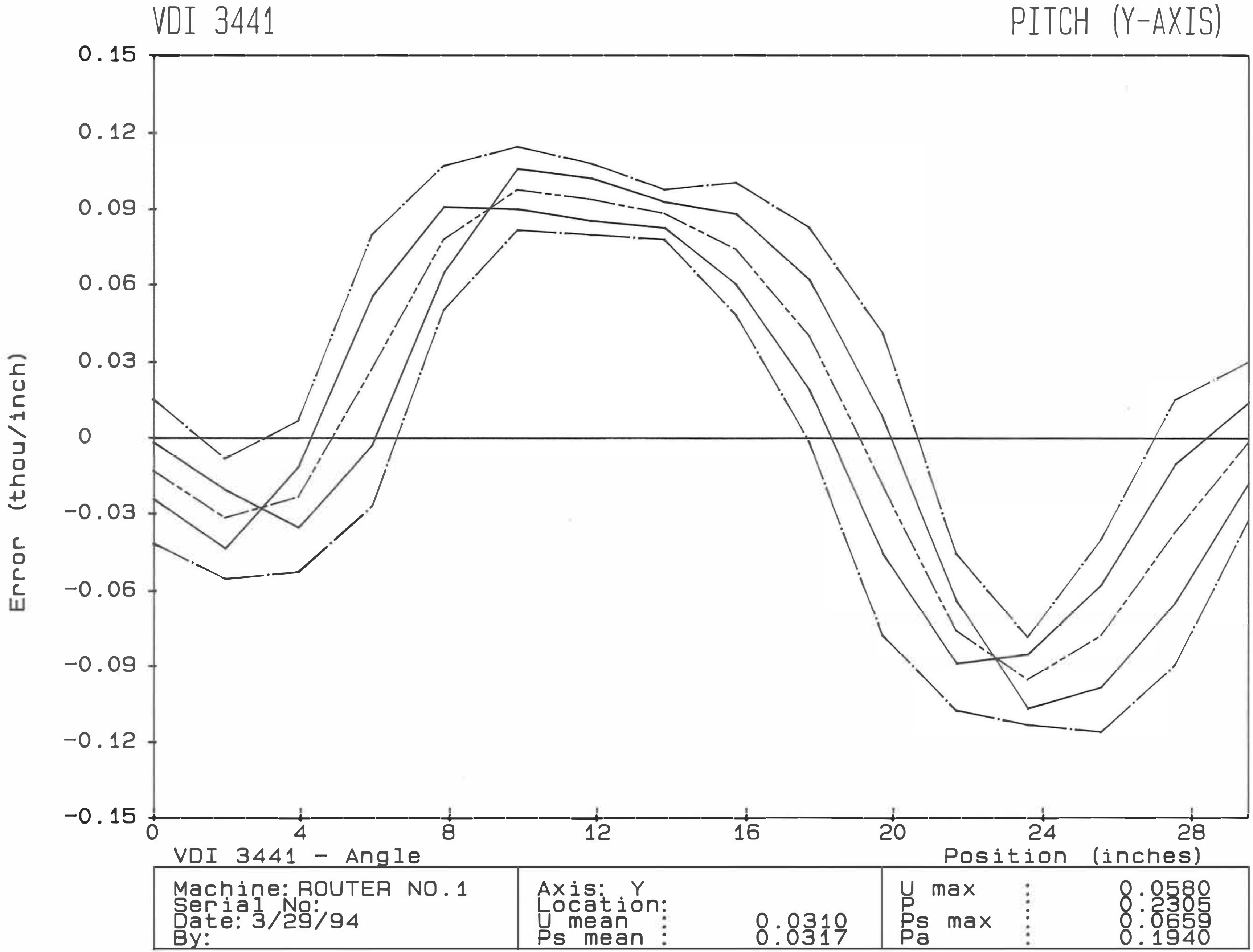
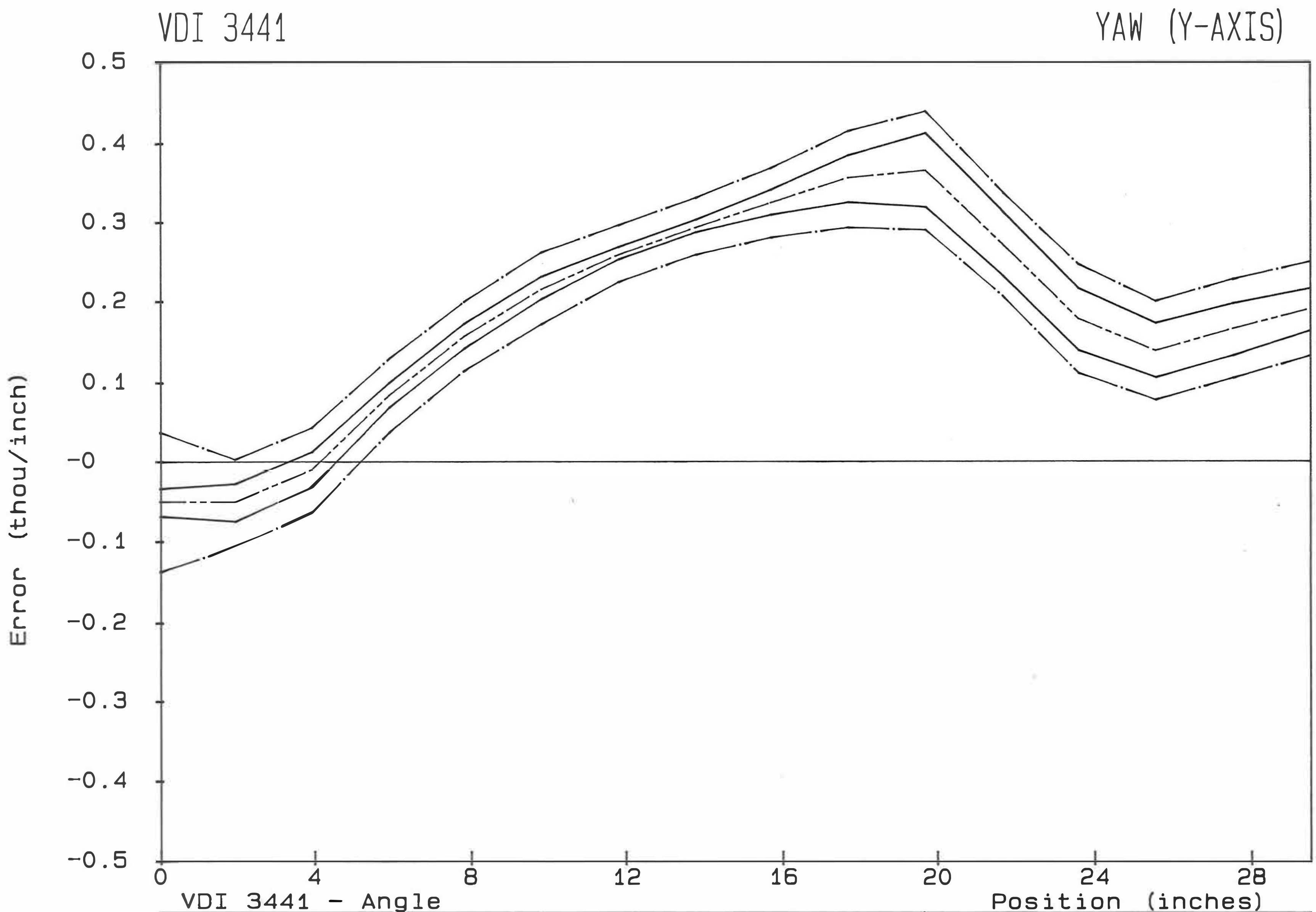


Figure 2.35—Results showing pitch in the Y-axis travel.



Machine: ROUTER NO.1	Axis: Y		U max	:	0.0907
Serial No:	Location:		P	:	0.5778
Date: 3/29/94	U mean :	0.0477	Ps max	:	0.1388
By:	Ps mean :	0.0641	Pa	:	0.4158

Figure 2.36—Results showing yaw in the Y-axis travel.

directions. After the measurement is recorded for the last point in a given direction, move the spindle/table ahead 0.25 inch. Then reverse the direction of travel 0.25 inch to the final point for the first measurement in the other direction. An example of this program and its subroutines, titled LINEAR POSITIONING IN Z-AXIS (STANDARD UNITS), is shown in Figure A.1.1 of Appendix A.1.

Step 2

Set up and align the laser for determining pitch as shown in Figure 2.37. If the table moves in the Z-axis, the laser is aligned down the middle of the table in the Z-axis. Be sure to follow the instructions in the laser user's manual concerning air turbulence, heaters, and air fans.

Step 3

Measure and record the pitch at the start point and at the end of each 1/4-inch move in both the +Z and the -Z directions. Repeat this procedure for five full forward and reverse cycles.

Step 4

Repeat Steps 2 and 3 with the laser set up for determining yaw as shown in Figure 2.38.

Results—Plot graphs of the pitch as shown in Figure 2.39. Plot graphs of the yaw as shown in Figure 2.40. Both plots are to be based on the German VDI 3441 standard. The graphs show mean angular errors in both the positive and negative directions, the bi-directional mean angular error, and the maximum "±3 sigma" repeatability bands from either direction of travel. See section 2.1.1 "X-axis Positioning" for a discussion of the data presented at the bottom of the graphics

2.5 Squareness

2.5.1 XY-Plan Squareness

Purpose—This procedure determines the ability of the router to make a right angle movement of the tool in the XY-plane. Router construction affects the movement, which may be a result of the table and/or the spindle moving. Basically, this reflects the straightness and perpendicular alignment of the ways used to guide the table and spindle during movement.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring squareness. The optics include a straightness interferometer, straightness reflector, and optical square. It is not necessary to make environmental compensations for air temperature, barometric pressure, and relative humidity. However, follow the recommendations of the laser manufacturer concerning air turbulence, heaters, and air fans. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning this evaluation, the servo motors and ball screws that control the movement in both the X-axis and the Y-axis should be exercised through at least 20 full cycles. This reduces the error in positioning for data collection that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1

Develop a program for the controller that moves the table/spindle the length of the X-axis in 2-inch increments. However, provide at least 1 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the deviation in straightness of travel. This program also must provide for bi-directional travel so that measurements can be taken in both the +X

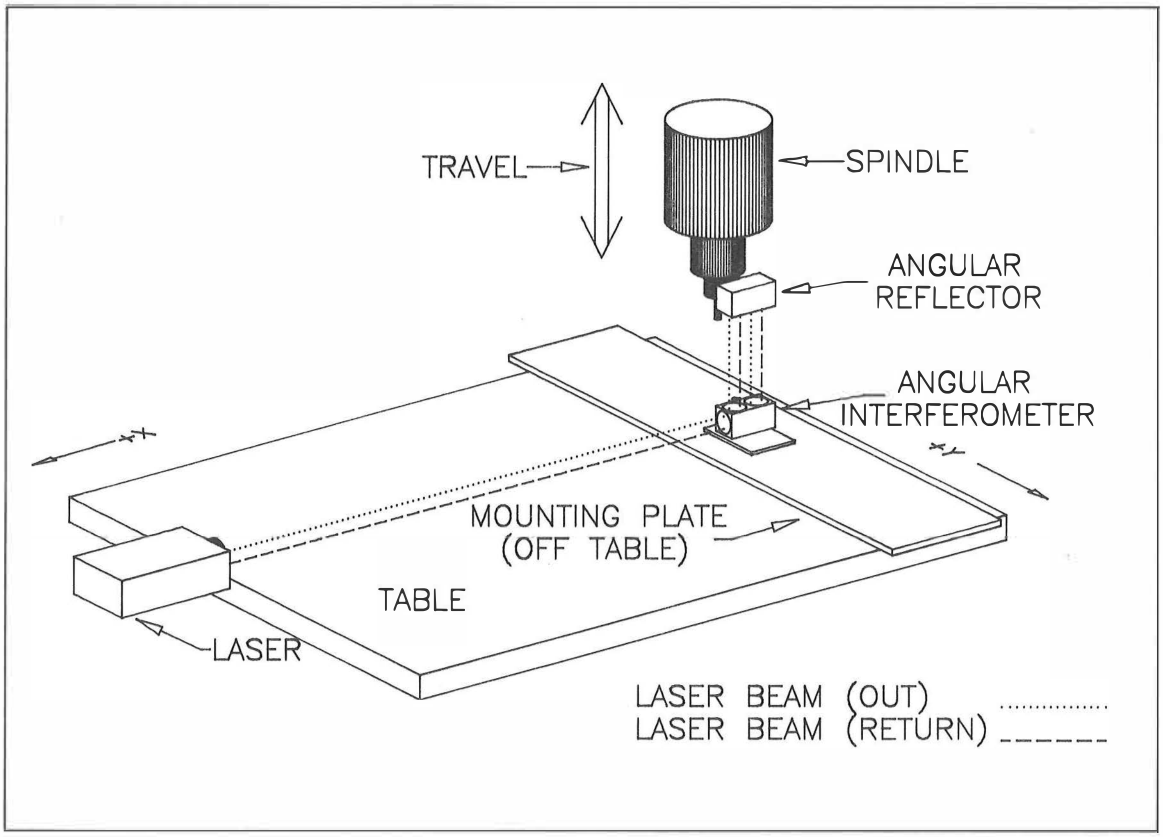


Figure 2.37—Laser setup for measuring pitch in the Z-axis travel.

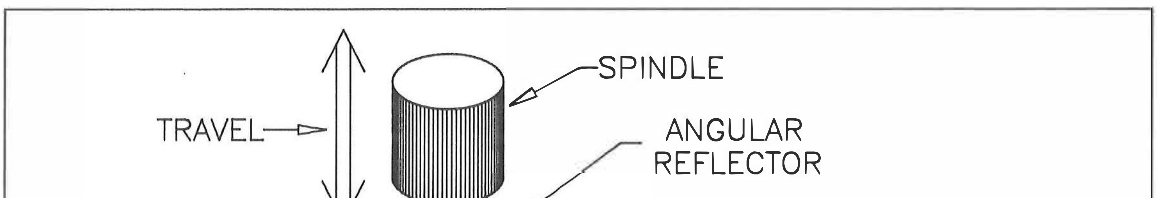


Figure 2.38—Laser setup for measuring yaw in the Z-axis travel.

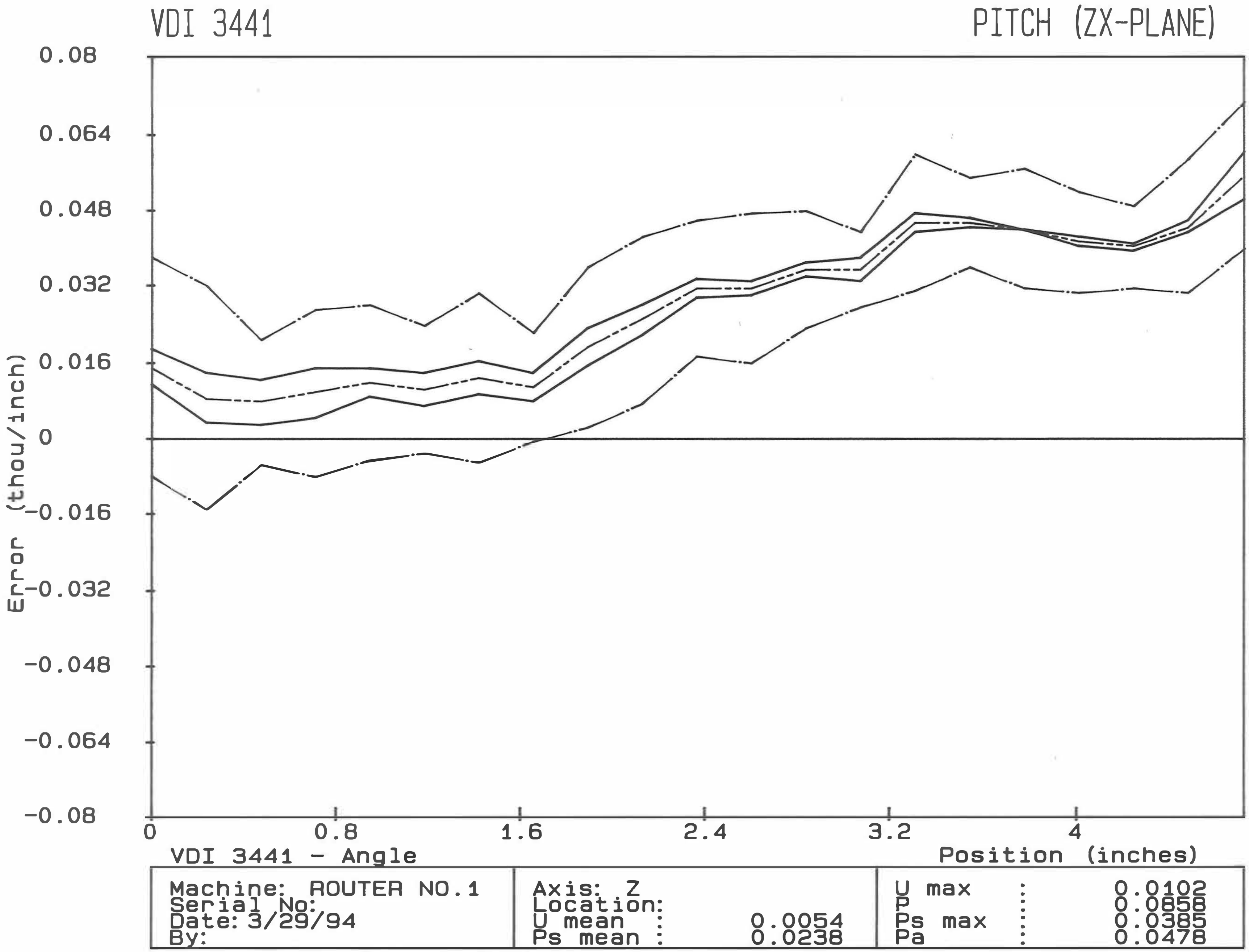
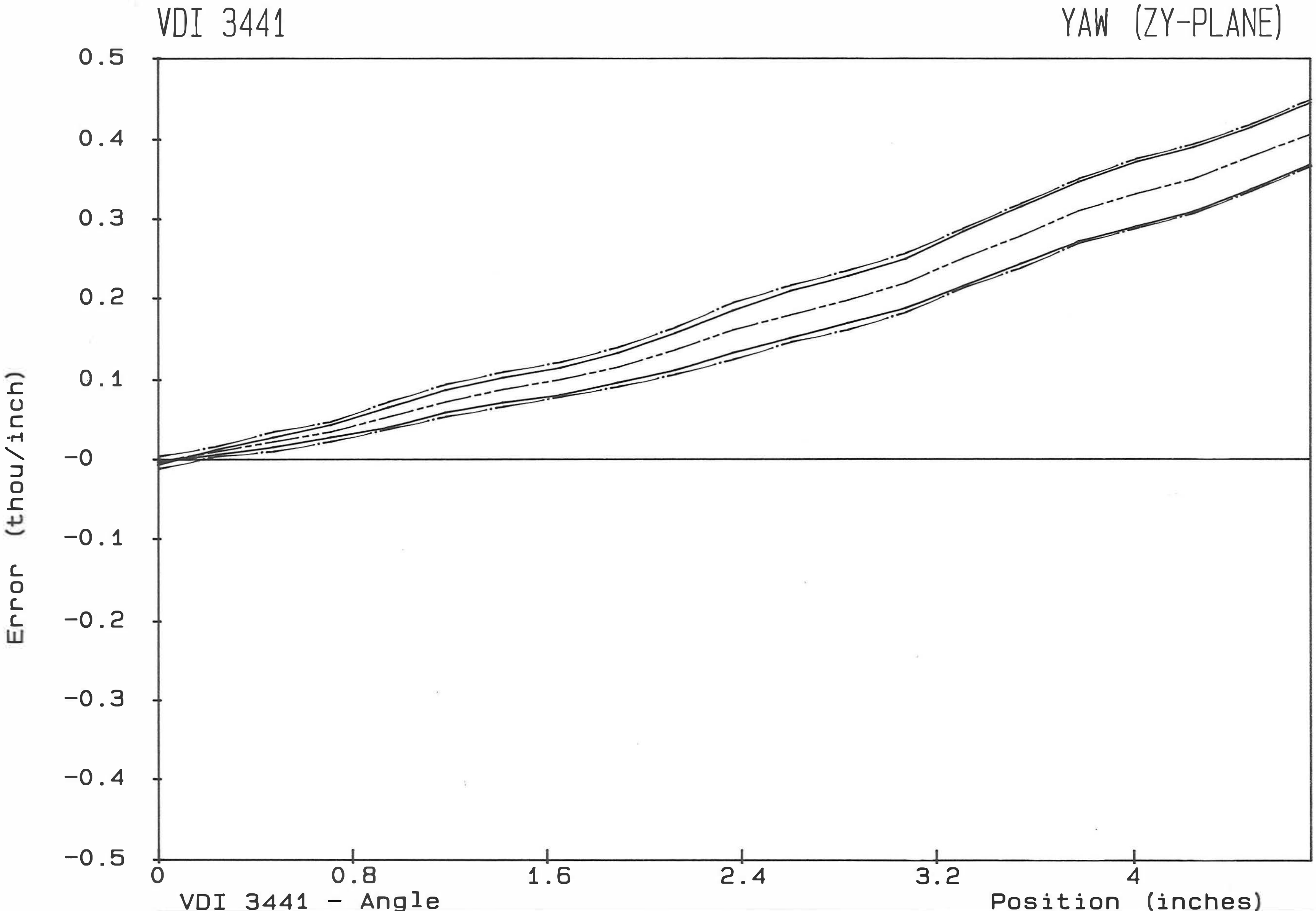


Figure 2.39—Results showing pitch in the Z-axis travel.



Machine: ROUTER NO.1	Axis: Z	U max : 0.0794
Serial No:	Location:	P : 0.4593
Date: 3/29/94	U mean : 0.0475	Ps max : 0.0183
By:	Ps mean : 0.0105	Pa : 0.4104

Figure 2.40—Results showing yaw in the Z-axis travel.

and -X directions. An example of this program and its subroutines, titled LINEAR POSITIONING IN X-AXIS (STANDARD UNITS), is shown in Figure A.1.1 of Appendix A.1.

Step 2

Develop a similar program for movement of the table/spindle in the Y-axis. An example of this program and its subroutines titled LINEAR POSITIONING IN Y-AXIS (STANDARD UNITS) is shown in Figure A.1.1 of Appendix A.1.

Step 3

Set up and align the laser for determining squareness of travel in the XY-plane as instructed by the user's manual for your laser. The setup used will depend on whether table and/or the spindle moves. Figure 2.41 shows the first setup for a router with a table that moves in the X-axis and a spindle that moves in the Y-axis. Be sure to follow the instructions in the laser user's manual concerning air turbulence, heaters, and air fans.

Step 4

Running the first program, measure and record the deviation in straightness of travel at the start point and at the end of each 2-inch move in both the +X and the -X directions of the X-axis. Repeat this procedure for five full forward and reverse cycles. After the measurement is recorded for the last point in a given direction, the spindle/table moves ahead 1 inch, and then the direction of travel reverses the 1 inch to the final point for the first measurement in the other direction.

Step 5

Without moving the straightness reflector, make the laser optics setup shown in Figure 2.42. When this is done, run the second program and measure the straightness of travel at the starting point and at the end of each 2-inch move in both the +Y and the -Y directions of the Y-axis. Repeat this procedure for five full forward and reverse cycles.

Results—Plot graphs showing the least squares fit of lines through the measured straightness errors for both the X-axis and the Y-axis. Also, provide a statement of squareness error in arc-seconds and thou/inch between the two lines. Figure 2.43 shows an example of this squareness information. The two graphs in this figure show the least-squares fit for the bi-directional straightness evaluation of the two axes. See section 2.3.1 "X-axis Straightness (Horizontal & Vertical Plane)" for a discussion of the data presented at the bottom of each graph. The bottom of the figure shows the slope of the two axes and the calculation of the squareness error. If the squareness error is positive, the angle between the two axes is greater than 90°.

2.5.2 XZ-Plane Squareness

Purpose—This procedure determines the ability of the router to make a right angle movement of the tool in the XZ-plane. Router construction affects the movement, which may be a result of the table and/or the spindle moving. Basically, this reflects the straightness and perpendicular alignment of the ways used to guide the table and spindle during movement.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring squareness. The optics include a straightness interferometer, straightness reflector, vertical turning mirror, optical square, and retroreflector. It is not necessary to make environmental compensations for air temperature, barometric pressure, and relative humidity. However, follow the recommendations of the laser manufacturer concerning air turbulence, heaters, and air fans. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

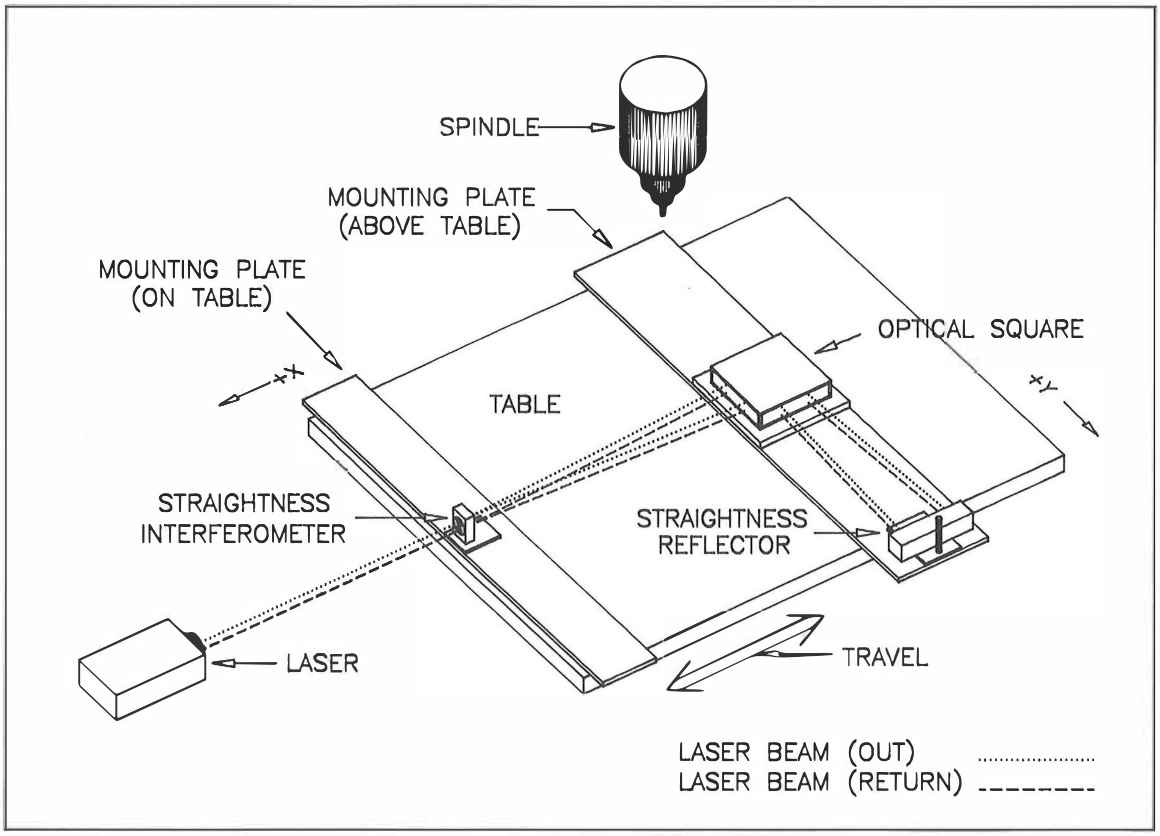


Figure 2.41—First laser setup for measuring squareness of travel in the XY-plan.

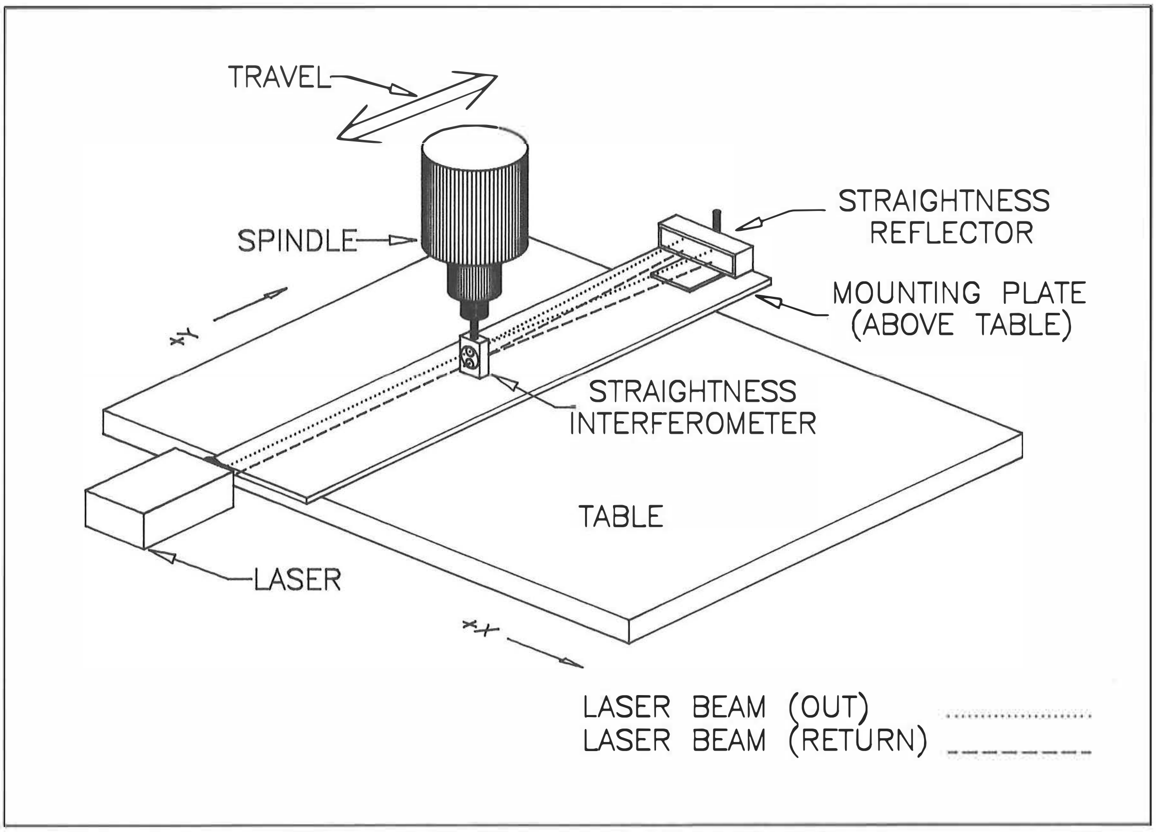
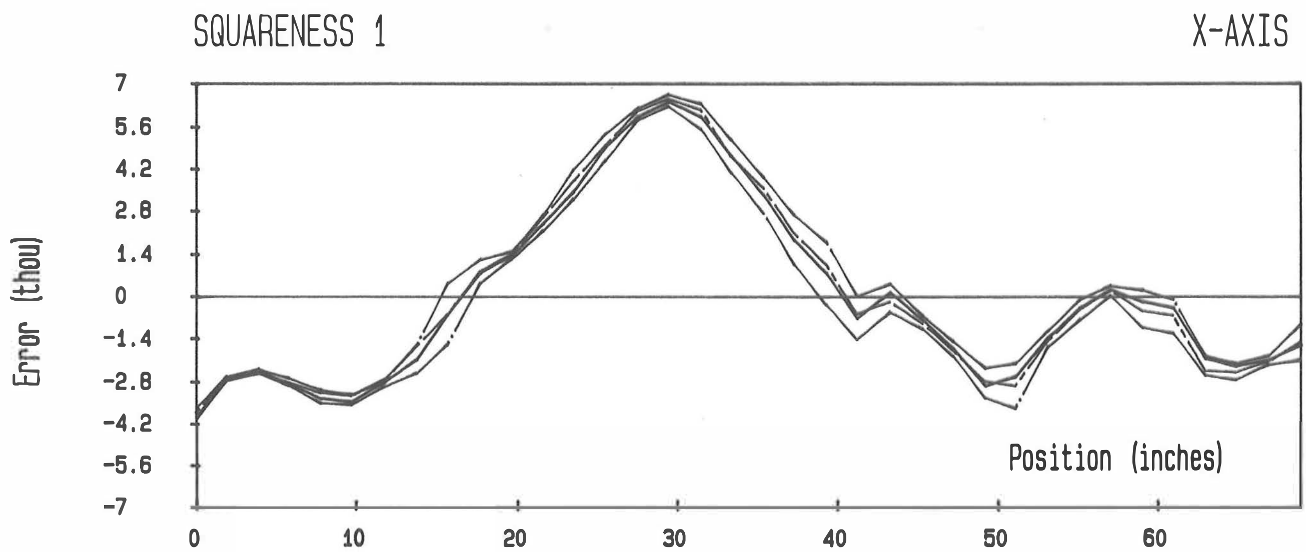
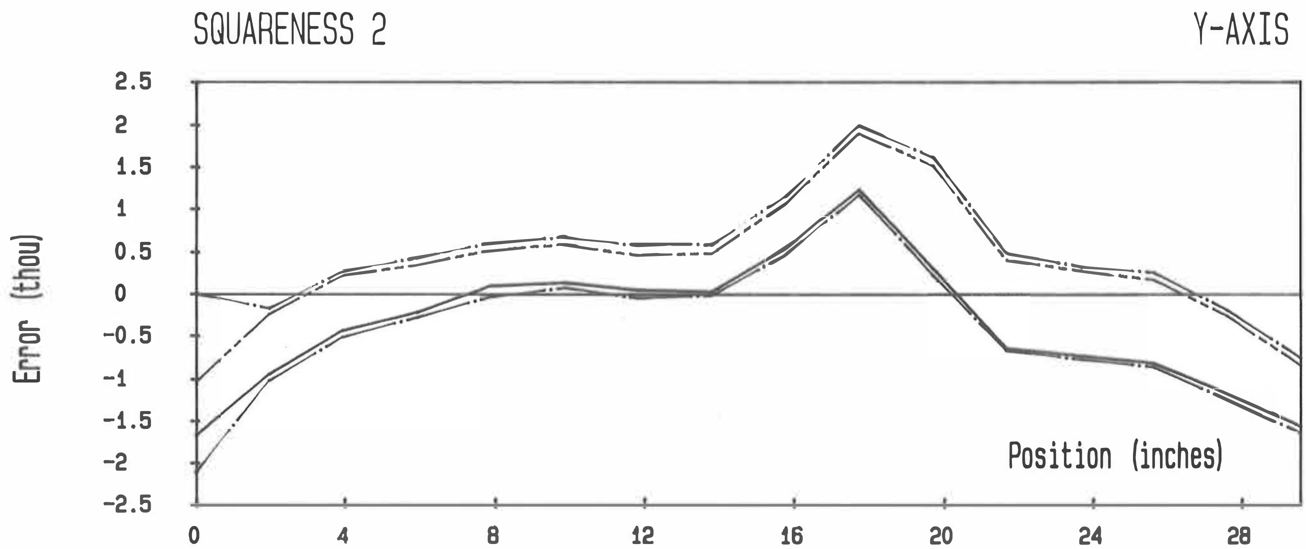


Figure 2.42—Second laser setup for measuring squareness of travel in the XY-plane.



Machine: ROUTER NO.1	Axis: X	Accuracy: 10.7266
Serial No:	Location:	Uni-dir. Rep: 2.0733
Date: 3/29/94	Slope: -8.86 ARCSEC	Bi-dir. Rep: 2.0733
By:	Str. Error : 10.4831	Mean rev: 0.0358



Machine: ROUTER NO.1	Axis: Y	Accuracy: 4.0750
Serial No:	Location:	Uni-dir. Rep: 2.1120
Date: 3/28/93	Slope: -285.12	Bi-dir. Rep: 2.1120
By:	Str. Error : 3.5770	Mean rev: 0.7156

Graph 1: NEWSQUX.STX Slope: -8.86 ARC-SECONDS
Graph 2: NEWSQUY.STY Slope: -285.12 ARC-SECONDS
(Prism error-(-285.12-8.86)) = 292.68 ARC-SECONDS
Squareness error: 292.68 ARC-SECONDS 1.41895 thou/inch

Figure 2.43—Results showing squareness of travel in the **XY**-plane.

Method—Before beginning this evaluation, the servo motor and ball screw that control the movement in the Z-axis should be exercised through at least 20 full cycles. This reduces the error in positioning for data collection that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1

Develop a program for the controller that moves the table/spindle the length of the Z-axis in 0.25-inch increments. However, provide at least 0.25 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the deviation in straightness of travel. This program also must provide for bi-directional travel so that measurements can be taken in both the +Z and -Z directions. An example of this program and its subroutines titled LINEAR POSITIONING IN Z-AXIS (STANDARD UNITS), is shown in Figure A.1.1 of Appendix A.1.

Step 2

Next, develop a similar program for movement of the table/spindle in the X-axis. An example of this program and its subroutines titled LINEAR POSITIONING IN X-AXIS (STANDARD UNITS) is shown in Figure A.1.1 of Appendix A.1.

Step 3

Set up and align the laser for determining squareness of travel in the XZ-plane as instructed by the user's manual for your laser. The setup used will depend on whether table and/or the spindle moves. Figure 2.44 shows the first setup for a router with a table that moves in the X-axis and a spindle that moves in the Z-axis. Be sure to follow the instructions in the laser user's manual concerning air turbulence, heaters, and air fans.

Step 4

Running the first program, measure and record the deviation in straightness of travel at the start point and at the end of each 0.25-inch move in both the +Z and the -Z directions of the Z-axis. Repeat this procedure for five full forward and reverse cycles. After the measurement is recorded for the last point in a given direction, the spindle/table moves ahead 0.25 inch and then the direction of travel reverses the 0.25 inch to the final point for the first measurement in the other direction.

Step 5

Without moving the straightness reflector, make the laser optics setup shown in Figure 2.45. Once this is done, run the second program and measure the straightness of travel at the starting point and at the end of each 2-inch move in both the +X and the -X directions of the X-axis. Repeat this procedure for five full forward and reverse cycles.

Results—Plot graphs showing the least-squares fit of lines through the measured straightness errors for both the X-axis and the Z-axis. Also provide a statement of squareness error in arc-seconds and thou/inch between the two lines. Figure 2.46 shows an example of this squareness information. The two graphs in this figure show the least-squares fit for the bi-directional straightness evaluation of the two axes. See section 2.3.1 "X-axis Straightness (Horizontal & Vertical Plane)" for a discussion of the data presented at the bottom of each graph. The bottom of the figure shows the slope of the two axes and the calculation of the squareness error. If the squareness error is positive, the angle between the two axes is greater than 90°.

2.5.3 YZ-Plane Squareness

Purpose—This procedure determines the ability of the router to make a right angle movement of the tool in the YZ-plane. Router construction affects the movement, which may be a result of the table and/or the spindle moving. Basically, this reflects the straightness and alignment of the ways used to guide the table and spindle during movement.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring squareness. The optics include a straightness interferometer, straightness reflector,

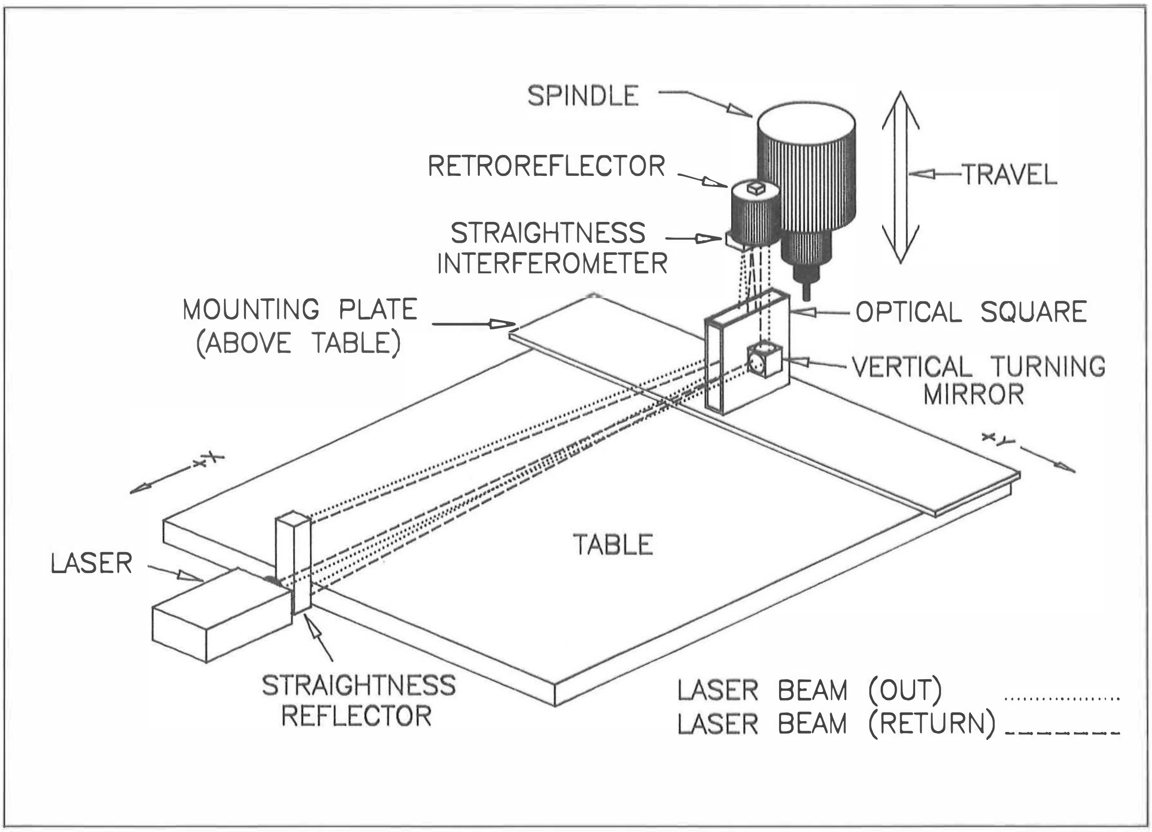


Figure 2.44—First laser setup for measuring squareness of travel in the XZ-plane.

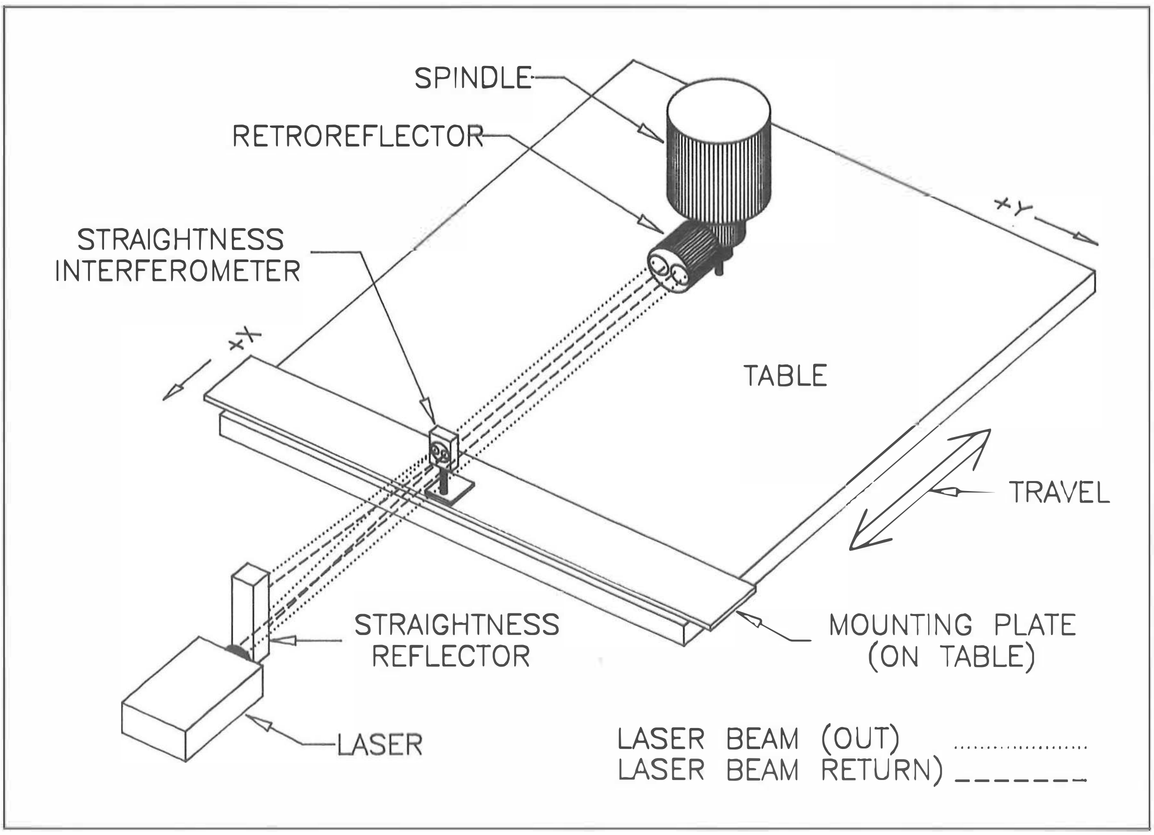
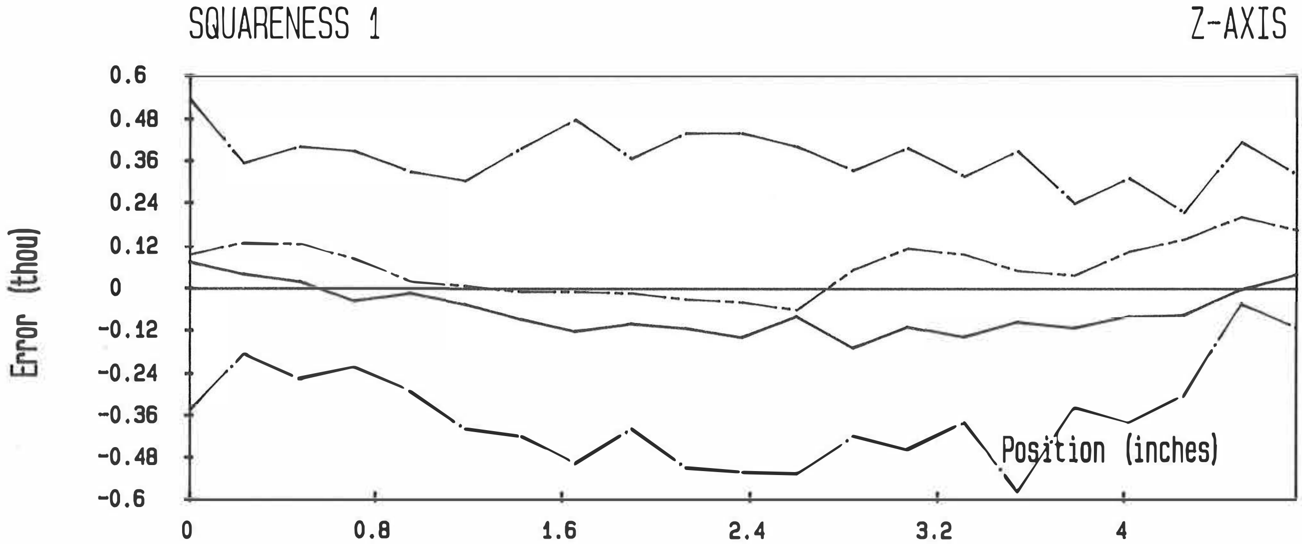
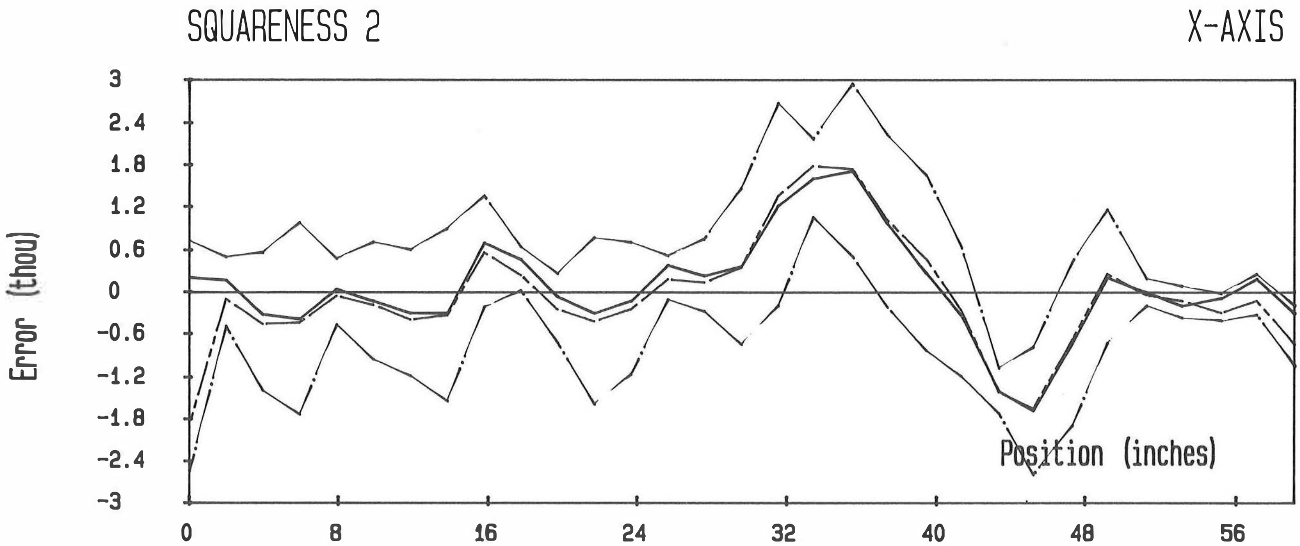


Figure 2.45—Second laser setup for measuring squareness of travel in the XZ-plane.



Machine: ROUTER NO.1	Axis: Z	Accuracy: 1.1055
Serial No:	Location:	Uni-dir. Rep: 0.9696
Date: 3/29/94	Slope: -23.94 ARCSEC	Bi-dir. Rep: 0.9696
By:	Str. Error : 0.3698	Mean rev: 0.1222



Machine: ROUTER NO.1	Axis: X	Accuracy: 5.5322
Serial No:	Location:	Uni-dir. Rep: 2.8316
Date: 3/28/93	Slope: 290.50	Bi-dir. Rep: 3.2650
By:	Str. Error : 3.6675	Mean rev: -0.1389

Graph 1: NEWSQZXZ.STZ Slope: -23.94 ARC-SECONDS
Graph 2: NEWSQZXX.STX Slope: 290.50 ARC-SECONDS
(Prism error-(290.50-23.94)) = -267.86 ARC-SECONDS
Squareness error: -267.86 ARC-SECONDS -1.29864 thou/inch

Figure 2.46—Results showing squareness of travel in the XZ-plane.

vertical turning mirror, optical square, and retroreflector. It is not necessary to make environmental compensations for air temperature, barometric pressure, and relative humidity. However, follow the recommendations of the laser manufacturer concerning air turbulence, heaters, and air fans. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning this evaluation, the servo motors and ball screws that control the movement in the X-axis and the Z-axis should be exercised through at least 20 full cycles. This reduces the error in positioning for data collection that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1

Develop a program for the controller that moves the table/spindle the length of the Z-axis in 0.25-inch increments. However, provide at least 0.25 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the deviation in straightness of travel. This program also must provide for bi-directional travel so that measurements can be taken in both the +Z and -Z directions. An example of this program and its subroutines titled LINEAR POSITIONING IN Z-AXIS (STANDARD UNITS), is shown in Figure A.1.1 of Appendix A.1.

Step 2

Develop a similar program for movement of the table/spindle in the Y-axis. An example of this program and its subroutines titled LINEAR POSITIONING IN Y-AXIS (STANDARD UNITS) is shown in Figure A.1.1 of Appendix A.1.

Step 3

Set up and align the laser for determining squareness of travel in the YZ-plane as instructed by the user's manual for your laser. The setup used will depend on whether table and/or the spindle moves. Figure 2.47 shows the first setup for a router with a spindle that moves in both the Y-axis and the Z-axis. Be sure to follow the instructions in the laser user's manual concerning air turbulence, heaters, and air fans.

Step 4

Running the first program, measure and record the deviation in straightness of travel at the start point and at the end of each 0.25-inch move in both the +Z and the -Z directions of the Z-axis. Repeat this procedure for five full forward and reverse cycles. After the measurement is recorded for the last point in a given direction, the spindle/table moves ahead 0.25 inch and then the direction of travel reverses the 0.25 inch to the final point for the first measurement in the other direction.

Step 5

Without moving the straightness reflector, make the laser optics setup shown in Figure 2.48. Once this is done, run the second program and measure the straightness of travel at the starting point and at the end of each 2-inch move in both the +Y and the -Y directions of the Y-axis. Repeat this procedure for five full forward and reverse cycles.

Results—Plot graphs showing the least-squares fit of lines through the measured straightness errors for both the Y-axis and the Z-axis. Also provide a statement of squareness error in arc-seconds and thou/inch between the two lines. Figure 2.49 shows an example of this squareness information. The two graphs in this figure show the least-squares fit for the bi-directional straightness evaluation of the two axes. See section 2.3.1 "X-axis Straightness (Horizontal & Vertical Plane)" for a discussion of the data presented at the bottom of each graph. The bottom of the figure shows the slope of the two axes and the calculation of the squareness error. If the squareness error is positive, the angle between the two axes is greater than 90°.

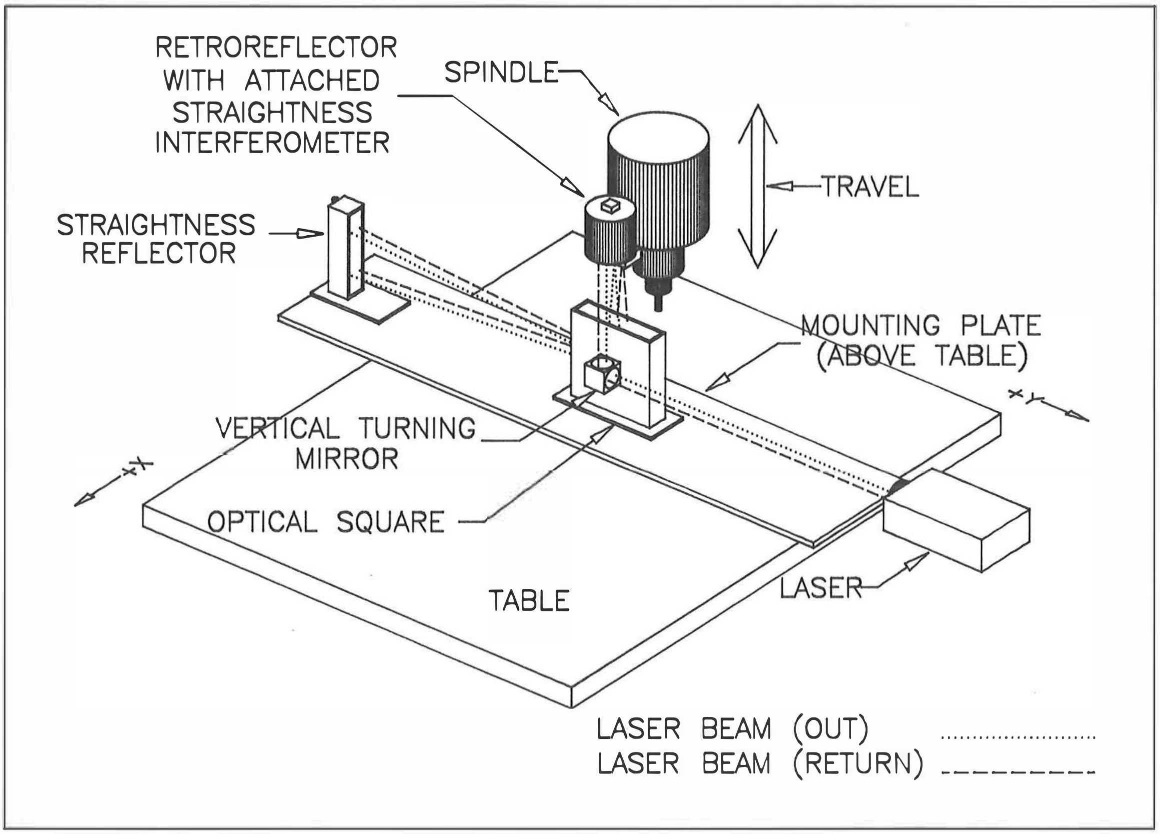


Figure 2.47—First laser setup for measuring squareness of travel in the **YZ**-plane.

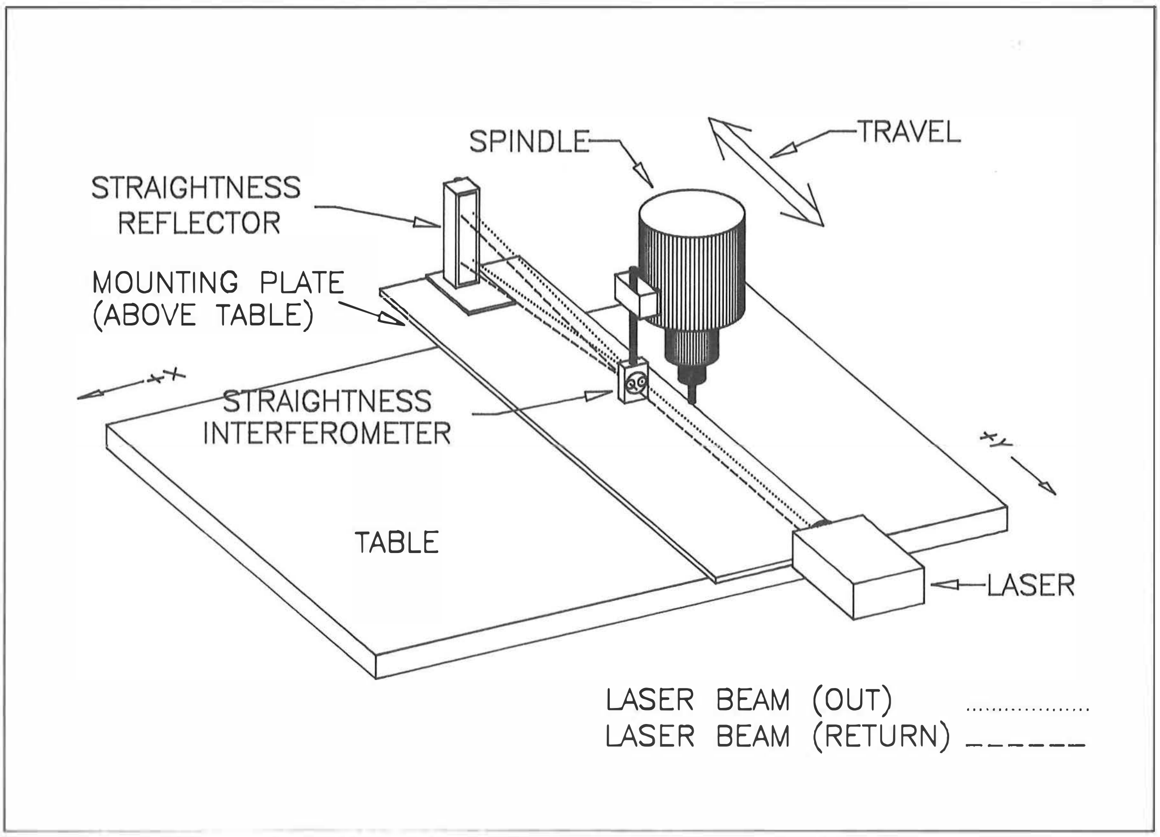
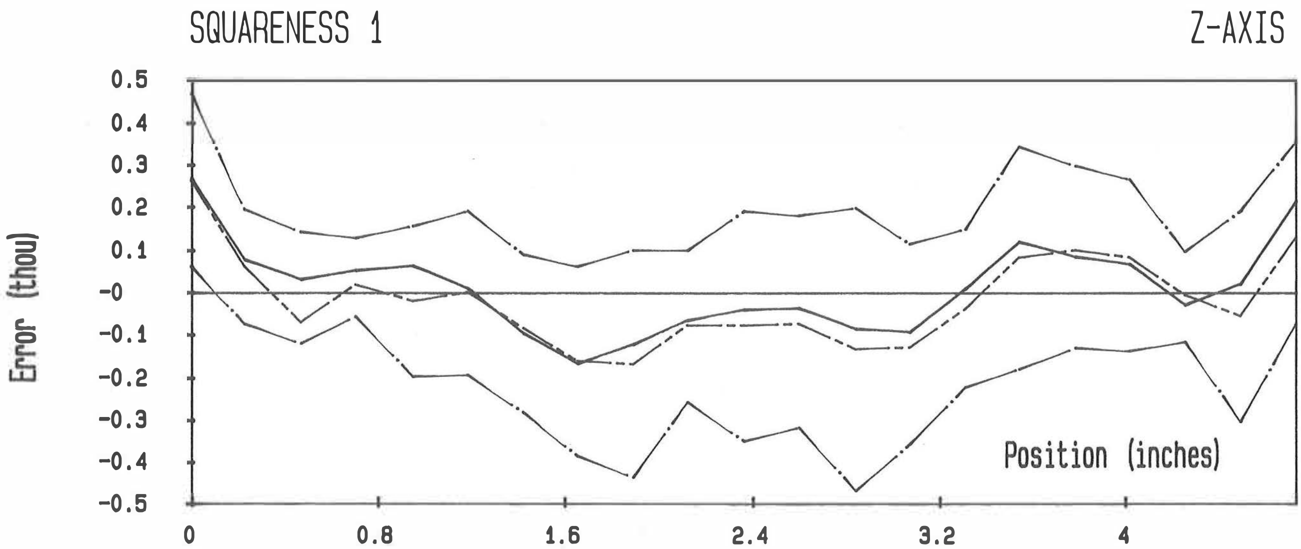
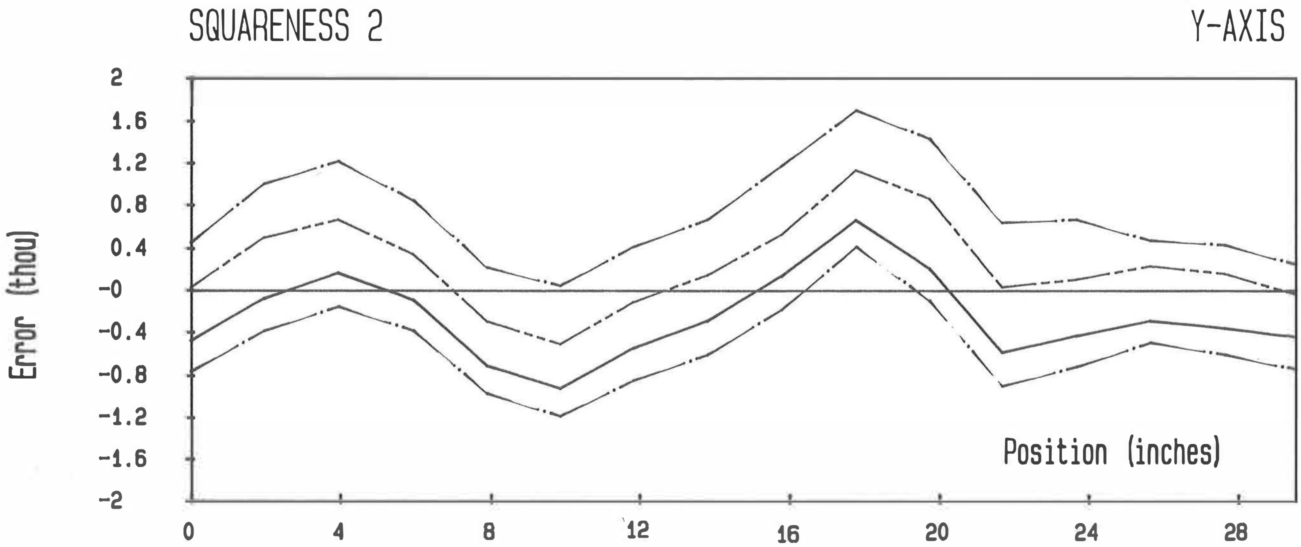


Figure 2.48—Second laser setup for measuring squareness of travel in the **YZ**-plane.



Machine: ROUTER NO.1	Axis: Y	Accuracy: 0.9308
Serial No:	Location:	Uni-dir. Rep: 0.6644
Date: 3/29/94	Slope: 24.03 ARCSEC	Bi-dir. Rep: 0.6644
By:	Str. Error : 0.4344	Mean rev: -0.0287



Machine: ROUTER NO.1	Axis: Y	Accuracy: 2.8872
Serial No:	Location:	Uni-dir. Rep: 1.3098
Date: 3/28/93	Slope: -385.96	Bi-dir. Rep: 1.5387
By:	Str. Error : 2.0606	Mean rev: 0.4946

Graph 1: NEWSQZYZ.STZ Slope: 24.03 ARC-SECONDS
Graph 2: NEWSQZYY.STY Slope: -385.96 ARC-SECONDS
(Prism error-(-385.96+24.03)) = 360.63 ARC-SECONDS
Squareness error: 360.63 ARC-SECONDS 1.74837 thou/inch

Figure 2.49—Results showing squareness of travel in the YZ-plane.

3.0 Machining Evaluation

3.1 Accuracy (Cuts in Acrylic Sheets)

3.1.1 Circles Cut in Acrylic Sheets

Purpose—This procedure determines the ability of the router to accurately cut circles at different feed rates with minimal effects of cutting pressures.

Recommended equipment:

- A 1/4-inch-thick, 12-inch-square sheet of cast acrylic (Lucite'L or equivalent) is required for each feed rate to be evaluated.
- Blunt-nosed calipers that read to 0.001 of an inch and have a jaw opening of 12 inches. The calipers must meet national standards.
- Program for the CNC controller to cut the circles used in the procedure. This is discussed later.
- A 0.25-inch collet and 0.25-inch upcut spiral tool for cutting the acrylic.
- Dial gauge that has graduations of 0.0001 inch, reading of 0-4-0, and range of 0.008 inch with an accuracy of at least 0.00008 inch over the full range.

Method—The feed rate(s) used in the procedure will be specified by the potential user of the machine. For each feed rate, the circles are cut in 1/4-inch-thick cast acrylic sheets. Because the final cuts only remove 0.0625 inch of material, there is minimal cutting pressure. The following steps describe the procedure in detail.

Step 1
Develop and load a program into the CNC controller for cutting two circles with finish diameters of 2 and 8 inches. First, roughing cuts are made with an offset of 0.0625 inch from the finish circles' diameters to a depth of 0.1875 of an inch. Then, the final cuts are made to the target dimensions to a depth of 0.1562 of an inch. The program also must provide for cutting 1.25-inch slots with the center of the tool starting 1 inch from the outer circle and radiating out at 0°, 90°, 180°, and 270°. The center of the tool should be offset to the right for the 0° and 270° slots and offset to the left for the 90° and 180° slots. These slots are used as guides for a straightedge to mark the circles for measurements. Figure 3.1 shows the cuts made in the material. Appendix A.3 provides a procedure for developing the program along with a sample program that will work on most computer controllers with little or no modification.

Step 2
Using procedure 1.1.1, warm up the spindle motor to the steady-state temperature and power (kW) condition.

Step 3
Mount the 0.25-inch tool for cutting the acrylic into the spindle collet/chuck. Measure and record both the actual tool diameter and total runout to 0.0001 of an inch. Add these two values to determine the offset value required by the CNC controller. Note that some controllers use the tool radius instead of the diameter to set the offset. In that situation, one-half of the tool runout would be added to the actual tool radius.

Step 4
Using a proper fixture, attach a 12-inch-square, 1/4-inch-thick acrylic sheet to the router table (centered in both the X-axis and the Y-axis). Enter the first feed rate into the circle program and cut the first group of circles. Be sure to mark the feet rate used on the acrylic sheet.

Step 5
Repeat Step 4 with a new acrylic sheet for each feed rate for which the cutting accuracy is to be evaluated.

Results—Using the 1.25-inch slots as guides, mark or scratch lines through the center of the circles in both the X-axis and Y-axis on the acrylic squares as shown in Figure 3.1. Identify the points where the lines intersect the circles with letters of the alphabet as shown in the figure. Measure and record diameters A-B and C-D of the large circle and diameters E-F and G-H of the small circle. These measurements are made with the blunt-nosed calipers. Repeat this procedure for each acrylic square representing the different feed speeds. Here is an example of the study router's circle cutting accuracy at three different feed rates:

Circle Cutting Accuracy						
	Feed Speed					
Measurement	100 IPM		200 IPM		300 IPM	
Location	Target	Actual	Target	Actual	Target	Actual
	- - - - - - - - - - Diameter (*Inches*) - - - - - - - - -					
A-B	8.000	7.977	8.000	7.975	8.000	7.973
C-D	8.000	7.982	8.000	7.980	8.000	7.978
E-F	2.000	1.992	2.000	1.985	2.000	1.974
G-H	2.000	1.992	2.000	1.986	2.000	1.975

Note: The above procedure evaluates the cutting accuracy only at the center of the router table. However, if accuracy is a critical factor, the same procedure can be done at other locations on the table.

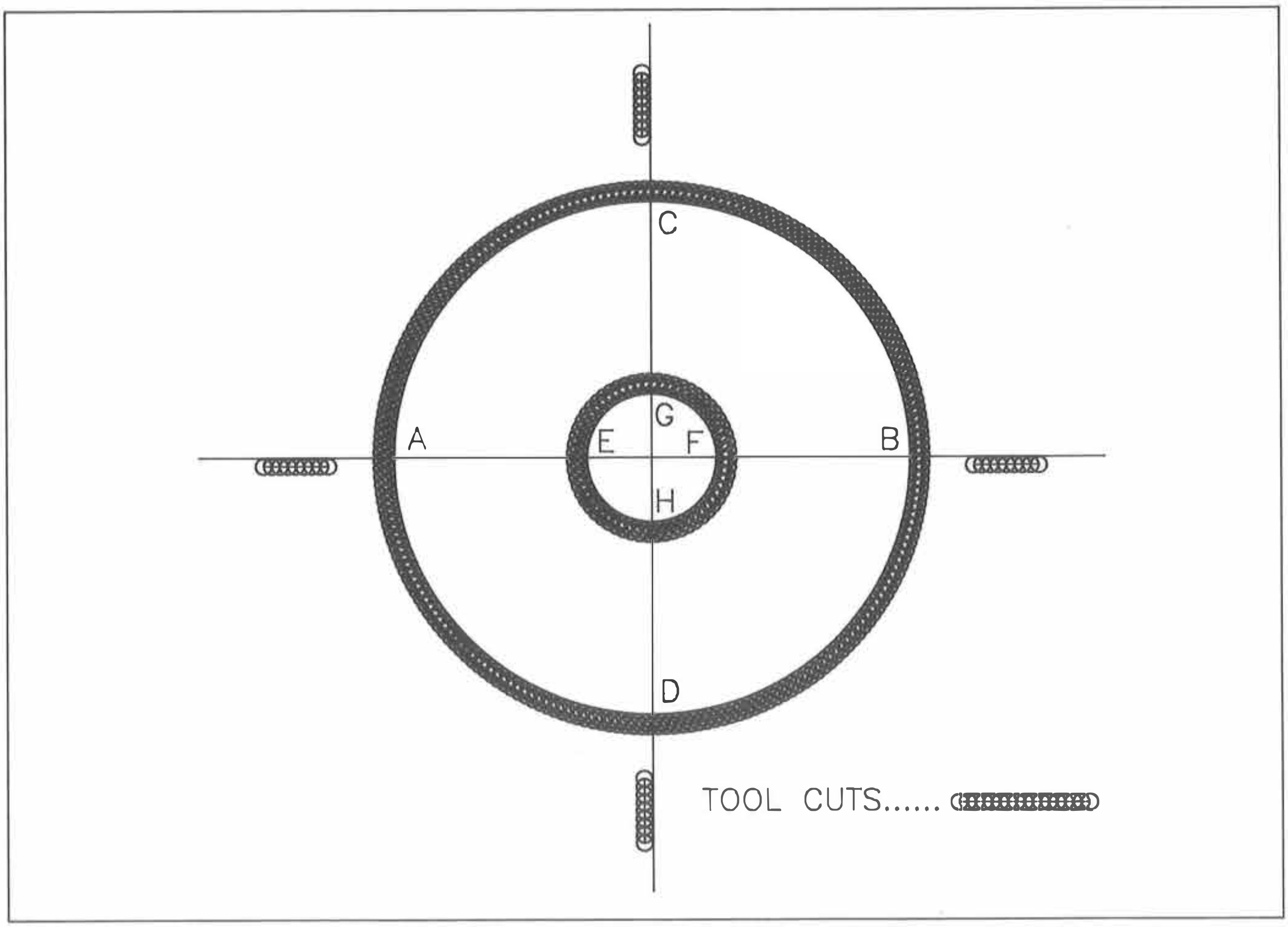


Figure 3.1—Drawing showing accuracy cuts in acrylic sheet and measurement points for both the 2-inch and 8-inch circles.

3.1.2 Squares Cut in Acrylic Sheets

Purpose—This procedure determines the ability of the router to accurately cut squares at different feed rates with minimal effects of cutting pressures.

Recommended equipment:

- A 1/4-inch-thick, 12-inch-square sheet of cast acrylic (Lucite'L or equivalent) is required for each feed rate to be evaluated.
- Blunt-nosed calipers that read to 0.001 of an inch and have a jaw opening of 12 inches. The calipers must meet national standards.
- Programs for the CNC controller to cut the squares used in the procedure. This is discussed later.
- A 0.25-inch collet and 0.25-inch upcut spiral tool for cutting the acrylic.
- Dial gauge that has graduations of 0.0001 inch, reading of 0-4-0, and range of 0.008 inch with an accuracy of at least 0.00008 inch over the full range.

Method—The feed rate(s) used in the procedure will be specified by the potential user of the machine. For each feed rate, the squares are cut in 1/4-inch-thick cast acrylic sheets. Because the final cuts only remove 0.0625 inch of material, there is minimal cutting pressure. The following steps describe the procedure in detail.

Step 1

Develop and load a program into the CNC controller for cutting two squares with finish dimensions of 2 and 8 inches. First, roughing cuts are made with an offset of 0.0625 inch from the finish squares' dimensions to a depth of 0.1875 of an inch. Then, the final cuts are made to the target dimensions to a depth of 0.1562 of an inch. The program also must provide for cutting 1.25-inch slots with the center of the tool starting 1 inch from the outer square and radiating out at 0°, 90°, 180°, and 270°. The center of the tool should be offset to the right for the 0° and 270° slots and offset to the left for the 90° and 180° slots. These slots are used as guides for a straightedge to mark the squares for measurements. Figure 3.2 shows the cuts made in the material. Appendix A.4 provides a procedure for developing the program along with a sample program that will work on most computer controllers with little or no modification. Notice in the program that there is a G4 exact stop code at each corner of the square when making the finish cuts. These stop codes must be used to assure that the corners of the square are not rounded off.

Step 2

Using procedure 1.1.1, warm up the spindle motor to the steady-state temperature and power (kW) condition.

Step 3

Mount the 0.25-inch tool for cutting the acrylic into the spindle collet/chuck. Measure and record both the actual tool diameter and total runout to 0.0001 of an inch. Add these two values to determine the offset value required by the CNC controller. Note that some controllers use the tool radius instead of the diameter to set the offset. In that situation, one-half of the tool runout would be added to the actual tool radius.

Step 4

Using a proper fixture, attach a 12-inch-square, 1/4-inch-thick acrylic sheet to the router table (centered in both the X-axis and the Y-axis). Enter the first feed rate into the square program and cut the first group of squares. Be sure to mark the feed rate used on the acrylic sheet.

Step 5

Repeat Step 4 with a new acrylic sheet for each feed rate for which the cutting accuracy is to be evaluated.

Results—Using the 1.25-inch slots as guides, mark or scratch lines through the center of the squares in both the X-axis and Y-axis on the acrylic squares as shown in Figure 3.2. Identify the points where the lines intersect the squares and the corners of the squares with letters of the alphabet as shown in the figure. Measure and record dimensions A-B, C-D, E-F, and G-H of the large square and dimensions I-J, K-L, M-N, and O-P of the small square. These measurements are made with the blunt-nosed calipers. Repeat this procedure for each acrylic square representing the different feed speeds. Here is an example of the study router's square cutting accuracy at three different feed rates:

Square Cutting Accuracy						
	Feed Speed					
Measurement Location	100 IPM		200 IPM		300 IPM	
	Target	Actual	Target	Actual	Target	Actual
	- - - - - - - - - Dimension (*Inches*) - - - - - - - - -					
A-B	8.000	8.003	8.000	8.003	8.000	8.003
C-D	8.000	8.007	8.000	8.008	8.000	8.008
E-F	11.314	11.317	11.314	11.316	11.314	11.315
G-H	11.314	11.318	11.314	11.319	11.314	11.318
I-J	2.000	2.001	2.000	2.002	2.000	2.003
K-L	2.000	2.004	2.000	2.005	2.000	2.003
M-N	2.828	2.829	2.828	2.827	2.828	2.828
O-P	2.828	2.828	2.828	2.827	2.828	2.828

Note: The above procedure evaluates the cutting accuracy only at the center of the router table. However, if accuracy is a critical factor, the same procedure can be done at other locations on the table.

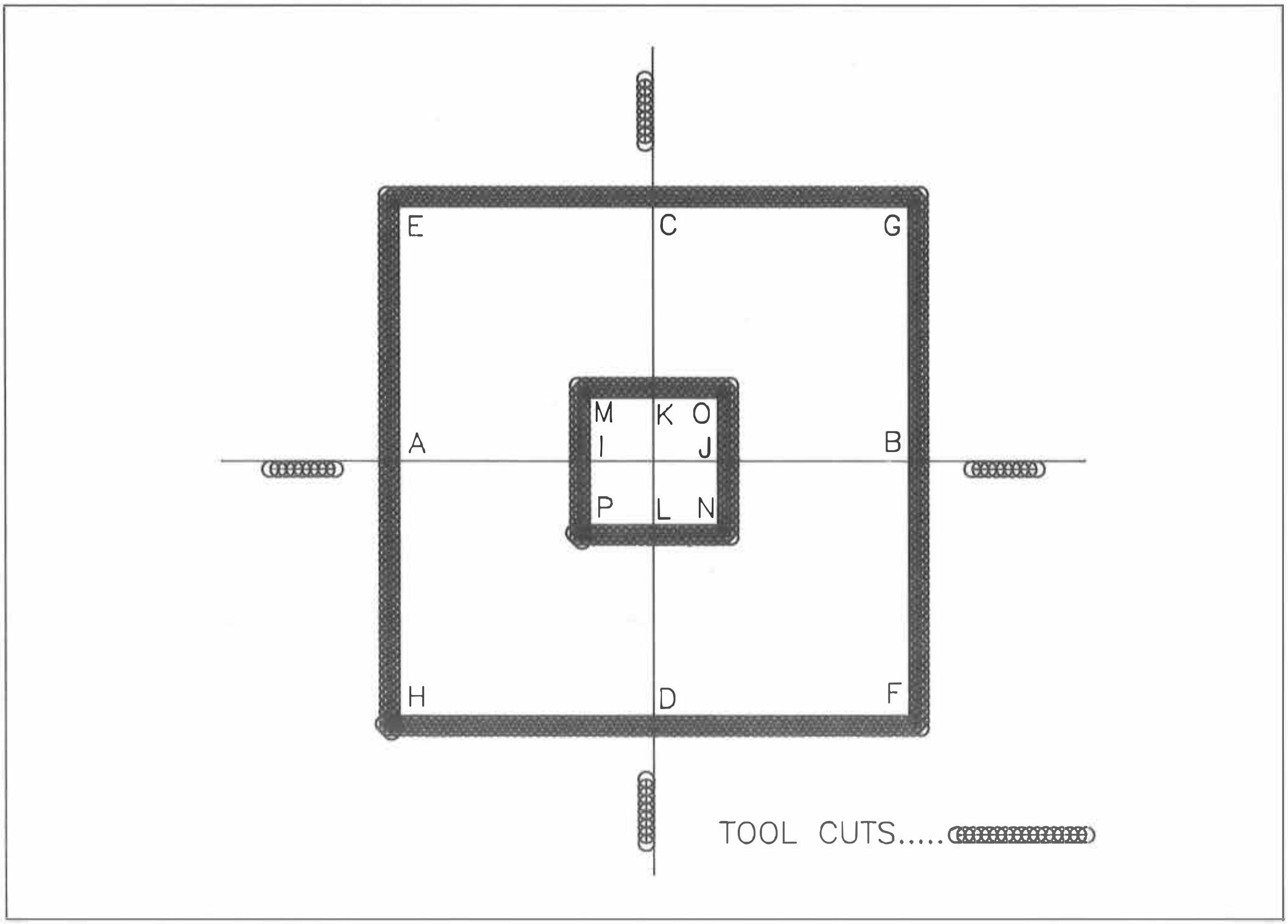


Figure 3.2—Drawing showing accuracy cuts in acrylic sheet and measurement points for both the 2-inch and 8-inch squares.

3.1.3 Diamonds Cut in Acrylic Sheets

Purpose—This procedure determines the ability of the router to accurately cut diamonds at different feed rates with minimal effects of cutting pressures.

Recommended equipment:

- A 1/4-inch-thick, 12-inch-square sheet of cast acrylic (Lucite'L or equivalent) is required for each feed rate to be evaluated.

- Blunt-nosed calipers that read to 0.001 of an inch and have a jaw opening of 12 inches. The calipers must meet national standards.

- Programs for the CNC controller to cut the diamonds used in the procedure. This is discussed later.

- A 0.25-inch collet and 0.25-inch upcut spiral tool for cutting the acrylic.

- Dial gauge that has graduations of 0.0001 inch, reading of 0-4-0, and range of 0.008 inch with an accuracy of at least 0.00008 inch over the full range.

Method—The feed rate(s) used in the procedure will be specified by the potential user of the machine. For each feed rate, the diamonds are cut in 1/4-inch-thick cast acrylic sheets. Because the final cuts only remove 0.0625 inch of material, there is minimal cutting pressure. The following steps describe the procedure in detail.

Step 1

Develop and load a program into the CNC controller for cutting two diamonds with finish dimensions of 2 and 8 inches. First, roughing cuts are made with an offset of 0.0625 inch from the finish diamonds' dimensions to a depth of 0.1875 of an inch. Then, the final cuts are made to the target dimensions to a depth of 0.1562 = of an inch. The program also must provide for cutting 1.25-inch slots with the center of the tool starting 1 inch from the outer diamond and radiating out at 45°,135°, 225°, and 315°. The center of the tool should be offset to the right for the 225° and 315° slots and offset to the left for the 45° and 135° slots. These slots are used as guides for a straightedge to mark the diamonds for measurements. Figure 3.3 shows the cuts made in the material. Appendix A.5 provides a procedure for developing the program along with a sample program that will work on most computer controllers with little or no modification. Notice in the program that there is a G4 exact stop code at each corner of the diamond when making the finish cuts. These stop codes must be used to assure that the corners of the diamonds are not rounded off.

Step 2

Using procedure 1.1.1, warm up the spindle motor to the steady-state temperature and power (kW) condition.

Step 3

Mount the 0.25-inch tool for cutting the acrylic into the spindle collet/chuck. Measure and record both the actual tool diameter and total runout to 0.0001of an inch. Add these two values to determine the offset value required by the CNC controller. Note that some controllers use the tool radius instead of the diameter to set the offset. In that situation, one-half of the tool runout would be added to the actual tool radius.

Step 4

Using a proper fixture, attach a 12-inch square, 1/4-inch-thick acrylic sheet to the router table (centered in both the X-axis and the Y-axis). Enter the first feed rate into the diamond program and cut the first group of diamonds. Be sure to mark the feed rate used on the acrylic sheet.

Step 5

Repeat Step 4 with a new acrylic sheet for each feed rate for which the cutting accuracy is to be evaluated.

Results—Using the 1.25-inch slots as guides, mark or scratch lines through the center of the diamonds on the acrylic squares as shown in Figure 3.3. Identify the points where the lines intersect the diamonds and the corners of the diamonds with letters of the alphabet as shown in the figure. Measure and record dimensions A-B, C-D, E-F, and G-H of the large diamond and dimensions I-J, K-L, M-N, and O-P of the small diamond. These measurements are made with the blunt-nosed calipers. Repeat this procedure for each acrylic square representing the different feed speeds. Here is an example of the study router's diamond cutting accuracy at three different feed rates:

	Diamond Cutting Accuracy					
	Feed Speed					
Measurement	100 IPM		200 IPM		300 IPM	
Location	Target	Actual	Target	Actual	Target	Actual
	- - - - - - - - - Dimension (Inches) - - - - - - - - -					
A-B	8.000	8.005	8.000	8.009	8.000	8.009
C-D	8.000	8.004	8.000	8.009	8.000	8.007
E-F	11.314	11.313	11.314	11.311	11.314	11.316
G-H	11.314	11.323	11.314	11.328	11.314	11.323
I-J	2.000	2.002	2.000	2.006	2.000	2.006
K-L	2.000	2.002	2.000	2.004	2.000	2.006
M-N	2.828	2.827	2.828	2.823	2.828	2.828
O-P	2.828	2.829	2.828	2.832	2.828	2.828

Note: The above procedure evaluates the cutting accuracy only at the center of the router table. However, if accuracy is a critical factor, the same procedure can be done at other locations on the table.

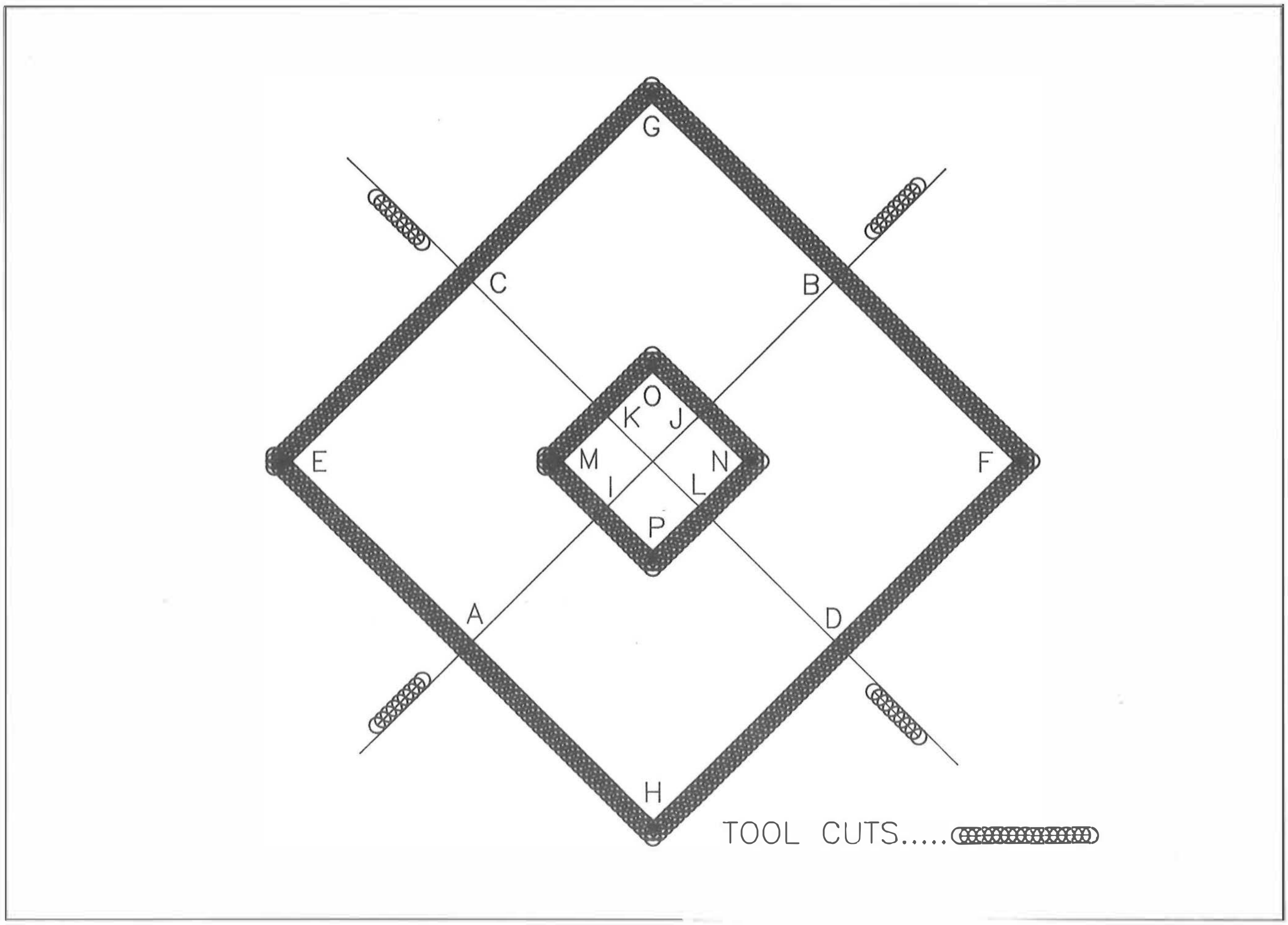


Figure 3.3—Drawing showing accuracy cuts in acrylic sheet and measurement points for both the 2-inch and 8-inch diamonds.

3.2 Accuracy (Cuts in Specified Raw Material)

3.2.1 Circles Cut in Specified Raw Material

Purpose—This procedure determines the ability of the router to accurately cut circles in specified raw material at specified feed rates.

Recommended equipment:

- A 3/4-inch-thick, 12-inch-square piece of the specified raw material is required for each feed rate to be evaluated.
- Blunt-nosed calipers that read to 0.001 of an inch and have a jaw opening of 12 inches. The calipers must meet national standards.
- Program for the CNC controller to cut the circles used in the procedure. This is discussed later.
- A tool/bit with a 0.5-inch diameter cutting head.
- Dial gauge that has graduations of 0.0001 inch, reading of 0-4-0, and range of 0.008 inch with an accuracy of at least 0.00008 inch over the full range.

Method—The feed rate(s) and raw material used in the procedure will be specified by the potential user of the machine. For each feed rate, the circles are cut in the 3/4-inch-thick raw material. The final cuts remove material from only one side of the tool. The resulting side pressure is transferred to the spindle. This procedure measured how the side pressure affects cutting accuracy. The following steps describe the procedure in detail.

Step 1

Develop and load a program into the CNC controller for cutting two circles with diameters of 2 and 8 inches with 0.5-inch lead-in and lead-out cuts of "0°" at the start and end of the cut for each circle. First, roughing cuts are made with an offset from the finish circles' diameters to a depth of 0.625 of an inch. Then, the final cuts are made to the target dimensions to a depth of 0.625 of an inch. The program also must provide for cutting 1.5-inch slots, with the center of the tool starting 1 inch from the outer circle and radiating out at 0°, 90°, 180°, and 270°. The center of the tool should be offset to the right for the 0° and 270° slots and offset to the left for the 90° and 180° slots. These slots are used as guides for a straightedge to mark the circles for measurements. Figure 3.4 shows the cuts made in the material. Appendix A.6 provides a procedure for developing the program along with a sample program that will work on most computer controllers with little or no modification.

Step 2

Using procedure 1.1.1, warm up the spindle motor to the steady-state temperature and power (kW) condition.

Step 3

Mount the 0.5-inch tool into the collet/chuck. Measure and record both the actual tool diameter and total runout to 0.0001 of an inch. Add these two values to determine the offset value required by the CNC controller. Note that some controllers use the tool radius instead of the diameter to set the offset. In that situation, one-half of the tool runout would be added to the actual tool radius.

Step 4

Using a proper fixture, attach the 12-inch-square panel to the router table (centered in both the X-axis and the Y-axis). Enter the first feed rate into the circle program and cut the first group of circles. Be sure to mark the feed rate used on the panel.

Step 5

Repeat Step 4 with a new raw material panel for each feed rate for which the cutting accuracy is to be evaluated.

Results—Using the 1.5-inch slots as guides, mark or scratch lines through the center of the circles in both the X-axis and Y-axis on the raw material panels as shown in Figure 3.4. Identify the points where the lines intersect the circles with letters of the alphabet as shown in the figure. Measure and record diameters A-B and C-D of the large circle and diameters E-F and G-H of the small circle. These measurements are made with the blunt-nosed calipers. Repeat this procedure for each raw material panel representing the different feed speeds. Here is an example of the study router's circle cutting accuracy in the specified raw material at a feed rate of 315 IPM.

Circle Cutting Accuracy		
Measurement Location	Target	Actual
	- Diameter (*Inches*) -	
A-B	8.000	7.984
C-D	8.000	7.994
E-F	2.000	1.987
G-H	2.000	1.995

Note: The above procedure evaluates the cutting accuracy only at the center of the router table. However, if accuracy is a critical factor, the same procedure can be done at other locations on the table.

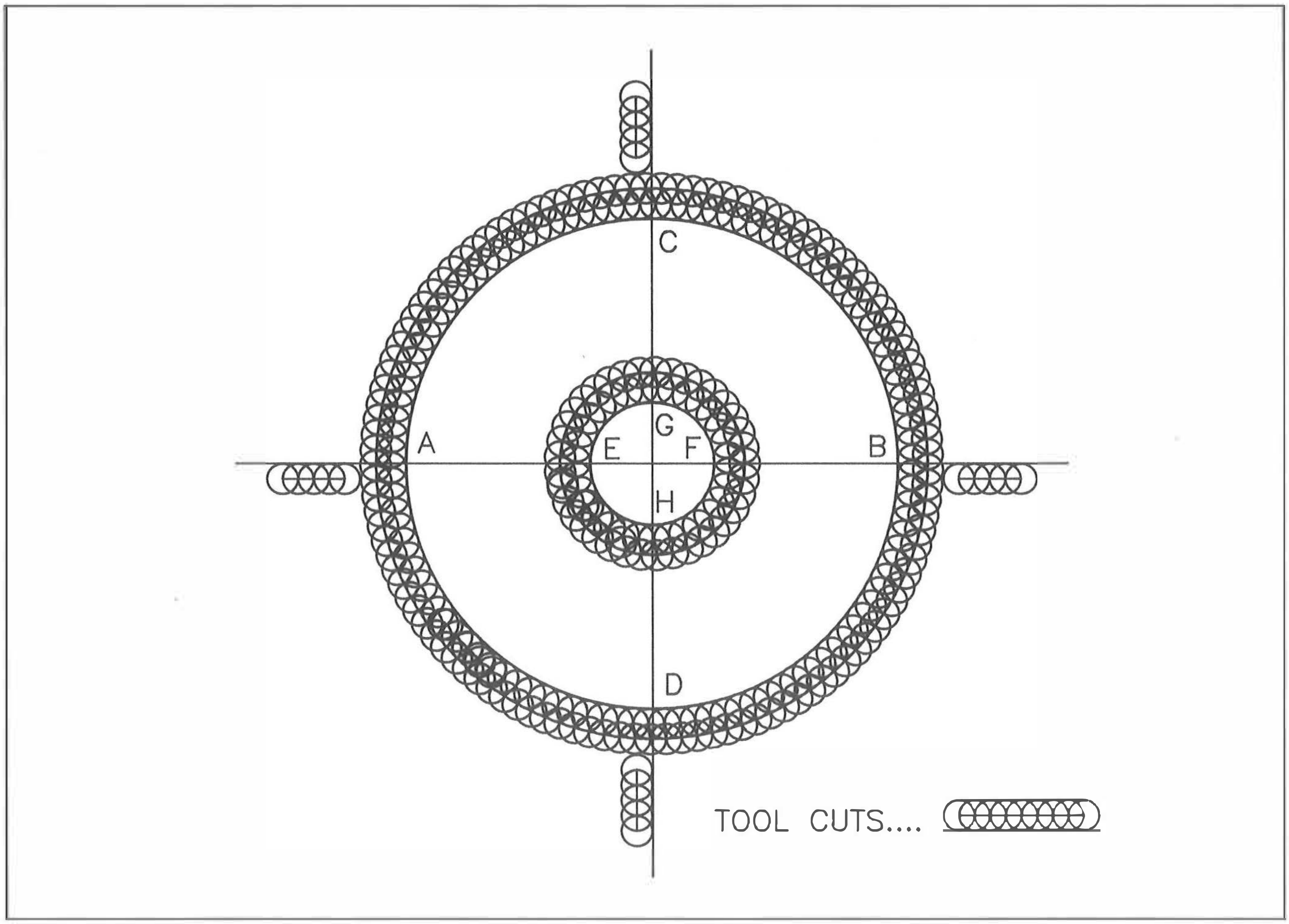


Figure 3.4—Drawing showing accuracy cuts in specified raw material and measurement points for both the 2-inch and 8-inch circles.

3.2.2 Squares Cut in Specified Raw Material

Purpose—This procedure determines the ability of the router to accurately cut squares in specified raw material at specified feed rates.

Recommended equipment:

- A 3/4-inch-thick, 12-inch-square piece of the specified raw material is required for each feed rate to be evaluated.
- Blunt-nosed calipers that read to 0.001 of an inch and have a jaw opening of 12 inches. The calipers must meet national standards.
- Program for the CNC controller to cut the squares used in the procedure. This is discussed later.
- A tool/bit with a 0.5-inch diameter cutting head.
- Dial gauge that has graduations of 0.0001 inch, reading of 0-4-0, and range of 0.008 inch with an accuracy of at least 0.00008 inch over the full range.

Method—The feed rate(s) and raw material used in the procedure will be specified by the potential user of the machine. For each feed rate, the squares are cut in the 3/4-inch-thick raw material. The final cuts remove material from only one side of the tool. The resulting side pressure is transferred to the spindle. This procedure measures how the side pressure affects cutting accuracy. The following steps describe the procedure in detail.

Step 1

Develop and load a program into the CNC controller for cutting two squares with sides of 2 and 8 inches with 0.5-inch lead-in and lead-out cuts of "0°" at the start and end of the cut for each square. First, roughing cuts are made with an offset from the finish squares' dimensions to a depth of 0.625 of an inch. Then, the final cuts are made to the target dimensions to a depth of 0.625 of an inch. The program also must provide for cutting 1.5-inch slots with the center of the tool starting 1 inch from the outer square and radiating out at 0°, 90°, 180°, and 270°. The center of the tool should be offset to the right for the 0° and 270° slots and offset to the left for the 90° and 180° slots. These slots are used as guides for a straightedge to mark the squares for measurements. Figure 3.5 shows the cuts made in the material. Appendix A.7 provides a procedure for developing the program along with a sample program that will work on most computer controllers with little or no modification. Notice in the program that there is a G4 exact stop code at each corner of the square when making the finish cuts. These stop codes must be used to assure that the corners of the square are not rounded off.

Step 2

Using procedure 1.1.1, warm up the spindle motor to the steady-state temperature and power (kW) condition.

Step 3

Mount the 0.5-inch tool into the collet/chuck. Measure and record both the actual tool diameter and total runout to 0.0001 of an inch. Add these two values to determine the offset value required by the CNC controller. Note that some controllers use the tool radius instead of the diameter to set the offset. In that situation, one-half of the tool runout would be added to the actual tool radius.

Step 4

Using a proper fixture, attach a 12-inch-square panel to the router table (centered in both the X-axis and the Y-axis). Enter the first feed rate into the square program and cut the first group of squares. Be sure to mark the feet rate used on the acrylic sheet.

Step 5

Repeat Step 4 with a new raw material panel for each feed rate for which the cutting accuracy is to be evaluated.

Results—Using the 1.5-inch slots as guides, mark or scratch lines through the center of the squares in both the X-axis and Y-axis on the raw material panels as shown in Figure 3.5.

Identify the points where the lines intersect the squares and the corners of the squares with letters of the alphabet as shown in the figure. Measure and record dimensions A-B, C-D, E-F, and G-H of the large square and dimensions I-J, K-L, M-N, and O-P of the small square. These measurements are made with the blunt-nosed calipers. Repeat this procedure for each raw material panel representing the different feed speeds. Here is an example of the study router's square cutting accuracy in the specified raw material at a feed rate of 315 inches per minute.

Square Cutting Accuracy		
Measurement Location	Target	Actual
	- Dimension (*Inches*) -	
A-B	8.000	8.015
C-D	8.000	8.025
E-F	11.314	11.332
G-H	11.314	11.332
I-J	2.000	2.018
K-L	2.000	2.022
M-N	2.828	2.845
O-P	2.828	2.842

Note: The above procedure evaluates the cutting accuracy only at the center of the router table. However, if accuracy is a critical factor, the same procedure can be done at other locations on the table.

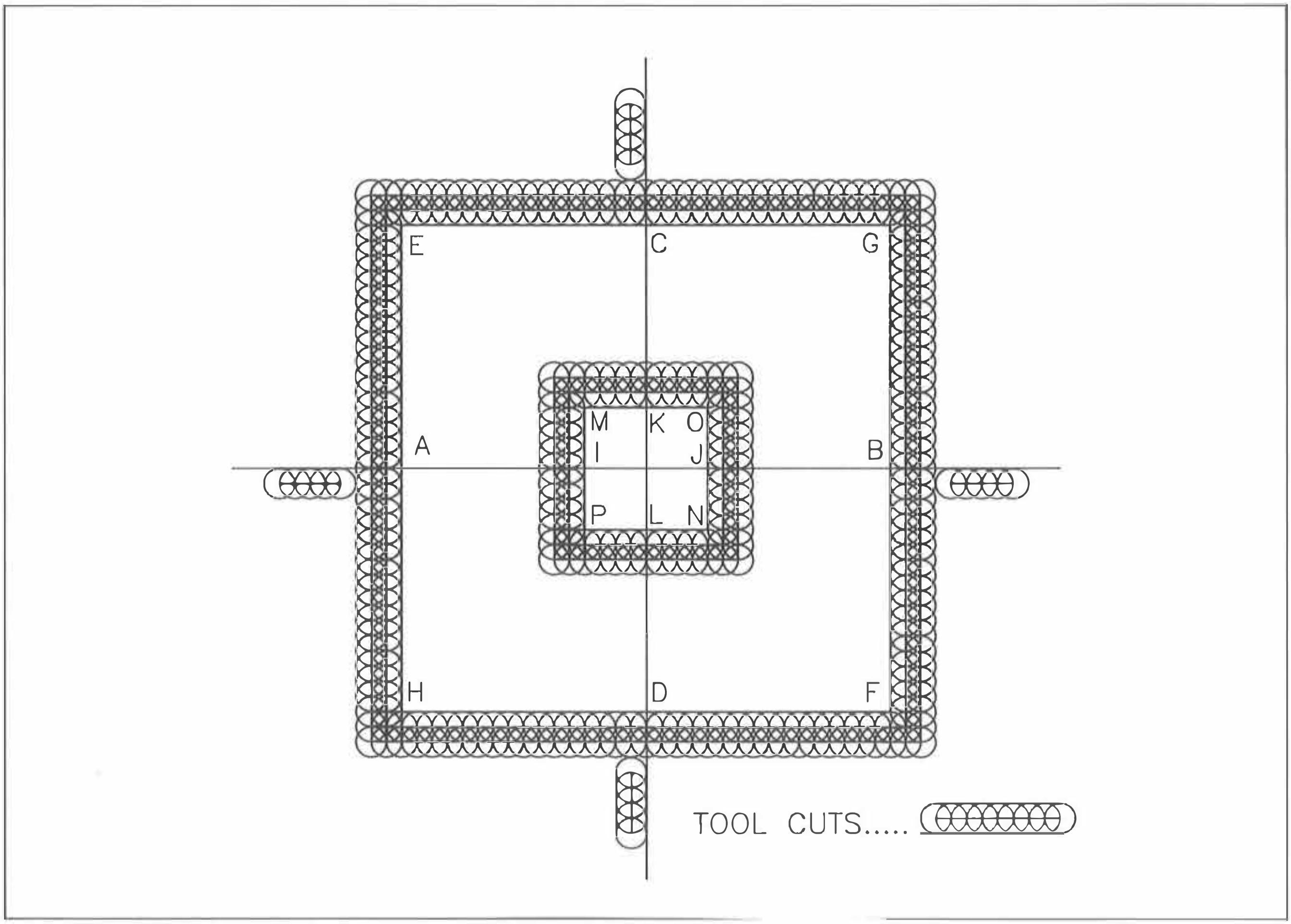


Figure 3.5—Drawing showing accuracy cuts in specified raw material and measurement points for both the 2-inch and 8-inch squares.

3.2.3 Diamonds Cut in Specified Raw Material

Purpose—This procedure determines the ability of the router to accurately cut diamonds in specified raw material at specified feed rates.

Recommended equipment:

- A 3/4-inch-thick, 12-inch-square piece of the specified raw material is required for each feed rate to be evaluated.
- Blunt-nosed calipers that read to 0.001 of an inch and have a jaw opening of 12 inches. The calipers must meet national standards.
- Program for the CNC controller to cut the diamonds used in the procedure. This is discussed later.
- A tool/bit with a 0.5-inch diameter cutting head.
- Dial gauge that has graduations of 0.0001 inch, reading of 0-4-0, and range of 0.008 inch with an accuracy of at least 0.00008 inch over the full range.

Method—The feed rate(s) and raw material used in the procedure will be specified by the potential user of the machine. For each feed rate, the diamonds are cut in the 3/4-inch-thick raw material. The final cuts remove material from only one side of the tool. The resulting side pressure is transferred to the spindle. This procedure measures how this side pressure affects cutting accuracy. The following steps describe the procedure in detail.

Step 1

Develop and load a program into the CNC controller for cutting two diamonds with sides of 2 and 8 inches with 0.5-inch lead-in and lead-out cuts of "0°" at the start and end of the cut for each diamond. First, roughing cuts are made with an offset from the finish diamonds' dimensions to a depth of 0.625 of an inch. Then, the final cuts are made to the target dimensions to a depth of 0.625 of an inch. The program also must provide for cutting 1.5-inch slots, with the center of the tool starting 1 inch from the outer diamond and radiating out from the center of the diamonds at 45°, 135°, 225°, and 315°. The center of the tool should be offset to the right for the 225° and 315° slots and offset to the left for the 45° and 135° slots. These slots are used as guides for a straightedge to mark the diamonds for measurements. Figure 3.6 shows the cuts made in the material. Appendix A.8 provides a procedure for developing the program along with a sample program that will work on most computer controllers with little or no modification. Notice in the program that there is a G4 exact stop code at each corner of the diamond when making the finish cuts. These stop codes must be used to assure that the corners of the diamond are not rounded off.

Step 2

Using procedure 1.1.1, warm up the spindle motor to the steady-state temperature and power (kW) condition.

Step 3

Mount the 0.5-inch-tool into the collet/chuck. Measure and record both the actual tool diameter and total runout to 0.0001 of an inch. Add these two values to determine the offset value required by the CNC controller. Note that some controllers use the tool radius instead of the diameter to set the offset. In that situation, one-half of the tool runout would be added to the actual tool radius.

Step 4

Using a proper fixture, attach a 12-inch-square raw material panel to the router table (centered in both the X-axis and the Y-axis). Enter the first feed rate into the diamond program and cut the first group of diamonds. Be sure to mark the feed rate used on the acrylic sheet.

Step 5

Repeat Step 4 with a new raw material panel for each feed rate for which the cutting accuracy is to be evaluated.

Results—Using the 1.5-inch slots as guides, mark or scratch lines through the center of the diamonds on the raw material panels as shown in Figure 3.6. Identify the points where the lines intersect the diamonds and the corners of the diamonds with letters of the alphabet as shown in the figure. Measure and record dimensions A-B, C-D, E-F, and G-H of the large diamond and dimensions I-J, K-L, M-N, and O-P of the small diamond. These measurements are made with the blunt-nosed calipers. Repeat this procedure for each raw material panel representing the different feed speeds. Here is an example of the study router's diamond cutting accuracy in the specified raw material at a feed rate of 315 inches per minute:

Diamond Cutting Accuracy		
Measurement Location	Target	Actual
	- Dimension (*Inches*) -	
A-B	8.000	8.021
C-D	8.000	8.022
E-F	11.314	11.325
G-H	11.314	11.338
I-J	2.000	2.020
K-L	2.000	2.020
M-N	2.828	2.840
O-P	2.828	2.847

Note: The above procedure evaluates the cutting accuracy only at the center of the router table. However, if accuracy is a critical factor, the same procedure can be done at other locations on the table.

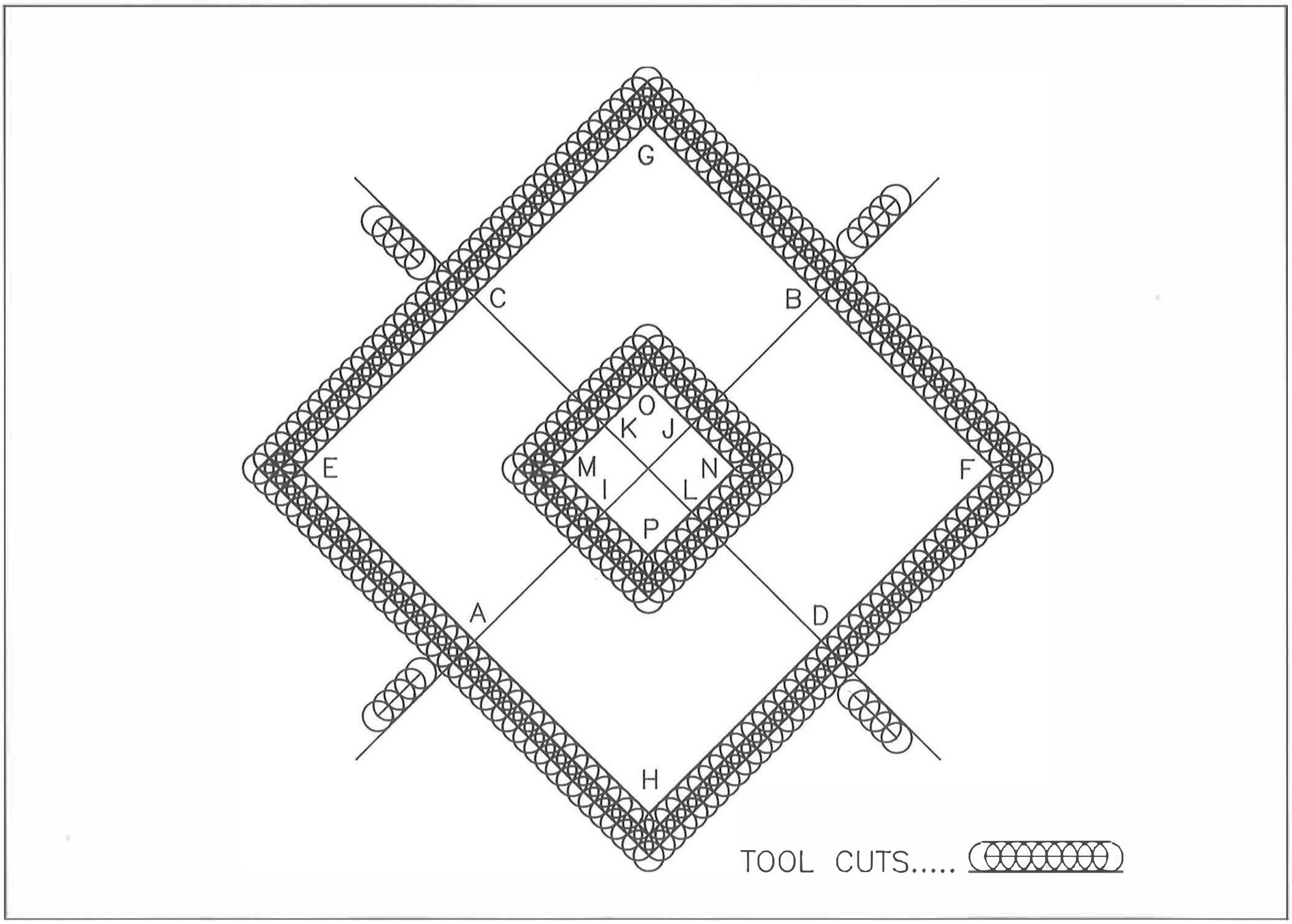


Figure 3.6—Drawing showing accuracy cuts in specified raw material and measurement points for both the 2-inch and 8-inch diamonds.

3.3 Repeatability (Cuts in Acrylic Sheets)

3.3.1 Circles Cut in Acrylic Sheets

Purpose—This procedure determines the repeatability of the router when cutting circles in acrylic sheets at specified feed rates.

Recommended Equipment:

- A 1/4-inch-thick, 12-inch-square sheet of cast acrylic (Lucite'L or equivalent) is required for each feed rate to be evaluated.
- Blunt-nosed calipers that read to 0.001 of an inch and have a jaw opening of 12 inches. The calipers must meet national standards.
- Program for the CNC controller to cut the circles used in the procedure. This is discussed later.
- A 0.25-inch collet and 0.25-inch upcut spiral tool for cutting the acrylic.
- Dial gauge that has graduations of 0.0001 inch, reading of 0-4-0, and range of 0.008 inch with an accuracy of at least 0.00008 inch over the full range.

Method—The feed rate(s) used in the procedure will be specified by the potential user of the machine. For each feed rate, the circles are cut in 1/4-inch-thick cast acrylic sheets. The following steps describe the procedure in detail.

Step 1

Develop and load a program into the CNC controller for cutting two circles with diameters of 2 and 8 inches with 0.5-inch lead-in and lead-out cuts of "0°" at the start and end of the cut for each circle. First, roughing cuts are made with an offset of 0.0625 inch from the finish circles' diameters to a depth of 0.1875 of an inch. Then, cuts are made to the target dimensions to a depth of 0.1562 of an inch. At that point, the cuts to target dimensions are repeated 50 times. The program also must provide for cutting 1.25-inch slots with the center of the tool starting 1 inch from the outer circle and radiating out at 0°, 90° 180°, and 270°. The center of the tool should be offset to the right for the 0° and 270° slots and offset to the left for the 90° and 180° slots. These slots are used as guides for a straightedge to mark the circles for measurements. Figure 3.7 shows the cuts made in the material. Appendix A.9 provides a procedure for developing the program along with a sample program that will work on most computer controllers with little or no modification.

Step 2

Using procedure 1.1.1, warm up the spindle motor to the steady-state temperature and power (kW) condition.

Step 3

Mount the 0.25-inch tool for cutting the acrylic into the spindle collet/chuck. Measure and record both the actual tool diameter and total runout to 0.0001 of an inch. Add these two values to determine the offset value required by the CNC controller. Note that some controllers use the tool radius instead of the diameter to set the offset. In that situation, one-half of the tool runout would be added to the actual tool radius.

Step 4

Using a proper fixture, attach a 12-inch-square, 1/4-inch-thick acrylic square to the router table (centered in both the X-axis and the Y-axis). Enter the first feed rate into the circle program and cut the first group of circles. Be sure to mark the feed rate used on the acrylic sheet.

Step 5

Repeat Step 4 with a new acrylic sheet for each feed rate for which the cutting repeatability is to be evaluated.

Results—Using the 1.25-inch slots as guides, mark or scratch lines through the center of the circles in both the X-axis and Y-axis on the acrylic squares as shown in Figure 3.7. Identify the points where the lines intersect the circles with letters of the alphabet as shown in the figure. Measure and record diameters A-B and C-D of the large circle and diameters E-F and G-H of the small circle. These measurements are made with the blunt-nosed calipers. This procedure is repeated for each acrylic square representing the different feed speeds. Any significant difference between the two diameters for a given circle indicates drift in the computer's control system. Here is an example of the study router's circle cutting repeatability at three different feed rates:

Circle Cutting Repeatability						
	Feed Speed					
Measurement	100 IPM		200 IPM		300 IPM	
Location	Target	Actual	Target	Actual	Target	Actual
	- - - - - - - - - Diameter (*Inches*) - - - - - - - - - -					
A-B	8.000	7.978	8.000	7.975	8.000	7.972
C-D	8.000	7.982	8.000	7.980	8.000	7.978
E-F	2.000	1.992	2.000	1.985	2.000	1.973
G-H	2.000	1.993	2.000	1.986	2.000	1.974

Note: The above procedure evaluates the cutting repeatability only at the center of the router table. However, if repeatability is a critical factor, the same procedure can be done at other locations on the table.

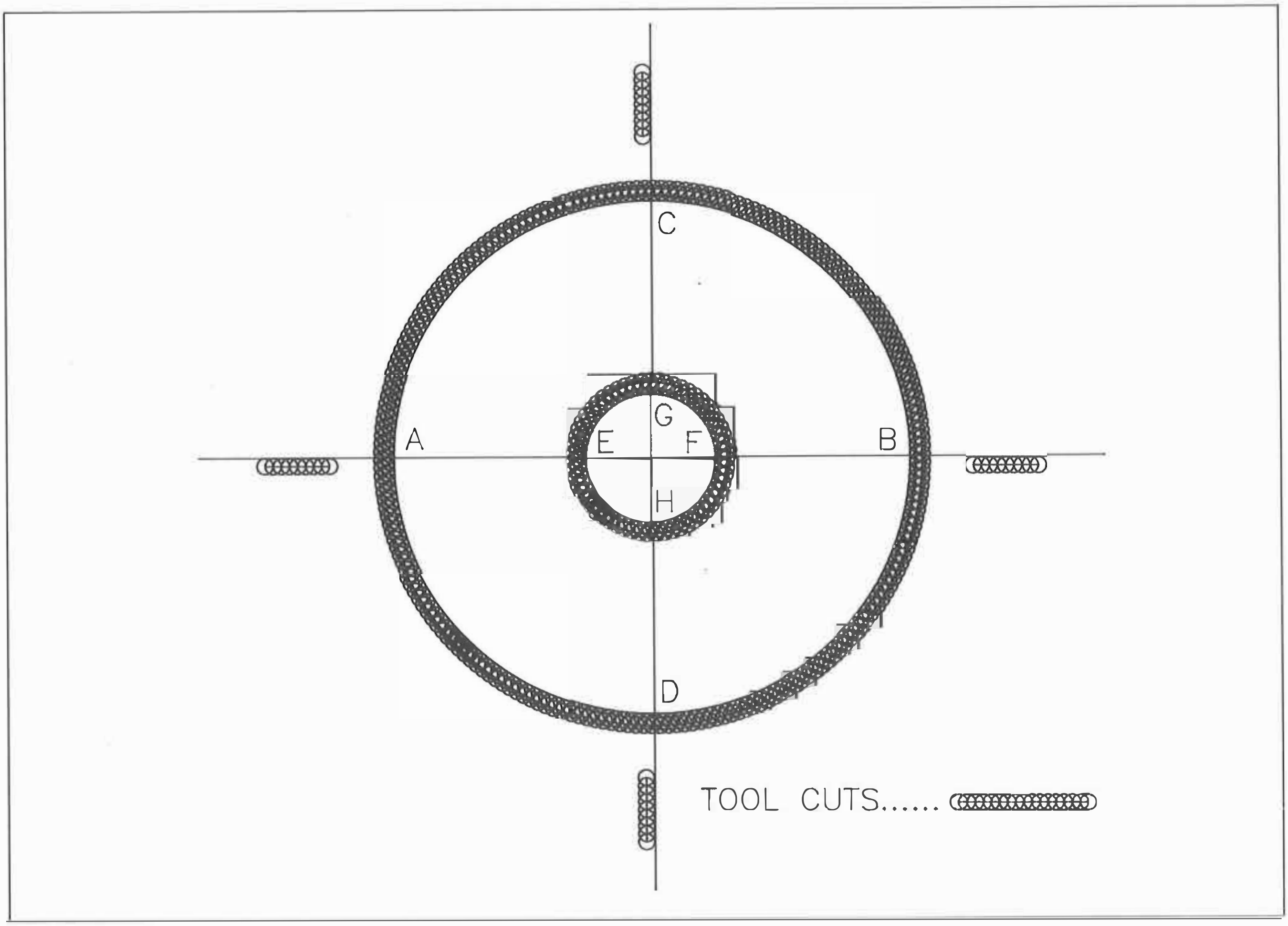


Figure 3.7—Drawing showing repeatability cuts in acrylic sheet and measurement points for both the 2-inch and 8-inch circles.

3.3.2 Squares Cut in Acrylic Sheets

Purpose—This procedure determines the repeatability of the router when cutting squares in acrylic sheets at specified feed rates.

Recommended Equipment:

- A 1/4-inch-thick, 12-inch-square sheet of cast acrylic (Lucite'L or equivalent) is required for each feed rate to be evaluated.
- Blunt-nosed calipers that read to 0.001 of an inch and have a jaw opening of 12 inches. The calipers must meet national standards.
- Program for the CNC controller to cut the squares used in the procedure. This is discussed later.
- A 0.25-inch collet and 0.25-inch upcut spiral tool for cutting the acrylic.
- Dial gauge that has graduations of 0.0001 inch, reading of 0-4-0, and range of 0.008 inch with an accuracy of at least 0.00008 inch over the full range.

Method—The feed rate(s) used in the procedure will be specified by the potential user of the machine. For each feed rate, the squares are cut in 1/4-inch-thick cast acrylic sheets. The following steps describe the procedure in detail.

Step 1

Develop and load a program into the CNC controller for cutting two squares with sides of 2 and 8 inches with 0.5-inch lead-in and lead-out cuts of "0°" at the start and end of the cut for each square. First, roughing cuts are made with an offset of 0.0625 inch from the finish squares' dimensions to a depth of 0.1875 of an inch. Then, cuts are made to the target dimensions to a depth of 0.1562 of an inch. At that point, the cuts to target dimensions are repeated 50 times. The program also must provide for cutting 1.25-inch slots with the center of the tool starting 1 inch from the outer square and radiating out at 0°, 90°, 180°, and 270°. The center of the tool should be offset to the right for the 0° and 270° slots and offset to the left for the 90° and 180° slots. These slots are used as guides for a straightedge to mark the squares for measurements. Figure 3.8 shows the cuts made in the material. Appendix A.10 provides a procedure for developing the program along with a sample program that will work on most computer controllers with little or no modification. Notice in the program that there is a G4 exact stop code at each corner of the square when making the finish cuts. These stop codes must be used to assure that the corners of the square are not rounded off.

Step 2

Using procedure 1.1.1, warm up the spindle motor to the steady state temperature and power (kW) condition.

Step 3

Mount the 0.25-inch tool for cutting the acrylic into the spindle collet/chuck. Measure and record both the actual tool diameter and total runout to 0.0001 of an inch. Add these two values to determine the offset value required by the CNC controller. Note that some controllers use the tool radius instead of the diameter to set the offset. In that situation, one-half of the tool runout would be added to the actual tool radius.

Step 4

Using a proper fixture, attach a 12-inch-square, 1/4-inch-thick acrylic square to the router table (centered in both the X-axis and the Y-axis). Enter the first feed rate into the square program and cut the first group of squares. Be sure to mark the feed rate used on the acrylic sheet.

Step 5

Repeat Step 4 with a new acrylic sheet for each feed rate for which the cutting accuracy is to be evaluated.

Results—Using the 1.25-inch slots as guides, mark or scratch lines through the center of the squares in both the X-axis and Y-axis on the acrylic squares as shown in Figure 3.8. Identify the points where the lines intersect the squares and the corners of the squares with letters of the alphabet as shown in the figure. Measure and record dimensions A-B, C-D, E-F, and G-H of the large square and dimensions I-J, K-L, M-N, and O-P of the small square. These measurements are made with the blunt-nosed calipers. Repeat this procedure for each acrylic square representing the different feed speeds. Any significant difference between the width and height measurements and/or the two diagonal measurements indicates drift in the computer's control system. Here is an example of the study router's square cutting repeatability at three different feed rates:

Square Cutting Repeatability						
	Feed Speed					
Measurement	100 IPM		200 IPM		300 IPM	
Location	Target	Actual	Target	Actual	Target	Actual
	- - - - -- - - - - Dimension (*Inches*) - - - - - - - - - -					
A-B	8.000	8.003	8.000	8.003	8.000	8.002
C-D	8.000	8.006	8.000	8.007	8.000	8.007
E-F	11.313	11.316	11.312	11.311	11.314	11.315
G-H	11.314	11.317	11.311	11.317	11.313	11.317
I-J	2.000	2.002	2.000	2.001	2.000	2.001
K-L	2.000	2.001	2.000	2.001	2.000	2.002
M-N	2.828	2.828	2.828	2.827	2.827	2.828
O-P	2.828	2.828	2.827	2.827	2.828	2.828

Note: The above procedure evaluates the cutting repeatability only at the center of the router table. However, if repeatability is a critical factor, the same procedure can be done at other locations on the table.

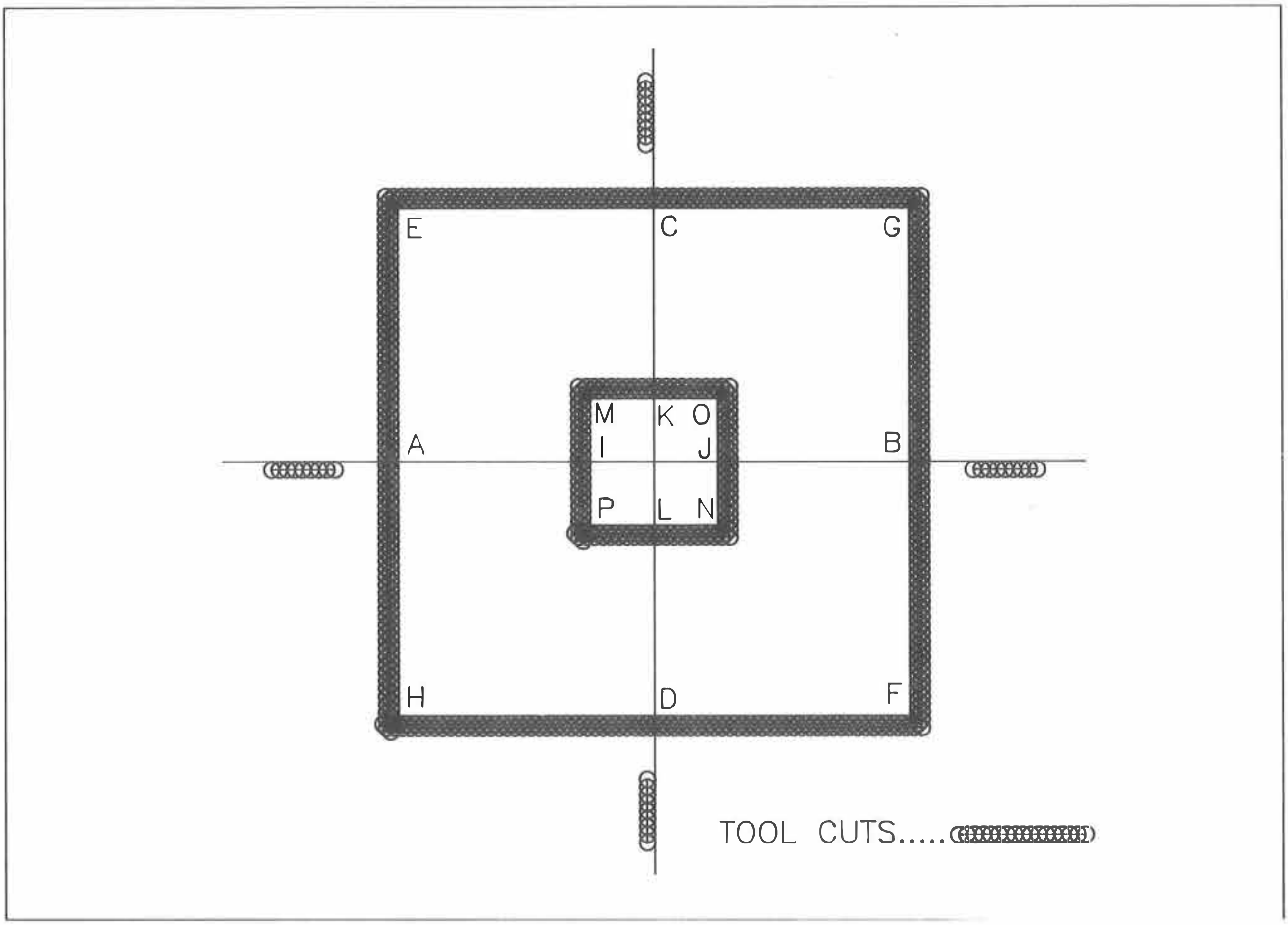


Figure 3.8—Drawing showing repeatability cuts in acrylic sheet and measurement points for both the 2-inch and 8-inch squares.

3.3.3 Diamonds Cut in Acrylic Sheets

Purpose—This procedure determines the repeatability of the router when cutting diamonds in acrylic sheets at specified feed rates.

Recommended equipment:

- A 1/4-inch-thick, 12-inch-square sheet of cast acrylic (Lucite'L or equivalent) is required for each feed rate to be evaluated.
- Blunt-nosed calipers that read to 0.001 of an inch and have a jaw opening of 12 inches. The calipers must meet national standards.
- Program for the CNC controller to cut the diamonds used in the procedure. This is discussed later.
- A 0.25-inch collet and 0.25-inch upcut spiral tool for cutting the acrylic.
- Dial gauge that has graduations of 0.0001 inch, reading of 0-4-0, and range of 0.008 inch with an accuracy of at least 0.00008 inch over the full range.

Method—The feed rate(s) used in the procedure will be specified by the potential user of the machine. For each feed rate, the diamonds are cut in 1/4-inch-thick cast acrylic sheets. The following steps describe the procedure in detail.

Step 1

Develop and load a program into the CNC controller for cutting two diamonds with sides of 2 and 8 inches with 0.5-inch lead-in and lead-out cuts of "0^{o}" at the start and end of the cut for each diamond. First, roughing cuts are made with an offset of 0.0625 of an inch from the finish diamonds' dimensions to a depth of 0.1875 of an inch. Then, cuts are made to the target dimensions to a depth of 0.1562 of an inch. At that point, the cuts to target dimensions are repeated 50 times. The program also must provide for cutting 1.25-inch slots with the center of the tool starting 1 inch from the outer diamond and radiating out at 45°, 135°, 225°, and 315°. The center of the tool should be offset to the right for the 225° and the 315° slots and offset to the left for the 45° and 135° slots. These slots are used as guides for a straightedge to mark the diamonds for measurements. Figure 3.9 shows the cuts made in the material. Appendix A.11 provides a procedure for developing the program along with a sample program that will work on most computer controllers with little or no modification. Notice in the program that there is a G4 exact stop code at each corner of the diamond when making the finish cuts. These stop codes must be used to assure that the corners of the diamond are not rounded off.

Step 2

Using procedure 1.1.1, warm up the spindle motor to the steady-state temperature and power (kW) condition.

Step 3

Mount the 0.25-inch tool for cutting the acrylic into the spindle collet/chuck. Measure and record both the actual tool diameter and total runout to 0.0001 of an inch. Add these two values to determine the offset value required by the CNC controller. Note that some controllers use the tool radius instead of the diameter to set the offset. In that situation, one-half of the tool runout would be added to the actual tool radius.

Step 4

Using a proper fixture, attach a 12-inch-square, 1/4-inch-thick acrylic square to the router table (centered in both the X-axis and the Y-axis). Enter the first feed rate into the diamond program and cut the first group of diamonds. Be sure to mark the feed rate used on the acrylic sheet.

Step 5

Repeat Step 4 with a new acrylic sheet for each feed rate for which the cutting accuracy is to be evaluated.

Results—Using the 1.25-inch slots as guides, mark or scratch lines through the center of the diamonds on the acrylic squares as shown in Figure 3.9. Identify the points where the lines intersect the diamonds and the corners of the diamonds with letters of the alphabet as shown in the figure. Measure and record dimensions A-B, C-D, E-F, and G-H of the large diamond and dimensions I-J, K-L, M-N, and O-P of the small diamond. These measurements are made with the blunt-nosed calipers. This procedure is repeated for each acrylic square representing the different feed speeds. Any significant difference between the two width measurements and/or the two diagonal measurements indicates drift in the computer's control system. Here is an example of the study router's diamond cutting repeatability at three different feed rates:

Diamond Cutting Repeatability

Measurement Location	Feed Speed					
	100 IPM		200 IPM		300 IPM	
	Target	Actual	Target	Actual	Target	Actual
	- - - - - - - - - Dimension (*Inches*) - - - - - - - - -					
A-B	8.000	8.006	8.000	8.005	8.000	8.006
C-D	8.000	8.004	8.000	8.003	8.000	8.002
E-F	11.312	11.313	11.313	11.310	11.312	11.313
G-H	11.313	11.320	11.311	11.325	11.313	11.319
I-J	2.000	2.002	2.000	2.002	2.000	2.001
K-L	2.000	2.001	2.000	2.000	2.000	2.003
M-N	2.826	2.827	2.826	2.822	2.826	2.827
O-P	2.827	2.828	2.828	2.830	2.827	2.826

Note: The above procedure evaluates the cutting repeatability only at the center of the router table. However, if repeatability is a critical factor, the same procedure can be done at other locations on the table.

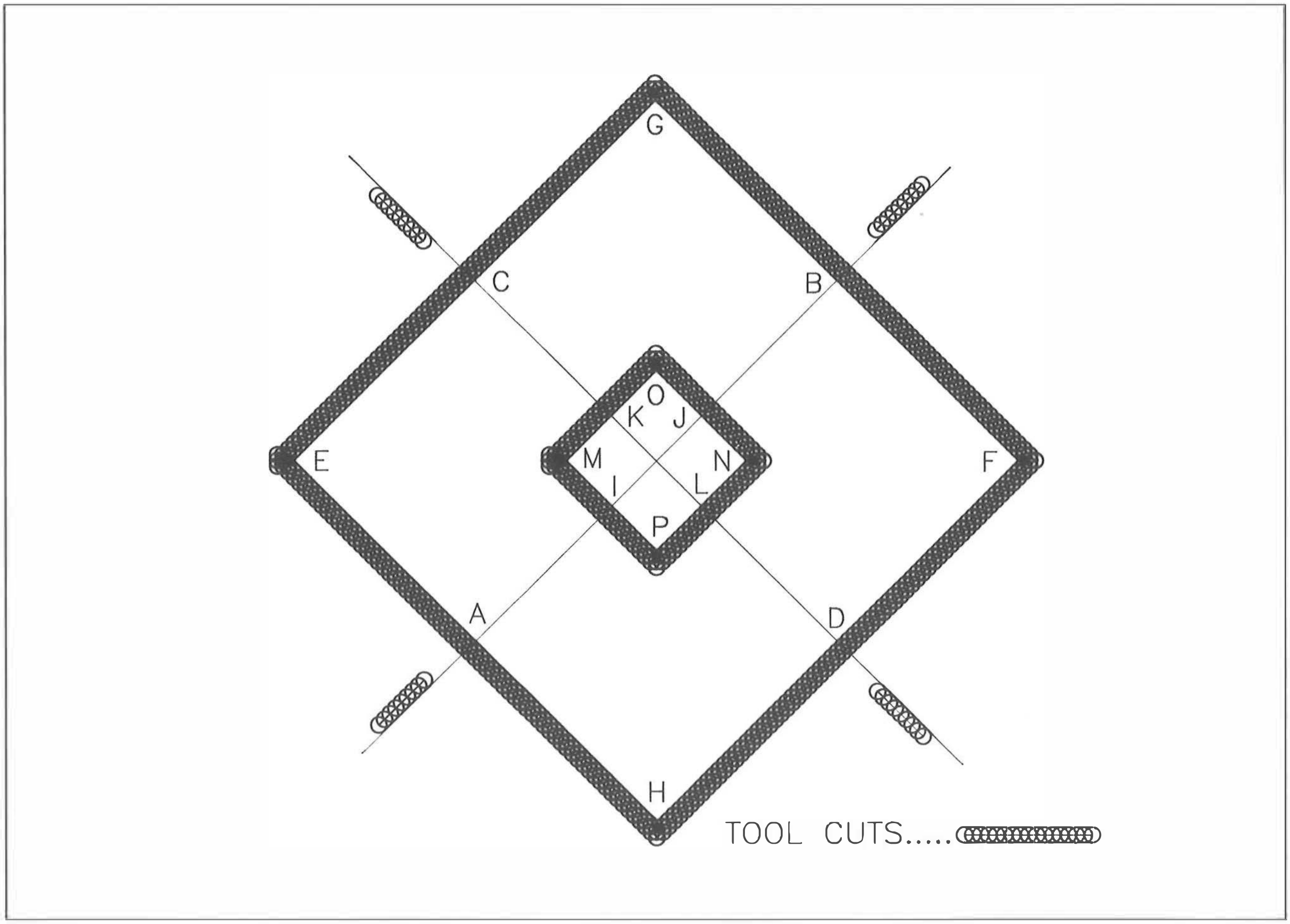


Figure 3.9—Drawing showing repeatability cuts in acrylic sheet and measurement points for both the 2-inch and 8-inch diamonds.

APPENDIX A.1

Figure A.1.1. is an example of positioning programs (G&M code) that are required by many of the laser measurement procedures for evaluating router spindle/table movements.

```
LINEAR POSITIONING IN X-AXIS
*******************************
STANDARD UNITS    METRIC UNITS
**************    **************
O0001;            O0005;
M98 P50002;       M98 P50006;
M30;              M30;
O0002;            O0006;
G20;              G21;
G91 G1 F100;      G91 G1 F2540;
M98 P350003;      M98 P350007;
X1;               X25;
X-1;              X-25;
G4 X5;            G4 X5;
M98 P350004;      M98 P350008;
X-1;              M99;
X1;               O0007
G4 X5;            X50;
M99;              G4 X5;
O0003;            M99;
X2;               O0008;
G4 X5;            X-50;
M99;              G4 X5;
O0004;            M99;
X-2;
G4 X5;
M99;
```

```
LINEAR POSITIONING IN Y-AXIS
*******************************
STANDARD UNITS    METRIC UNITS
**************    **************
O0009;            O0013;
M98 P50010        M98 P50014;
M30;              M30;
O0010;            O0014;
G20;              G21;
G91 G1 F100;      G91 G1 F2540;
M98 P160011;      M98 P160015;
Y1;               Y25;
Y-1;              Y-25;
G4 X5;            G4 X5;
M98 P160012       M98 P160016;
Y-1;              M99;
Y1;               O0015;
G4 X5;            Y50;
M99;              G4 X5;
O0011;            M99;
Y2;               O0016
G4 X5;            Y-50;
M99;              G4 X5;
O00012;           M99;
Y-2;
G4 X5;
M99;
```

```
LINEAR POSITIONING IN Z-AXIS
*******************************
STANDARD UNITS    METRIC UNITS
**************    **************
O0017;            O0021;
M98 P50018;       M98 P50022;
M30;              M30;
O0018;            O0022;
G20;              G21;
G91 G1 F25;       G91 G1 F762;
M98 P210019;      M98 P210023;
Z.25;             Z6;
Z-.25;            Z-6;
G4 X5;            G4 X5;
M98 P210020;      M98 P210024;
Z-.25;            M99;
Z.25              O0023;
G4 X5;            Z6;
M99;              G4 X5;
O0019;            M99;
Z.25;             O0024;
G4 X5;            Z-6;
M99;              G4 X5;
O0020             M99;
Z-.25;
G4 X5;
M99;
```

Figure A.1.1—Programs (G&M codes) for linear positioning evaluation in the X-axis, Y-axis, and Z-axis.

APPENDIX A.2

Figure A.2.1. is an example of programs (G&M code) that are required when measuring the router spindle/table feed rates with the laser measurement system.

SAMPLE FEED RATE PROGRAMS

(X-AXIS)

```
O0040;
G90G1F50X0;
M98 P0041;
F100;
M98 P0041;
F150;
M98 P0041;
F200;
M98 P0041;
F250;
M98 P0041;
F300;
M98 P0041;
F350;
M98 P0041;
F400;
M98 P0041;
F450;
M98 P0041;
F500;
M98 P0041;
F550;
M98 P0041;
F600;
M98 P0041;
M30;

O0041;
X72;
G4X2;
F200;
X0;
G4X2;
M99;
```

(Y-AXIS)

```
O0042;
G90G1F50Y0;
M98 P0043;
F100;
M98 P0043;
F150;
M98 P0043;
F200;
M98 P0043;
F250;
M98 P0043;
F300;
M98 P0043;
F350;
M98 P0043;
F400;
M98 P0043;
F450;
M98 P0043;
F500;
M98 P0043;
F550;
M98 P0043;
F600;
M98 P0043;
M30;

O0043;
Y31;
G4X2;
F200;
Y0;
G4X2;
M99;
```

(Z-AXIS)

```
O0044;
G90G1F50Z0;
M98 P0045;
F100;
M98 P0045;
F150;
M98 P0045;
F200;
M98 P0045;
F250;
M98 P0045;
F300;
M98 P0045;
F350;
M98 P0045;
F400;
M30;

O0045;
Z6;
G4X2;
F100;
Z0;
G4X2;
M99;
```

Figure A.2.1—Programs (G&M codes) for feed rate evaluations in the X-axis, Y-axis, and Z-axis.

APPENDIX A.3

Program for Circles Cut in Acrylic Sheets (Accuracy)

Following are procedures for developing a G&M program for determining the accuracy of cutting circles in acrylic sheets. Figure A.3.1 provides information to assist in this development. Figure A.3.2 shows the tool path for all moves including cutter compensations, lead-in/lead-out cuts, roughing cuts, and final cuts. Figure A.3.3 shows only the actual cuts made in the material. Use the following steps to develop the required program in an absolute mode. Although feed rates are not discussed in these steps, they must be included in the program so they can be changed as necessary.

Step 1

Set the absolute zero position at a point -7 inches in the X-axis and -7 inches in the Y-axis from the exact center of the table.

Step 2

Make a positioning move to Point A (X0.5,Y7.0) in line with and 0.5 inch from the left end of the horizontal line that represents the left slot. Move 0.5 inch to the right at 0° to provide a cutter compensation to the right side of the horizontal line. Next, lower the tool to a depth of -0.1875 inch and make a cutting move for 1 inch. Then raise the tool to 0.25 inch above the material and move 0.5 inch to the right at 0° to remove the cutter compensation.

Step 3

Make a positioning move to Point B (X11.5,Y7.0) in line with and 0.5 inch from the left end of the horizontal line that represents the right slot. Then, repeat the cutter compensation and cutting moves as discussed in Step 1.

Step 4

Make a positioning move to Point C (X7.0,Y13.5) in line with and 0.5 inch from the upper end of the vertical line that represents the upper slot. Move down 0.5 inch at 0° to provide a cutter compensation to the right side of the horizontal line. Next, lower the tool to a depth of -0.1875 inch and make a cutting move down for 1 inch. Then raise the tool to 0.25 inch above the material and move down 0.5 inch at 0° to remove the cutter compensation.

Step 5

Make a positioning move to Point D (X7.0,Y2.5) in line with and 0.5 inch above the upper end of the vertical line representing the lower slot. Then, repeat the cutter compensation and cutting moves as discussed in Step 4.

Step 6

Make a positioning move to Point E (X11.1875,Y7.0) at the right edge of the circle with a diameter of 8.375 inches. Lower the tool to a depth of -0.1875 inch and make a 360° move (roughing cut) in a counter clockwise direction without cutter compensation.

Step 7

Raise the tool to 0.25 inch above the material and make a positioning move to Point F (X3.6599,Y4.6108) to start the finish cut of the 8-inch circle. From this point, make a right cutter compensation move to point (X4.0429,Y2.2894). Next, lower the tool to -0.1562 inch and make a lead-in cut in a clockwise arc with a radius of 2 inches to point (X4.1716,Y4.1716). Then make the 360° counter clockwise finish cut to the 8-inch circle. From the finish point of the circle, make a lead-out cut in a clockwise arc with a radius of 2 inches to point (X4.2894,Y4.0429). Raise the tool to 0.25 inch above the material and remove the cutter compensation with a move to point (X4.6108,Y3.6599).

Step 8

Make a positioning move to Point G (X8.1875,Y7.0) at the right edge of the circle with a diameter of 2.375 inches. Lower the tool to a depth of -0.1875 inch and make a 360° move (roughing cut) in a counter clockwise direction without cutter compensation.

Step 9

Raise the tool to 0.25 inch above the material and make a positioning move to Point H (X5.7812,Y6.7322) to start the finish cut of the 2-inch circle. From this point, make a right cutter compensation move to point (X6.1643,Y6.4108). Next, lower the tool to -0.1562 inch and make a lead-in cut in a clockwise arc with a radius of 2 inches to point (X6.2929,Y6.2929). Then make the 360° counter clockwise finish cut to the 2-inch circle. From the finish point of the circle, make a lead-out cut in a clockwise arc with a radius of 2 inches to point (X6.4108,Y6.1643). Then, raise the tool to 0.25 inch above the material and remove the cutter compensation with a move to point (X6.7322,Y5.7812). End with a move to machine reference zero.

Figure A.3.4 shows a sample program for this procedure. Due to differences in controllers, it may be necessary to make minor changes in this program.

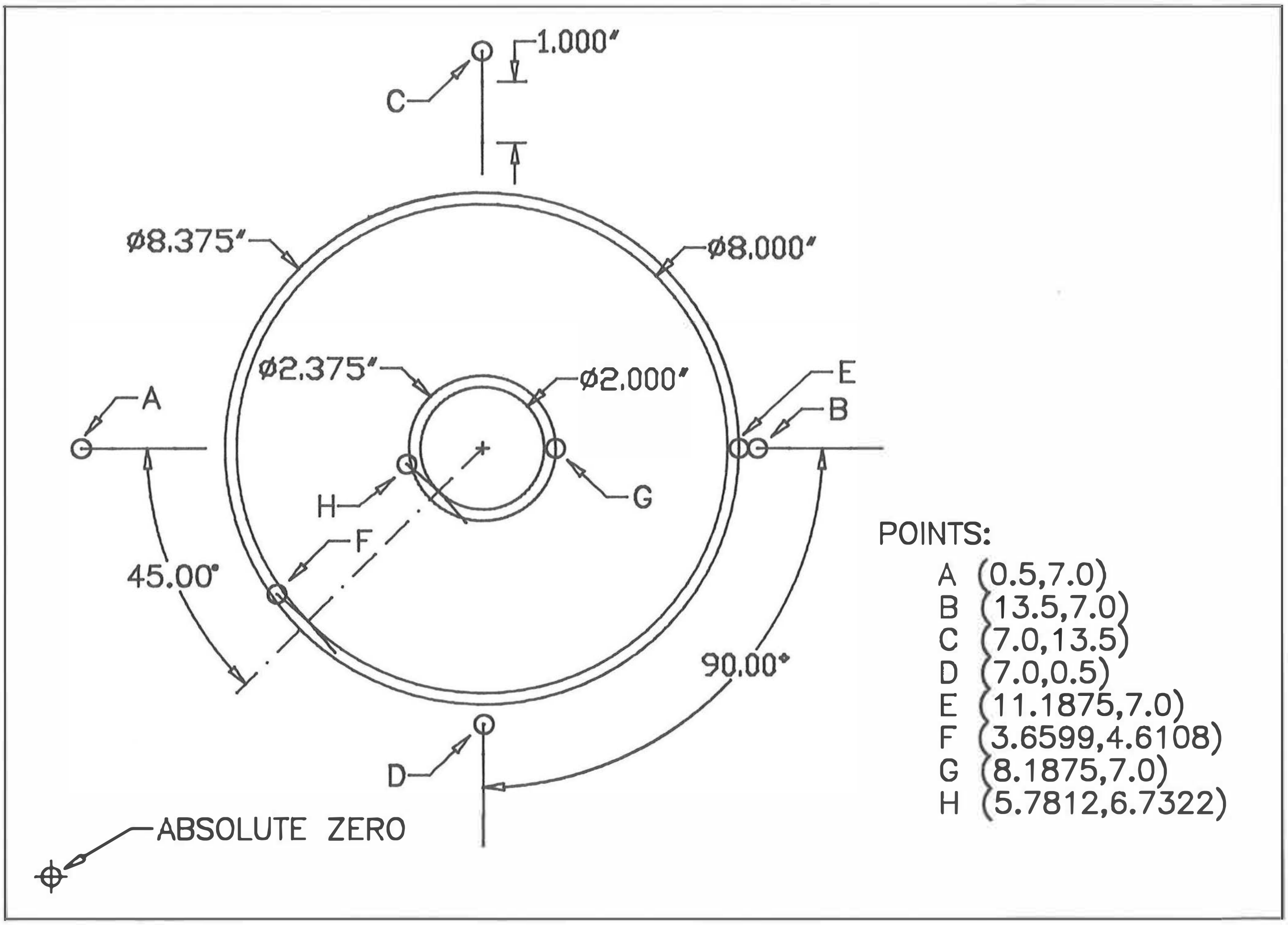


Figure A.3.1—Drawing showing information for developing a program (G&M code) needed to make circle accuracy cuts in acrylic sheets.

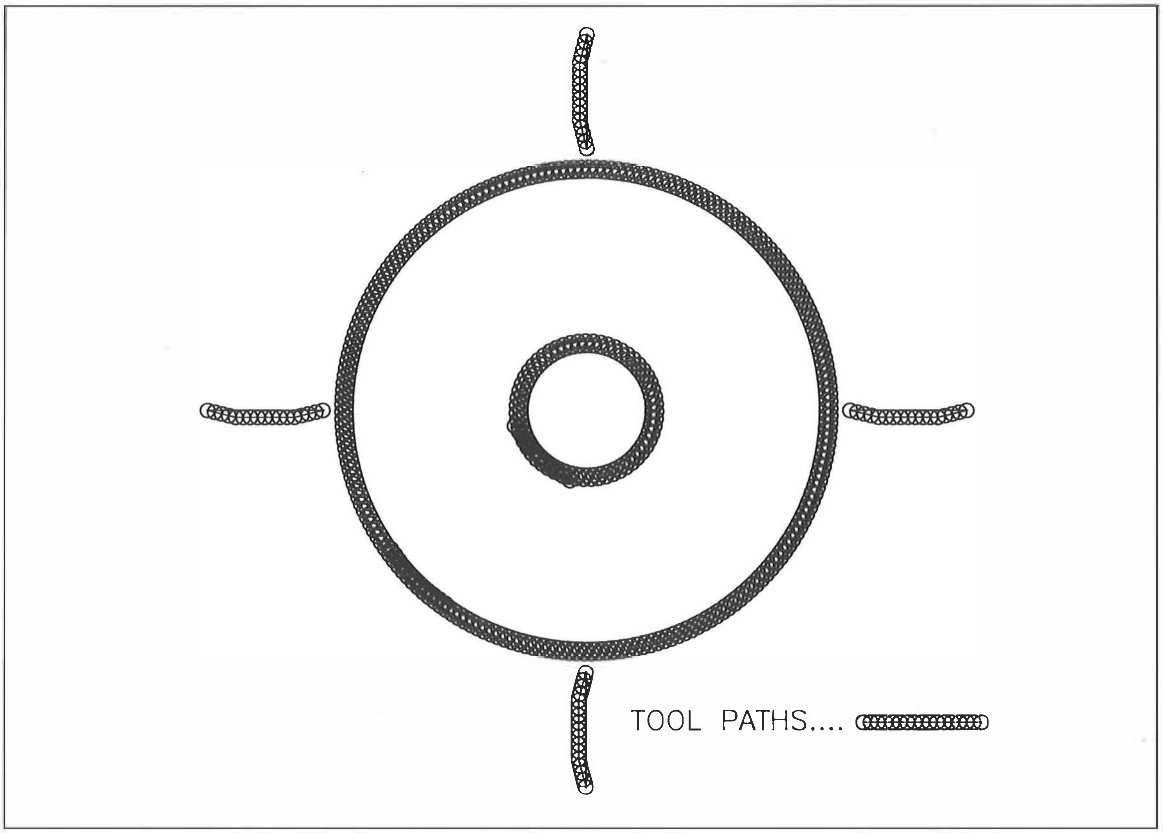


Figure A.3.2—Drawing showing tool paths (roughing cuts, offset moves, lead-in cuts, and finish cuts) used to cut both the 2-inch and 8-inch circles in an acrylic sheet for accuracy evaluation.

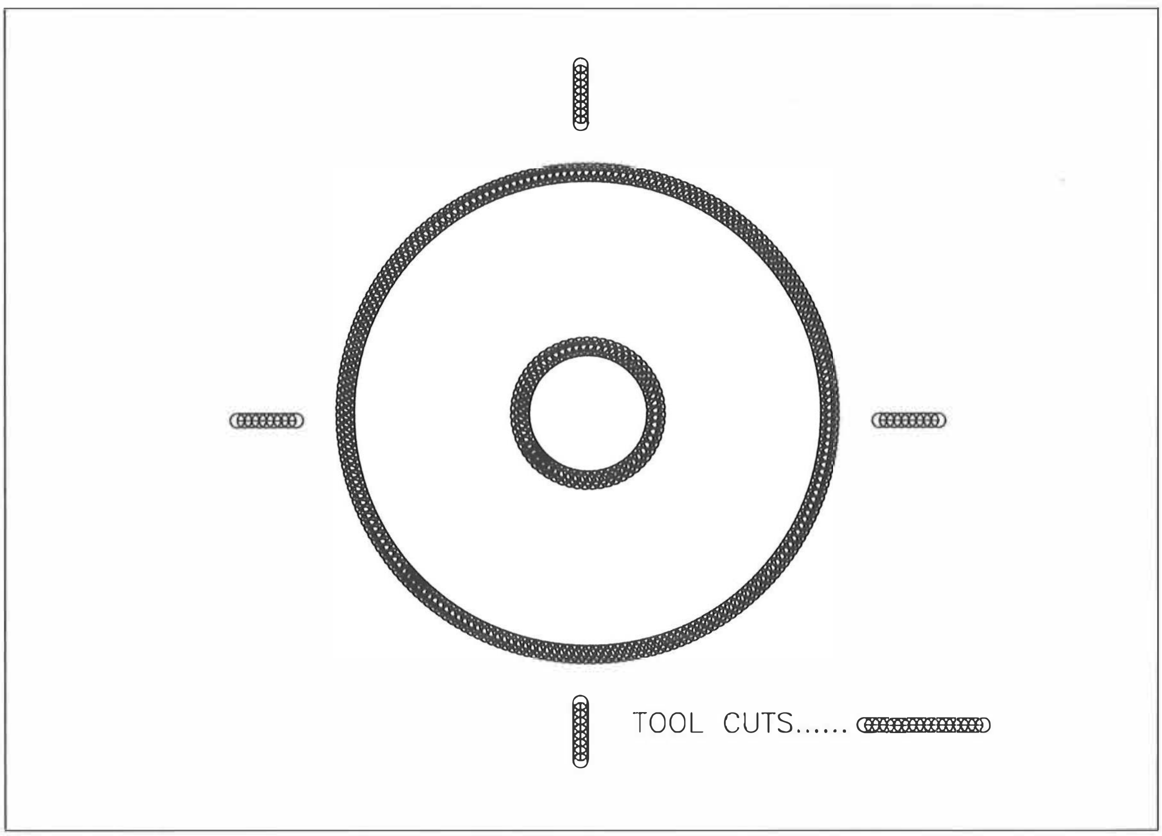


Figure A.3.3—Drawing showing only the actual cuts made in an acrylic sheet for the 2-inch and 8-inch circles used in accuracy evaluation.

PROGRAM FOR CIRCLES CUT IN ACRYLIC SHEETS (ACCURACY)

```
O0050;
N5G91;
N10G28X0Y0Z0;
N15G92X-31.5Y22.5;
N20G90;
N25G00X0.5Y7.0;
N27Z0.25;
N30G42H1G01X1.0F100;
N35Z-0.1875;
N40X2.0;
N42Z0.25;
N45G40H1X2.5;
N50G00X11.5Y7.0;
N55G42H1G01X12.0F100;
N60Z-0.1875;
N65X13.0;
N70Z0.25;
N75G40H1X13.5;
N80G00X7.0Y13.5;
N85G42H1G01Y13.0F100;
N90Z-0.1875;
N95Y12.0;
N100Z0.25;
N105G40H1Y11.5;
N115G00X7.0Y2.5;
N120G42H1G01Y2.0F100;
N125Z-0.1875;
N130Y1.0;
N132Z0.25;
N135G40H1Y0.5;
N145G00X11.1875Y7.0;
N147Z-0.1875;
N150G03I-4.1875F100;
N155G00Z0.25;
N160G00X3.6599Y4.6108;
N165G42H1G01X4.0429Y4.2894F100;
N170Z-0.1562;
N175G02X4.1716Y4.1716R2.0;
N180G03X9.8284Y9.8284R4;
N182G03X4.1716Y4.1716R4;
N185G02X4.2894Y4.0429R2.0;
N187G1Z0.25;
N190G40H1G01X4.6108Y3.6599;
N200G00X8.1875Y7.0;
N202Z-0.1875;
N205G03I-1.1875F100;
N210G00Z0.25;
N215G00X5.7812Y6.7322;
N220G42H1G01X6.1643Y6.4108F100;
N225Z-0.1562;
N230G02X6.2929Y6.2929R2.0;
N235G03X7.7071Y7.7071R1;
N237X6.2929Y6.2929R1;
N240G02X6.4108Y6.1643R2.0;
N242G1Z0.25;
N245G40H1G01X6.7322Y5.7812;
N250G28X0Y0Z0;
N255M30;
```

NOTE:
The feed speeds in Statements N165 and N220 are changed to match the desired feed speed.

Figure A.3.4—Sample program (G&M code) for accuracy cutting of circles in acrylic sheets.

APPENDIX A.4

Program for Squares Cut in Acrylic Sheets
(Accuracy)

Following are procedures for developing a G&M program for determining the accuracy of cutting squares in acrylic sheets. Figure A.4.1 provides information to assist in this development. Figure A.4.2 shows the tool path for all moves including cutter compensations, lead-in/lead-out cuts, roughing cuts, and final cuts. Figure A.4.3 shows only the actual cuts made in the material. Use the following procedures to develop the required program in an absolute mode. Although feed rates are not discussed in these procedures, they must be included in the program so they can be changed as necessary.

Step 1

Set the absolute zero position at a point -7 inches in the X-axis and -7 inches in the Y-axis from the exact center of the table.

Step 2

Make a positioning move to Point A (X0.5,Y7.0) in line with and 0.5 inch from the left end of the horizontal line that represents the left slot. Move 0.5 inch to the right at 0^{o} to provide a cutter compensation to the right side of the horizontal line. Next, lower the tool to a depth of -0.1875 inch and make a cutting move for 1 inch. Then raise the tool to 0.25 inch above the material move 0.5 inch to the right at 0^{o} to remove the cutter compensation.

Step 3

Make a positioning move to Point B (X11.5,Y7.0) in line with and 0.5 inch from the left end of the horizontal line that represents the right slot. Then, repeat the cutter compensation and cutting moves as discussed in Step 1.

Step 4

Make a positioning move to Point C (X7.0,Y13.5) in line with and 0.5 inch from the upper end of the vertical line that represents the upper slot. Move down 0.5 inch at 0^{o} to provide a cutter compensation to the right side of the horizontal line. Next, lower the tool to a depth of -0.1875 inch and make a cutting move down for 1 inch. Then, raise the tool to 0.25 inch above the material and move down 0.5 inch at 0^{o} to remove the cutter compensation.

Step 5

Make a positioning move to Point D (X7.0,Y2.5) in line with and 0.5 inch above the upper end of the vertical line representing the lower slot. Then, repeat the cutter compensation and cutting moves as discussed in Step 4.

Step 6

Make a positioning move to Point E (X2.8125,Y2.8125) at lower left corner of the 8.375-inch square. Lower the tool to a depth of -0.1875 inch and without cutter compensation make counter clockwise cutting moves horizontally to point (X11.1875), vertically to point (Y11.1875), horizontally to point (X2.8125), and vertically back to point (Y2.8125).

Step 7

Raise the tool to 0.25 inch above the material and make a positioning move to Point F (X2.25,Y3.0) to start the finish cut of the 8-inch square. From this point, make a horizontal cutter compensation move to point (X2.75). Next, lower the tool to -0.1562 inch and make counter clockwise cutting moves horizontally to point (X11.0), vertically to point (Y11.0), horizontally to point (X3.0), and vertically to point (Y2.75). Then, raise the tool to 0.25 inch above the material and remove the cutter compensation with a vertical move to point (Y2.25).

Step 8

Make a positioning move to Point G (X5.8125,Y5.8125) at lower left corner of the 2.375-inch square. Lower the tool to a depth of -0.1875 inch and without cutter compensation make counter clockwise cutting moves horizontally to point (X8.1875), vertically to point (Y8.1875), horizontally to point (X5.8125), and vertically back to point (Y5.8125).

Step 9

Raise the tool to 0.25 inch above the material and make a positioning move to Point H (X5.25,Y6.0) to start the finish cut of the 2-inch square. From this point, make a horizontal cutter compensation move to point (X5.75). Next, lower the tool to -0.1562 inch and make counter clockwise cutting moves horizontally to point (X8.0), vertically to point (Y8.0), horizontally to point (X6.0), and vertically to point (Y5.75). Then, raise the tool to 0.25 inch above the material and remove the cutter compensation with a vertical move to point (Y5.25). End with a move to machine reference zero.

Figure A.4.4 shows a sample program for this procedure. Due to differences in controllers, it may be necessary to make minor changes in this program.

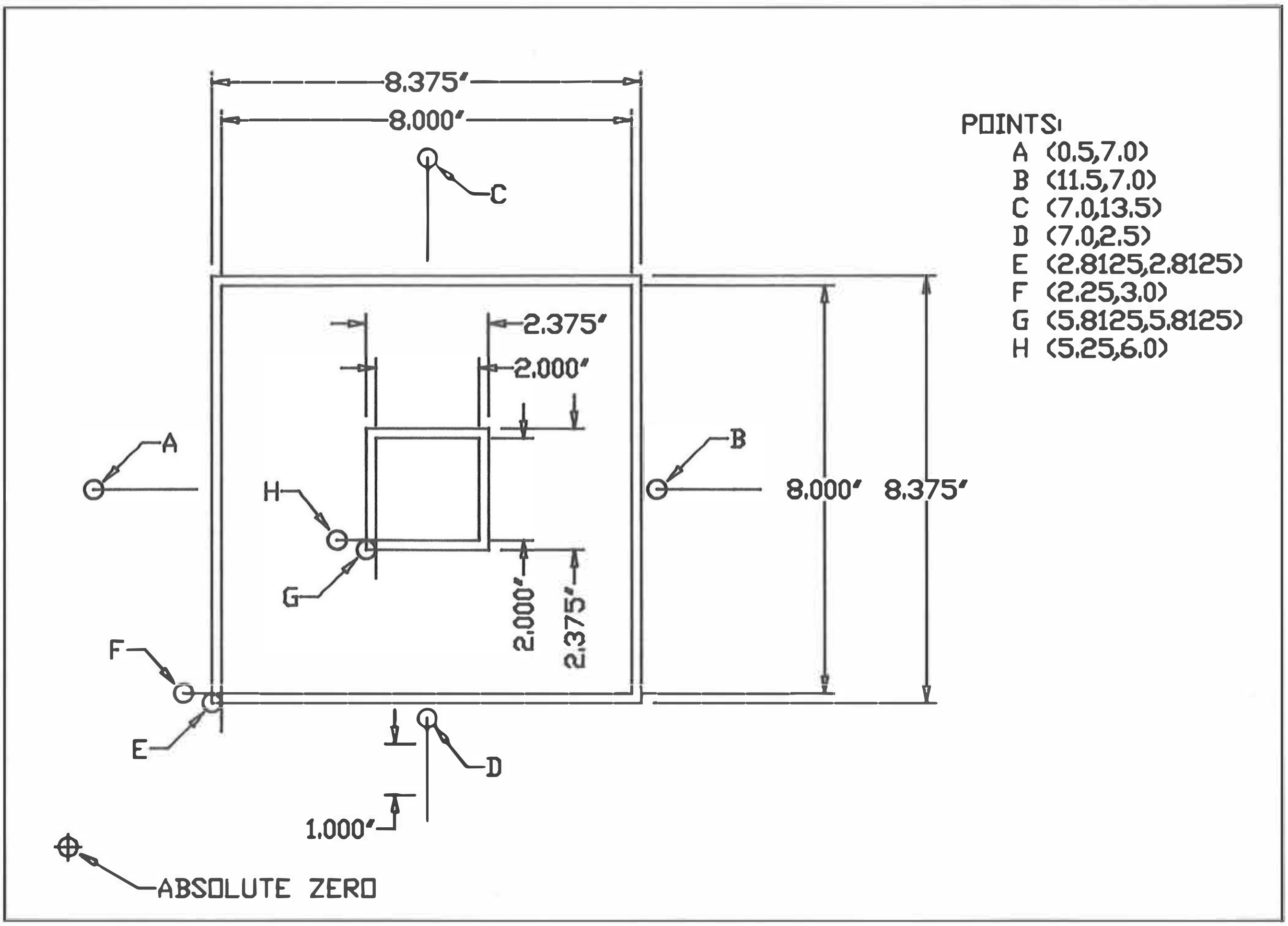


Figure A.4.1—Drawing showing information for developing a program (G&M code) needed to make square accuracy cuts in acrylic sheets.

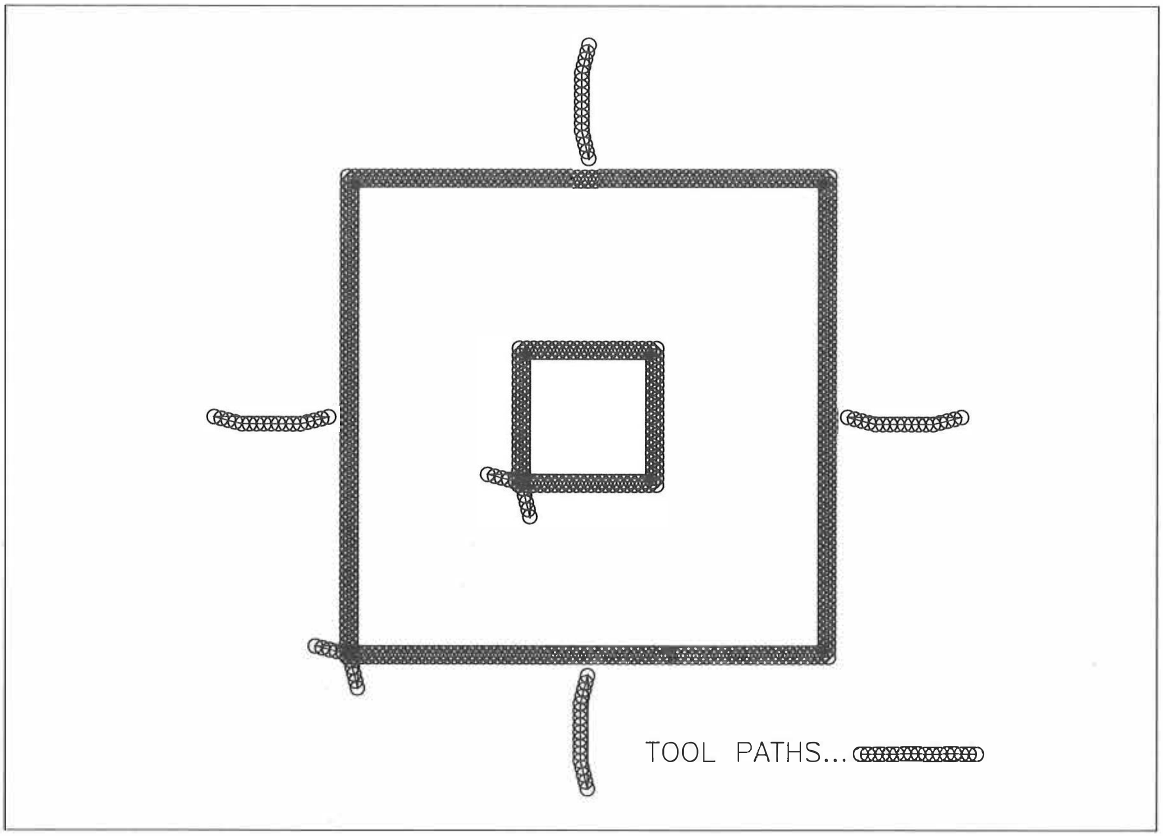


Figure A.4.2—Drawing showing tool paths (roughing cuts, offset moves, lead-in cuts, and finish cuts) used to cut both the 2-inch and 8-inch squares in an acrylic sheet for accuracy evaluation.

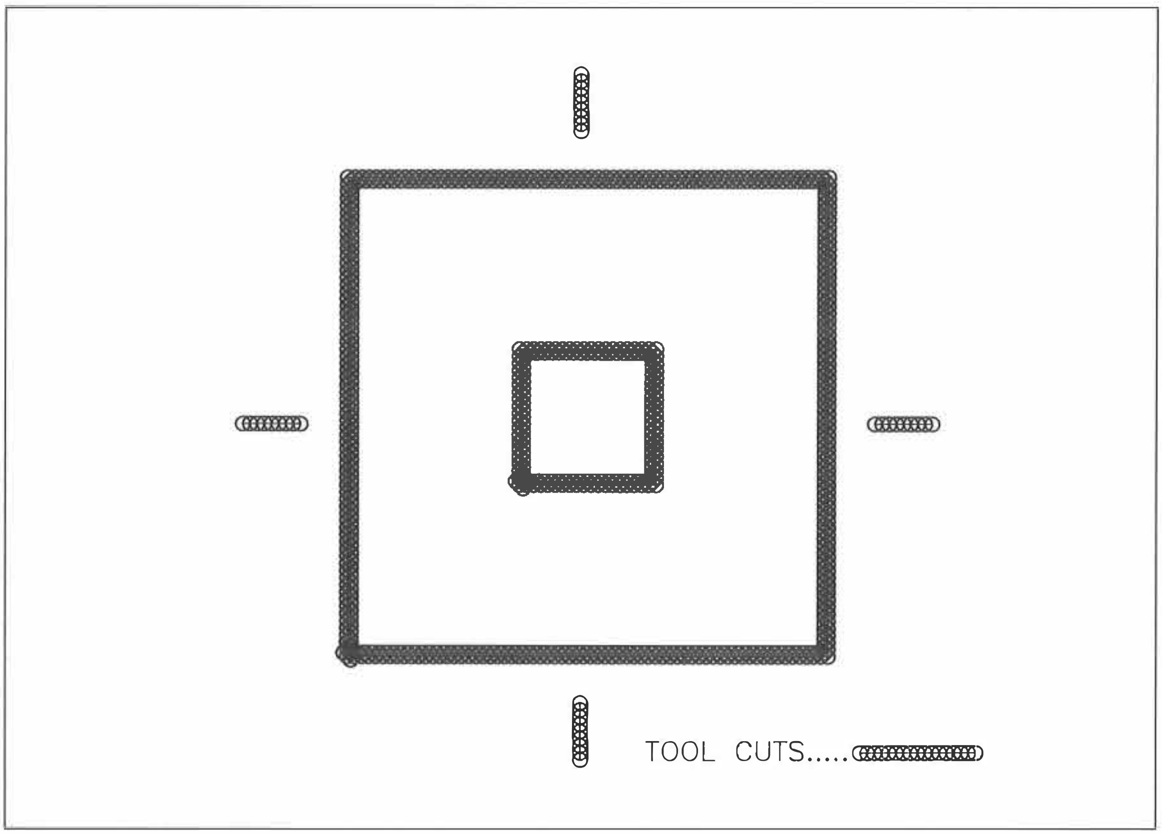


Figure A.4.3—Drawing showing only the actual cuts made in an acrylic sheet for the 2-inch and 8-inch squares used in accuracy evaluation.

PROGRAM FOR SQUARES CUT IN ACRYLIC SHEETS
(ACCURACY)

```
O0051;
N5G91;
N10G28X0Y0Z0;
N15G92X-31.5Y22.5;
N20G90;
N25G00X0.5Y7.0;
N27Z0.25;
N30G42H1G01X1.0F100;
N35Z-0.1875;
N40X2.0;
N42Z0.25;
N45G40H1X2.5;
N50G00X11.5Y7.0;
N55G42H1G01X12.0F100;
N60Z-0.1875;
N65X13.0;
N70Z0.25;
N75G40H1X13.5;
N80G00X7.0Y13.5;
N85G42H1G01Y13.0F100;
N90Z-0.1875;
N95Y12.0;
N100Z0.25;
N105G40H1Y11.5;
N115G00X7.0Y2.5;
N120G42H1G01Y2.0F100;
N125Z-0.1875;
N130Y1.0;
N132Z0.25;
N135G40H1Y0.5;
N140G00Z0.25;
N145G00X2.8125Y2.8125;
N147Z-0.1875;
N150G01X11.1875F100;
N160Y11.1875;
N165X2.8125;
N170Y2.8125;
N175G00Z0.25;
N180G00X2.25Y3.0;
N185G42H1G01X2.75F100;
N190Z-0.1562;
N195X11.0;
N197G4;
N200Y11.0;
N202G4;
N205X3.0;
N207G4;
N210Y2.75;
N211G4;
N212Z0.25;
N215G40H1Y2.25;
N225G00X5.8125Y5.8125;
N227Z-0.1875;
N230G01X8.1875F100;
N240Y8.1875;
N245X5.8125;
N250Y5.8125;
N255G00Z0.25;
N260G00X5.25Y6.0;
N265G42H1G01X5.75F100;
N270Z-0.1562;
N275X8.0;
N277G4;
NN280Y8.0;
N282G4;
N285X6.0;
N287G4;
N290Y5.75;
N291G4;
N292Z0.25;
N295G40H1Y5.25;
N300G28X0Y0Z0;
N305M30;
```

NOTE:
The feed speeds in Statements N185 and N265 are changed to match the desired feed speed.

Figure A.4.4—Sample program (G&M code) for accuracy cutting of squares in acrylic sheets.

APPENDIX A.5

Program for Diamonds Cut in Acrylic Sheets (Accuracy)

Following are procedures for developing a G&M program for determining the accuracy of cutting diamonds in acrylic sheets. Figure A.5.1 provides information to assist in this development. Figure A.5.2 shows the tool path for all moves including cutter compensations, lead-in/lead-out cuts, roughing cuts, and final cuts. Figure A.5.3 shows only the actual cuts made in the material. Use the following procedures to develop the required program in an absolute mode. Although feed rates are not discussed in these procedures, they must be included in the program so they can be changed as necessary.

Step 1

Set the absolute zero position at a point -7 inches in the X-axis and -7 inches in the Y-axis from the exact center of the table.

Step 2

Make a positioning move to Point A (X2.4038,Y2.4038) in line with and 0.5 inch from the lower left end of the line that represents the lower left slot. Move 0.5 inch to point (X2.7574,Y2.7574) with a left cutter compensation. Next, lower the tool to a depth of -0.1875 inch and make a cutting move to point (X3.4645,Y3.4645). Then raise the tool to 0.25 inch above the material and move to point (X3.818,Y3.818) to remove the cutter compensation.

Step 3

Make a positioning move to Point B (X10.182,Y10.182) in line with and a 0.5 inch from the lower left end of the line that represents the upper right slot. Move 0.5 inch move to point (X10.5355,Y10.5355) with a left cutter compensation. Next, lower the tool to a depth of -0.1875 inch and make a cutting move to point (X11.2426,Y11.2426). Then raise the tool to 0.25 inch above the material and move to point (X11.5962,Y11.5962) to remove the cutter compensation.

Step 4

Make a positioning move to Point C (X2.4038,Y11.5962) in line with and 0.5 inch from the upper left end of the line that represents the upper left slot. Move 0.5 inch to point (X2.7574,Y11.2426) with a right cutter compensation. Next, lower the tool to a depth of -0.1875 inch and make a cutting move to point (X3.4645,Y10.5355). Then raise the tool to 0.25 inch above the material and move to point (X3.818,Y10.182) to remove the cutter compensation.

Step 5

Make a positioning move to Point D (X10.182,Y3.818) in line with and 0.5 inch from the upper left end of the line that represents the lower right slot. Move 0.5 inch to point (X10.5355,Y3.4645) with a right cutter compensation. Next, lower the tool to a depth of -0.1875 inch and make a cutting move to point (X11.2426,Y2.7574). Then raise the tool to 0.25 inch above the material and move to point (X11.5962,Y2.4038) to remove the cutter compensation.

Step 6

Make a positioning move to Point E (X1.078,Y7.0) at left corner of the 8.375-inch diamond. Lower the tool to a depth of -0.1875 inch and without cutter compensation make counter clockwise cutting moves to point (X7.0,Y1.078), to point (X12.922,Y7.0), to point (X7.0,Y12.922), and back to point (X1.078,Y7.0).

Step 7

Raise the tool to 0.25 inch above the material and make a positioning move to Point F (X0.8128,Y7.5303) to start the finish cut of the 8-inch diamond. From this point, make a right cutter compensation move to point (X1.1664,Y7.1768). Next, lower the tool to -0.1562 inch and make counter clockwise cutting moves to point (X7.0,Y1.3431), to point (X12.6569,Y7.0), to point (X3.0), and to point (X1.1664,Y6.8232). Then, raise the tool to 0.25 inch above the material and remove the cutter compensation with a move to point (X0.8128,Y6.4697).

Step 8

Make a positioning move to Point G (X5.3206,Y7.0) at left corner of the 2.375-inch diamond. Lower the tool to a depth of -0.1875 inch and without cutter compensation make counter clockwise cutting moves to point (X7.0,Y5.3206), to point (X8.6794,Y7.0), to point (X7.0,Y8.6794), and back to point (X5.3206,Y7.0).

Step 9

Raise the tool to 0.25 inch above the material and make a positioning move to Point H (X5.0555,Y7.5303) to start the finish cut of the 2-inch diamond. From this point, make a cutter compensation move to point (X5.409,Y7.1768). Next, lower the tool to -0.1562 inch and make counter clockwise cutting moves to point (X7.0,Y5.5858), to point (X8.4142,Y7.0), to point (X7.0,Y8.4142), and to point (X5.409,Y6.8232). Then, raise the tool to 0.25 inch above the material and remove the cutter compensation with a move to point (X5.0555,Y6.4697). End with a move to machine reference zero.

Figure A.5.4 shows a sample program for this procedure. Due to differences in controllers, it may be necessary to make minor changes in this program.

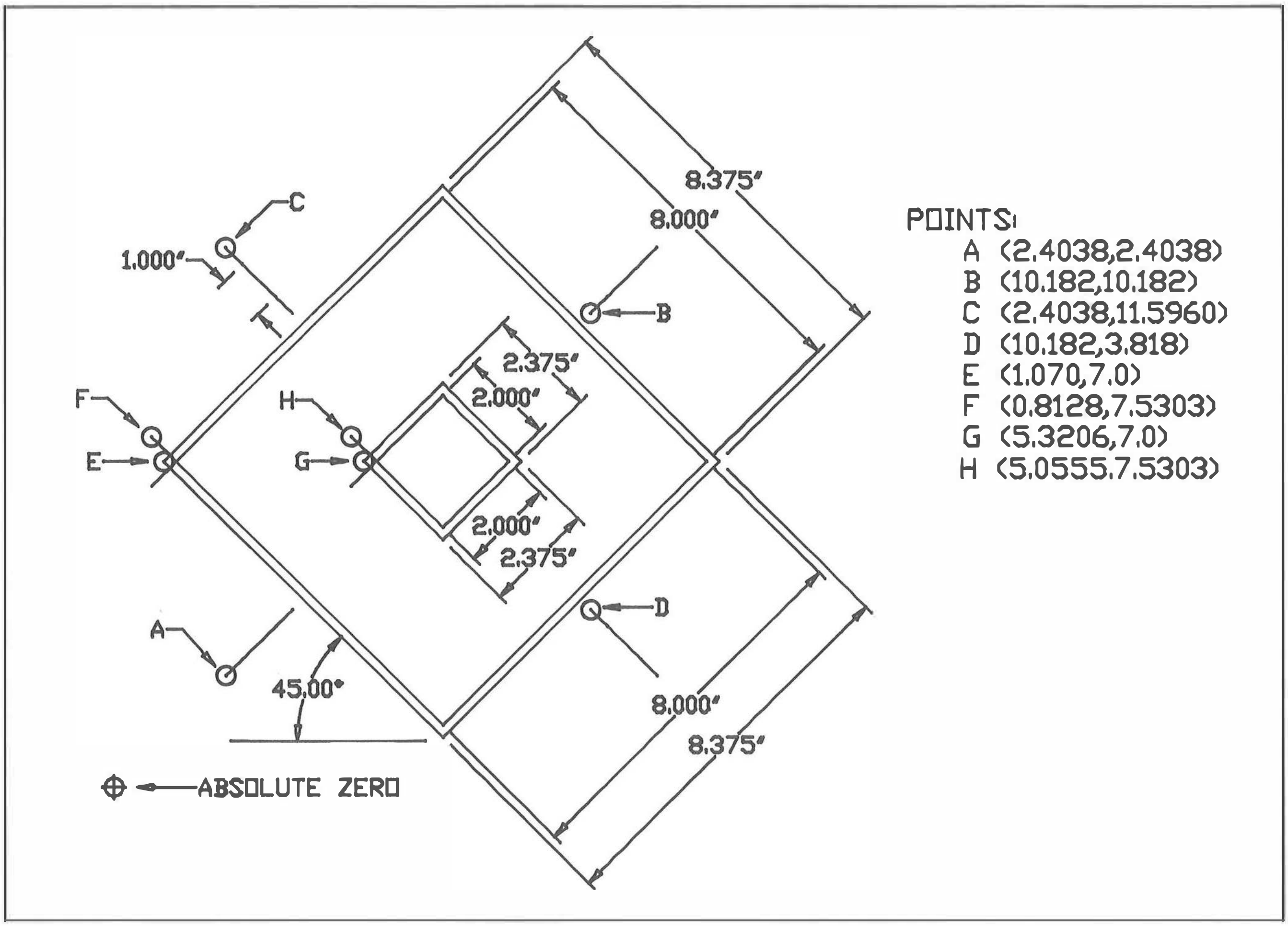


Figure A.5.1—Drawing showing information for developing a program (G&M code) needed to make diamond accuracy cuts in acrylic sheets.

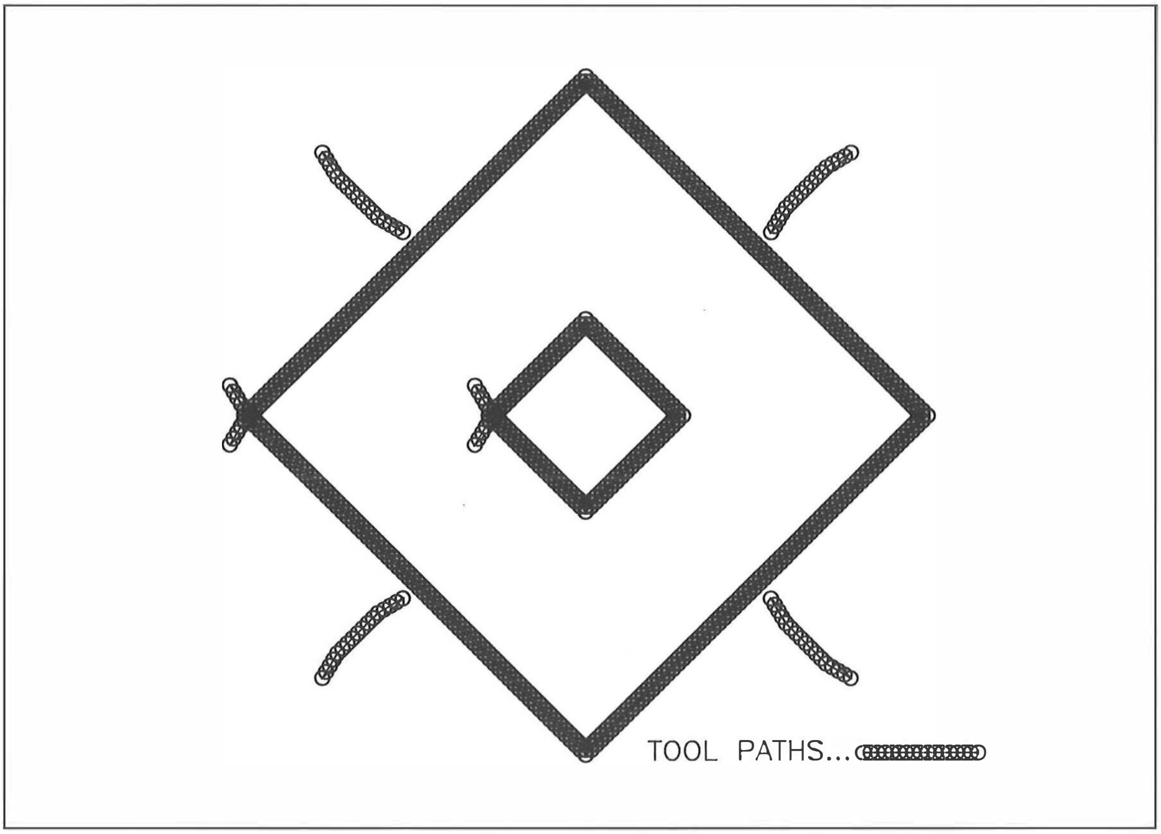


Figure A.5.2—Drawing showing tool paths (roughing cuts, offset moves, lead-in cuts, and finish cuts) used to cut both the 2-inch and 8-inch diamonds in an acrylic sheet for accuracy evaluation.

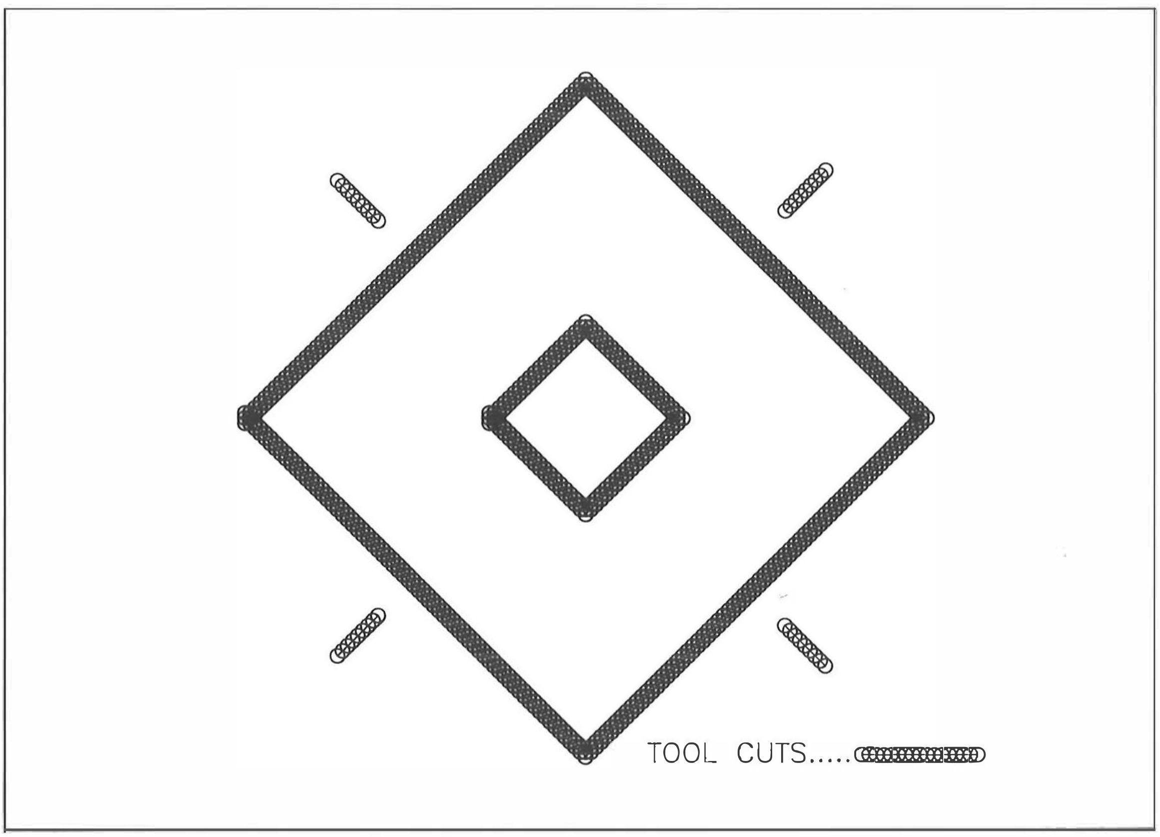


Figure A.5.3—Drawing showing only the actual cuts made in an acrylic sheet for the 2-inch and 8-inch diamonds used in accuracy evaluation.

PROGRAM FOR DIAMONDS CUT IN ACRYLIC SHEETS (ACCURACY)

```
O0052;
N5G91;
N10G28X0Y0Z0;
N15G92X-31.5Y22.5;
N20G90;
N25G00X2.4038Y2.4038;
N27Z0.25;
N30G41H1G01X2.7574Y2.7574F100;
N35Z-0.1875;
N40X3.4645Y3.4645;
N42Z0.25;
N45G40H1X3.818Y3.818;
N50G00X10.182Y10.182;
N55G41H1G01X10.5355Y10.5355F100;
N60Z-0.1875;
N65X11.2426Y11.2426;
N70Z0.25;
N75G40H1X11.5962Y11.5962;
N80G00X2.4038Y11.5962;
N85G42H1G01X2.7574Y11.2426F100;
N90Z-0.1875;
N95X3.4645Y10.5355;
N100Z0.25;
N105G40H1X3.818Y10.182;
N115G00X10.182Y3.818;
N120G42H1G01X10.5355Y3.4645F100;
N125Z-0.1875;
N130X11.2426Y2.7574;
N132Z0.25;
N135G40H1X11.5962Y2.4038;
N145G00X1.078Y7.0;
N147Z-0.1875;
N150G01X7.0Y1.078F100;
N160X12.922Y7.0;
N165X7.0Y12.922;
N170X1.078Y7.0;
N175G00Z0.25;
N180G00X0.8128Y7.5303;
N185G42H1G01X1.1664Y7.1768F100;
N190Z-0.1562;
N195X7.0Y1.3431;
N197G4;
N200X12.6569Y7.0;
N202G4;
N205X7.0Y12.6569;
N207G4;
N210X1.1664Y6.8232;
N211G4;
N212Z0.25;
N215G40H1X0.8128Y6.4697;
N225G00X5.3206Y7.0;
N227Z-0.1875;
N230G01X7.0Y5.3206F100;
N240X8.6794Y7.0;
N245X7.0Y8.6794;
N250X5.3206Y7.0;
N255G00Z0.25;
N260G005.0555Y7.5303;
N265G42H1G01X5.409
                  Y7.1768F100;
N270Z-0.1562;
N275X7.0Y5.5858;
N277G4;
N280X8.4142Y7.0;
N282G4;
N285X7.0Y8.4142;
N287G4;
N290X5.409Y6.8232;
N291G4;
N292Z0.25;
N295G40H1X5.0555Y6.4697;
N297G28X0Y0Z0;
N305M30;
```

NOTE:
The feed speeds in Statements N185 and N265 are changed to match the desired feed speed.

Figure A.5.4—Sample program (G&M code) for accuracy cutting of diamonds in acrylic sheets.

APPENDIX A.6

Program for Circles Cut in Specified Raw Material (Accuracy)

Following are procedures for developing a G&M program for determining the accuracy of cutting circles in the specified raw material. Figure A.6.1 provides information to assist in this development. Figure A.6.2 shows the tool path for all moves including cutter compensations, lead-in/lead-out cuts, roughing cuts, and final cuts. Figure A.6.3 shows only the actual cuts made in the material. Use the following procedures to develop the required program in an absolute mode. Although feed rates are not discussed in these procedures, they must be included in the program so that they can be changed as necessary.

Step 1

Set the absolute zero position at a point -7 inches in the X-axis and -7 inches in the Y-axis from the exact center of the table.

Step 2

Make a positioning move to Point A (X0.25,Y7.0) in line with and 0.75 inch from the left end of the horizontal line that represents the left slot. Move 0.75 inch to the right at 0° to provide a cutter compensation to the right side of the horizontal line. Next, lower the tool to a depth of -0.625 inch and make a cutting move for 1 inch. Then raise the tool to 0.5 inch above the material and move 0.75 inch to the right at 0° to remove the cutter compensation.

Step 3

Make a positioning move to Point B (X11.25,Y7.0) in line with and 0.75 inch from the left end of the horizontal line that represents the right slot. Then, repeat the cutter compensation and cutting moves as discussed in Step 1.

Step 4

Make a positioning move to Point C (X7.0,Y13.75) in line with and 0.75 inch from the upper end of the vertical line that represents the upper slot. Move down 0.75 inch at 0° to provide a cutter compensation to the right side of the horizontal line. Next, lower the tool to a depth of -0.625 inch and make a cutting move down for 1 inch. Then raise the tool to 0.5 inch above the material and move down 0.75 inch at 0° to remove the cutter compensation.

Step 5

Make a positioning move to Point D (X7.0,Y2.75) in line with and 0.75 inch above the upper end of the vertical line representing the lower slot. Then, repeat the cutter compensation and cutting moves as discussed in Step 4.

Step 6

Make a positioning move to Point E (X11.5,Y7.0) at the right edge of the circle with a diameter of 9.0 inches. Lower the tool to a depth of -0.625 inch and make a 360° move (roughing cut) in a counter clockwise direction without cutter compensation.

Step 7

Raise the tool to 0.5 inch above the material and make a positioning move to Point F (X4.9692,Y3.0854) to start the finish cut of the 8-inch circle. From this point, make a right cutter compensation move to point (X4.3957,Y3.9045). Next, lower the tool to -0.625 inch and make a lead-in cut in a clockwise arc with a radius of 2 inches to the point (X4.1716,Y4.1716). Then make the 360° counter clockwise finish cut to the 8-inch circle. From the finish point of the circle, make a lead-out cut in a clockwise arc with a radius of 2 inches to the point (X3.9045,Y4.3957). Raise the tool to 0.5 inch above the material and remove the cutter compensation with a move to the point (X3.0854,Y4.9692).

Step 8

Make a positioning move to Point G (X8.5,Y7.0) at the right side of the circle with a diameter of 3.0 inches. Lower the tool to a depth of -0.625 inch and make a 360° move (roughing cut) in a counter clockwise direction without cutter compensation.

Step 9

Raise the tool to 0.5 inch above the material and make a positioning move to Point H (X7.0906,Y5.2067) to start the finish cut of the 2-inch circle. From this point, make a right cutter compensation move to point (X6.517,Y6.0258). Next, lower the tool to -0.625 inch and make a lead-in cut in a clockwise arc with a radius of 2 inches to the point (X6.2929,Y6.2929). Then make the 360° counter clockwise finish cut to the 2-inch circle. From the finish point of the circle, make a lead-out cut in a clockwise arc with a radius of 2 inches to the point (X6.0258,Y6.517). Raise the tool to 0.5 inch above the material and remove the cutter compensation with a move to the point (X5.2067,Y7.0906). End with a move to machine reference zero.

Figure A.6.4 shows a sample program for this procedure. Due to differences in controllers, it may be necessary to make minor changes in this program.

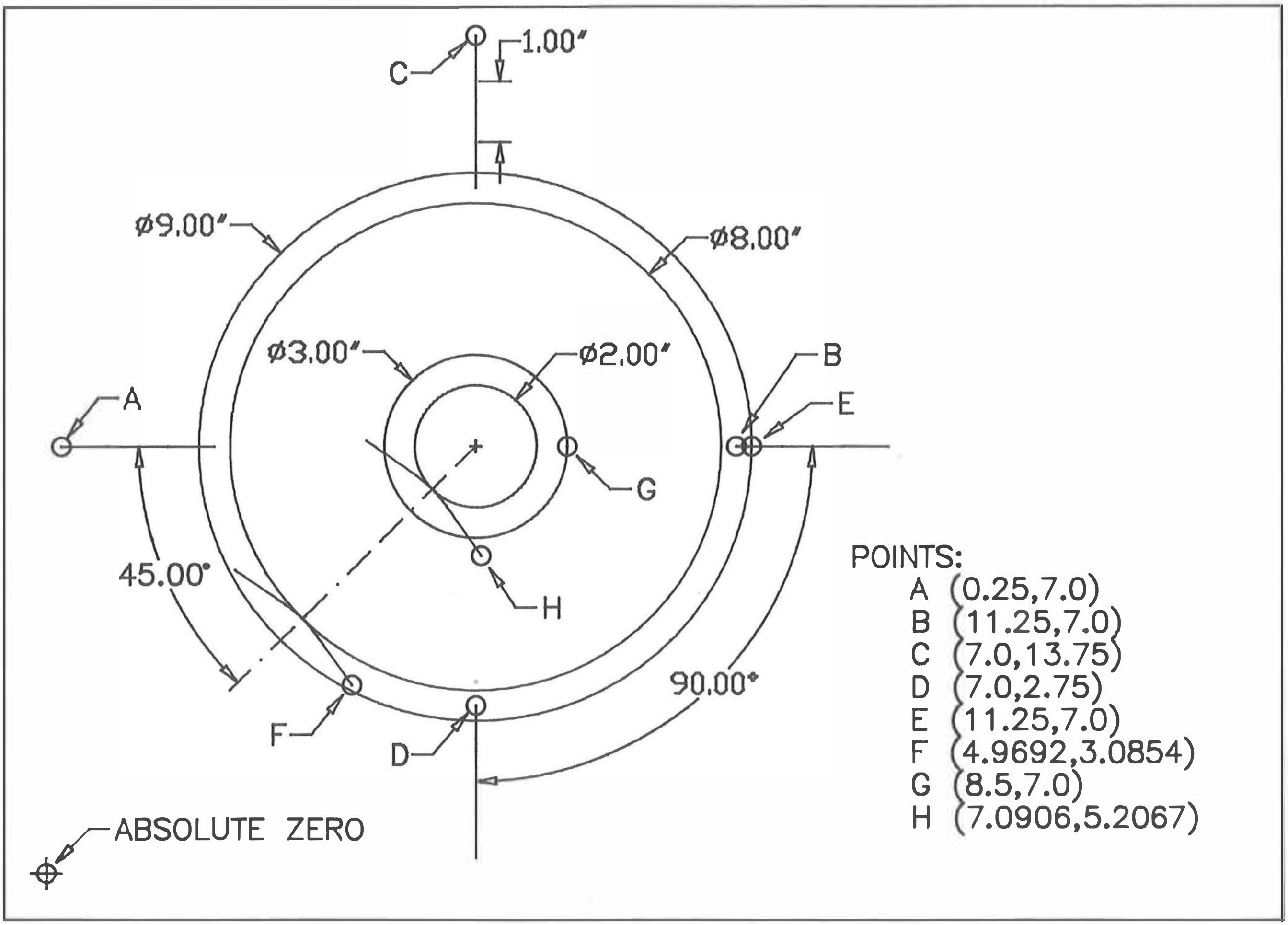


Figure A.6.1—Drawing showing information for developing a program (G&M code) needed to make circle accuracy cuts in specified raw material.

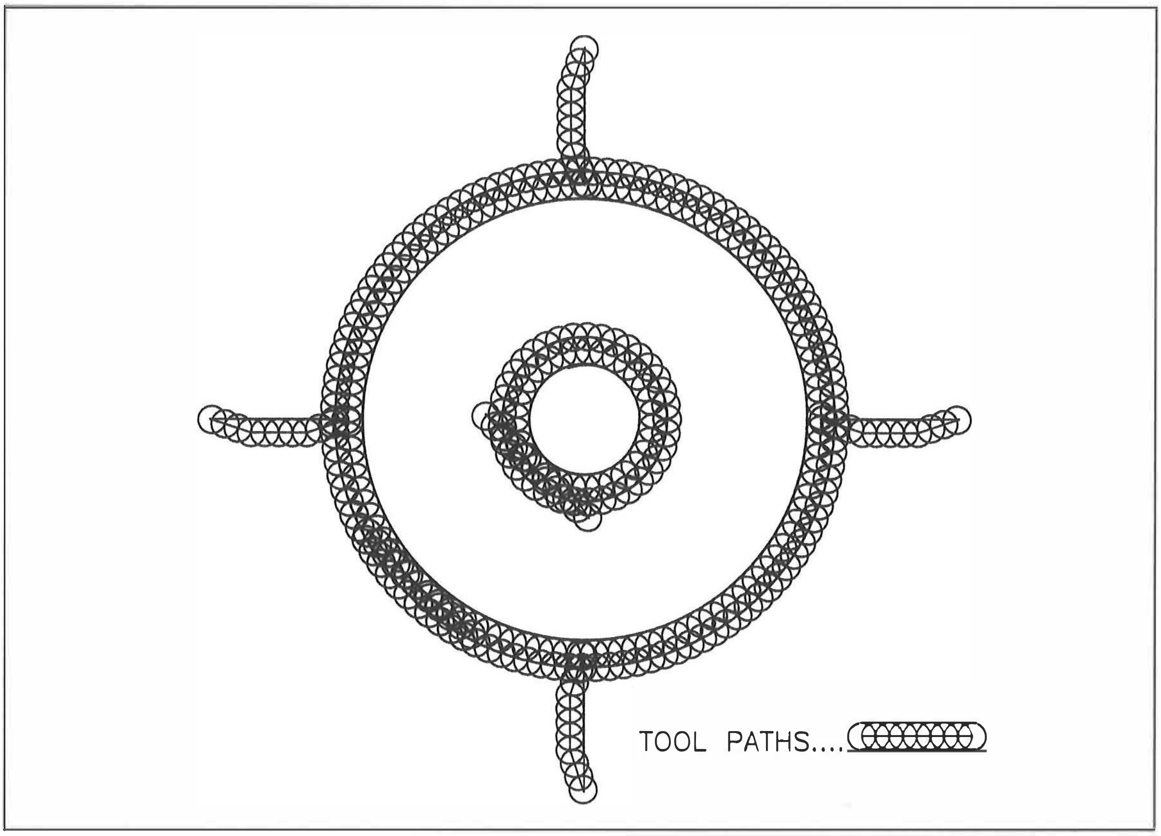


Figure A.6.2—Drawing showing tool paths (roughing cuts, offset moves, lead-in cuts, and finish cuts) used to cut both the 2-inch and 8-inch circles in the specified raw material for accuracy evaluation.

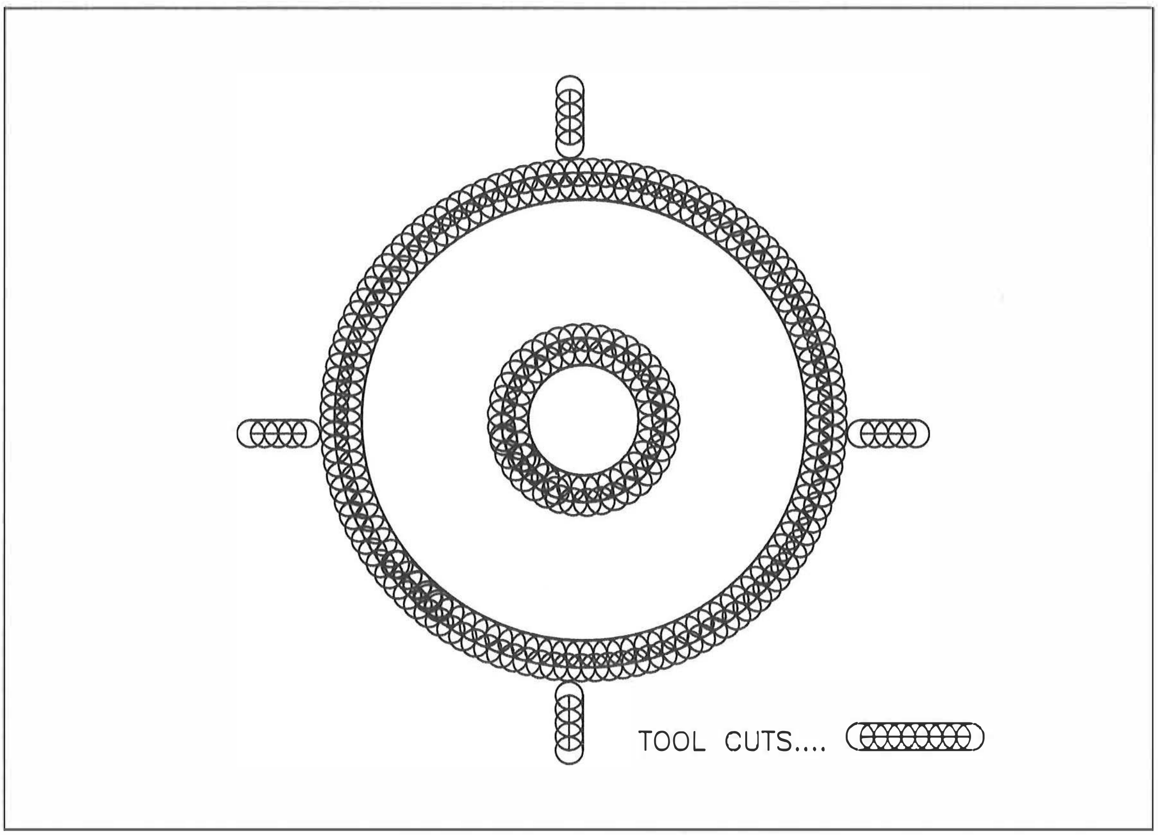


Figure A.6.3—Drawing showing only the actual cuts made in the specified raw material for the 2-inch and 8-inch circles used in accuracy evaluation.

PROGRAM FOR CIRCLES CUT IN SPECIFIED RAW MATERIAL (ACCURACY)

```
O0053;
N5G91;
N10G28X0Y0Z0;
N15G92X-31.5Y22.5;
N20G90;
N25G00X0.25Y7.0;
N27F50Z0.5;
N30G42H2G01X1.0F315;
N35Z-0.625;
N40X2.0;
N42Z0.5;
N45G40H2X2.75;
N50G00X11.25Y7.0;
N55G42H2G01X12.0F315;
N60Z-0.625;
N65X13.0;
N70Z0.5;
N72G40H2X13.75;
N75G00X7.0Y13.75;
N80G42H2G01Y13.0F315;
N85Z-0.625;
N90Y12.0;
N95Z0.5;
N100G40H2Y11.25;
N105G00X7.0Y2.75;
N120G42H2G01Y2.0F315;
N125Z-0.625;
N130Y1.0;
N132Z0.5;
N135G40H2Y0.25;
N145G00X11.5Y7.0;
N147Z-0.625G1F100;
N150G02I-4.5F315;
N155G00Z0.5;
N160G00X4.9692Y3.0854;
N165G41H2G01X4.3957Y3.9045F315;
N170Z-0.625;
N175G03X4.1716Y4.1716R2.0;
N180G02X9.8284Y9.8284R4;
N182X4.1716Y4.1716R4;
N185G03X3.9045Y4.3957R2.0;
N190G40H2G01X3.0854Y4.9692;
N195G00Z0.5;
N200G00X8.5Y7.0;
N202Z-0.625G1F100;
N205G02I-1.5F315;
N210G00Z0.5;
N215G00X7.0906Y5.2067;
N220G41H2G01X6.517Y6.0258F315;
N225Z-0.625;
N230G03X6.2929Y6.2929R2.0;
N235G02X7.7071Y7.7071R1;
N237X6.2929Y6.2929R1;
N240G03X6.0258Y6.517R2.0;
N247G1Z0.5;
N245G40H2G01X5.2067Y7.0906;
N247G28X0Y0Z0;
N255M30;
```

NOTE:
All feed speeds in the program are changed to match the desired feed speed.

Figure A.6.4—Sample program (G&M code) for accuracy cutting of circles in specified raw material.

APPENDIX A.7

Program for Squares Cut in Specified Raw Material (Accuracy)

Following are procedures for developing a G&M program for determining the accuracy of cutting squares in the specified raw material. Figure A.7.1 provides information to assist in this development. Figure A.7.2 shows the tool path for all moves including cutter compensations, lead-in/lead-out cuts, roughing cuts, and final cuts. Figure A.7.3 shows only the actual cuts made in the material. Use the following steps to develop the required program in an absolute mode. Although feed rates are not discussed in these steps, they must be included in the program so that they can be changed as necessary.

Step 1

Set the absolute zero position at a point -7 inches in the X-axis and -7 inches in the Y-axis from the exact center of the table.

Step 2

Make a positioning move to Point A (X0.25,Y7.0) in line with and 0.75 inch from the left end of the horizontal line that represents the left slot. Move 0.75 inch to the right at 0° to provide a cutter compensation to the right side of the horizontal line. Next, lower the tool to a depth of -0.625 inch and make a cutting move for 1 inch. Then raise the tool to 0.5 inch above the material and move 0.75 inch to the right at 0° to remove the cutter compensation.

Step 3

Make a positioning move to Point B (X11.75,Y7.0) in line with and 0.75 inch from the left end of the horizontal line that represents the right slot. Then, repeat the cutter compensation and cutting moves as discussed in Step 1.

Step 4

Make a positioning move to Point C (X7.0,Y13.75) in line with and 0.75 inch from the upper end of the vertical line that represents the upper slot. Move down 0.75 inch at 0° to provide a cutter compensation to the right side of the horizontal line. Next, lower the tool to a depth of -0.625 inch and make a cutting move down for 1 inch. Then raise the tool to 0.5 inch above the material and move down 0.75 inch at 0° to remove the cutter compensation.

Step 5

Make a positioning move to Point D (X7.0,Y2.75) in line with and 0.75 inch above the upper end of the vertical line representing the lower slot. Then, repeat the cutter compensation and cutting moves as discussed in Step 4.

Step 6

Make a positioning move to Point E (X2.5,Y2.5) at lower left corner of the 9-inch square. Lower the tool to a depth of -0.625 inch and without cutter compensation make counter clockwise cutting moves horizontally to point (X11.5), vertically to point (Y11.5), horizontally to point (X2.5), and vertically back to point (Y2.5).

Step 7

Raise the tool to 0.5 of an inch above the material and make a positioning move to Point F (X3.0,Y1.5) to start the finish cut of the 8-inch square. From this point, make a horizontal cutter compensation move to point (X2.5). Next, lower the tool to -0.625 inch and make counter clockwise cutting moves horizontally to point (X11.0), vertically to point (Y11.0), horizontally to point (X3.0), and vertically to point (Y2.5). Then, raise the tool to 0.5 inch above the material and remove the cutter compensation with a vertical move to point (Y1.5).

Step 8

Make a positioning move to Point G (X5.5,Y5.5) at lower left corner of the 3-inch square. Lower the tool to a depth of -0.625 inch and without cutter compensation make counter clockwise cutting moves horizontally to point (Y8.5), vertically to point (X8.5), horizontally to point (Y5.5), and vertically back to point (X5.5).

Step 9

Raise the tool to 0.5 of an inch above the material and make a positioning move to Point H (X6.0,Y4.5) to start the finish cut of the 2-inch square. From this point, make a horizontal cutter compensation move to point (Y5.5). Next, lower the tool to -0.625 inch and make counter clockwise cutting moves horizontally to point (Y8.0), vertically to point (X8.0), horizontally to point (Y6.0), and vertically to point (X5.5). Then, raise the tool to 0.5 inch above the material and remove the cutter compensation with a vertical move to point (X4.5). End with a move to machine reference zero.

Figure A.7.4 shows a sample program for this procedure. Due to differences in controllers, it may be necessary to make minor changes in this program.

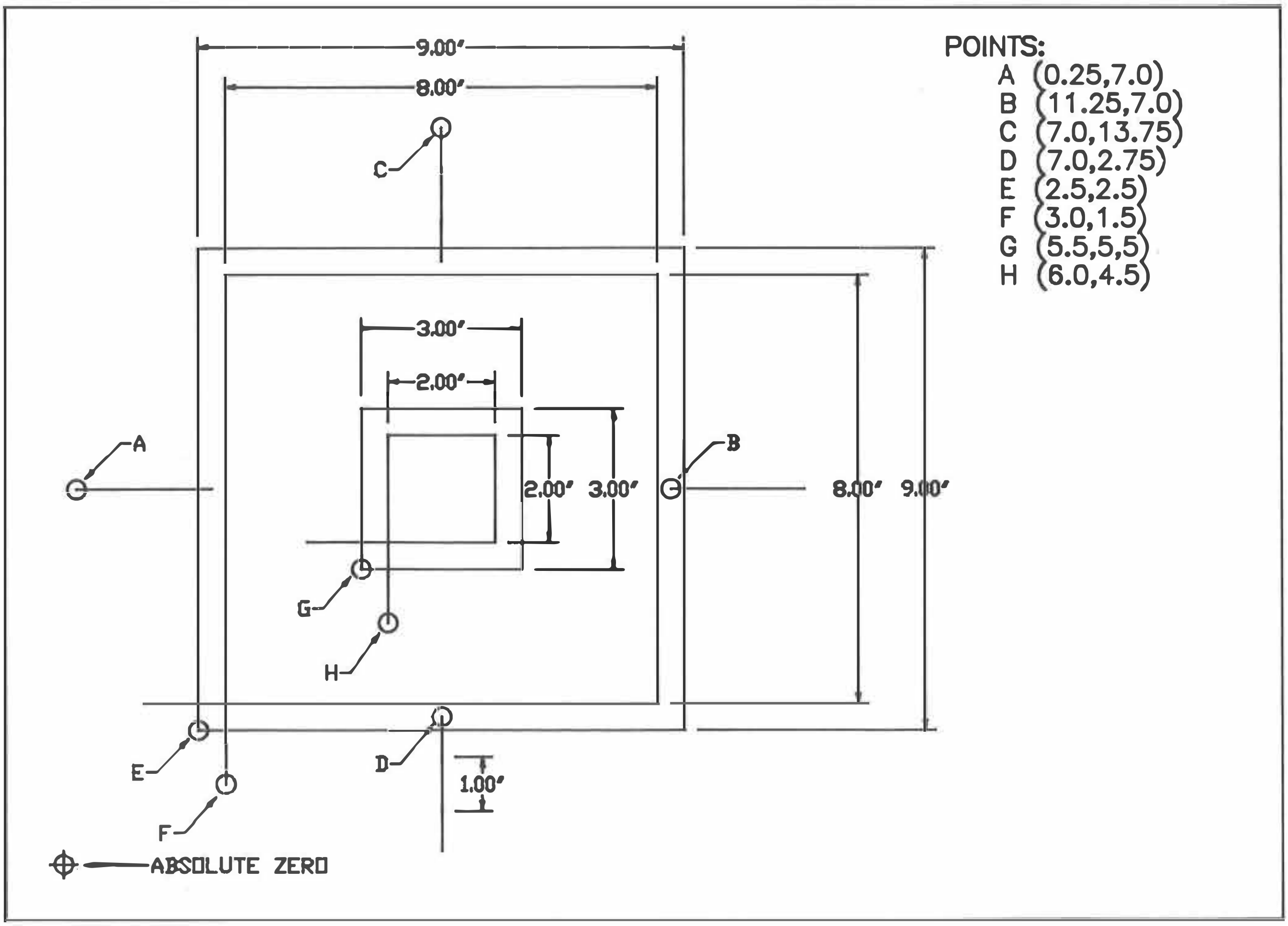


Figure A.7.1—Drawing showing information for developing a program (G&M code) needed to make square accuracy cuts in specified raw material.

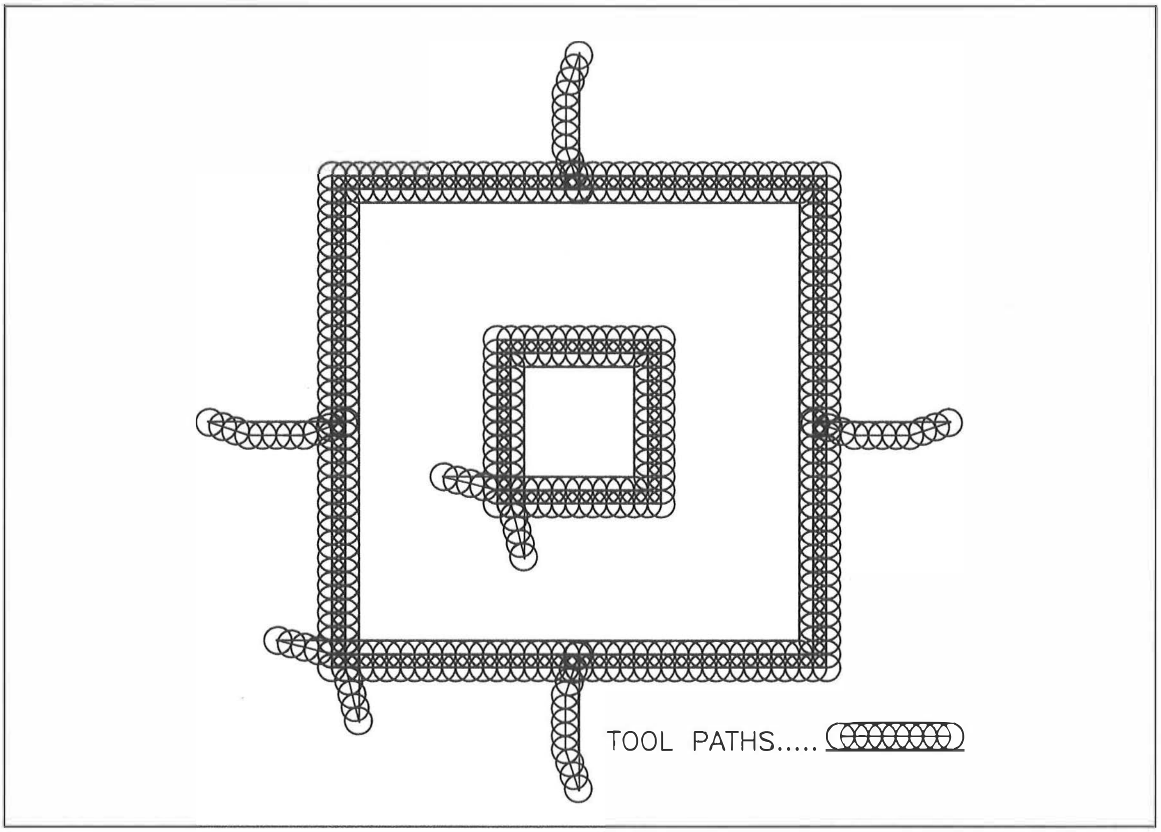


Figure A.7.2—Drawing showing tool paths (roughing cuts, offset moves, lead-in cuts, and finish cuts) used to cut both the 2-inch and 8-inch squares in the specified raw material for accuracy evaluation.

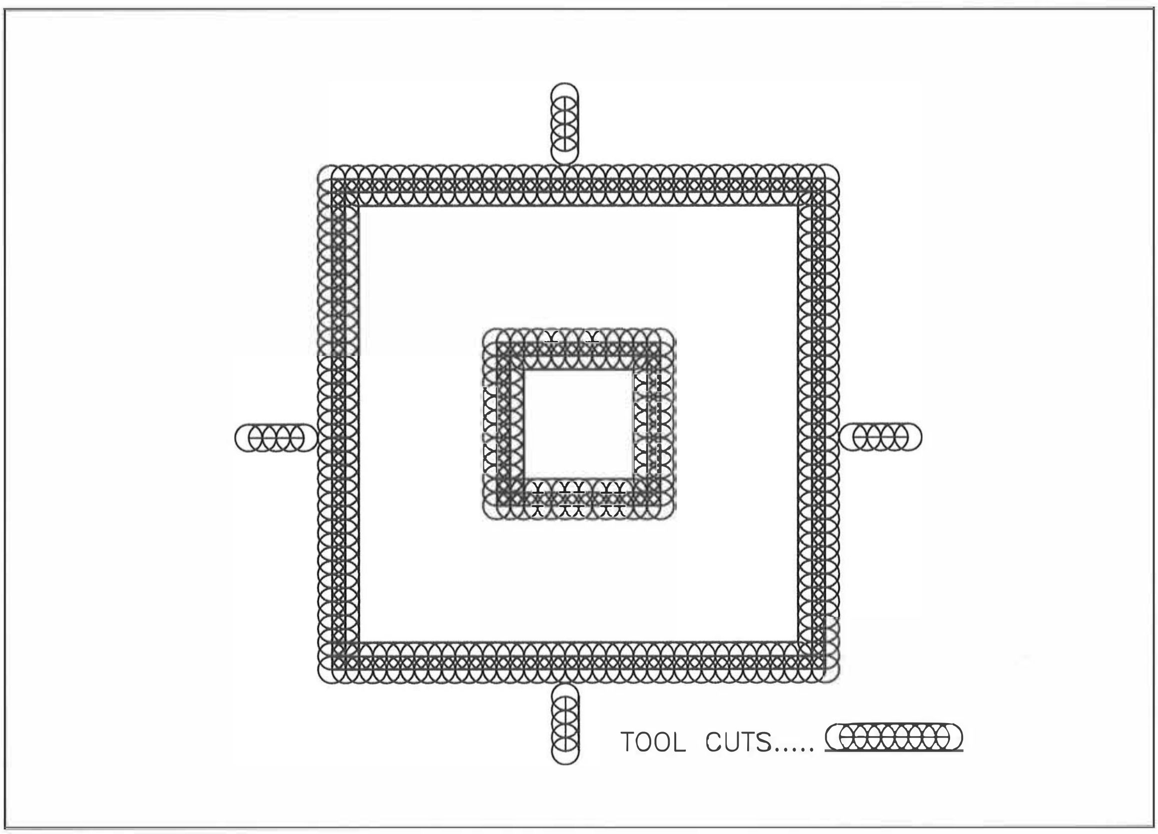


Figure A.7.3—Drawing showing only the actual cuts made in the specified raw material for the 2-inch and 8-inch squares used in accuracy evaluation.

PROGRAM FOR SQUARES CUT IN SPECIFIED RAW MATERIAL (ACCURACY)

```
O0054;
N5G91;
N10G28X0Y0Z0;
N15G92X-31.5Y22.5;
N20G90;
N25G00X0.25Y7.0;
N27Z0.5;
N30G42H2G01X1.0F315;
N35Z-0.625;
N40X2.0;
N47Z0.5;
N45G40H2X2.75;
N50G00X11.25Y7.0;
N55G42H2G01X12.0F315;
N60Z-0.625;
N65X13.0;
N70Z0.5;
N75G40H2X13.75;
N80G00X7.0Y13.75;
N85G42H2G01Y13.0F315;
N90Z-0.625;
N95Y12.0;
N100Z0.5;
N105G40H2Y11.25;
N115G00X7.0Y2.75;
N120G42H2G01Y2.0F315;
N125Z-0.625;
N130Y1.0;
N132Z0.5;
N135G40H2Y0.25;
N145G00X2.5Y2.5;
N147Z-0.625;
N150G01Y11.5F315;
N160X11.5;
N165Y2.5;
N170X2.5;
N175G00Z0.5;
N180G00X3.0Y1.5;
N185G41H2G01Y2.5F315;
N190Z-0.625;
N195Y11.0;
N197G4;
N200X11.0;
N202G4;
N205Y3.0;
N207G4;
N210X2.5;
N211G4;
N212Z0.5;
N215G40H2X1.5;
N225G00X5.5Y5.5;
N227Z-0.625;
N230G01Y8.5F315;
N240X8.5;
N245Y5.5;
N250X5.5;
N255G00Z0.5;
N260G00X6.0Y4.5;
N265G41H2G01Y5.5F315;
N270Z-0.625
275Y8.0;
N277G4;
N280X8.0;
N282G4;
N285Y6.0;
N287G4;
N290X5.5;
N291G4;
N292Z0.5;
N295G40H2X4.5;
N297G28X0Y0Z0;
N305M30;
```

Note: All feed speeds in the program are changed to match the desired feed speed.

Figure A.7.4—Sample program (G&M code) for accuracy cutting of squares in specified raw material.

APPENDIX A.8

Program for Diamonds Cut in Specified Raw Material (Accuracy)

Following are procedures for developing a G&M program for determining the accuracy of cutting diamonds in the specified raw material. Figure A.8.1 provides information to assist in this development. Figure A.8.2 shows the tool path for all moves including cutter compensations, lead-in/lead-out cuts, roughing cuts, and final cuts. Figure A.8.3 shows only the actual cuts made in the material. Use the following steps to develop the required program in an absolute mode. Although feed rates are not discussed in these steps, they must be included in the program so that they can be changed as necessary.

Step 1

Set the absolute zero position at a point -7 inches in the X-axis and -7 inches in the Y-axis from the exact center of the table.

Step 2

Make a positioning move to Point A (X2.227,Y2.227) in line with and 0.75 inch from the lower left end of the line that represents the lower left slot. Move 0.75 inch to point (X2.7574,Y2.7574) with a left cutter compensation. Next, lower the tool to a depth of -0.625 inch and make a cutting move to point (X3.4645,Y3.4645). Then raise the tool to 0.5 inch above the material and move to point (X3.9948,Y3.9948) to remove the cutter compensation.

Step 3

Make a positioning move to Point B (X10.0052,Y10.0052) in line with and 0.75 inch from the lower left end of the line that represents the upper right slot. Move 0.75 inch to point (X10.5355,Y10.5355) with a left cutter compensation. Next, lower the tool to a depth of -0.625 inch and make a cutting move to point (X11.2426,Y11.2426). Then raise the tool to 0.5 inch above the material and move to point (X11.773,Y11.773) to remove the cutter compensation.

Step 4

Make a positioning move to Point C (X2.227,Y11.773) in line with and a 0.75 inch from the upper left end of the line that represents the upper left slot. Move 0.5 inch to point (X2.7574,Y11.2426) with a right cutter compensation. Next, lower the tool to a depth of -0.625 inch and make a cutting move to point (X3.4645,Y10.5355). Then raise the tool to 0.5 inch above the material and move to point (X3.9948,Y10.0052) to remove the cutter compensation.

Step 5

Make a positioning move to Point D (X10.0052,Y3.9948) in line with and a 0.75 inch from the upper left end of the line that represents the lower right slot. Move 0.75 inch to point (X10.5355,Y3.4645) with a right cutter compensation. Next, lower the tool to a depth of -0.625 inch and make a cutting move to point (X11.2426,Y2.7574). Then, raise the tool to 0.5 inch above the material and move to point (X11.773,Y2.227) to remove the cutter compensation.

Step 6

Make a positioning move to Point E (X0.636,Y7.0) at left corner of the 9-inch diamond. Lower the tool to a depth of -0.625 inch and without cutter compensation make counter clockwise cutting moves to point (X7.0,Y13.364), to point (X13.364,Y7.0), to point (X7.0,Y0.636), and back to point (X0.636,Y7.0).

Step 7

Raise the tool to 0.5 inch above the material and make a positioning move to Point F (X0.2825,Y5.9393) to start the finish cut of the 8-inch diamond. From this point, make a right cutter compensation move to point (X0.9896,Y6.6464). Next, lower the tool to -0.625 inch and make counter clockwise cutting moves to point (X7.0,Y12.6569), to point (X12.6569,Y7.0), to point (X7.0,Y1.3431), and to point (X0.9896,Y7.3536). Then, raise the tool to 0.5 inch above the material and remove the cutter compensation with a move to point (X0.2825,Y8.0607).

Step 8

Make a positioning move to Point G (X4.8787,Y7.0) at left corner of the 3-inch diamond. Lower the tool to a depth of -0.625 inch and without cutter compensation make counter clockwise cutting moves to point (X7.0,Y9.1213), to point (X9.1213,Y7.0), to point (X7.0,Y4.8787), and back to point (X4.8787,Y7.0).

Step 9

Raise the tool to 0.5 inch above the material and make a positioning move to Point H (X4.5251,Y5.9393) to start the finish cut of the 2-inch diamond. From this point, make a cutter compensation move to point (X5.2322,Y6.6464). Next, lower the tool to -0.625 inch and make counter clockwise cutting moves to point (X7.0,Y8.4142), to point (X8.4142,Y7.0), to point (X7.0,Y5.5858), and to point (X5.2322,Y7.3536). Then, raise the tool to 0.5 inch above the material and remove the cutter compensation with a move to point (X4.5251,Y8.0607). End with a move to machine reference zero.

Figure A.5.4 shows a sample program for this procedure. Due to differences in controllers, it may be necessary to make minor changes in this program.

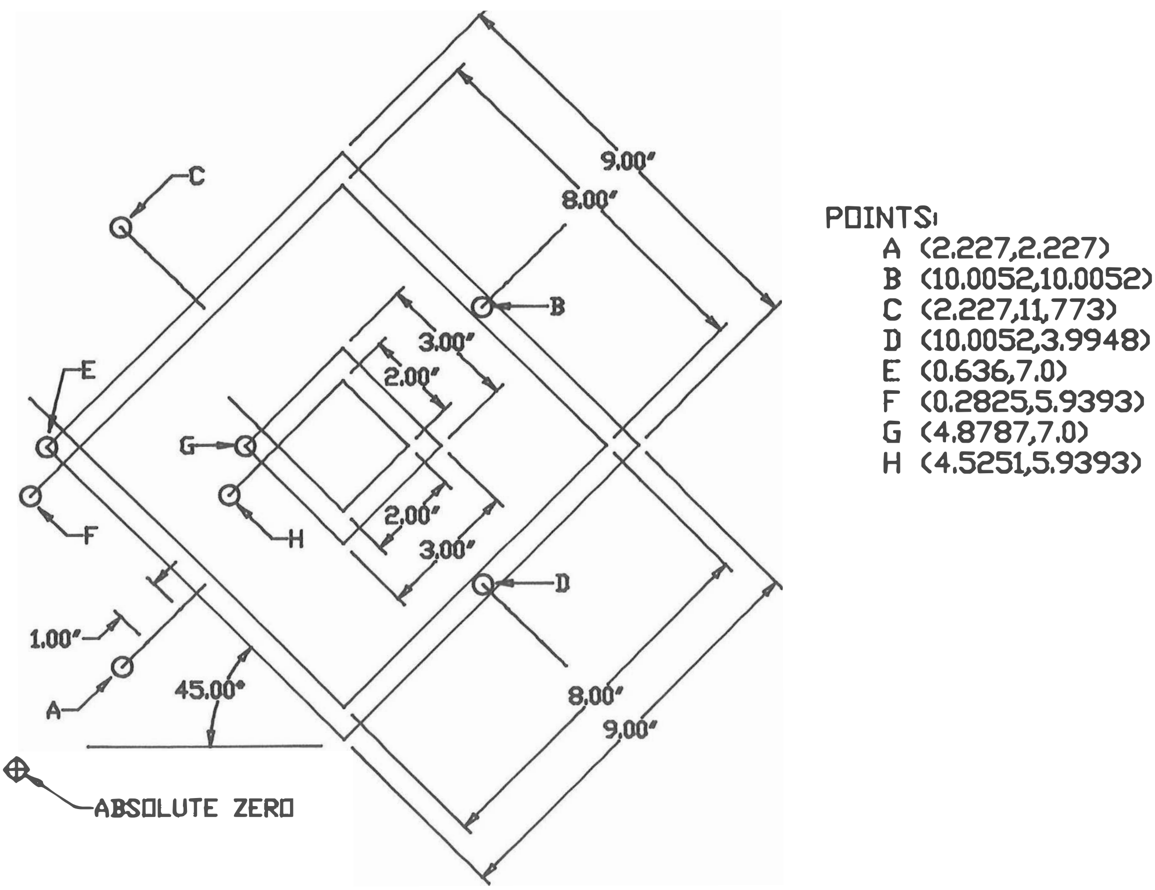


Figure A.8.1—Drawing showing information for developing a program (G&M code) needed to make diamond accuracy cuts in specified raw material.

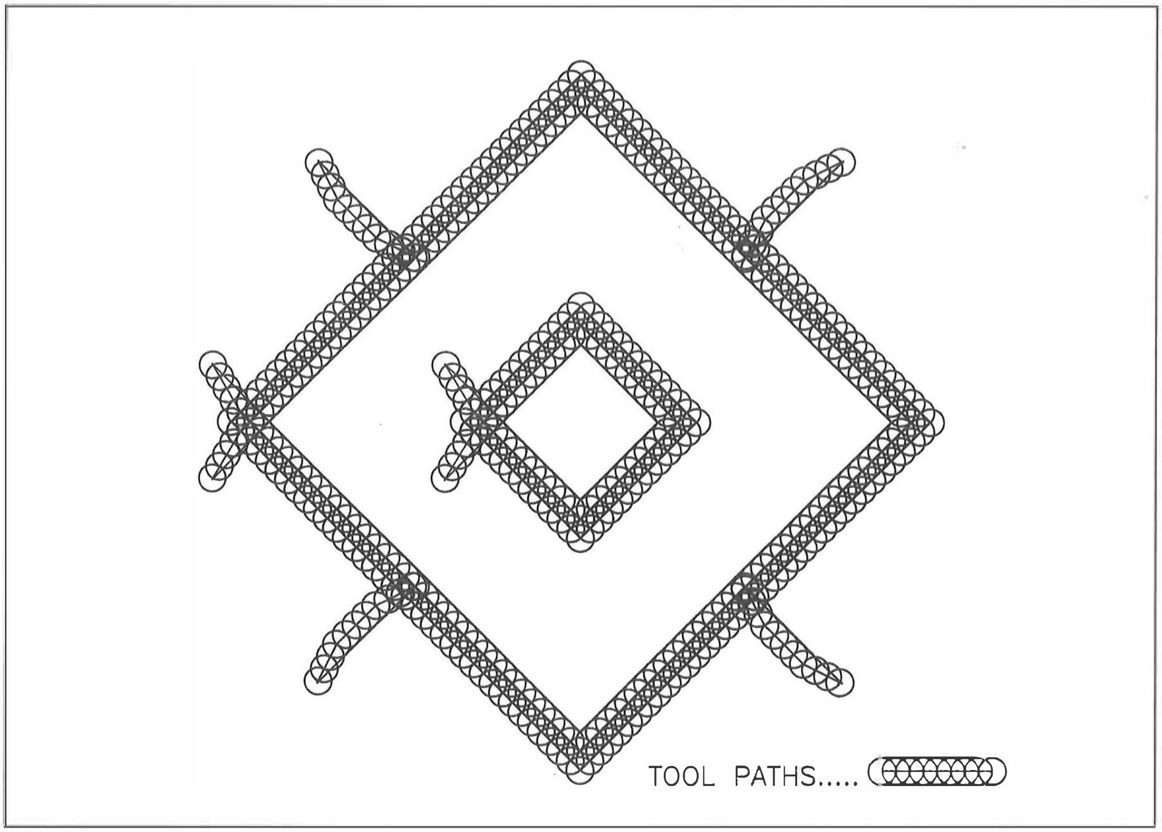


Figure A.8.2—Drawing showing tool paths (roughing cuts, offset moves, lead-in cuts, and finish cuts) used to cut both the 2-inch and 8-inch diamonds in the specified raw material for accuracy evaluation.

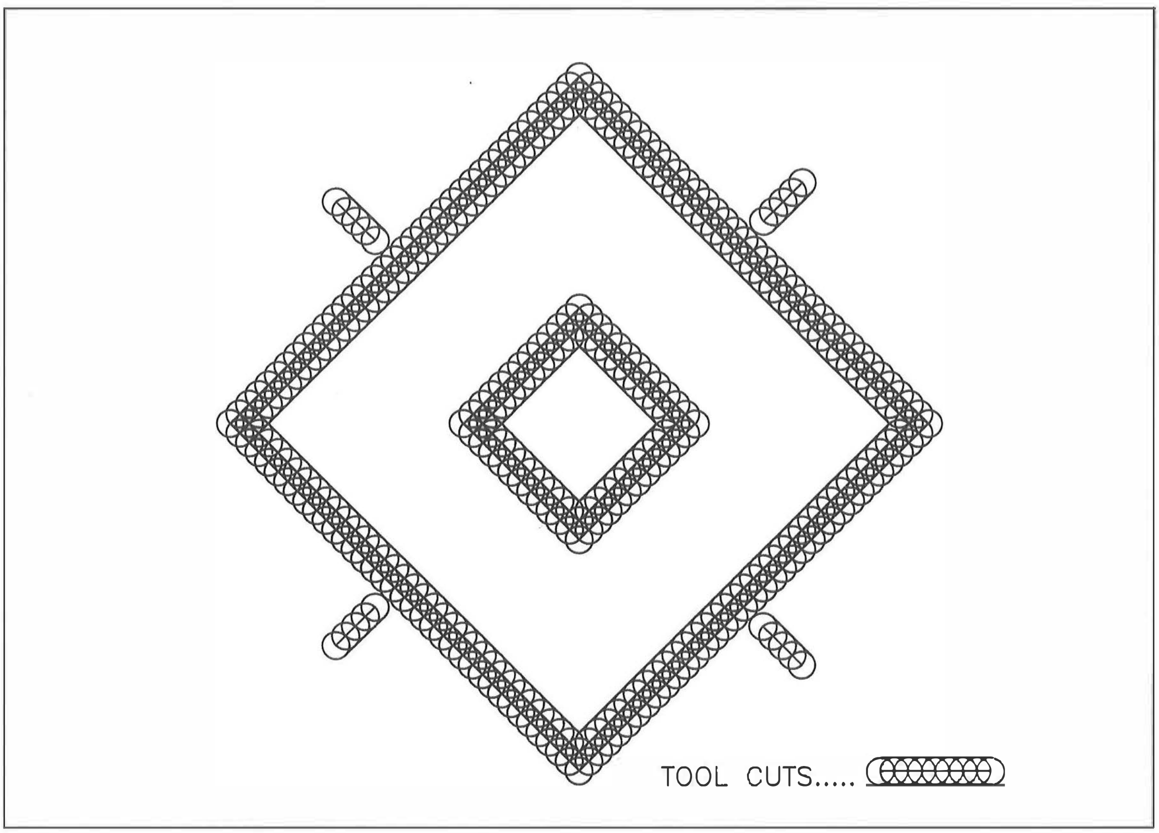


Figure A.8.3—Drawing showing only the actual cuts made in the specified raw material for the 2-inch and 8-inch diamonds used in accuracy evaluation.

PROGRAM FOR DIAMONDS CUT IN SPECIFIED RAW MATERIAL (ACCURACY)

```
O0055;
N5G91;
N10G28X0Y0Z0;
N15G92X-31.5Y22.5;
N20G90;
N25G00X2.227Y2.227;
N27Z0.5;
N30G41H2G01X2.7574Y2.7574F315;
N35Z-0.625;
N40X3.4645Y3.4645;
N42Z0.5;
N45G40H2X3.9948Y3.9948;
N50G00X10.0052Y10.0052;
N55G41H2G01X10.5355Y10.5355F315;
N60Z-0.625;
N65X11.2426Y11.2426;
N70Z0.5;
N75G40H2X11.773Y11.773;
N80G00X2.227Y11.773;
N85G42H2G01X2.7574Y11.2426F315;
N90Z-0.625;
N95X3.4645Y10.5355;
N100Z0.5;
N105G40H2X3.9948Y10.0052;
N115G00X10.0052Y3.9948;
N120G42H2G01X10.5355Y3.4645F315;
N125Z-0.625;
N130X11.2426Y2.7574;
N132Z0.5;
N135G40H2X11.773Y2.227;
N145G00X0.636Y7.0;
N147Z-0.625;
N150G01X7.0Y13.364F315;
N160X13.364Y7.0;
N165X7.0Y0.636;
N170X0.636Y7.0;
N175G00Z0.5;
N180G00X0.2825Y5.9393;
N185G41H2G01X0.9896Y6.6464F315;
N190Z-0.625;
N195X7.0Y12.6569;
N197G4;
N200X12.6569Y7.0;
N202G4;
N205X7.0Y1.3431;
N207G4;
N210X0.9896Y7.3536;
N211G4;
N212Z0.5;
N215G40H2X0.2825Y8.0607;
N225G00X4.8787Y7.0;
N227Z-0.625;
N230G01X7.0Y9.1213F315;
N240X9.1213Y7.0;
N245X7.0Y4.8787;
N250X4.8787Y7.0;
N255G00Z0.5;
N260G00X4.5251Y5.9393;
N265G41H2G01X5.2322
           Y6.6464F315;
N270Z-0.625;
N275X7.0Y8.4142;
N277G4;
N280X8.4142Y7.0;
N282G4;
N285X7.0Y5.5858;
N287G4;
N290X5.2322Y7.3536;
N291G4;
N292Z0.5;
N295G40H2X4.5251Y8.0607;
N297G28X0Y0Z0;
N305M30;
```

Note: All feed speeds in the program are changed to match the desired feed speed.

Figure A.8.4—Sample program (G&M code) for accuracy cutting of diamonds in specified raw material.

APPENDIX A.9

Program for Circles Cut in Acrylic Sheets (Repeatability)

Following are procedures for developing a G&M program for determining the repeatability of cutting circles in acrylic sheets. Figure A.9.1 provides information to assist in this development. Figure A.9.2 shows the tool path for all moves including cutter compensations, lead-in/lead-out cuts, roughing cuts, and final cuts. Figure A.9.3 shows only the actual cuts made in the material. Use the following steps to develop the required main program and its subroutine in an absolute mode. Although feed rates are not discussed in these steps, they must be included in the program so that they can be changed as necessary.

Step 1

Set the absolute zero position at a point -7 inches in the X-axis and -7 inches in the Y-axis from the exact center of the table.

Step 2

To start the main program, make a positioning move to Point A (X0.5,Y7.0) in line with and 0.5 inch from the left end of the horizontal line that represents the left slot. Move 0.5 inch to the right at 0^{o} to provide a cutter compensation to the right side of the horizontal line. Next, lower the tool to a depth of -0.1875 inch and make a cutting move for 1 inch. Then, raise the tool to 0.25 inch above the material and move 0.5 inch to the right at 0^{o} to remove the cutter compensation.

Step 3

Make a positioning move to Point B (X11.5,Y7.0) in line with and 0.5 inch from the left end of the horizontal line that represents the right slot. Then, repeat the cutter compensation and cutting moves as discussed in Step 1.

Step 4

Make a positioning move to Point C (X7.0,Y13.5) in line with and 0.5 inch from the upper end of the vertical line that represents the upper slot. Move down 0.5 inch at 0^{o} to provide a cutter compensation to the right side of the horizontal line. Next, lower the tool to a depth of -0.1875 inch and make a cutting move down for 1 inch. Then, raise the tool to a 0.25 inch above the material and move down 0.5 inch at 0^{o} to remove the cutter compensation.

Step 5

Make a positioning move to Point D (X7.0,Y2.5) in line with and 0.5 inch above the upper end of the vertical line representing the lower slot. Then, repeat the cutter compensation and cutting moves as discussed in Step 4.

Step 6

Make a positioning move to Point E (X11.1875,Y7.0) at the right edge of the circle with a diameter of 8.375 inches. Lower the tool to a depth of -0.1875 inch and make a 360^{o} move (roughing cut) in a counter clockwise direction without cutter compensation. Then, raise the cutter to 0.5 inch.

Step 7

Make a positioning move to Point G (X8.1875,Y7.0) at the right edge of the circle with a diameter of 2.375 inches. Lower the tool to a depth of -0.1875 inch and make a 360^{o} move (roughing cut) in a counter clockwise direction without cutter compensation. Then, raise the cutter to 0.5 inch.

Step 8

At the end of the main program, include a subroutine call statement to run the subroutine 25 times. After the subroutine is called 25 times, move to machine reference zero.

Step 9

Start the subroutine by making a positioning move to Point F (X3.6599Y4.6108) to start the finish cut of the 8-inch circle. From this point, make a right cutter compensation move to point (X4.0429,Y4.2894). Next, lower the tool to -0.1562 inch and make a lead-in cut in a clockwise arc with a radius of 2 inches to the point (X4.1716,Y4.1716). Then, make the 360° counter clockwise finish cut to the 8-inch circle. From the finish point of the circle, make a lead-out cut in a clockwise arc with a radius of 2 inches to the point (X4.2894,Y4.0429). Raise the tool to 0.25 inch above the material and remove the cutter compensation with a move to the point (X4.6108,Y3.6599).

Step 10

Raise the tool to 0.25 inch above the material and make a positioning move to Point H (X5.7812,Y6.7322) to start the finish cut of the 2-inch circle. From this point, make a right cutter compensation move to point (X6.1643,Y6.4108). Next, lower the tool to -0.1562 inch and make a lead-in cut in a clockwise arc with a radius of 2 inches to the point (X6.2929,Y6.2929). Then make the 360° counter clockwise finish cut to the 2-inch circle. From the finish point of the circle, make a lead-out cut in a clockwise arc with a radius of 2 inches to the point (X6.4108,Y6.1643). Raise the tool to 0.25 inch above the material and remove the cutter compensation with a move to the point (X6.7322,Y5.7812).

Figure A.9.4 shows a sample program for this procedure. Due to differences in controllers, it may be necessary to make minor changes in this program.

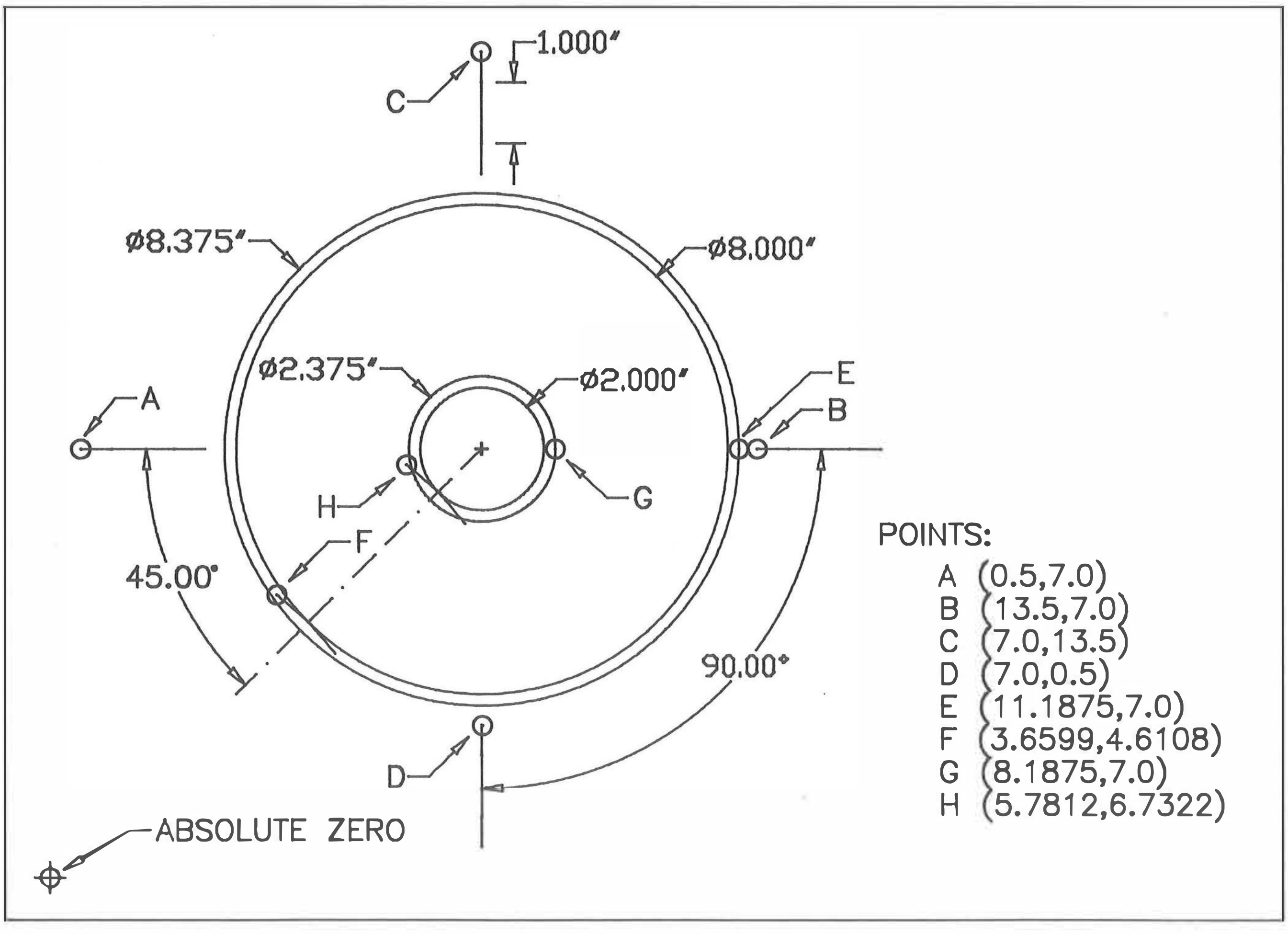


Figure A.9.1—Drawing showing information for developing a program (G&M code) needed to make circle repeatability cuts in acrylic sheets.

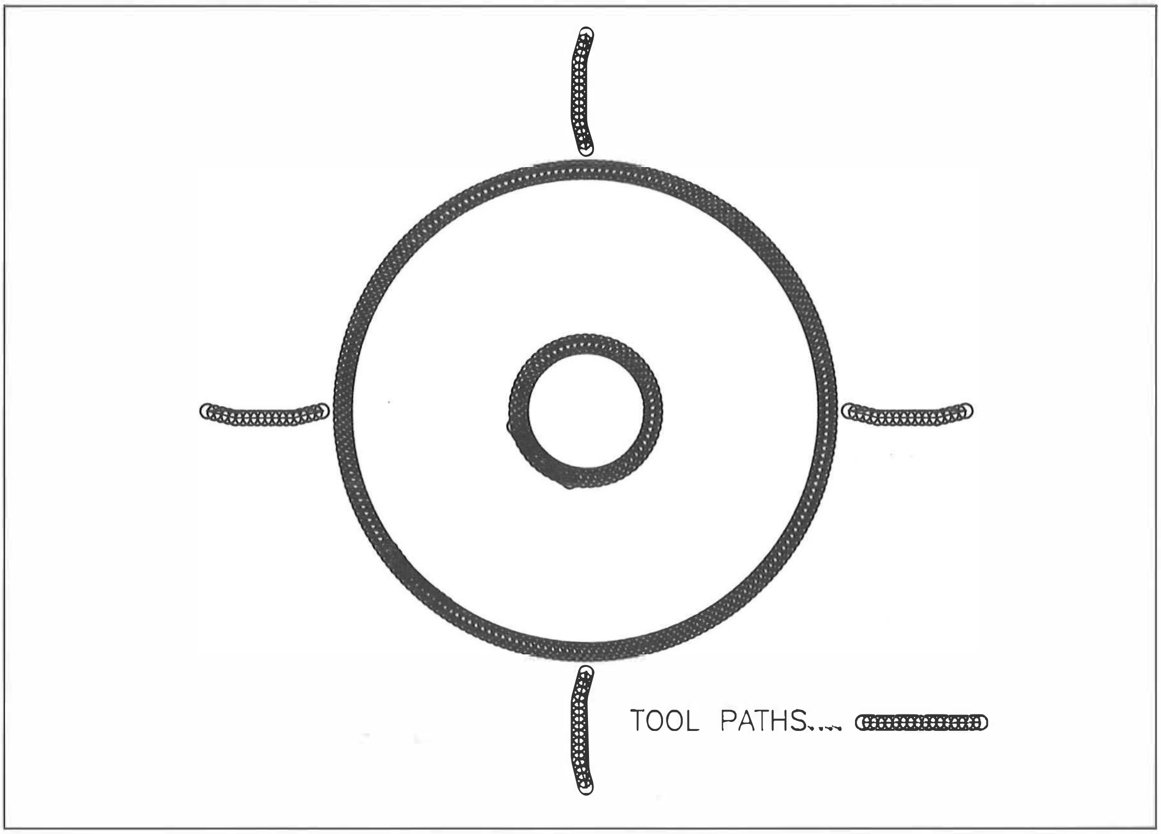


Figure A.9.2—Drawing showing tool paths (roughing cuts, offset moves, lead-In cuts, and finish cuts) used to cut both the 2-inch and 8-inch circles in an acrylic sheet for repeatability evaluation.

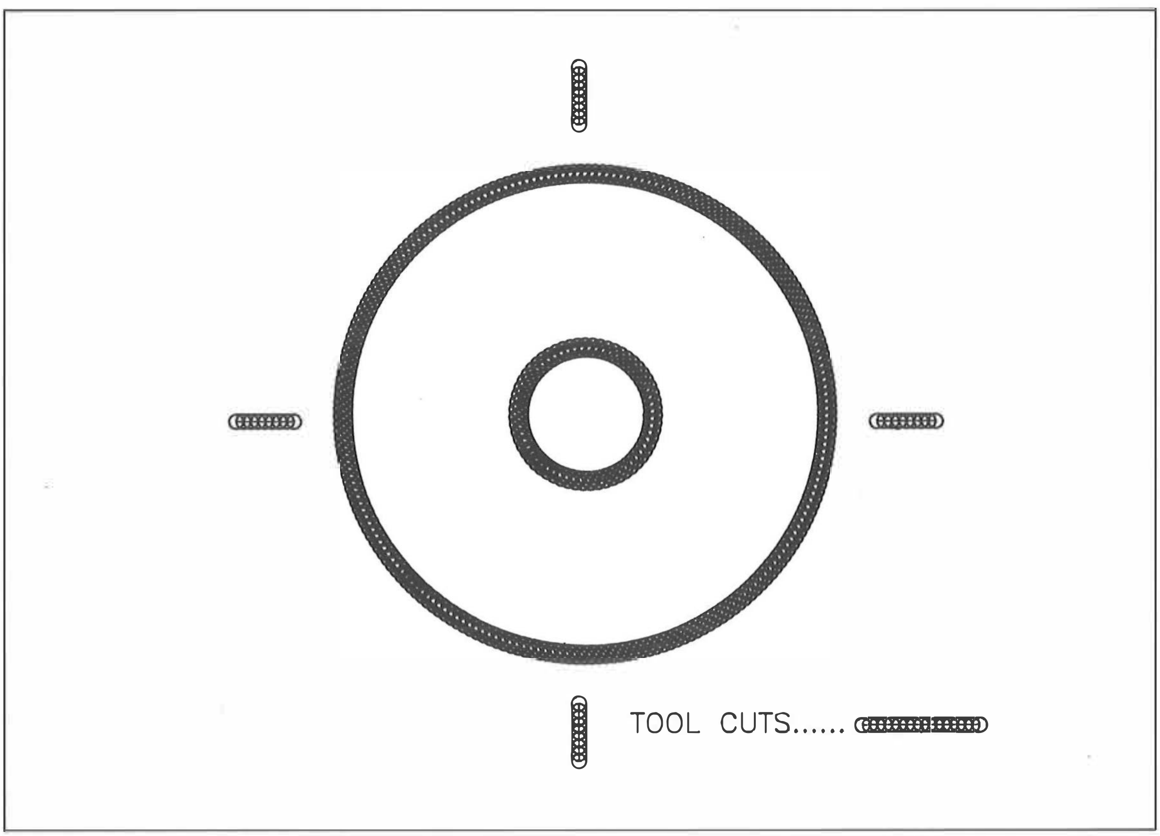


Figure A.9.3—Drawing showing only the actual cuts made in an acrylic sheet for the 2-inch and 8-inch circles used in repeatability evaluation.

PROGRAM FOR CIRCLES CUT IN ACRYLIC SHEETS (REPEATABILITY)

```
O0056;
N5G91;
N10G28X0Y0Z0;
N15G92X-31.5Y22.5;
N20G90;
N25G00X0.5Y7.0;
N27Z0.25;
N30G42H1G01X1.0F100;
N35Z-0.1875;
N40X2.0;
N42Z0.25;
N45G40H1X2.5;
N55G00X11.5Y7.0;
N60G42H1G01X12.0F100;
N65Z-0.1875;
N70X13.0;
N72Z0.25;
N75G40H1X13.5;
N85G00X7.0Y13.5;
N90G42H1G01Y13.0F100;
N95Z-0.1875;
N100Y12.0;
N102Z0.25;
N105G40H1Y11.5;
N115G00X7.0Y2.5;
N120G42H1G01Y2.0F100;
N125Z-0.1875;
N130Y1.0;
N132Z0.25;
N135G40H1Y0.5
N145G00X11.1875Y7.0;
N147Z-0.1875;
N150G03I-4.1875F100;
N155G00Z0.25;
N160G00X8.1875Y7.0;
N165Z-0.1875;
N170G03I-1.1875F100;
N175G1F100Z0.25;
N180M98P250057;
N185M30;
```

```
O0057;
N5X0Y0;
N10G1F100X3.6599Y4.6108;
N15G42H1G1X4.0429Y4.2894F90;
N20Z-0.1562;
N25G2X4.1716Y4.1716R2;
N30G3X9.8284Y9.8284R4;
N35G3X4.1716Y4.1716R4;
N40G2X4.2894Y4.0429R2;
N45G1F100Z0.25;
N50G40H1G1X4.6108Y3.6599;
N55Y3.25;
N60G1F100X5.7812Y6.7322;
N65G42H1G1X6.1643Y6.4108F100;
N70Z-0.1562;
N75G2X6.2929Y6.2929R2;
N80G3X7.7071Y7.7071R1;
N85X6.2929Y6.2929R1;
N90G2X6.4108Y6.1643R2;
N95G1F100Z0.25;
N100G40H1G1X6.7322Y5.7812;
N105M99;
```

NOTE:
The feed speeds in Statements N15 and N65 of Subroutine O0057 are changed to match the deired feed speed.

Figure A.9.4—Sample program (G&M code) for repeatability cutting of circles in acrylic sheets.

APPENDIX A.10

Program for Squares Cut in Acrylic Sheets (Repeatability)

Following are procedures for developing a G&M program for determining the repeatability of cutting squares in acrylic sheets. Figure A.10.1 provides information to assist in this development. Figure A.10.2 shows the tool path for all moves including cutter compensations, lead-in/lead-out cuts, roughing cuts, and final cuts. Figure A.10.3 shows only the actual cuts made in the material. Use the following steps to develop the required main program and its subroutine in an absolute mode. Although feed rates are not discussed in these steps, they must be included in the program so they can be changed as necessary.

Step 1

Set the absolute zero position at a point -7 inches in the X-axis and -7 inches in the Y-axis from the exact center of the table.

Step 2

To start the main program, make a positioning move to Point A (X0.5,Y7.0) in line with and 0.5 inch from the left end of the horizontal line that represents the left slot. Move 0.5 inch to the right at 0° to provide a cutter compensation to the right side of the horizontal line. Next, lower the tool to a depth of -0.1875 inch and make a cutting move for 1 inch. Then, raise the tool 0.25 inch above the material and move 0.5 inch to the right at 0° to remove the cutter compensation.

Step 3

Make a positioning move to Point B (X11.5,Y7.0) in line with and 0.5 inch from the left end of the horizontal line that represents the right slot. Then, repeat the cutter compensation and cutting moves as discussed in Step 1.

Step 4

Make a positioning move to Point C (X7.0,Y13.5) in line with and 0.5 inch from the upper end of the vertical line that represents the upper slot. Move down 0.5 inch at 0° to provide a cutter compensation to the right side of the horizontal line. Next, lower the tool to a depth of -0.1875 inch and make a cutting move down for 1 inch. Then, raise the tool 0.25 inch above the material and move down 0.5 inch at 0° to remove the cutter compensation.

Step 5

Make a positioning move to Point D (X7.0,Y2.5) in line with and 0.5 inch above the upper end of the vertical line representing the lower slot. Then, repeat the cutter compensation and cutting moves as discussed in Step 4.

Step 6

Make a positioning move to Point E (X2.8125,Y2.8125) at lower left corner of the 8.375-inch square. Lower the tool to a depth of -0.1875 inch and without cutter compensation make counter clockwise cutting moves horizontally to point (X11.1875), vertically to point (Y11.1875), horizontally to point (X2.8125), and vertically back to point (Y2.8125). Then, raise the cutter to 0.25 inch.

Step 7

Make a positioning move to Point G (X5.8125,Y5.8125) at lower left corner of the 2.375-inch square. Lower the tool to a depth of -0.1875 inch and without cutter compensation make counter clockwise cutting moves horizontally to point (X8.1875), vertically to point (Y8.1875), horizontally to point (X5.8125), and vertically back to point (Y5.8125). Then, raise the cutter to 0.25 inch.

Step 8

At the end of the main program, include a subroutine call statement to run the subroutine 25 times. After the subroutine is called 25 times, move to machine reference zero.

Step 9

Start the subroutine by making a positioning move to Point F (X2.25,Y3.0) to start the finish cut of the 8-inch square. From this point, make a horizontal cutter compensation move to point (X2.75). Next, lower the tool to -0.1562 inch and make counter clockwise cutting moves horizontally to point (X11.0), vertically to point (Y11.0), horizontally to point (X3.0), and vertically to point (Y2.75). Then, raise the tool to 0.25 inch above the material and remove the cutter compensation with a vertical move to point (Y2.25).

Step 10

Raise the tool to 0.25 inch above the material and make a positioning move to Point H (X5.25,Y6.0) to start the finish cut of the 2-inch square. From this point, make a horizontal cutter compensation move to point (X5.75). Next, lower the tool to -0.1562 inch and make counter clockwise cutting moves horizontally to point (X8.0), vertically to point (Y8.0), horizontally to point (X6.0), and vertically to point (Y5.75). Then, raise the tool to 0.25 inch above the material and remove the cutter compensation with a vertical move to point (Y5.25).

Figure A.10.4 shows a sample program for this procedure. Due to differences in controllers, it may be necessary to make minor changes in this program.

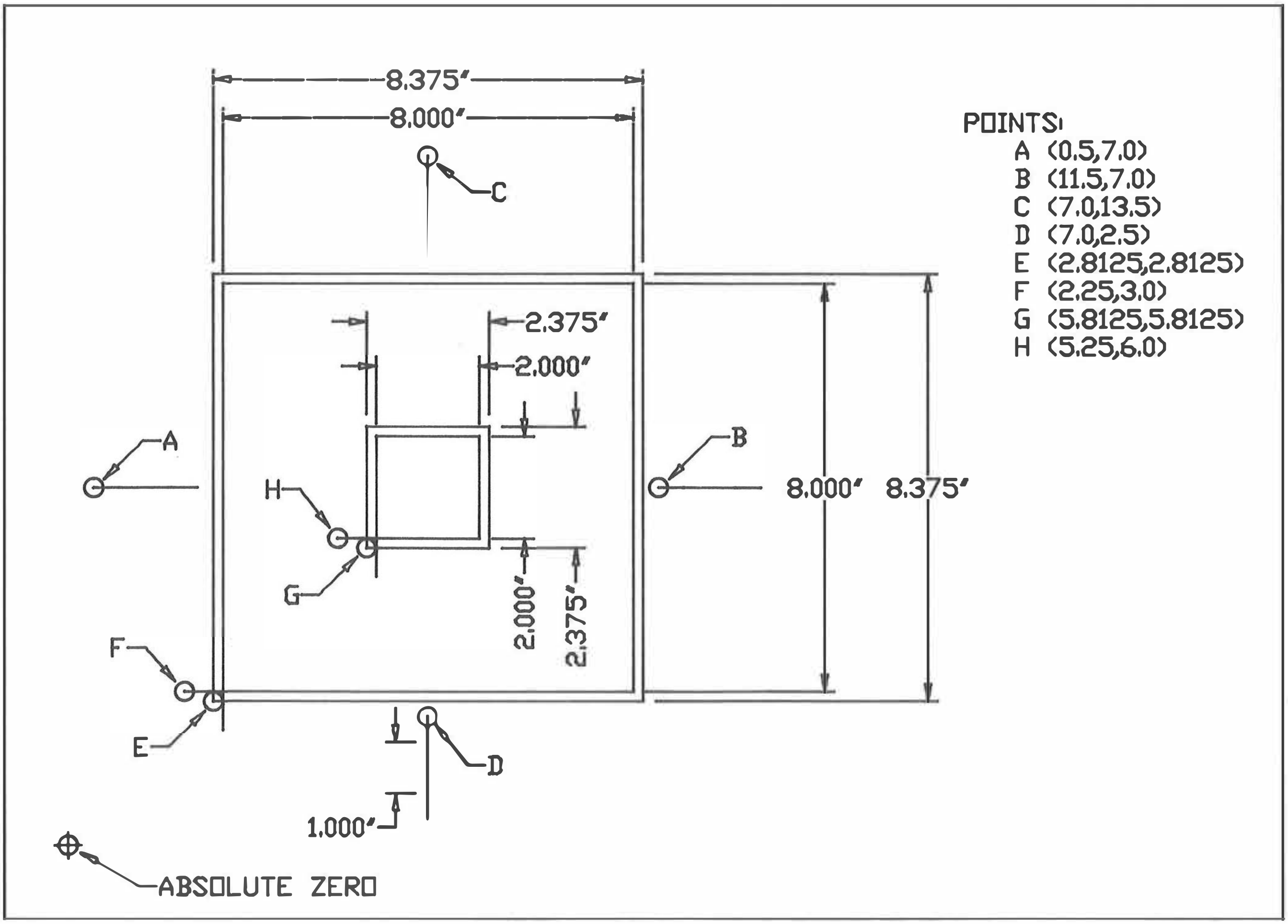


Figure A.10.1—Drawing showing information for developing a program (G&M code) needed to make square repeatability cuts in acrylic sheets.

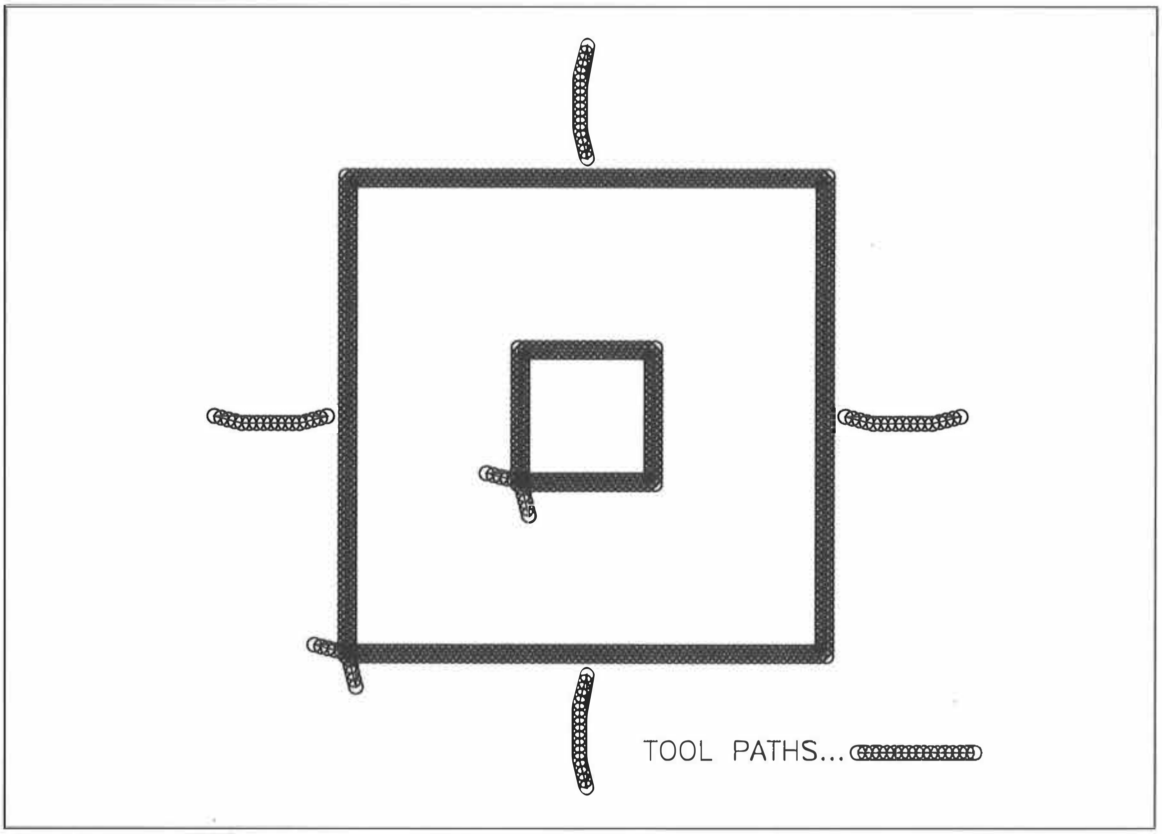


Figure A.10.2—Drawing showing tool paths (roughing cuts, offset moves, lead-in cuts, and finish cuts) used to cut both the 2-inch and 8-inch squares in an acrylic sheet for repeatability evaluation.

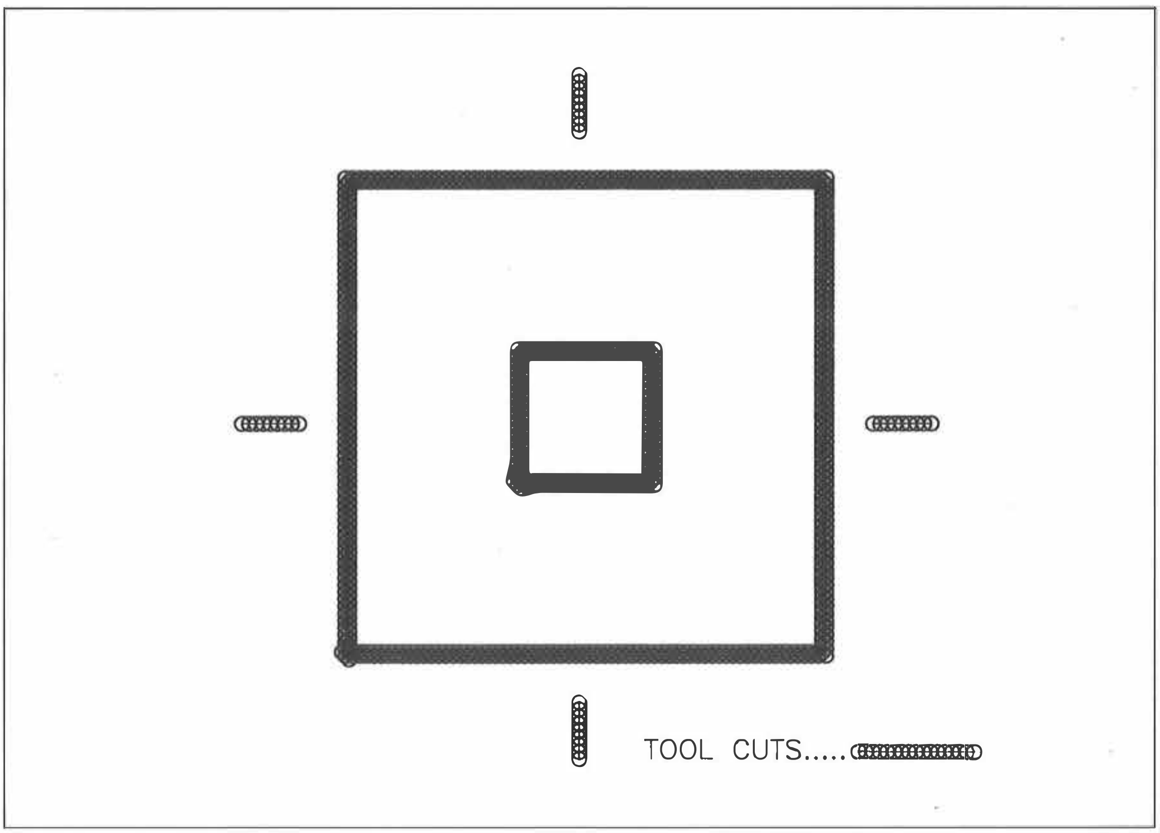


Figure A.10.3—Drawing showing only the actual cuts made in an acrylic sheet for the 2-inch and 8-inch squares used in repeatability evaluation.

PROGRAM FOR SQUARES CUT IN ACRYLIC SHEETS (REPEATABILITY)

```
O0058;
N5G91;
N10G28X0Y0Z0;
N15G92X-31.5Y22.5;
N20G90;
N25G00X0.5Y7.0;
N30Z0.25;
N35G42H1G01X1.0F100;
N40Z-0.1875;
N45X2.0;
N50Z0.25;
N55G40H1X2.5;
N60G00G1X11.5Y7.0;
N62G42H1G01X12.0F100;
N65Z-0.1875;
N70X13.0;
N72Z0.25;
N75G40H1X13.5;
N85G00X7.0Y13.5;
N90G42H1G01Y13.0F100;
N95Z-0.1875;
N100Y12.0;
N102Z0.25;
N105G40H1Y11.5;
N115G00X7.0Y2.5;
N120G42H1G01Y2.0F100;
N125Z-0.1875;
N130Y1.0;
N132Z0.25;
N135G40H1Y0.5;
N140G00Z0.25;
N145G00X2.8125Y2.8125;
N150Z-0.1875;
N155G01X11.1875F100;
N160Y11.1875;
N165X2.8125;
N170Y2.8125;
N175G00Z0.25;
N180G00X5.8125Y5.8125;
N185Z-0.1875;
N190G01X8.1875F100;
N195Y8.1875;
N200X5.8125;
N205Y5.8125;
N210G00Z0.25;
N215M98P250059;
N220M30;
```

```
O0059;
N2X0Y0;
N5G1F100X2.25Y3;
N10G42H1G1X2.75F100;
N15Z-0.1562;
N20X11;
N22G4;
N25Y11;
N27G4:
N30X3;
N32G4;
N35Y2.75;
N37G4;
N40Z0.25;
N45G40H1Y2.25;
N50Y2;
N55G1F100X5.25Y6.0;
N60G42H1G01X5.75F100;
N65Z-0.1562;
N70X8;
N72G4;
N75Y8;
N77G4;
N80X6;
N82G4;
N85Y5.75;
N87G4;
N90Z0.25;
N95G40H1Y5.25;
N100M99;
```

NOTE:
The feed speeds in Statements N10 and N60 of Subroutine O0059 are changed to match the desired feed speed.

Figure A.10.4—Sample program (G&M code) for repeatability cutting of squares in acrylic sheets.

APPENDIX A.11

Program for Diamonds Cut in Acrylic Sheets (Repeatability)

Following are procedures for developing a G&M program for determining the repeatability of cutting diamonds in acrylic sheets. Figure A.11.1 provides information to assist in this development. Figure A.11.2 shows the tool path for all moves including cutter compensations, lead-in/lead-out cuts, roughing cuts, and final cuts. Figure A.11.3 shows only the actual cuts made in the material. Use the following steps to develop the required main program and its subroutine in an absolute mode. Although feed rates are not discussed in these steps, they must be included in the program so that they can be changed as necessary.

Step 1

Set the absolute zero position at a point -7 inches in the X-axis and -7 inches in the Y-axis from the exact center of the table.

Step 2

To start the main program make a positioning move to Point A (X2.4038,Y2.4038) in line with and 0.5 inch from the lower left end of the line that represents the lower left slot. Move 0.5 inch to point (X2.7574,Y2.7574) with a left cutter compensation. Next, lower the tool to a depth of -0.1875 inch and make a cutting move to point (X3.4645,Y3.4645). Then, raise the tool to 0.25 inch above the material and move to point (X3.818,Y3.818) to remove the cutter compensation.

Step 3

Make a positioning move to Point B (X10.182,Y10.182) in line with and 0.5 inch from the lower left end of the line that represents the upper right slot. Move 0.5 inch to point (X10.5355,Y10.5355) with a left cutter compensation. Next, lower the tool to a depth of -0.1875 inch and make a cutting move to point (X11.2426,Y11.2426). Then, raise the tool to 0.25 inch above the material and move to point (X11.5962,Y11.5962) to remove the cutter compensation.

Step 4

Make a positioning move to Point C (X2.4038,Y11.5962) in line with and 0.5 inch from the upper left end of the line that represents the upper left slot. Move 0.5 inch to point (X2.7574,Y11.2426) with a right cutter compensation. Next, lower the tool to a depth of -0.1875 inch and make a cutting move to point (X3.4645,Y10.5355). Then, raise the tool to 0.25 inch above the material and move to point (X3.818,Y10.182) to remove the cutter compensation.

Step 5

Make a positioning move to Point D (X10.182,Y3.818) in line with and 0.5 inch from the upper left end of the line that represents the lower right slot. Move 0.5 inch to point (X10.5355,Y3.4645) with a right cutter compensation. Next, lower the tool to a depth of -0.1875 inch and make a cutting move to point (X11.2426,Y2.7574). Then, raise the tool to 0.25 inch above the material and move to point (X11.5962,Y2.4038) to remove the cutter compensation.

Step 6

Make a positioning move to Point E (X1.078,Y7.0) at left corner of the 8.375-inch diamond. Lower the tool to a depth of -0.1875 inch and without cutter compensation make counter clockwise cutting moves to point (X7.0,Y1.078), to point (X12.922,Y7.0), to point (X7.0,Y12.922), and back to point (X1.078,Y7.0). Then, raise the cutter to 0.25 inch.

Step 7

Make a positioning move to Point G (X5.3206,Y7.0) at left corner of the 2.375-inch diamond. Lower the tool to a depth of -0.1875 inch and without cutter compensation make counter clockwise cutting moves to point (X7.0,Y5.3206), to point (X8.6794,Y7.0), to point (X7.0,Y8.6794), and back to point (X5.3206,Y7.0). Then, raise the cutter to 0.25 inch.

Step 8

At the end of the main program, include a subroutine call statement to run the subroutine 25 times. After the subroutine is called 25 times, move to machine reference zero.

Step 9

Start the subroutine by making a positioning move to Point F (X0.8128,Y7.5303) to start the finish cut of the 8-inch diamond. From this point, make a right cutter compensation move to point (X1.1664,Y7.1768). Next, lower the tool to -0.1562 inch and make counter clockwise cutting moves to point (X7.0,Y1.3431), to point (X12.6569,Y7.0), to point (X3.0), and to point (X1.1664,Y6.8232). Then, raise the tool to 0.25 inch above the material and remove the cutter compensation with a move to point (X0.8128,Y6.4697).

Step 10

Raise the tool to 0.25 inch above the material and make a positioning move to Point H (X5.0555,Y7.5303) to start the finish cut of the 2-inch diamond. From this point, make a cutter compensation move to point (X5.409,Y7.1768). Next, lower the tool to -0.1562 inch and make counter clockwise cutting moves to point (X7.0,Y5.5858), to point (X8.4142,Y7.0), to point (X7.0,Y8.4142), and to point (X5.409,Y6.8232). Then, raise the tool to 0.25 inch above the material and remove the cutter compensation with a move to point (X5.0555,Y6.4697).

Figure A.11.4 shows a sample program for this procedure. Due to differences in controllers, it may be necessary to make minor changes in this program.

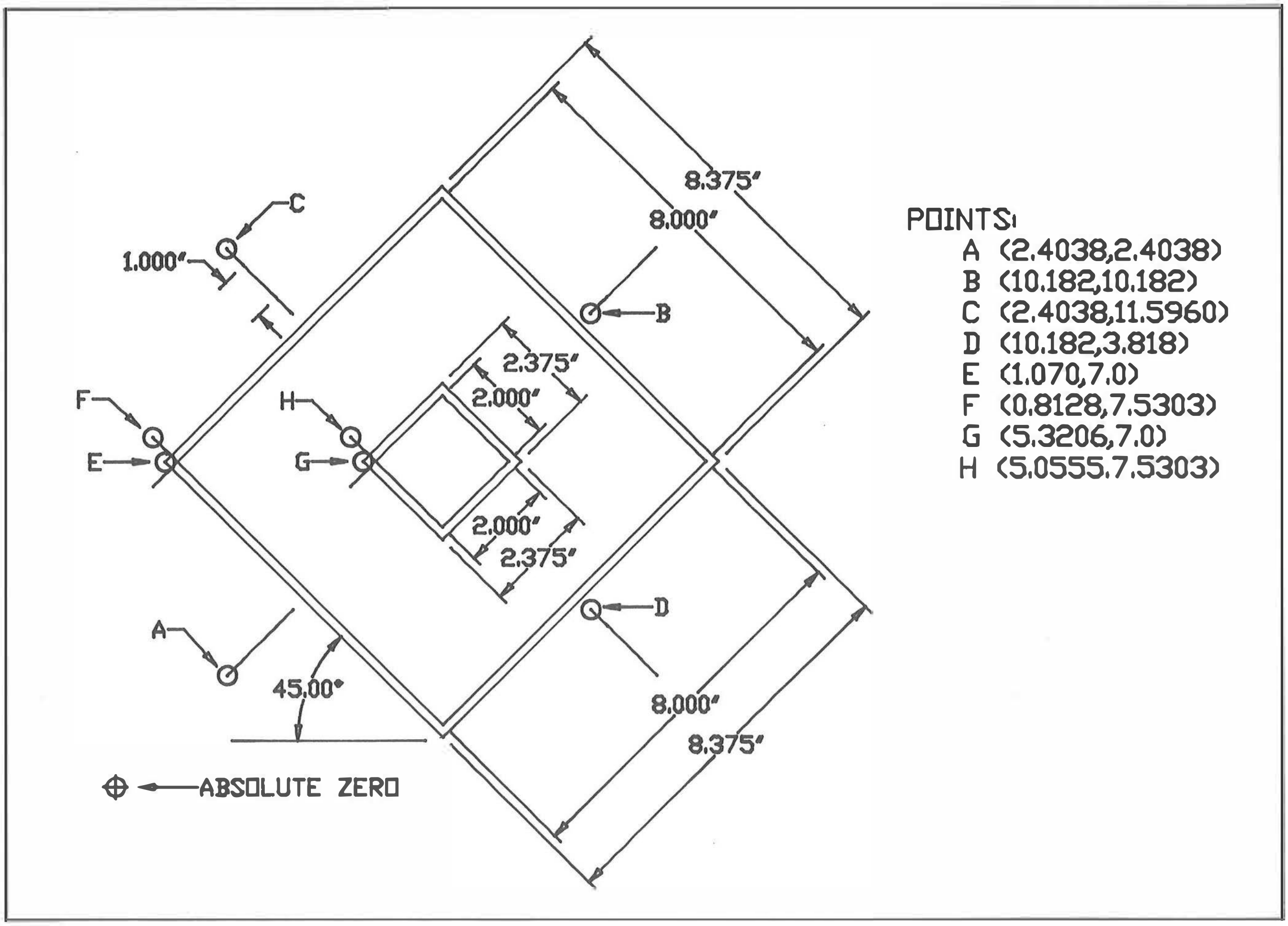


Figure A.11.1—Drawing showing information for developing a program (G&M code) needed to make diamond repeatability cuts in acrylic sheets.

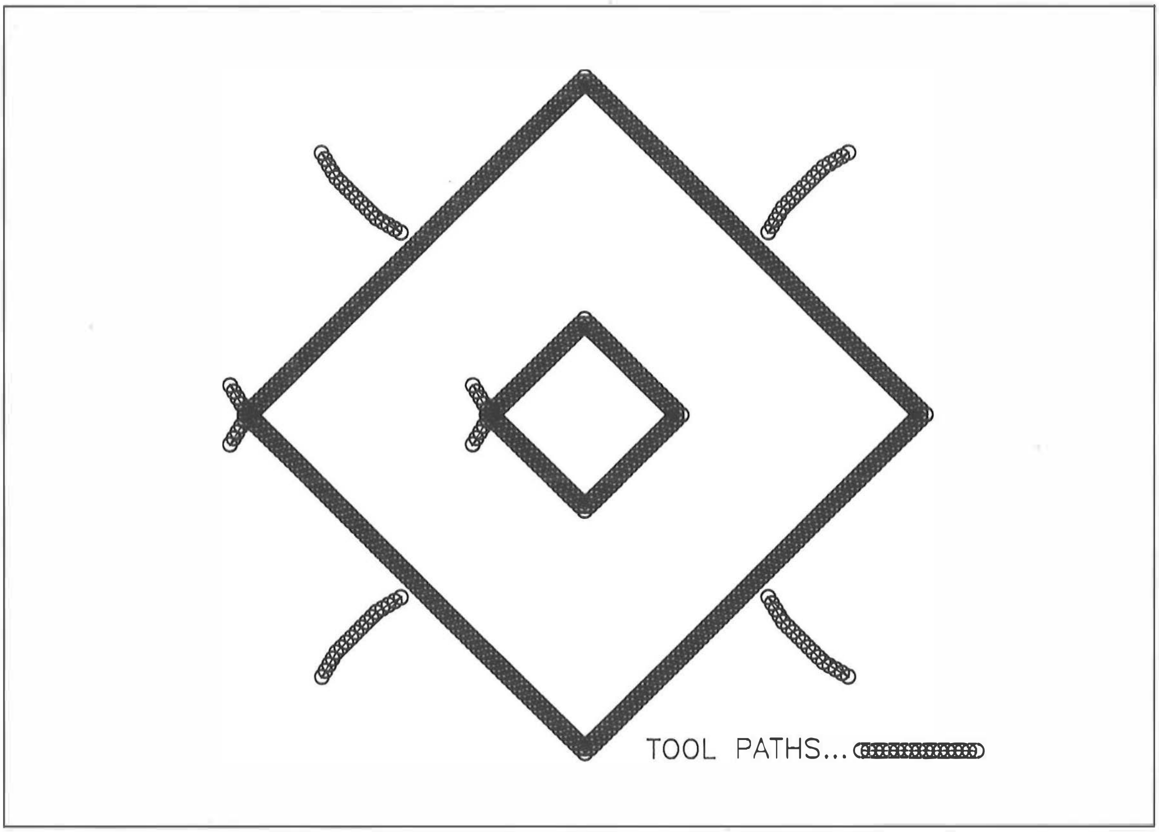


Figure A.11.2—Drawing showing tool paths (roughing cuts, offset moves, lead-in cuts, and finish cuts) used to cut both the 2-inch and 8-inch diamonds in an acrylic sheet for repeatability evaluation.

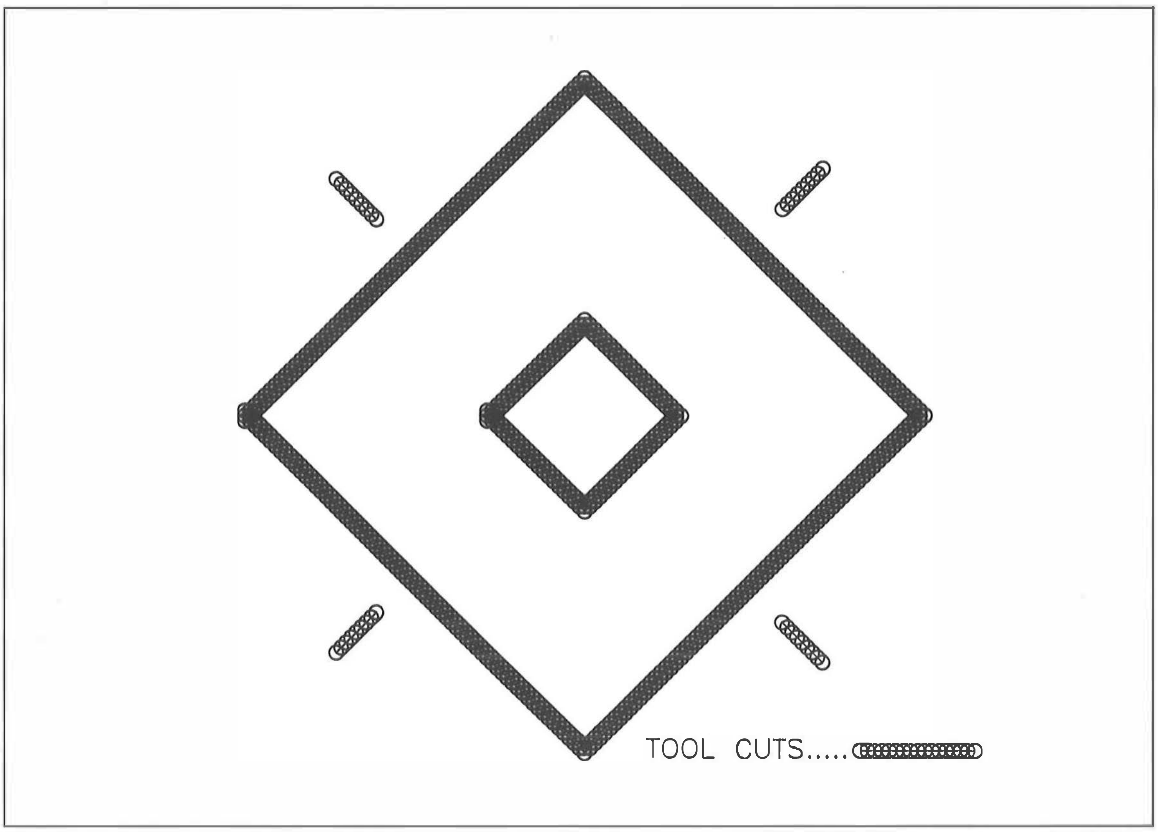


Figure A.11.3—Drawing showing only the actual cuts made in an acrylic sheet for the 2-inch and 8-inch diamonds used in repeatability evaluation.

PROGRAM FOR DIAMONDS CUT IN ACRYLIC SHEETS
(REPEATABILITY)

```
O0060;
N5G91;
N10G28X0Y0Z0;
N15G92X-31.5Y22.5;
N20G90;
N25G00X2.4038Y2.4038;
N27Z0.25;
N30G41H1G01X2.7574Y2.7574F100;
N35Z-0.1875;
N40X3.4645Y3.4645;
N42Z0.25;
N45G40H1X3.818Y3.818;
N55G00X10.182Y10.182;
N60G41H1G01X10.5355Y10.5355F100;
N65Z-0.1875;
N70X11.2426Y11.2426;
N72Z0.25;
N75G40H1X11.5962Y11.5962;
N85G00X2.4038Y11.5962;
N90G42H1G01X2.7574Y11.2426F100;
N95Z-0.1875;
N100X3.4645Y10.5355;
N102Z0.25;
N105G40H1X3.818Y10.182;
N115G00X10.182Y3.818;
N120G42H1G01X10.5355Y3.4645F100;
N125Z-0.1875;
N130X11.2426Y2.7574;
N132Z0.25;
N135G40H1X11.5962Y2.4038;
N145G00X1.078Y7.0;
N147Z-0.1875;
N150G01X7.0Y1.078F100;
N160X12.922Y7.0;
N165X7.0Y12.922;
N170X1.078Y7.0;
N175G00Z0.25;
N180G00X5.3206Y7.0;
N185Z-0.1875;
N190G01X7.0Y5.3206F100;
N195X8.6794Y7.0;
N200X7.0Y8.6794;
N205X5.3206Y7.0;
N210G00Z0.25;
N215M98P250061;
N220M30;
```

```
O0061;
N5X0Y0;
N10G1F100X0.8128Y7.5303;
N15G42H1G1X1.1664
          Y7.1768F100;
N20Z-0.1562;
N25X7Y1.3431;
N27G4;
N30X12.6569Y7;
N32G4;
N35X7Y12.6569;
N37G4;
N40X1.1664Y6.8232;
N42G4;
N45Z0.25;
N50G40H1X0.8128Y6.4697;
N55G1F100X5.0555Y7.5303;
N60G42H1G1X5.409
          Y7.1768F100;
N65Z-0.1562;
N70X7Y5.5858;
N72G4;
N75X8.4142Y7;
N77G4;
N80X7Y8.142;
N82G4;
N85X5.409Y6.8232;
N87G4;
N90X0.25;
N95G40H1X5.0555Y6.4697;
N100M99;
```

NOTE:
The feed speeds in Statements N15 and N60 of Subroutine O0061 are changed to match the desired feed speed.

Figure A.11.4—Sample program (G&M code) for repeatability cutting of diamonds in acrylic sheets.

Adams, Edward L.; Rast, Everette, D.; Bennett, Neal D. 1995. **CNC router evaluation procedures.** Gen. Tech. Rep. NE-201. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 138 p. https://doi.org/10.2737/NE-GTR-201

The lack of procedures for evaluating computer numerically controlled (CNC) routers makes it difficult for the buyers and sellers of these machines to communicate when trying to determine the best machine for a given production situation. This report provides procedures to evaluate specific machine capabilities as related to production situations. By using the procedures, both the buyers and the sellers will know how the evaluations were made and what the results mean.

Keywords: Woodworking equipment; engineering.

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