KNOW YOUR MACHINE TOOL

An Organized Approach
Using Capacitance Sensors

by Tim Sheridan

LION
PRECISION

Preface to the 2008 Electronic Reprint

In 1991, *Know Your Machine Tool* became an instant classic for professionals in the machine tool metrology industry. The book was written before the power of computer data acquisition systems and analytical software were harnessed to measure machine tool spindle performance.

The entire book is based on measurements made with Targa single-channel capacitive sensors. The Targa is referred to frequently and shown in the illustrations. That version of the Targa has been out of production for many years. Our current technology, the Elite Series, has considerably higher performance and is designed to connect directly to National Instruments™ data acquisition systems. In addition to better sensors, ten years of development have resulted in an advanced version of the Spindle Error Analyzer software system.

This new Spindle Error Analyzer system was used in the creation of a new book on the state-of-the-art of machine tool measurements: *Precision Spindle Metrology*. The book was authored by Eric Marsh Ph.D. of The Pennsylvania State University Machine Dynamics Lab and is published by DesTech Publishers and is available at Amazon.com or from Lion Precision.

More information about the Spindle Error Analyzer is available at:
www.spindleanalysis.com

More information about the book, Precision Spindle Measurement is available at:
www.precisionspindlemetrology.com

More information on the Elite Series Capacitive Sensors is available at:
www.elitesensors.com

Preface

"When you cannot measure what you are speaking about, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the stage of <u>*science*</u>*, whatever the matter may be."*

— Lord Kelvin

Lord Kelvin paraphrased by Allen Sanner of Professional Instruments Co.: *"If you can measure it, you can make it."*

This treatise is about measurement as it applies to machine tools and the evaluation of their performance. Measurement is a fundamental aspect of the science of machine tool design as well as the science of making things with machine tools.

I would like to thank Debra Condit, Jane Bechaka and Michael Rioux of Lion Precision for their unrelenting cheerfulness and technical competence in the preparation of the manuscript and illustrations. Also, I would like to thank Professional Instruments Company for 12 years of opportunities to learn how to make things right. Finally, I would like to thank Maureen for putting up with me.

Tim Sheridan
September, 1991

Foreword

By James B. Bryan, *Registered Mechanical Engineer, State of California.*

This book fills an important need by describing the proper use of capacitance gages in the field of Machine Tool Metrology. Don Martin, President of Lion Precision, believed there was a market for capacitance gages in the maintenance of precision machine tools if he could provide reliable and simple information on how to use the gages and how to interpret the results.

Tim Sheridan, the author of this book, has done an excellent job presenting the relevant material in a well organized, well written, honest, and understandable form. He must have worked very hard to reduce the mass of technical papers, engineering standards, product instruction manuals, and his personal experience to a document that can be read in a few hours.

Having been involved in the field of Machine Tool Metrology and Precision Engineering for the past 40 years, I am always concerned that new papers and books on the subject should indicate a proper respect for prior work and for standardized terminology. Tim Sheridan has carefully avoided the temptation to invent new terminology without purpose.

I am quite sure that the great Machine Tool Design Engineer and pioneer of Machine Tool Metrology, George Schlesinger (1873 - 1949), would find this book to be to his liking and a significant extension of his work.

Brief Biography on Jim Bryan

Jim Bryan has been involved in precision engineering for his entire career. A scientist at Livermore National Laboratory, now retired, he has worked on many projects relating to spindle and machine tool performance. Jim sits on the ANSI B89 committee for Dimensional Metrology, the editorial board of Precision Engineering, and is now proprietor of "Bryan Associates," consultants in the area of precision engineering.

Know Your Machine Tool: An Organized Approach Using Capacitance Sensors

List of Figures

List of Plots

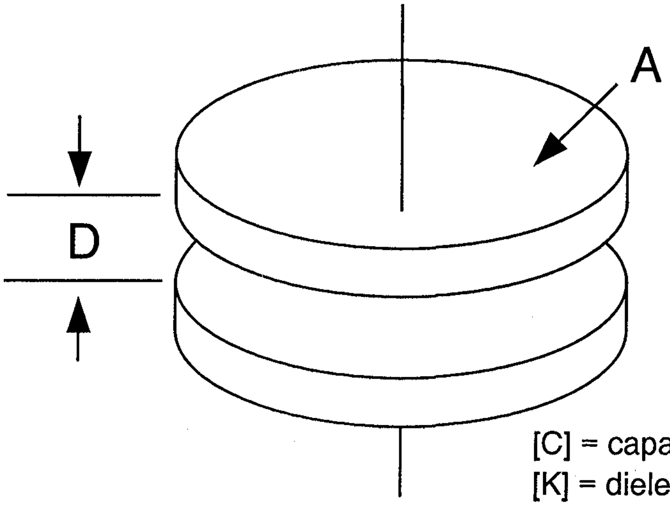
Purpose

The purpose of this manual is several fold. First and foremost, this manual is an introduction to the use of capacitive displacement sensors for the analysis of machine performance. However, an underlying theme of the manual will be to use these sensors to acquire the greatest amount of information with the least amount of effort. Emphasis will be placed on simple setups that can provide enough information to make the decision whether or not to continue analysis using more sophisticated techniques, leading to the prediction of machine tool performance and the identification of areas of improvement.

Second, this manual serves as an introduction to several ANSI/ASME Standards. Two are published (ANSI/ASME B89.3.4M-1985 Axes of Rotation: Methods for Specifying and Testing, and ANSI/ASME B89.3.1-1972, Measurement of Out-of-Roundness) while the other (ANSI/ASME B5.54-1991, Methods For Performance Evaluation of Computer Numerically Controlled Machine Centers) is a draft Standard, subject to review and revision prior to initial publication. A final goal of this manual is to provide more direct insight into important aspects of machine tool design and performance such as servo control, vibration, thermal drift and distortion, accuracy of spindles and slides, and the influence of drive forces, nearby machines and other environmental noise sources.

THEORY OF OPERATION

A capacitor consists of two conductive surfaces separated by an insulating medium. The insulating medium is known as the dielectric. The capacitance (measured in farads, after Michael Faraday) of a capacitor is a function of the shape of the conductive surfaces, the physical properties of the dielectric and the distance separating the conductive surfaces. If the conductive surface shape and the dielectric are fixed, as in a capacitance probe, only the distance between the conductive surfaces can cause a change in capacitance. By constructing a probe in such a way that the target becomes one of the conductive surfaces and the probe the other conductive surface, then changing the distance between them changes the capacitance. Measuring and displaying the change in capacitance provides a way to show the change in position of the target with respect to the probe. Linearizing and calibrating the capacitance change as a function of probe to target separation provides a powerful tool for analyzing static and dynamic systems. A properly designed capacitive sensor is characterized by low noise, low drift, high sensitivity, wide bandwidth, and, of course, non-contact sensing. These properties make capacitive sensing ideal for a wide range of position sensing applications.



$$C = \frac{KAEo}{D}$$

[C] = capacitance (farads)
[K] = dielectric constant (dimensionless)
[A] = area of plate (meters^2)
[Eo] = permittitivity of free space (coulombs^2/N-m^2)
[D] = distance between plates (meters)

FIGURE 0.0 A Parallel Plate Capacitor

SECTION 1

EQUIPMENT DESCRIPTION

Section 1.1 System Equipment Description

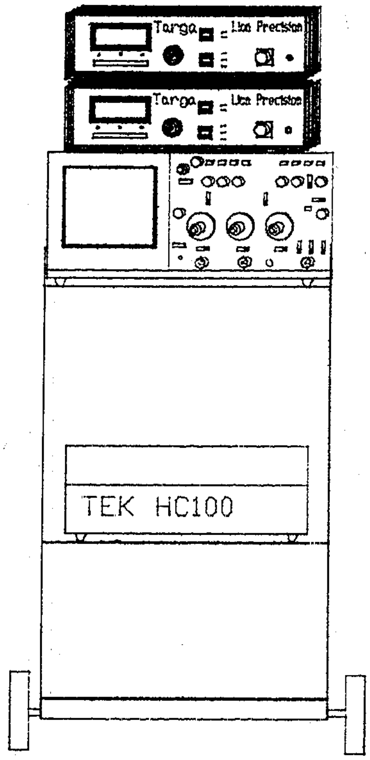


FIGURE 1.0 Machine Tool Evaluation System

Targa 1, Targa 2	- Targa single channel dimensional gaging system. +/-.002 range, .006 inch nominal standoff, 1 microinch resolution, DC-10 kHz, with selectable 2 Hz and 1 kHz filters.
Tek 2211	- Tektronix 2211 Analog/Digital Storage Oscilloscope, 2 channel with X-Y operation, 20 Megasamples/Second digitizing rate, 8 bit resolution, 4K record length.
Tek HC100	- Tektronix model HC100 pen plotter.
Tek 212	- Tektronix Model K212 Scopemobile Instrument Cart with plotter shelf.

This system is a two channel non-contact capacitive displacement sensing system with real time displacement display and permanent hard copy capabilities. As such, it is well suited for a wide variety of measurement tasks related to spindle error motion, slide error motion, vibration, axis settling time, etc. Depending upon the kind of measurement, either one or both of the Targa units will be used. In keeping with the maximum information/minimum effort theme of this manual, single Targa applications will be covered first, followed by dual Targa applications.

Section 1.2 Equipment Interconnect Diagram

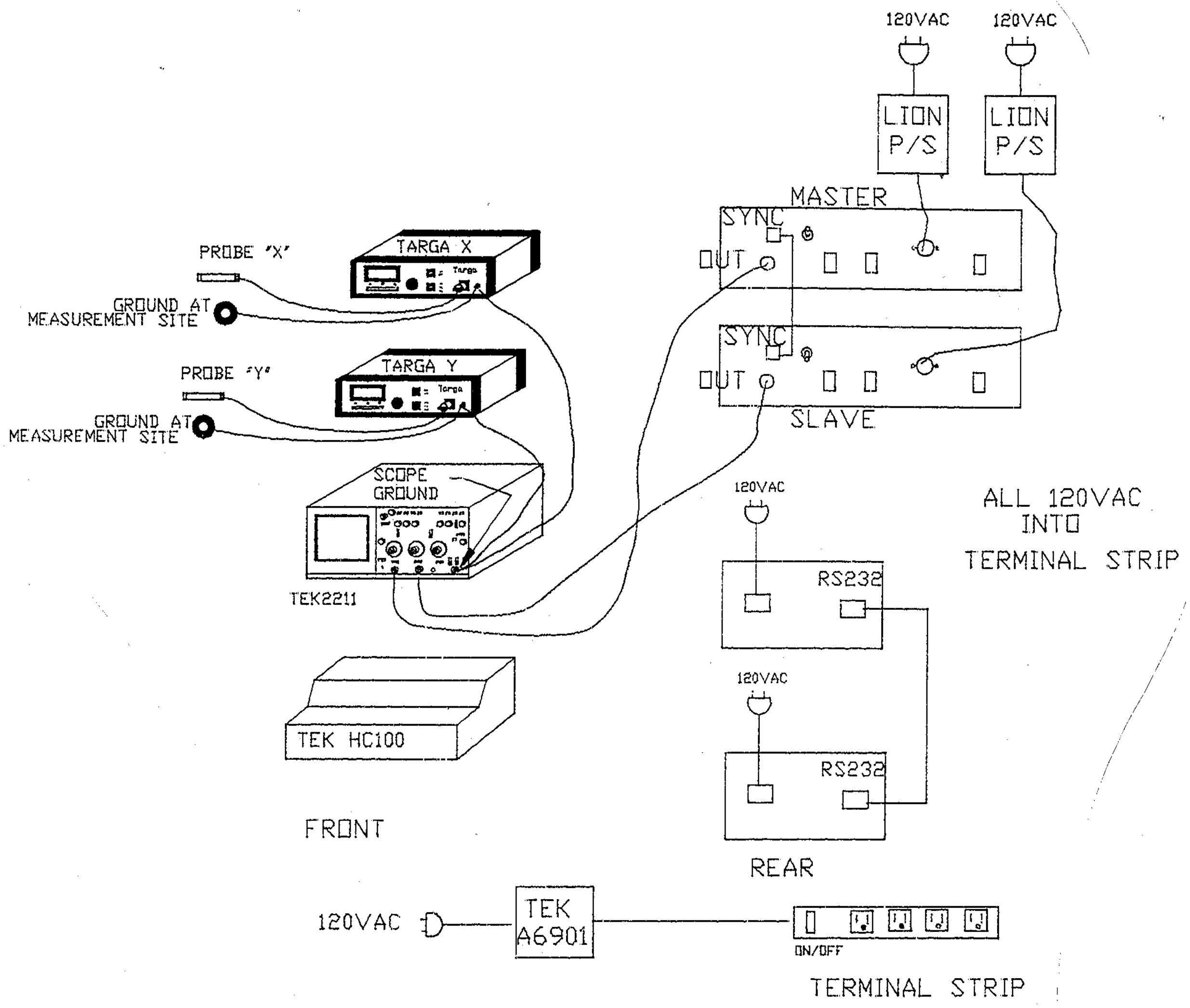


FIGURE 1.1 Equipment Interconnect Diagram

Section 2

Probe Mounting Considerations

Section 2 Probe Mounting Considerations

At first it might seem that minimal attention to probe mounts or holders is required; after all, this is a non-contact sensor so there is no elastic deformation of the structure between the probe and the target due to contact forces. In reality, the mounting of the probe requires some care in order to obtain repeatable readings. This is especially true for dynamic measurements. Generally, probe holders should grip the precision diameter of the probe near the active end. The grip length should be at least equal to the diameter of the probe. Some probes have a guard ring (used to shield the measuring capacitance from static capacitance shifts due to nearby structures) at the very end of the probe. Do not allow the probe mount to contact the guard ring. Pinch-type holders generally work the best as long as the pinch hole is straight, round, and provides a close slip fit when the pinch screw is loose - see Figure 2.1.

A straight, round pinch hole provides the best support, allows easy high precision adjustment of the standoff distance, and minimal shift when the pinch screw is tightened. A barrel shaped hole is acceptable but may damage the probe due to high local forces when the pinch screw is tightened. Waisted or tapered holes grip the probe at only one location, allowing the probe to pivot easily and should be avoided. The rest of the probe mount should be as short and stiff as possible to minimize vibrations when excited by the

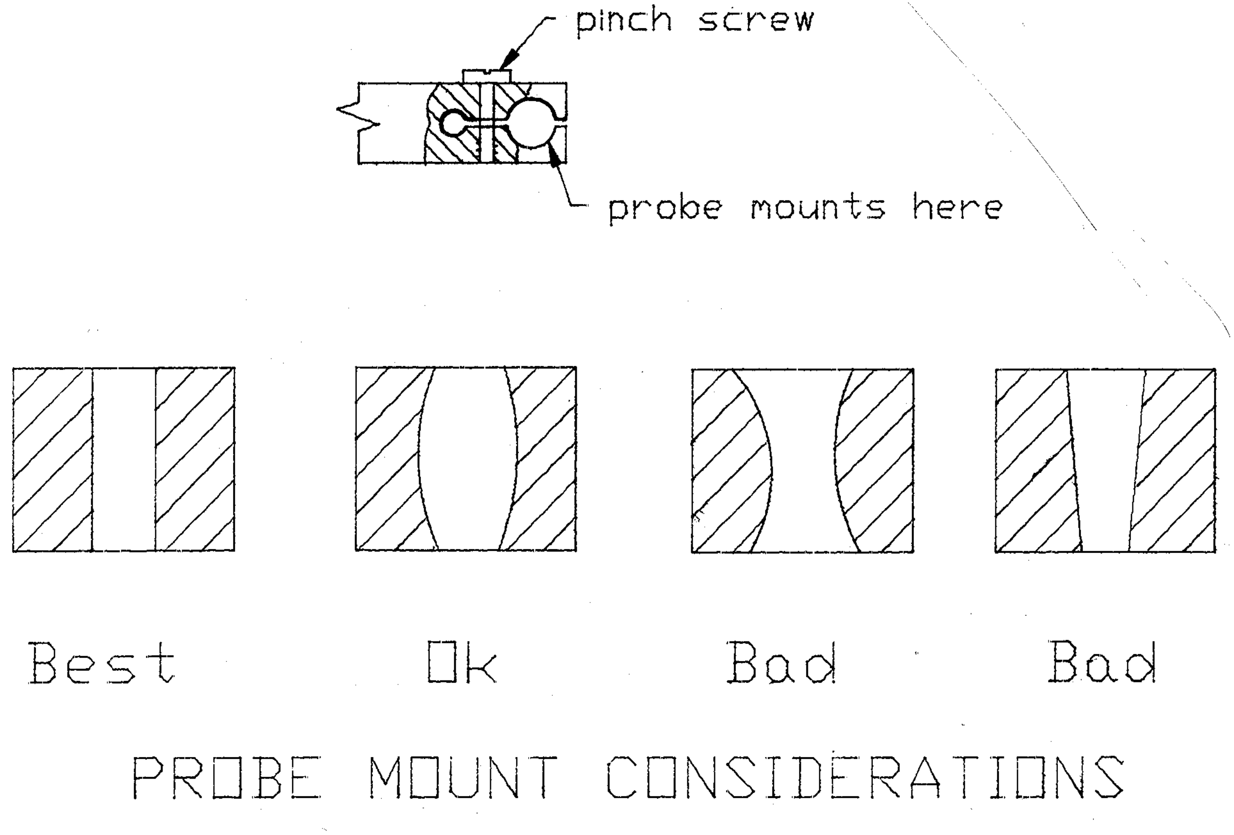


FIGURE 2.1 Probe Mount Considerations

system being measured. As a rule of thumb, the natural or resonant frequency of the probe holder should be at least 2 times higher than the highest structural vibration frequency <u>component</u> of the system to be measured. It should be noted this situation may be difficult to achieve on some roller bearing spindles due to the high frequency, impact-like nature of their motion (See Section 4.5 on vibration for a method of measuring the natural frequency). Additionally, when the probe mount is attached to the structure of interest, the joint should be hard and hysteresis free. The hysteresis can be directly measured using the Targa. When the probe mount is attached and the probe is brought into the measuring range, simply note the Targa reading, then push on the probe mount to deflect it elastically. Release the probe mount and check to see if the Targa reading returns to the previously noted reading. A good mount should return to the same reading within plus or minus a millionth of an inch.

High grade joints between the mount and the structure of interest are easiest to achieve when the mating surfaces are flat, and preferably ground. This type of joint is a must for repeatable, millionth inch dynamic measurements. Other types of joints (V-blocks, 3-pad, etc.) will be acceptable for lower precision, low frequency measurements. The hysteresis test is a quick, practical method to evaluate a probe mount. <u>Probe mounting is the greatest single cause of erroneous readings</u>. If something doesn't look right, or changes suddenly, look first to the mechanics of the situation, and then the electronics.

Section 2.1 Probe Mount Materials

Nickel plated mild steel makes an excellent material for probe mounts. It is readily available, easy to machine, has a high modulus of elasticity, good corrosion resistance when plated, and excellent electrical conductivity. Also, if the nickel plating is electroless nickel, the as-plated hardness of the nickel (RC 52) results in a relatively non-galling interface between the probe and the probe holder. This allows easy sliding of the probe in the holder for standoff adjustment. Aluminum is also an adequate probe holder material provided several precautions are taken. First, mounting and pinch screws should have hardened steel washers under the heads to eliminate loosening or hysteresis due to yielding of the material. Second, hard-coat anodize the aluminum to provide a hard non-galling interface between the probe and the mount to facilitate adjustment. Finally, grind away or machine through the anodize to provide a good electrical ground for the probe holder. See Section 3 for information on grounding.

A variety of probe holders, hard washers, and other fixturing components are available from Professional Instruments Company,
4601 Highway 7, Minneapolis, MN 55416.
Telephone: 612-933-1222.

Section 3

Grounding, Interference, and Electrical Noise

Section 3 Grounding, Interference, and Electrical Noise

The Targa instrument has an internal noise level low enough to allow it to resolve to 1 millionth of an inch (0.025 micrometer). In this system composed of 2 Targas, an oscilloscope and a plotter, the goal has been to retain that capability in spite of the distributed nature of the system. A distributed system is one that is not in the same box, or does not share the same power supplies, or it is physically separated so the "ground" or "+15 volts" in one element of the system is not necessarily "ground" or "+15 volts" in another element. Since 1 millivolt is equal to 1 microinch in the Targa, the difference between "ground" in any of the instruments (excluding the plotter) must be significantly less than 1 millivolt for best results. A 10-1 rule for signal-to-noise ratio is a good one; if 50 microinches is the desired resolution, the measurement system noise should not exceed 5 millivolts.

Unfortunately, when the probes are mounted on a machine tool, spindle, or other devices to be analyzed, that device becomes part of the distributed system and can contaminate the signals from the probes. Several techniques may be employed to minimize these problems. The most common method is to use a separate ground lead connected between the Targa case ground (banana jack on front panel) and the spindle housing or machine tool element being analyzed. In some cases, a separate ground lead from the probe to the front panel banana jack may also be required. For spindle analysis, the ground lead would ideally be connected to the rotating component. For low speed ball bearing spindles the electrical connection through the bearing balls is usually quite good, and the ground lead can be connected to the spindle housing. For high speed ball bearing spindles, and fluid film (oil or gas) spindles, the potential on the rotating component may be of indeterminate nature. In such cases, a small wire, leaf spring, etc. connected for rubbing contact between the spindle housing or wherever the probe is mounted and the rotating component should be sufficient to ground the rotating component. In high vibration or high speed environments, multiple rubbing contacts might be required to insure the rotating components are always grounded. The rubbing contact should touch the rotating component on as small a diameter as possible to minimize the tendency to lift off due to hydrodynamic effects. One of the best locations for a rubbing contact is on the corner of a small diameter shoulder as shown in Figure 3.1:

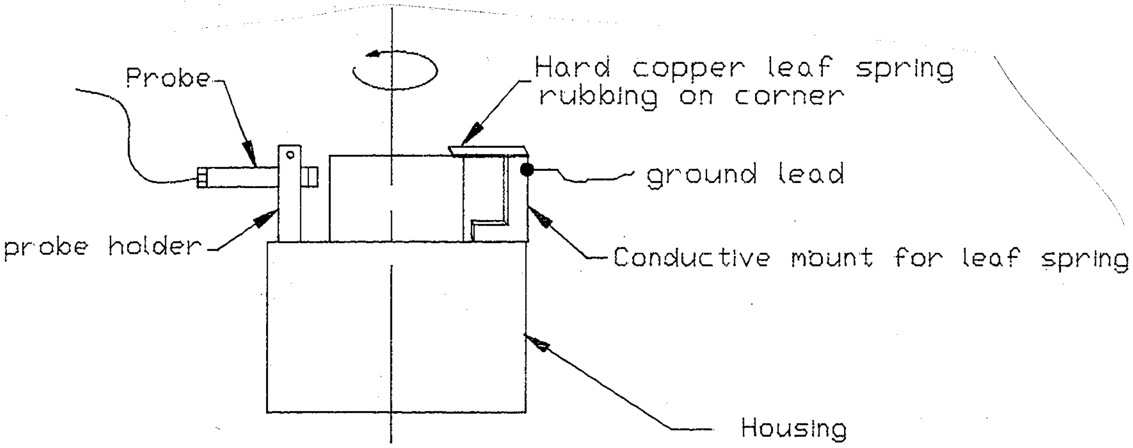
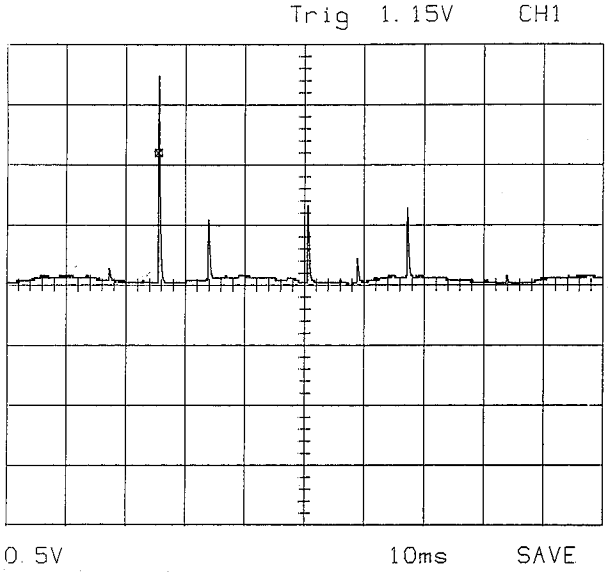
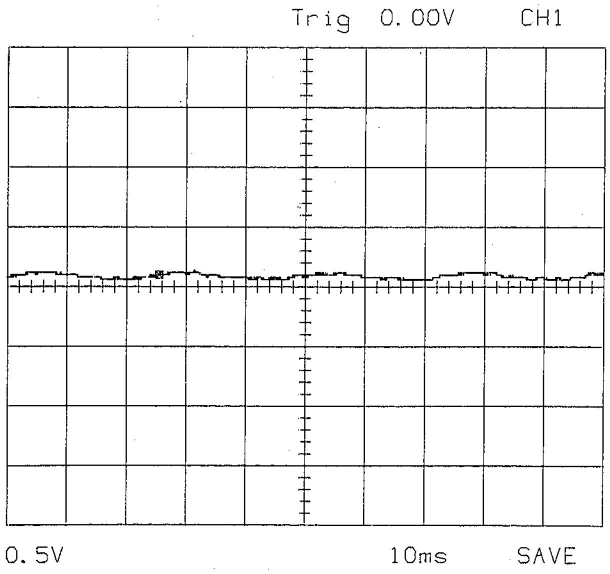


FIGURE 3.1 Proper Grounding Of Target

Plot 3.1 shows the Targa output of a gas bearing spindle driven by a DC motor and an SCR type controller without a ground to the rotating components. The sharp voltage spike produced when the SCRs turn on induces very large noise spikes (of over 0.0015 inches) in the Targa signal. Plot 3.2 shows the same situation with a small leaf spring grounding the spindle rotor. The controller induced noise is absent. Always insure the measured element is at the same potential as the Targa front panel banana jack.



PLOT 3.1 Spindle Rotor - Not Grounded. Noise Spikes of 0.0015 Inch Equivalent Size



PLOT 3.2 Spindle Rotor - Properly Grounded

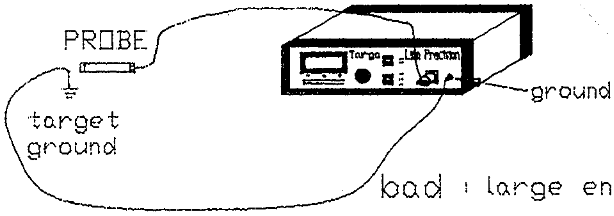
In some cases it is not possible to completely eliminate the noise from SCR or PWM (Pulse Width Modulation) type drives. In these cases, two approaches are commonly taken:

1. The spindle is run up to speed and then the drive power is turned off. Measurements are taken while the spindle is coasting.

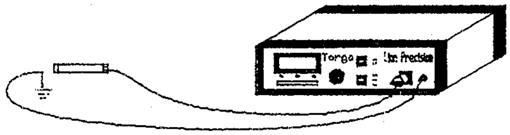
2. Recognize that the spikes are of electrical origin, not mechanical, and can be ignored.

When routing the probe and ground cables minimize the area enclosed by the loop that is formed by the probe and ground cables. The best method would be to twist the probe & ground cables together.

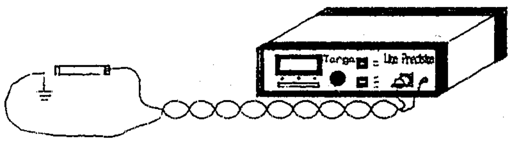
The reason for doing this is that the loop becomes an antenna and the area of the antenna loop determines its sensitivity to interference. The Targa capacitive system uses a 1 MHz carrier signal that is applied to the measuring circuit; changes in the carrier signal are detected, filtered, and amplified to produce the measurement signal. 1 MHz is in the AM broadcast band and a loop antenna that is the right size and shape formed out of the probe and ground leads could be susceptible to interference from nearby radio stations. Also, there are a variety of industrial noise sources (welders, switching power supplies, PWM motor controls, etc.) that may radiate energy in the carrier frequency range. A loop of the right size and shape may make the Targa susceptible to radiated noise pick-up from these sources. Twisting the probe and ground leads together minimizes the antenna loop area and results in minimum system sensitivity to such signals.



bad : large enclosed loop



better : small enclosed loop



Best : almost no enclosed loop

FIGURE 3.2 Ground Cable Routing

Section 3.1 Grounding Within the System Components

When the two Targa instruments are used with an oscilloscope, a continuous system ground is necessary for good system performance. The two Targa instruments should be connected to the oscilloscope ground on the front panel of the oscilloscope by independent ground leads. Do not "daisy-chain" the Targas together by connecting the ground of one into the other and then connecting the pair to the oscilloscope ground. Note that these grounds are in addition to the third wire safety ground supplied in the instrument power cords.

WARNING

Under no circumstances should the third wire safety ground be defeated by permanent, passive methods such as "cheaters" or removal of the ground prong from any instrument power cord or the system terminal strip power cord. To do so could allow the instrument chassis to float to a high voltage potential, resulting in a fatal shock to the operator.

The only time the oscilloscope chassis can be allowed to float is when the optional ground isolator is used. See Figure 1.2 System Interconnect Diagram, for details of grounded signal interconnections.

Since the Targa can operate from its internal battery, it is possible to isolate the Targa ground from earth/safety ground. To operate the Targa from its internal battery:

1. Turn Targa power switch to 'OFF' position.
2. Unplug AC power cord from outlet strip.
3. Unplug power adapter cord from rear panel on Targa.
4. Turn Targa power switch to 'ON' position.

Operation on battery power is useful when the Targa itself must be portable, i.e. taken to a remote location where there is no power available. Another instance where operation from batteries is helpful is in environments where there is significant conducted electrical noise on the AC line. The Targa power supplies have no line filters to reduce the effect of conducted noise. The oscilloscope does have line filters and will function properly in moderately noisy environments.

Section 3.2 Use of the Optional Ground Isolator

In some unusual cases, the measurement system ground might be different than the machine tool ground by a significant value (e.g. tens or hundreds of millivolts). This can happen when the machine tool AC power supply, usually a 4 or 5 wire polyphase source, is separated from the normal 120VAC single phase source. The ground for the 120 VAC and the polyphase ground might be connected together only at the service transformer, for example. If there are significant neutral or ground leakage currents in one or the other of the two power sources and the Targa system is far away from the point where the grounds are connected together, the potential difference between the two grounds can be significant. For example, if the resistance of the ground wire between the point of measurement and the point where the grounds are connected is .01 ohm and the leakage current in that ground wire is 2 amps, the voltage drop along that length of wire is .01 ohm x 2A = .02 V = 20 millivolts. Structural grounding systems are designed for safety considerations and not the ultimate in low noise grounding. Incidentally, leakage currents of 2 amps or more in neutral leads (for polyphase) or ground leads (for single phase) are not uncommon. Installations that have many personal computers, workstations, fax machines, copiers, etc. are particularly prone to have significant currents flowing in wires that are supposed to carry current only during fault conditions. The reason for this is that the switching power supplies in such equipment draw current from the source in short pulses, leading to harmonic distortion of the power source. The harmonics (at higher frequencies than 60 Hz) are much more readily capacitively coupled to the ground or neutral wires than is the 60 Hz fundamental. Also, the high switching frequency (hundreds of kilohertz in some cases) allow current to leak through the chassis of the power supply, which is nearly always grounded. The harmonic distortion problem is severe enough that legislation is pending concerning allowable limits. In any event, when the Targa system is connected and grounded and the machine tool has a different ground and the two grounds are connected, currents flow in the "ground loop" formed by the connections and can contaminate measurements. The most common effect is 60 Hz noise on the oscilloscope signal. The amount of 60 Hz noise can be readily measured by getting a trace on the oscilloscope (See Section 4.1.2) and setting the TRIGGER SOURCE to LINE. Line related signals will be synchronized to the oscilloscope sweep and easily displayed. The usual solution to this problem is to "float" the measurement system ground by disconnecting it from the 120 VAC ground. This is usually accomplished by using a 3-prong to 2-prong adapter, some times called a "cheater". The Targa system ground (oscilloscope chassis, Targa chassis) is then connected to the machine tool ground. This eliminates the ground loop problem

BUT IS VERY DANGEROUS AND MUST BE AVOIDED.

If the newly established ground should become disconnected, the measurement system chassis may charge up to a high voltage from, for example, the CRT power supply in the oscilloscope (accelerating voltage is about 15 KV!). This could render a fatal shock to the operator.

Fortunately, there is a solution to this problem. UL allows "indirect" grounding for potential differences between grounds of less than 42 volts peak. Tektronix has designed a ground isolator to take advantage of the UL rule. Basically, the ground isolator (Tek model A6901) contains a relay, a measuring circuit, a ground line cord, and several outlets. The relay disconnects the outlet grounds from the line cord ground. The measuring circuit monitors the potential difference between the two grounds and trips the relay, connecting the outlet grounds to the line ground if the potential exceeds 42 volts. This allows ground loops to be broken up while still providing operator safety.

Section 4

Single Targa Applications

Section 4.1 Runout

Section 4.1.1 Definition

Runout is defined as "the total displacement measured by an instrument sensing against a moving surface or moved with respect to a fixed surface" (ANSI B89.3.4M-1985, page 5.5, section 2.17). The term TIR (Total Indicator Reading) is equivalent to runout. In essence, all single channel Targa measurements, except thermal drift, are runout measurements. Two cases are portrayed in the definition. The first is when the probe is stationary and the surface of interest, or artifact, is moving. The other case is where the artifact is stationary and the probe is moving. Why is one interested in doing a runout test? There are several reasons. The principle reason is to establish the quality of the primary machine tool elements such as spindles and slides. Second, runout is an easy test to set up. It requires the least amount of equipment and is simple to understand. Because of this, runout allows a rapid, preliminary evaluation of a given system enabling one to either reject the system immediately or subject the system to further, more exhaustive analysis. Finally, a simple runout test can provide a surprising amount of information.

Section 4.1.2 Setup

Runout measurements are equivalent to using a single dial indicator against the surface of interest; therefore, setup is relatively straightforward (see Figure 4.1).

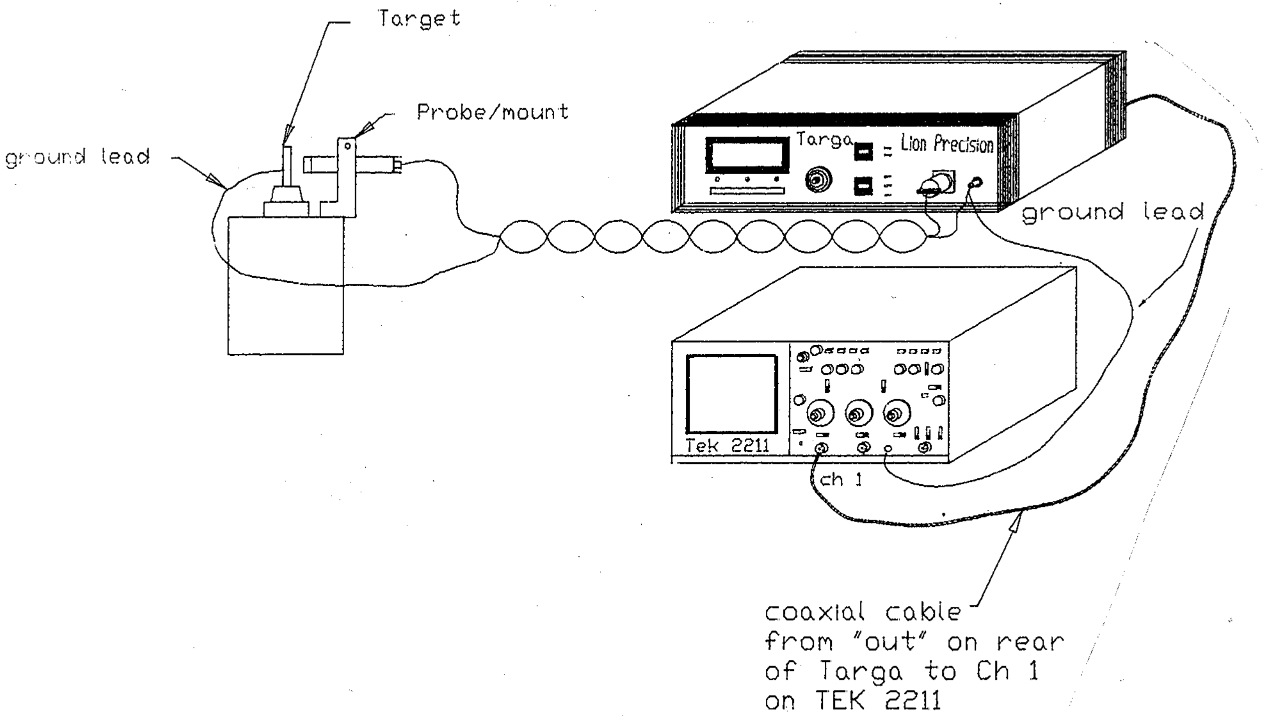


FIGURE 4.1 Set Up For Radial Runout And Radial Error Motion Measurements

1) Connect the probe to the Targa.

2) Connect a BNC-BNC coaxial cable between the "OUT" terminal on the rear of the Targa and the CH1 input on the front of the TEK oscilloscope.

3) Mount the probe and holder on the structure.

4) Insure that the target is grounded to the Targa front panel banana jack.

5) Connect the Targa front panel ground to the oscilloscope front panel ground.

6) Insure the Targa and oscilloscope are turned on, then turn on the terminal power strip.

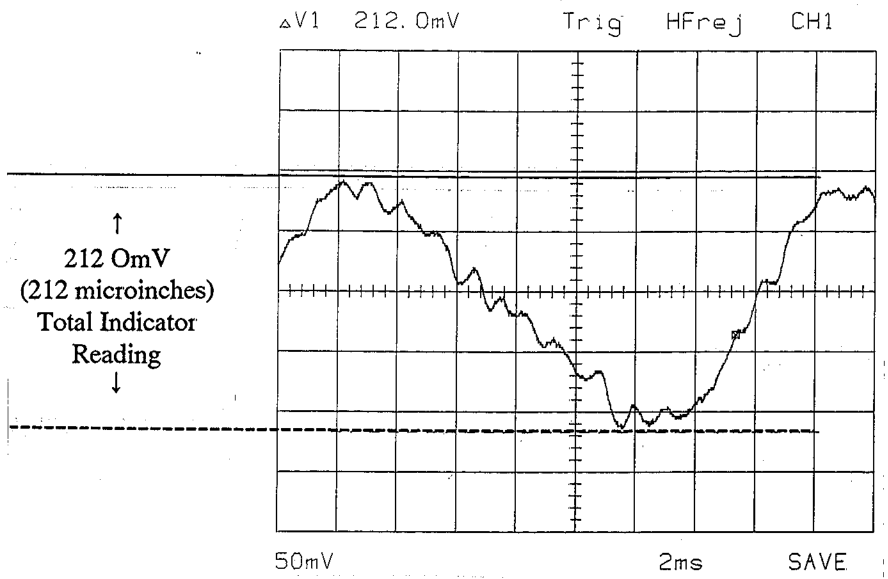
7) Set the filter switch on the rear panel of the Targa to the desired cutoff frequency (normally the 1 kHz position). There are 3 settings: 2Hz, 1kHz, and no filtering (approximately flat response to 5 kHz, -6 dB at 10 kHz). Adjust the probe standoff distance (the distance between the sensing end of the probe and the target) so the Targa 'Calibrated Range Display' indicator is centered and the panel meter reads approximately zero. Use the ZERO knob to set the display to exactly zero. The output from the Targa to the oscilloscope is now zero.

8) Make sure the TEK 2211 is in the NON-STORE mode. The STORE/ NON-STORE switch is in the upper right hand corner of the TEK front panel. Then set the vertical mode switches to CH1, NORM, and CHOP. The timebase (SEC/DIV) should be set to about 2 msec/div and the MAG switch set to X1. The trigger slope should be set to _/‾ and the trigger mode to P-P AUTO. The source should be CH1 and the coupling should be set to LF. At this time there should be a single trace across the CRT. If not, adjust the focus, intensity and CH1 vertical position to display a trace. Set the CH1 input coupling switch to GND and use the CH1 vertical position to position the sweep on the center horizontal line. Next, set the CH1 input coupling switch to DC. The sweep should not move vertically, although it may move slightly if the CH1 VOLTS/DIV is set to 5 mV or 10 mV.

9) If the Targa, probe, and 2211 have been set up properly, the trace should be about .1 division wide when the 2211 CH1 VOLTS/DIV is set to its highest sensitivity. (5 mv/division). The trace should move vertically when the Targa ZERO knob is adjusted, or the probe mount is deflected. The system sensitivity is 5 millionths of an inch per vertical division since the Targa transfer function is 1 millionth of an inch per millivolt. An additional factor of 10 in system sensitivity is available by pulling the CAL knob on the CH1 VOLTS/DIV switch out. The system sensitivity is then 0.5 millionths per vertical division. The trace may widen to 1 division as this level of sensitivity is near the system noise level even under the best circumstances.

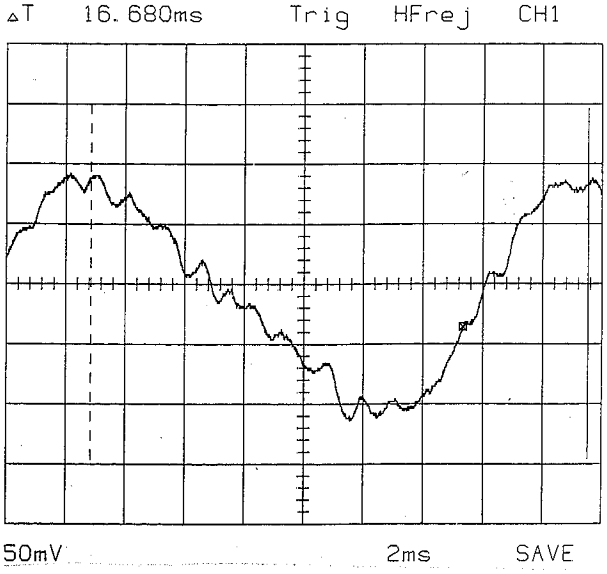
10) The Targa/Oscilloscope measuring system is now ready for use in the NON-STORE MODE.

Section 4.1.3 Oscilloscope Plots of Runout Signals



Plot 4.1 Radial Runout and Error Motion Plot

Radial runout measurement is the sum of the radial error motion of the spindle at the angle the probe is mounted, the form error of the workpiece and the eccentricity of the workpiece relative to the axis of rotation. The oscilloscope ΔV cursors have been positioned to display the peak to peak voltage (TIR) as 212 mV which is equivalent to 212 millionths of an inch (0.000212 inches).



16.68 milliseconds
1 cycle equals 1
revolution

Plot 4.2 Determination of Rotational Speed

The ΔT/ 1/Δ T cursors can be used to measure the rotational speed of the spindle. The period is 16.68 milliseconds. The equation for conversion to RPM is 60/ T. In this case, the computed speed is 3597 RPM.

Section 4.1.4 Synchronous and Asynchronous Error Motion

Synchronous error motion is the motion of a spindle that is related to the angular position of the spindle. i.e. the spindle is at the same position in space over consecutive revolutions. Asynchronous error motion is the motion of a spindle that is not related to the angular position of the spindle. These motions occur simultaneously while the spindle rotates. The measurement of synchronous and asynchronous error motion of spindles is one of the principle applications of capacitive sensors. Fundamentally, synchronous error predicts the potential part geometry the spindle is capable of producing. Asynchronous motion, on the other hand, is useful in predicting the potential surface finish capability of the spindle. These statements are strictly true for single point machining operation like turning, facing, and boring. While they are not strictly true for processes like grinding, where an averaging effect takes place due to multiple sparkout passes and lack of rotational synchronization between the wheel and the work, practical experience has shown these concepts are useful in grinding applications. Spindles with low synchronous error motion cause less damage to the surface due to lack of impact while low asynchronous error motion results in less time (fewer sparkout passes) to achieve a certain surface finish. An example of a non-machine tool application where these characteristics are important is a disk drive spindle. The synchronous error motion would be used to predict the required motion of the head to access the same sequence of data bits over consecutive revolutions and the asynchronous error motion would be used to predict how tightly the data can be packed on the surface, assuming all other operating parameters such as sensor design, flying height, magnetic properties, etc., remain fixed.

While a single Targa analysis of these two important aspects of spindle performance does not completely characterize a spindle, the single Targa set-up can yield a surprising amount of information. Error motion and asynchronous error motion estimates are made from the oscilloscope CRT while the spindle is rotating. The best measurements are made when the surface that the probe is measuring against is as close to a "perfect workpiece" (ANSI B89.3.4-1985, page 1, Section 2.5) as possible. Spheres are the best workpieces from a cost and geometry standpoint; Grade 3 balls (maximum deviation from sphericity of less than 3 millionths of an inch) are available from several of the established ball manufacturers (Spheric, Metal Techtonics, etc.) at a surprisingly modest cost. For cylindrical workpieces, class XXX gage pins (e.g. Deltronics) usually have a cross sectional circularity of less than 5 millionths of an inch and are amazingly straight as well. The use of such high quality workpieces allows error motion estimates in the 10-15 microinch range to be made without resorting to workpiece mapping or reversal techniques (ANSI B89.3.4M-1985, Appendix B and section 7) to remove the errors introduced by an imperfect workpiece (assuming the centering error of the workpiece on the spindle is on the same order as the workpiece geometry errors). Asynchronous error motion estimates (ANSI B89.3.4M-1985, page 2, Section 2.12C) are relatively unaffected by minor geometry and centering errors.

To make measurements:

1) Mount the workpiece on the spindle.

2) Center the workpiece on the spindle for minimum runout. The Targa can be used as a dial indicator for this purpose. Rotate the spindle by hand and note the position of the high and low readings. If the workpiece is far off center, the high and low will be approximately 180 degrees apart. Note the difference between the two readings, then rotate the spindle until the Targa reads the lowest value. At this point, the target will be farthest away from the probe. Use whatever adjustment technique is available (screw adjustment, tapping with a small hammer, etc.) to move the workpiece half of the difference between the high and low readings. Rotate the spindle by hand again and note the difference between the high and low readings. Position the spindle to the low point and again adjust the workpiece toward the probe an amount equal to one-half of the difference between the high and low readings. Continue to repeat until the difference between the high and low values is as close to zero as possible. At some point, the high and low values will not be 180 degrees apart. When this happens, the workpiece is close to being as perfectly centered as the error motion of the spindle will allow. This may also indicate the form error of the workpiece. At this point, minimization of the TIR is dependent of the shape of the TIR signal. Generally, the TIR is minimized by adjusting the workpiece so the two high spots are 180° apart. This would correspond to the smallest perfect ring gage that the part (plug) would fit into. The residual error motion is the sum of the workpiece form error and the spindle error motion. The workpiece eccentricity is considered to be zero. If there are multiple highs and lows, however, the TIR would be minimized by getting two

highs 180 degrees apart to have the same value and two lows 180 degrees apart but at some other angular location than the highs, to have the same value. A TIR signal that is essentially round (unchanging) except for a "bump" would be adjusted to the major portion (circular) part of the signal. After final adjustment, the workpiece is locked in place and rechecked to insure that the locking mechanism does not disturb the workpiece position when activated. The locking mechanism should be rigid and not subject to drift or change due to rotational or vibrational influence.

3) Rotate the spindle at the desired test velocity.

4) The signal on the oscilloscope will generally be roughly sinusoidal in form; adjust the oscilloscope timebase (SEC/DIV) to display approximately 1 full cycle across the screen (as in Plots 4.1 and 4.2).

5) Adjust the vertical sensitivity (CH1 VOLTS/DIV) so the entire waveform is displayed on the screen.

6) The total runout is calculated by multiplying the waveform peak to peak amplitude in divisions by the vertical sensitivity (VOLTS/DIV) and multiplying this number by 1000. This will give runout in microinches. The use of the cursor feature built into the TEK 2211 oscilloscope makes the peak-to-peak measurement even easier. See pages 6-7 through 6-9 of the TEK 2211 manual. Caution: the cursor readout will give the scope waveform amplitude in millivolts or volts, depending on the VOLTS/DIV setting of the oscilloscope. If the reading is in millivolts, the cursor readout value is a direct measure of the runout in microinches. Remember, the Targa is calibrated so 1 microinch equals 1 millivolt. If the cursor readout is in volts, the number must be multiplied by 1000 to convert the measurement to microinches.

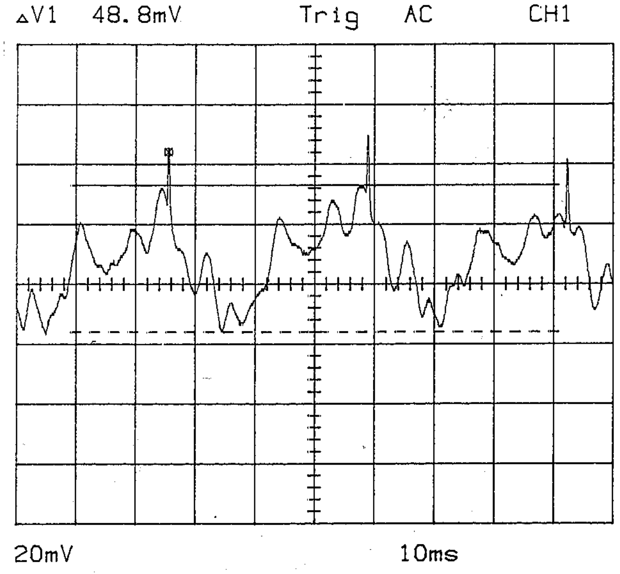
Example:

$$\underset{\substack{\updownarrow \\ \text{signal} \\ \text{amplitude}}}{(4.2\ \text{DIV})}\ \underset{\substack{\updownarrow \\ \text{vertical} \\ \text{sensitivity}}}{(.05\ \text{VOLTS/DIV})}\ \underset{\substack{\updownarrow \\ \text{Targa scale} \\ \text{factor}}}{(1\ \text{Microinch}/.001\ \text{Volt})} = \underset{\substack{\updownarrow \\ \text{actual runout} \\ \text{value}}}{210\ \text{microinches}}$$

7) There are 3 regimes of interest when using this method for error motion estimates:

   A: The spindle error motion is "large". In this situation, the error motion is at least 10 times greater than the form error of the workpiece and the ability to center the workpiece is almost completely dependent on the spindle error motion. Most rolling element machine tool spindles have error motions in the 50-100 microinch range and fall into this category. In this area, the form error of a Grade 3 ball used as the workpiece can be essentially ignored and the signal on the oscilloscope can be analyzed by considering it to be the sum of the error motion and the centering error. Plot 4.1 on page 24 is a typical example.

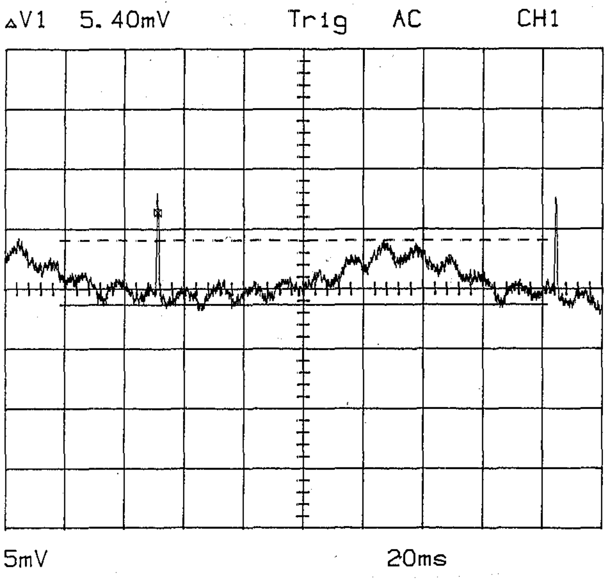
B: The spindle error motion is slightly larger than the workpiece form error and centering error. This regime, where the total signal amplitude is in the 10-30 microinch range, provides the least amount of information. This is because the form error may add to or subtract from the error motion, causing the sum of these two components range from near zero (form error equal to and opposite error motion) to near double (form error equal to and in phase with error motion). Centering error is always additive. See ANSI B89.3.4M-1985 page 23 Section A7.5 for more detailed information on centering error and page 28, Section A10 on error motion versus runout. Note: This regime is particularly troublesome when asynchronous error motion is also on the same order as the error motion. The non-repetitive nature of asynchronous error motion makes it difficult to center the workpiece as well as get a stable display on the oscilloscope for triggering and measurement. See Plot 4.3.



Plot 4.3 Error Motion Slightly Larger Than Workpiece Form

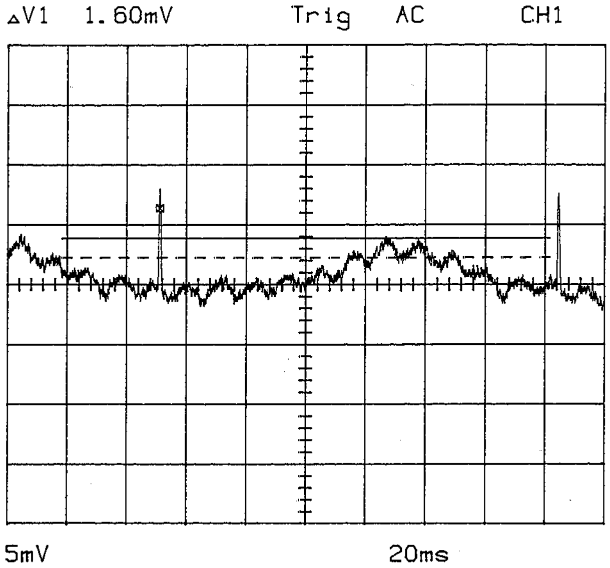
The "grease pencil" technique (see step 9, p. 32) is used to produce a sharp spike in the signal, making it easy for the oscilloscope to trigger properly and produce a stable display.

C: The spindle error motion is less than the form error of the workpiece. This circumstance is characterized by the ability to adjust the runout of the workpiece to near or possibly less than the workpiece form error. High quality hydrostatic spindles are available with error motions of less than 1 microinch and reliable measurements in this range are challenging at best (see Plot 4.4a and 4.4b). If this situation should occur, one technique is to center the workpiece to the best level possible and use the digital storage capability of the TEK 2211 to SAVE a display (see pages 5-6 through 6-7 in the 2211 manual), then reorient the workpiece on the spindle by rotating approximately 180 degrees and recenter it. Store the new display (at the same speed) and compare it to the SAVED previously. This procedure will reduce the probability that the workpiece form error and the spindle error motion cancelled each other out in the first test. A more complicated procedure would be to use the SAVE capability of the TEK 2211 in conjunction with the Reversal Technique (Section 7.1) to separate the form error from the spindle error motion. The Reversal Technique involves moving the probe and reorienting the workpiece as well as creating some tables from the SAVED displays, but will result in the best possible measurement performance in this situation. More advanced methods (dual probe) are required to fully confirm the spindle performance.



Plot 4.4a Almost No Error Motion Signal

The workpiece form error dominates the error motion of this spindle. Actually, the workpiece could be centered even better; note the definite once per revolution change in the signal. The real form error is smaller and mostly comes from the distortion of the workpiece surface due to the tension in 12 attachment screws. See Plot 4.4b.



Plot 4.4b Screw Tension Induced Workpiece Distortion

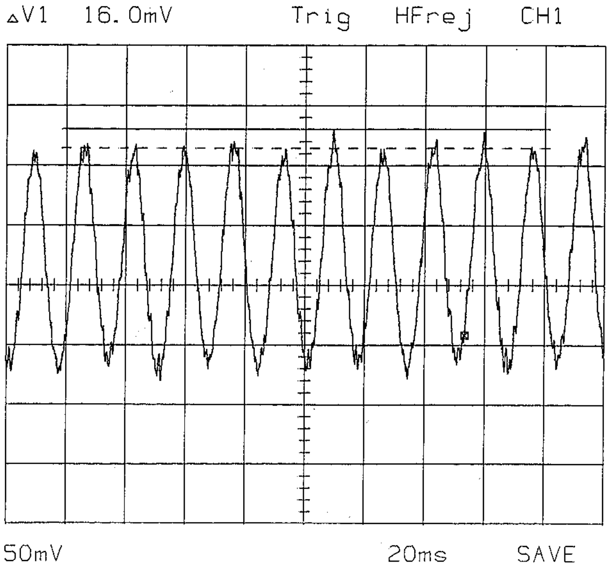
The regularly spaced distortion of the workpiece due to the tension of 12 attachment screws. The distortion measures about 1.6 microinches peak-to-peak and the number of instances can be readily determined by counting the cycles in one revolution.

8) Asynchronous error motion is much easier to characterize on a qualitative basis with a single probe than are other error motions. A spindle that has little or no asynchronous error motion is one that does exactly the same thing every revolution. This means that the waveform on the screen does not change at all. Therefore, to get a qualitative assessment of asynchronous error motion, one need only study a single point on the waveform. The best one to study is usually the peak point.

   A: Set the CH1 VOLTS/DIV to a high sensitivity.

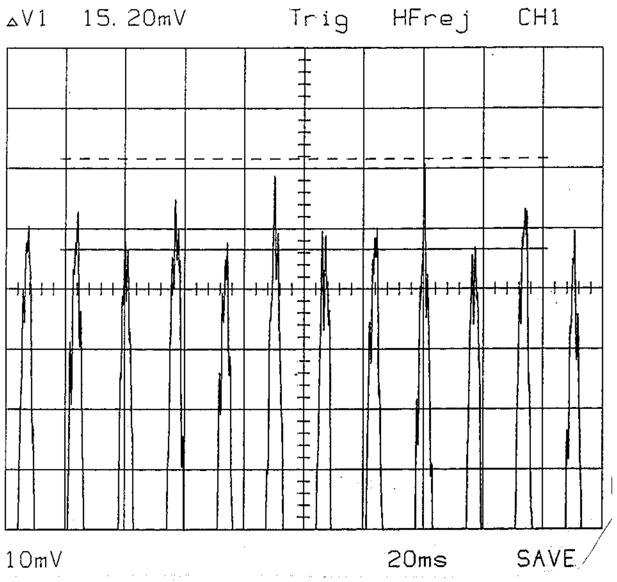
   B: Use the CH1 POSITION knob to adjust the position of the peak point to the center of the screen. It may be necessary to use the ZERO knob on the Targa in addition to the POSITION knob on the 2211.

   C: Observe the signal. Spindles with low asynchronous error motion show little activity. High quality (See Plot 4.4) hydrostatic spindles behave this way. Rolling element spindles, with their multitude of surfaces in contact and differential motion between the inner race, rolling elements, and outer race show little spikes, traveling waves and other aberrations on the waveform (See Plot 4.9). Note: If the waveform slowly drifts on the screen, set the CH1 input coupling to AC. This should eliminate the drift (if it is thermal drift) but unfortunately will make the ZERO knob on the Targa ineffective for adjusting the waveform position on the screen. Only the CH1 POSITION knob will be effective. Plots 4.5 and 4.6 show typical asynchronous error motion of a high quality ball bearing spindle.



Plot 4.5 Asynchronous Radial Error Motion of 16 Microinches

Asynchronous radial error motion measured over 12 consecutive revolutions. The measurement resolution is set low to display the entire waveform.

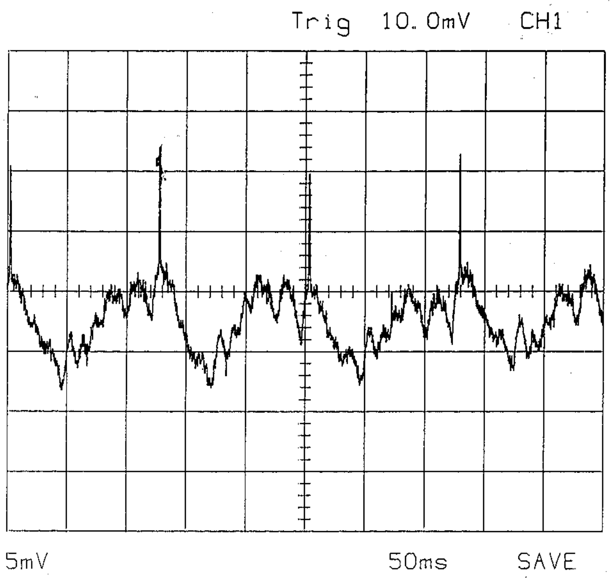


Plot 4.6 High Resolution Display of Asynchronous Radial Error Motion of 15.2 Microinches

The same measurement as in the previous plot except the vertical resolution is 5 times higher. The ZERO knob on the Targa and the vertical position knob on the oscilloscope are used to move most of the signal off the oscilloscope screen so only the changing peak heights are shown.

9) The "Grease Pencil" test: occasionally, it will be necessary to provide an artifact on the workpiece that will result in a sharp spike in the oscilloscope signal. Observing only the tip of this spike over several consecutive revolutions is an improved technique for measuring the asynchronous error motion. This also has the advantage of providing a more stable signal for the oscilloscope trigger. A common technique is to simply draw a line (approximately .1 inch wide) on the workpiece, parallel to the axis of rotation. A "magic marker" is frequently used; the thickness of the ink film is about 20 microinches and the dielectric constant of the ink is different than air, so the probe can "see" the line. For this reason, this technique has been colloquially called the "grease pencil" test. This technique is generally attributed to Bill Bryan.

Rotate the spindle at the test velocity. The roughly sinusoidal waveform will have a narrow spike in it, occurring once per revolution (See Plot 4.7). Set the TRIGGER MODE to NORM and adjust the level so the oscilloscope is triggering on the spike. Offset the waveform as in the previous section, until the peaks are centered on the oscilloscope screen. Change the timebase(SEC/DIV) until 10 to 15 peaks are displayed on the oscilloscope. Variations in peak height can be considered asynchronous error motion. Use of the cursors can easily measure the total variation from the highest peak to the lowest peak.



Plot 4.7 "Grease Pencil" Test

"Grease Pencil" test on a high quality spindle. The asynchronous error motion measures about 2 microinches, however, the probe mounting arrangement used here is not optimized for measurements at this level, so some caution must be used in considering these values.

The digital storage capabilities of the Tektronix oscilloscope can be quite useful in producing a permanent hardcopy of the spindle error motion. Use the following procedure:

1) Put the oscilloscope in the STORE mode by pushing the STORE/NON-STORE button in.

2) The oscilloscope will begin storing the waveform displayed on the CRT.

3) Push the SAVE button. The oscilloscope will acquire 1 record length (4 K) of data. The number of peaks will be determined by the SEC/DIV setting. The oscilloscope will stop acquiring data when the memory is full.

4) Load a sheet of paper into the plotter.

5) Push the PLOT button (on the right hand side of the TEK 2211 oscilloscope) to plot the information displayed on the CRT.

Please be aware that the previous sections on synchronous error motion should be used for qualitative analysis only. Single probe measurements can be used for weeding out candidate spindles and deciding which should be analyzed further. Dual and sometimes triple probe measurements are required for full quantitative analysis and comparison.

Section 4.1.5 Imbalance

Imbalance of rotating components produces a sinusoidal once per revolution force that varies with the square of the angular velocity. A single probe system can qualitatively show whether or not a significant amount of imbalance exists. It is useful but not necessary to be able to vary the spindle speed in order to do this procedure.

1. Obtain a stable display at a moderate speed which is less than normal operating speed.

2. Double the speed so it is above the normal operating speed. If there is little imbalance, the amplitude of the display will not change. If there is a significant imbalance, there are two cases that can be looked at:

   A: Hydrostatic bearings: here the stiffness of the bearing films is usually reasonably linear and doubling the speed would have the effect of increasing the imbalance induced runout by a factor of 4. Some quantitative data might be drawn from this.

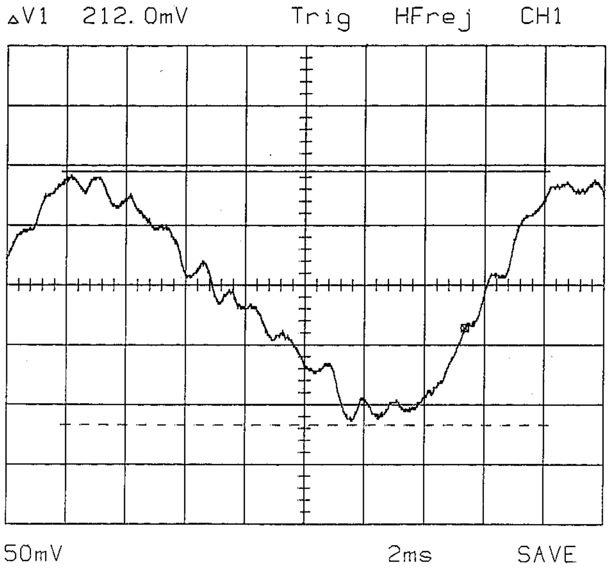
   B: Hydrodynamic or rolling element bearings: the stiffness of these types of spindles is generally very nonlinear. Quantitative conclusions are difficult if not impossible to draw without detailed information about the force versus deflection characteristics of the spindle. See ANSI B89.3.4M-1985, pages 27-28, Section A8).

   In both cases, the linear or nonlinear response is a property of the bearings themselves, not of the spindle as a whole. For example, in a spindle with a small diameter shaft and widely spaced bearings, the shaft between the bearings may deflect more than the bearings themselves when an external load such as imbalance is applied. The shaft deflection is linear and the system will appear to be linear even though the response of the bearings is nonlinear. Fortunately, most modern machine tool spindles have a great deal of attention lavished on the concept of stiffness and the shaft is made as robust as possible in order to make full use of the bearings.

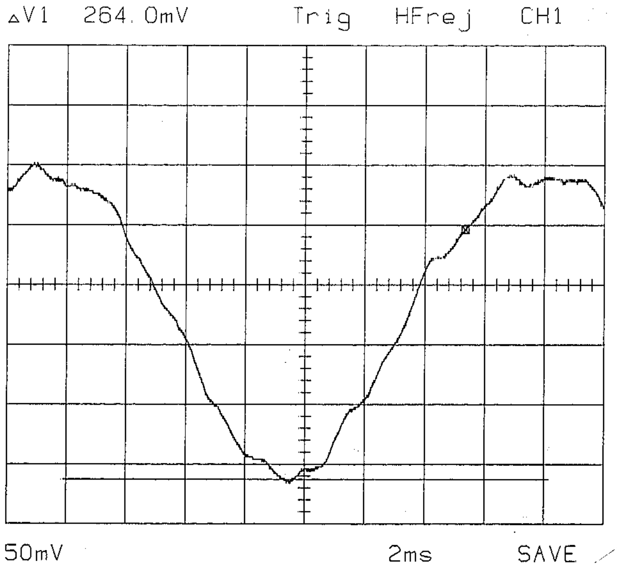
   In both cases above there is a small chance that imbalance may cause a reduction in runout if the imbalance is located such that it opposes a once per revolution error motion. The cancellation will be complete (zero runout) at one speed only and varying the speed over a wide range can expose the situation.

3. If the spindle speed cannot be easily varied, as in the case of line operated AC spindles, the effect of imbalance can be seen by adding a small mass located off the axis of rotation. This procedure is used to produce Plot 4.8 (See also Plot 4.1, which is the radial error motion of the same spindle, nominally balanced).

Interestingly, imbalance does not affect the surface finish capability of a spindle because it is a synchronous effect. The force vector that is produced by the asymmetric mass distribution rotates with the spindle and therefore has a fixed relationship with the angular position of the spindle. Only effects that can change with respect to the angular position of the spindle can cause surface finish defects. For a more complete discussion of this phenomenon, see ANSI B89.3.34m-1985, pg. 27.



Plot 4.1A Radial Runout and Error Motion of a Nominally Balanced Spindle



Plot 4.8 Effect of Introducing an Unbalance Condition

Radial error motion after unbalancing the spindle (adding a 3.5 gram screw at a 1.88 inch radius). The fundamental amplitude increases from 212 to 264 microinches and the higher frequency effects of the balls are reduced. This might indicate that the spindle is improperly preloaded. A rough estimate of the spindle stiffness can be made from this plot. The force vector due to the imbalance is F=mrw^2 . Using consistent units (SI), the force in newtons is (.0035 Kg)(.048 m)(377 rad/sec)^2 = 23.7 newtons. This vector rotates with the spindle and "stretches" the "spring" 1/2 of the difference between the p-p value of the runout with the screw (Plot 4.8) and the runout without the screw (Plot 4.1A). The difference in these two plots is 52 mV (52 microinches) so 1/2 of the peak to peak difference is 26 microinches or .66 micrometers. The stiffness is calculated by dividing the force (23.7 N) by the deflection (.66 micrometers). This results in a stiffness of 35.9 x10^6 N/m. This is equal to 205,000 lb/in. This test works only if the residual imbalance of the spindle is low so that the dominant force in the system is due to the unbalancing. By varying the weight of the screw or the spindle speed, a force vs. deflection plot can be made.

Section 4.2 Axial Error Motion

Axial error motion can be fully quantified with a single probe system.

1) Mount a workpiece on the spindle and center it. A sphere is generally the best form although this test is relatively insensitive to geometry errors of the workpiece.
2) Mount the probe so the axis of the active region of the probe coincides with the axis of rotation.
3) Rotate the spindle at the test velocity and observe the axial error motion.

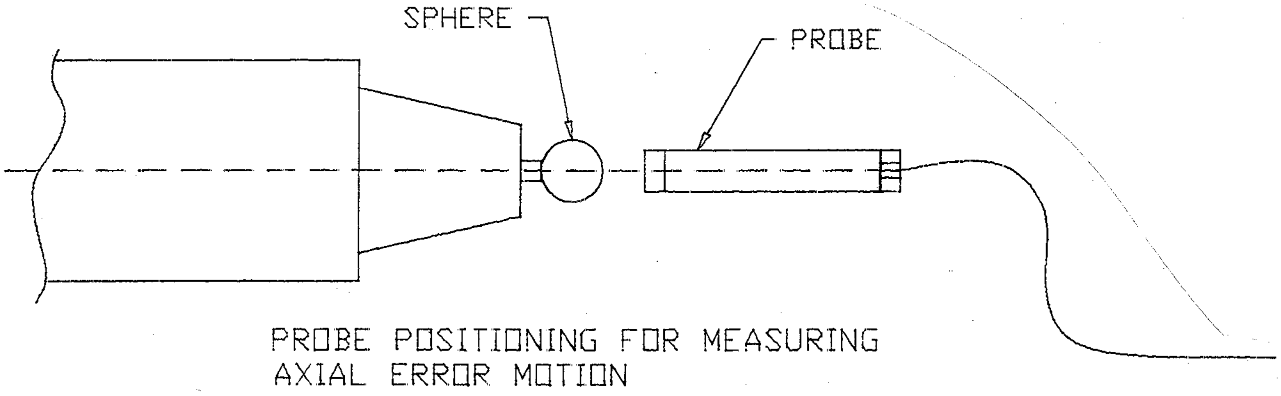
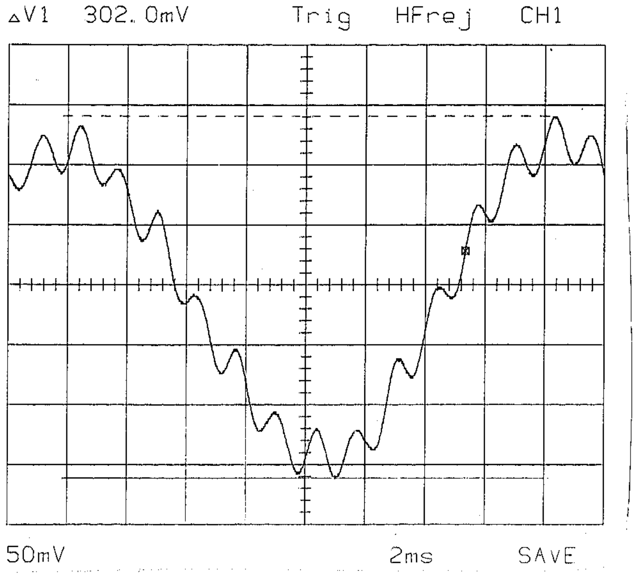
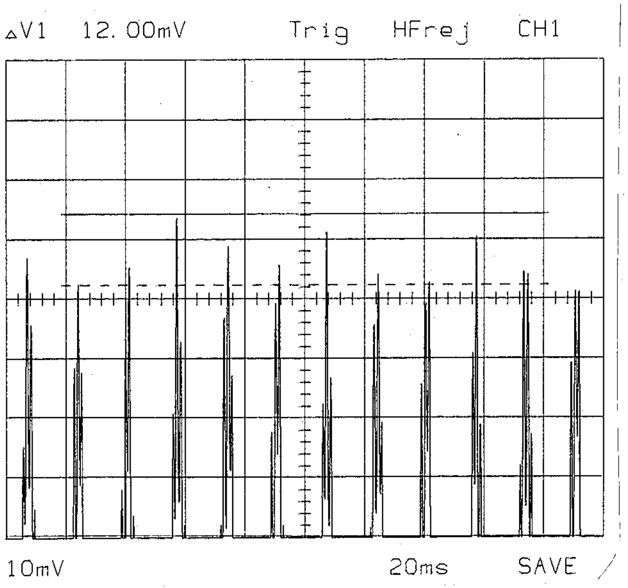


FIGURE 4.2 Set-up For Axial Error Motion Measurements



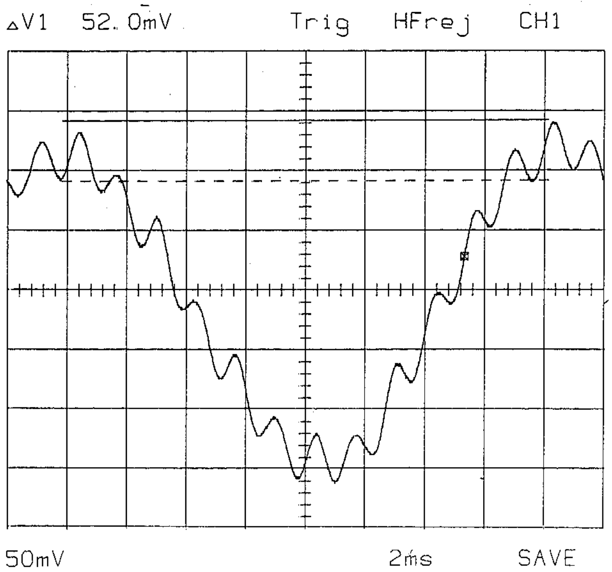
Plot 4.9 Axial Error Motion

Axial error motion of surface grinder spindle. A 3/8 inch diameter ball is glued to the 60 degree machine center in the end of the spindle shaft using a fast setting cyanoacrylate adhesive. The error motion has a magnitude of 302 microinches.



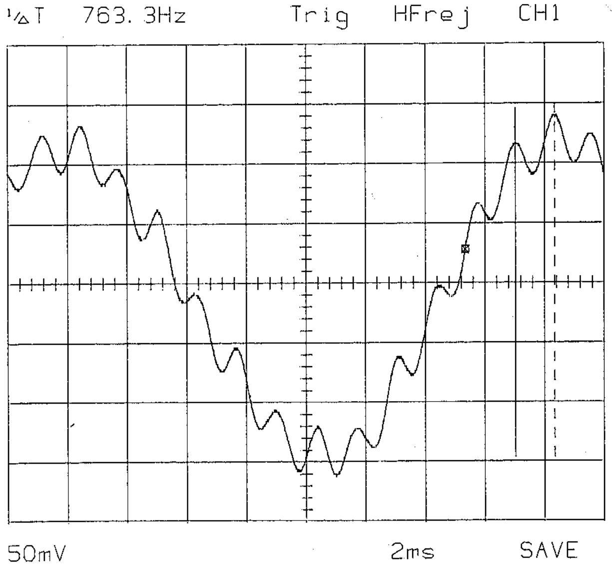
Plot 4.10 Asynchronous Axial Error Motion

Plot showing the asynchronous axial error motion over twelve consecutive revolutions to be 12 microinches in magnitude.



Plot 4.11 Individual Ball Error Motion

The error motion amplitude of the individual balls can be estimated from the axial error motion plots. The cursors help delineate the limits. The magnitude is the height of the smaller wave form which is between 40 and 50 mV (40 to 50 microinches).



Plot 4.12 Ball Frequency

The ball frequency can also be measured from the axial plot (or the radial plot for that matter). The ball frequency is determined to be 763 Hz.

Section 4.3 Thermal Drift and Distortion

Thermal Drift (or thermal distortion) can be divided into two areas. In the first area, thermal growth causes a slow change in the position of the probe with respect to the workpiece. This is indicated by a slow shift in the waveform on the screen over time but with no significant change in the waveform itself. The CH1 input must be set to DC for this measurement. Simply set the probe and workpiece up for radial and/or axial measurements, establish a baseline at time zero, start the spindle and observe the drift of the entire waveform over the time of interest. The other thermally induced problem is when heat input to the spindle causes thermal distortion that disturbs the geometry or operating characteristics of the spindle. This can occur when heat input causes the bearing mounting to become non-coaxial, changes bearing preload, or even changes lubricant characteristics. These changes will be seen as changes in the waveform rather than drift of the waveform as a whole. If spindle performance changes due to thermal input must be separated from probe/ workpiece position changes, use the CH1 input in the AC mode. This will eliminate the DC or low frequency drift while retaining the capability to view changes in the runout waveform.

Section 4 of ASME B5.54 titled Environmental Tests, Subsection 4.2 discusses measurement of machine tools relative to thermal growth of machining centers due to changes in the ambient temperature. Section 5.7.4 of the same standard titled Thermal Spindle Stability Tests, Fixed and Rotating Sensitive Direction, outlines measurement techniques for quantifying thermal spindle growth due to self-heating of the spindle during operation.

Section 4.4 Single Probe Linear Axis Applications

Section 4.4.1 Straightness

A single Targa/probe combination can be used to measure the straightness of travel of an axis in one plane at a time. A straightedge or some other reference surface is required. The probe is used as a non-contact dial indicator. The form error of the straightedge must be small compared to the expected measurement in order for qualitative measurements to be made directly. Unfortunately, high quality straightedges are considerably more expensive and difficult to procure than spheres or cylinders. Mitigating this situation considerably is the fact that the frequency content of a linear axis signal is usually much lower than a rotary axis. This makes workpiece mapping or reversal techniques much more attractive as a way to provide qualitative measurements. In fact, reversal is a excellent option in this situation. See section 7.2 for a reversal technique to eliminate workpiece form error in a linear application.

NOTE: The straightedge must be fabricated from a conductive material. Granite and ceramic straight edges will not produce a signal unless the reference surface is plated and properly grounded.

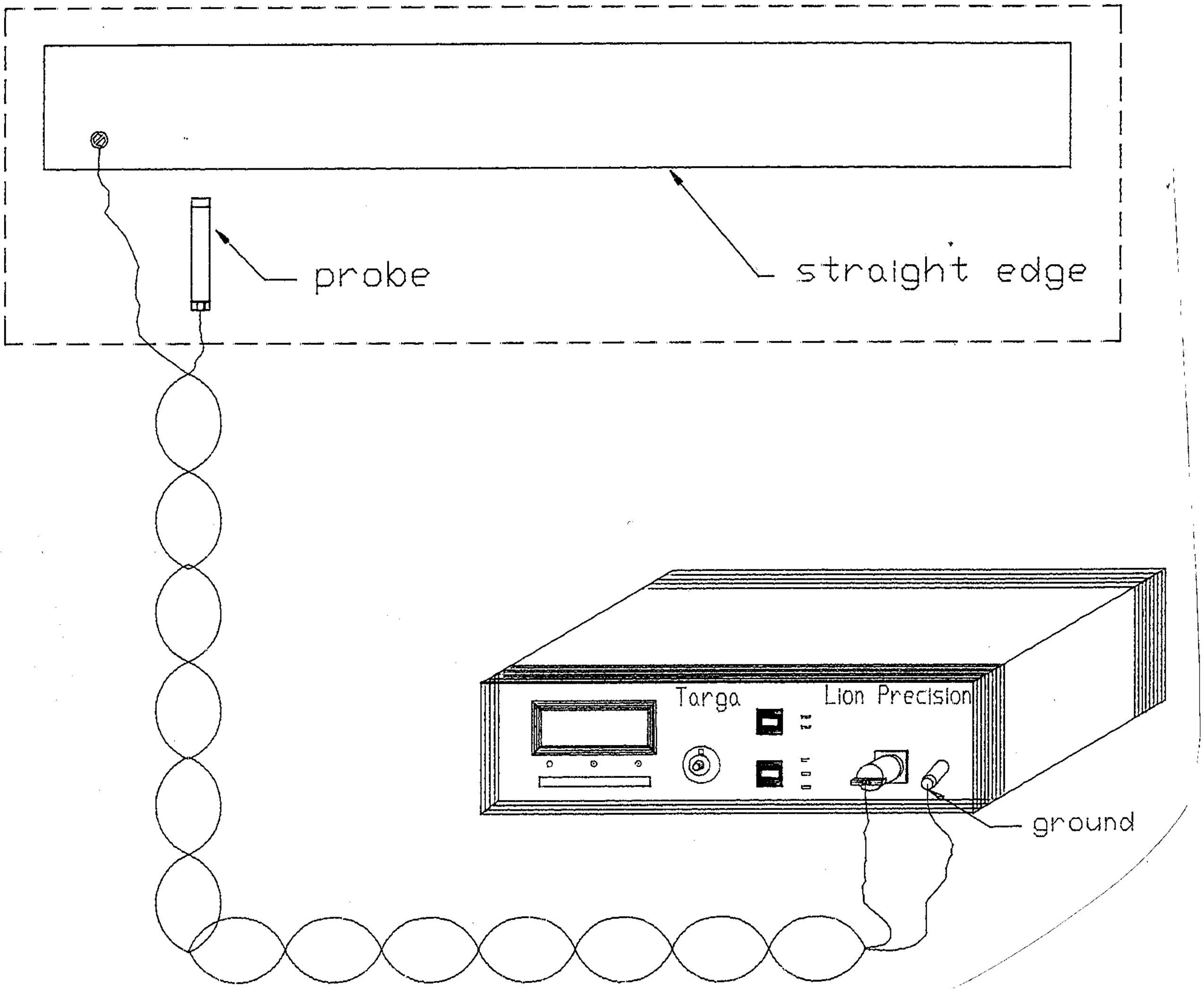


FIGURE 4.3 Set-up For Straightness Error Measurement

1) Set the straight edge on the axis to be measured.

2) Clamp the probe on some non-moving part of the machine.

3) Adjust the straightedge so the probe reads in the middle of the measurement range. Use the ZERO knob to adjust the digital display on the Targa to read zero. The probe should be positioned near one end of the straightedge.

4) Move the axis so the probe is positioned near the other end of the straightedge.

5) Adjust the straightedge so the digital meter on the Targa reads zero.

6) Move the axis so the probe is positioned near the first end of the straightedge and verify that the digital meter reads zero. If not, readjust the straightedge until the digital meter reads zero.

7) Repeat steps 4-7 until both ends of the straightedge read zero or as close to it as possible. Inability to get a zero reading at each end of the axis gives an indication of the lack of repeatability of the axis in the direction perpendicular to the direction of travel of the axis.

8) Move the axis in short increments (e.g. 1 inch) and record the deviation (+ and -) from zero. These may be plotted and connected to give an indication of the straightness errors. If a way to synchronize or otherwise time a strip chart recorder or plotter to the axis displacement can be arranged, the analog output signal on the rear of the Targa can be connected to the recording device to make a trace.

9) This test is only sensitive to translational errors in the direction perpendicular to the direction of travel (See Figure 4.4). If the errors are angular rather than translational, then two probes used in a differential configuration should be used. See Section 5.2 for a differential probe set-up.

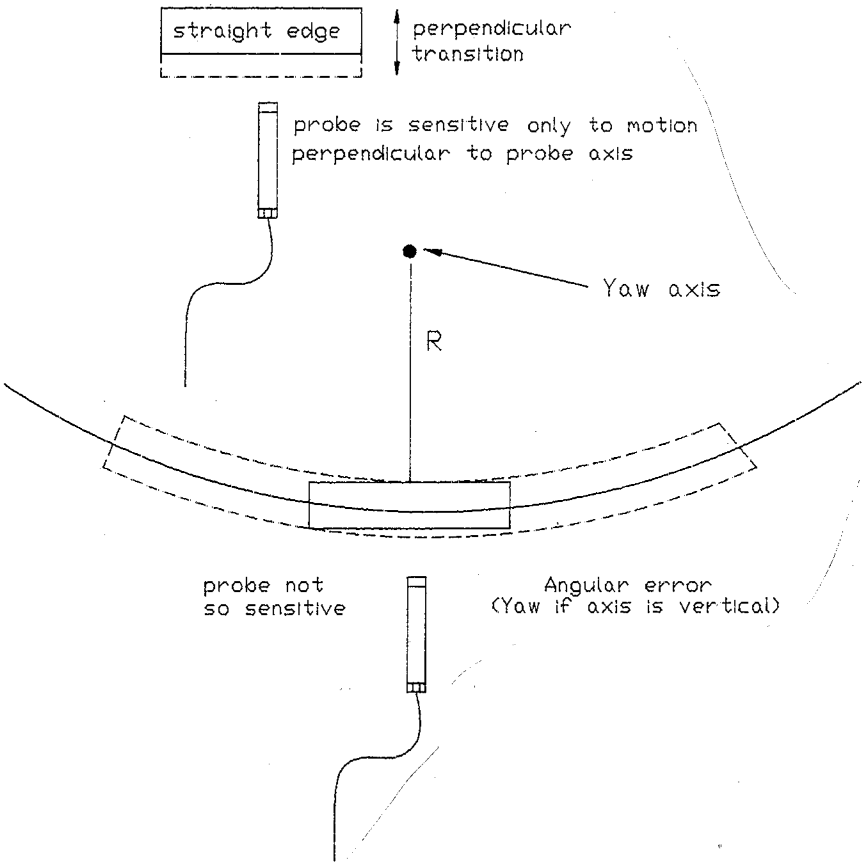


FIGURE 4.4 Explanation Of Angular Error

Section 4.4.2 Position Repeatability

Position repeatability is the ability of a system to return to the same position when commanded to move away and then commanded to return to the original position. This test is most applicable to systems that are under some form of servo control. However, the Targa system may also be used to position something manually.

1) Mount a target on the axis to be measured, with a reference (flat) surface perpendicular to the direction of travel. Insure that the target is grounded to the Targa front panel.

2) Mount the probe on some non-moving part of the machine. (Generally the spindle housing, etc.)

3) Move the axis or the probe until the probe reads in the middle of the measurement range. Use the ZERO knob to adjust the digital display to read zero.

4) Set the current axis position in the system position controller to zero or "home".

5) Using the system position controller, move the axis away from the probe and then command the axis to return to zero or home.

6) The axis position controller will return to zero or home internally (if it is functioning correctly); however, the mechanical axis may or may not (probably will not) return to exactly the same position. The digital meter on the Targa will indicate the error in repeatability. This error may be positive or negative. This test should be done several times in order to get a statistical picture of the extent of the non-repeatability.

7) For an axis with small position increments (e.g. 0.0001), the 0.006 inch standoff of the probe allows bi-directional repeatability tests to be accomplished. This involves moving the target toward the probe 30 or 40 position counts. (0.003 - 0.004 inches) and commanding the axis to return to zero. This can provide additional information about axis performance when direction changes are required during use as in contouring.

8) This test can also be done on a rotary table. For best results, the flat target should be located so its plane passes through the axis of rotation of the rotary table. This eliminates cosine errors. See Figure 4.5.

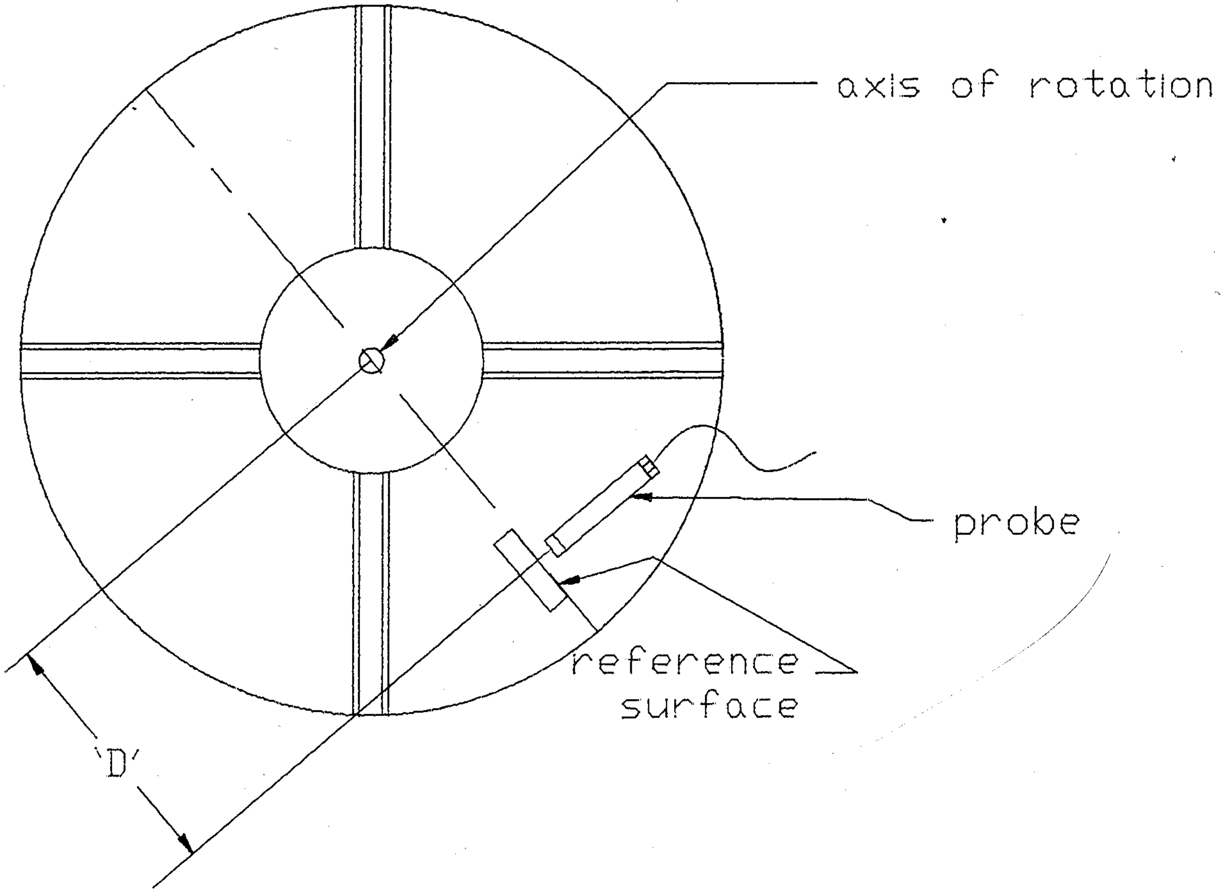


FIGURE 4.5 Rotary Table Angular Position Repeatability

The repeatability can be expressed as a linear value or used with the distance of the probe from the axis of rotation to calculate an angular repeatability. Simply divide the linear measurements from the Targa by the probe distance (D) from the axis of rotation. The result is in radians. To convert the radian value to arcseconds, multiply by 206,265. To convert the radian value to decimal degrees, multiply by 57.296. For example, if D = 5.5 inches and the Targa measurement is 337 microinches, the radian value would be .000061 radians or 61 microradians. This would be equal to 12.6 arcseconds or .00351 degrees.

Section 4.4.3 Settling Time

Settling time is the time required for a system (usually under servo control) to approach the final or commanded position within a certain error after a move or slew command.

1) The target, probe, and Targa are all set up as in the section on position repeatability (Section 4.4.2). The additional piece of equipment required is the TEK 2211 oscilloscope. Connect the output on the rear of the Targa to the CH1 input on the oscilloscope. Set the CH1 input coupling switch to DC.

2) Make sure the home or zero position of the axis corresponds to zero on the Targa digital meter. If not, adjust the ZERO knob until the meter reads zero.

3) Turn on the oscilloscope. Set it in NON-STORE. Set the VERTICAL MODE switch to CH1 and the TRIGGER MODE switch to P-P AUTO. The TRIGGER SOURCE should be CH1 and the TRIGGER coupling should be HF REJ. At this time there should be a single trace across the CRT near the middle. Use the VERTICAL POSITION knob to move the trace to halfway between the middle and the top of the CRT.

4) Move the target away from the probe.

5) Set the oscilloscope to STORE and the PRETRIG to 25%. Set the TRIGGER MODE to SGL SWP, the SLOPE TO _/¯ , and the LEVEL slightly toward '—' from its midrange position.

6) Press the TRIGGER RESET button. The READY LED should light.

7) Command the axis to return to zero or home.

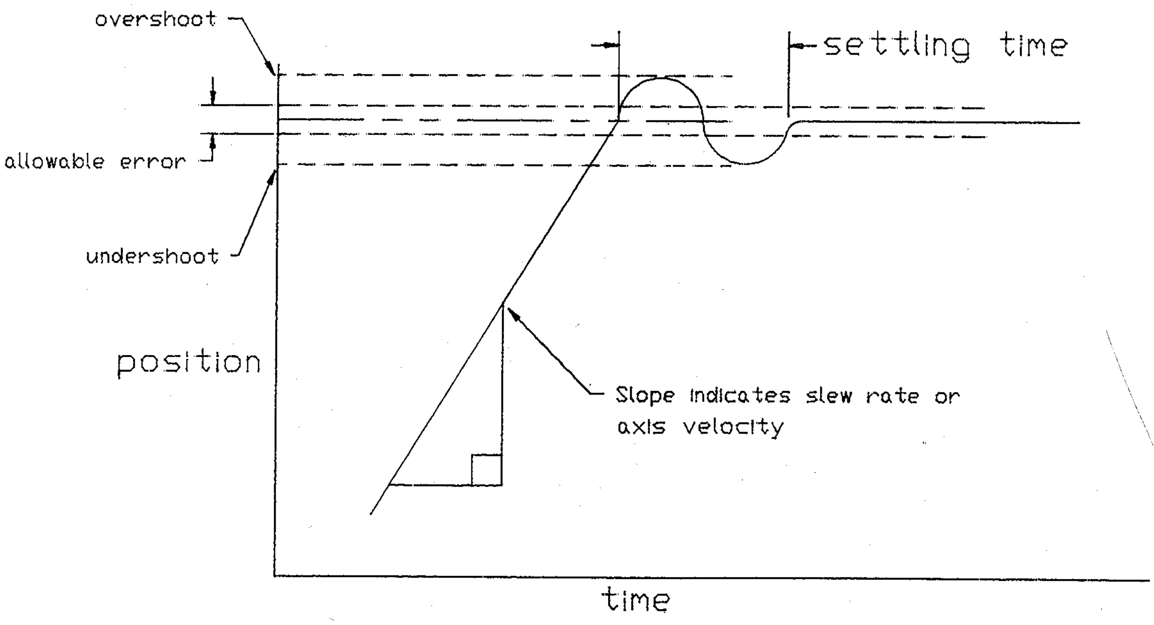


FIGURE 4.6 Explanation Of Settling Time

8) When the input to CH1 (output from Targa) is greater than the trigger level set by the LEVEL knob and the slope is positive, the TRIG'D/READY LED will go out, indicating the oscilloscope is digitizing and storing the input signal to CH1. When the oscilloscope is done acquiring a full record, it will display the record on the CRT. The cursors can be used to measure the settling time.

9) Adjustments will need to be made on the CH1 VOLTS/DIV, the timebase (SEC/DIV) and the TRIGGER LEVEL to get a trace similar to Plot 4.13 or Figure 4.6.

10) This test should be done several times, at different axis velocities and with different amounts of weight on the axis (if varying weight is an operational mode). The axis performance will change as the operating conditions change.

11) This test can be applied to rotary tables. The set-up is the same as in Section 4.2.2, #8.

12) This test can be used to determine if the axis position servo is properly compensated. Compensation involves adjusting the servo parameters so the axis settles in a minimum amount of time, usually with no overshoot. Such a system is said to be critically damped. Generally, there is a region in the operating range of the machine where the axis is critically damped i.e. average part weight, average feed rates, etc. Operation outside this range, as with a part near the maximum capacity of the machine, will cause the servo response to be non-optimum. There are several other well-known responses to be aware of.

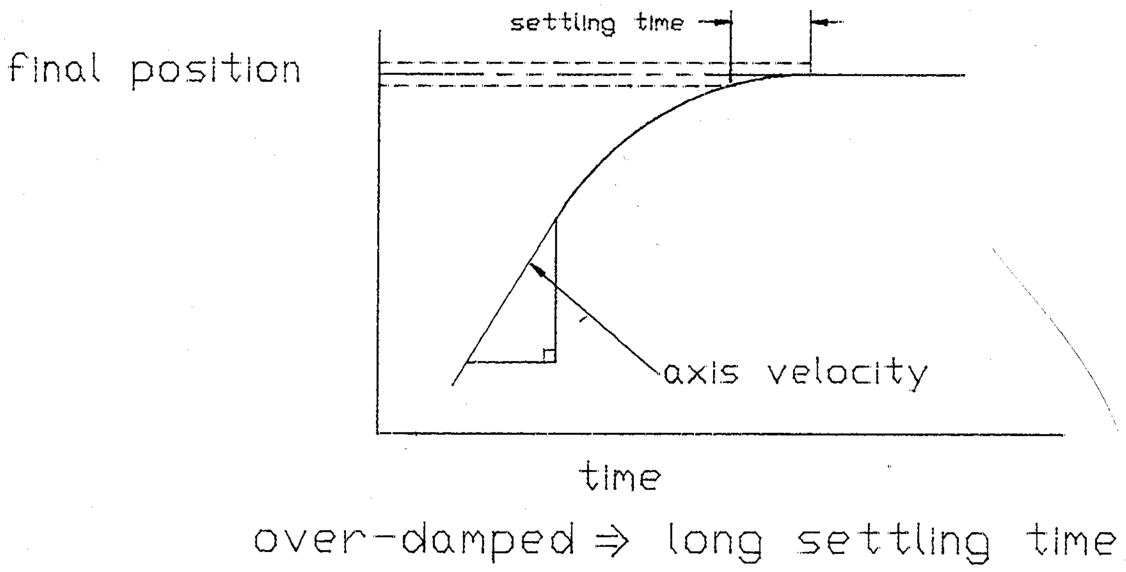


FIGURE 4.7 Settling Time: Over Damped

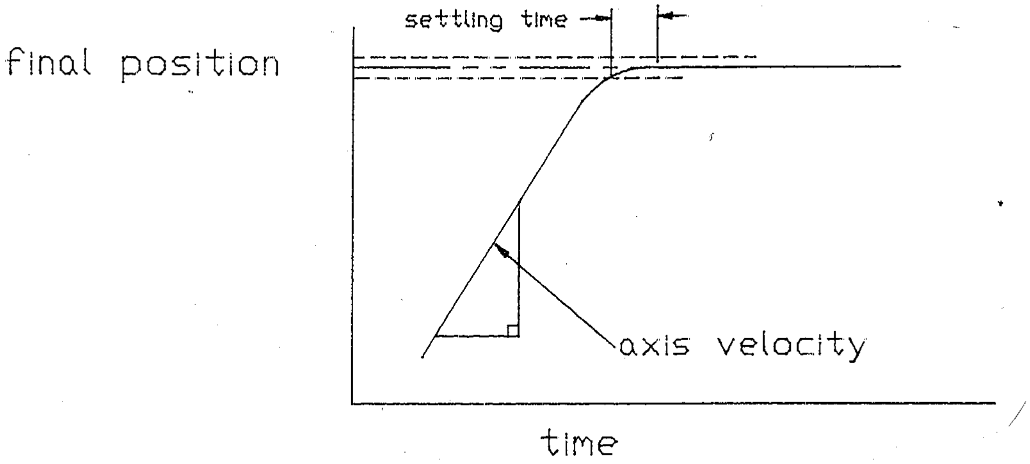


FIGURE 4.8 Settling Time: Critically Damped

Critically damped ⇒ shortest settling time with no overshoot

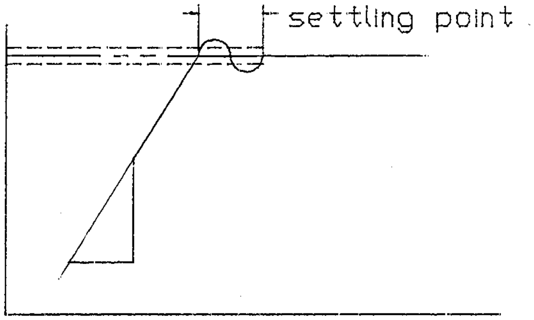


FIGURE 4.9 Settling Time: Under Damped

under-damped - shorter settling time than critically damped is possible, but there is some overshoot.

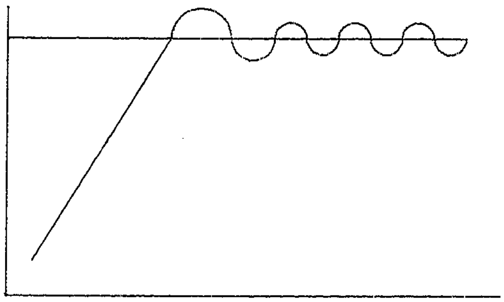
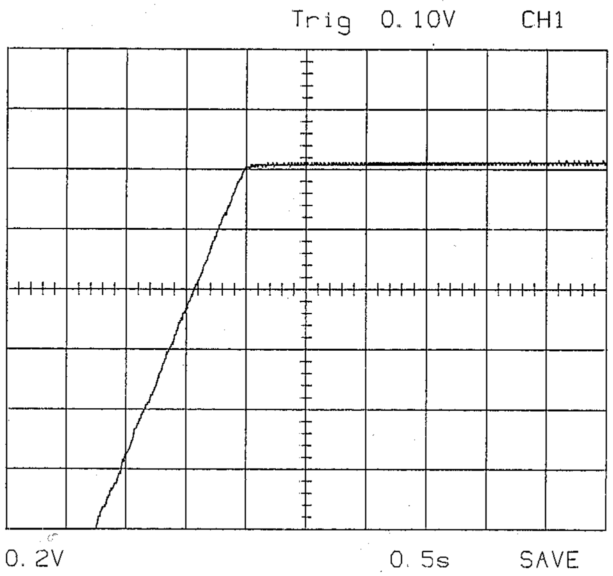


FIGURE 4.10 Settling Time: Oscillating

oscillatory - gain too high or damping too low, not an operational mode



Plot 4.13 Critically Damped Servo System

Slew and stop plot of a well-behaved (critically damped) servo system.

Gain and damping are usually adjustable servo parameters. In general, the gain is increased until the system oscillates, then the damping is adjusted until the oscillation stops. This process is repeated until maximum gain in conjunction with the appropriate amount of damping yields the best performance over the extremes of the axis variables. A system should never be allowed to operate in the oscillatory mode. Other names for gain and damping are proportional and derivative adjustments. Some servos also have integral adjustments designed to eliminate (or reduce) steady state errors. The integral adjustment will interact with the gain and damping adjustments and the methodology for parameter adjustment may differ depending on the servo. In all cases, please consult the operation manual for the servo or machine before making any changes.

13) Systems with little mechanical damping (usually friction) and digital position feedback may oscillate +/- 1 position count around a commanded position and not be considered to be operating improperly (See Figure 4.11).

This is due to the digital nature of the position feedback in that the controller cannot tell that the actual position of the axis is not at the commanded position until it is at least 1 count away. In a similar way, if axis position is determined by a digital position sensor (e.g. optical encoder) and the axis velocity is also derived from the same sensor (this is commonly done in many "all-digital" servos) then the axis velocity may appear jerky at very slow axis velocities. These circumstances represent fundamental limitations to axis performance and should not be viewed as operational problems.

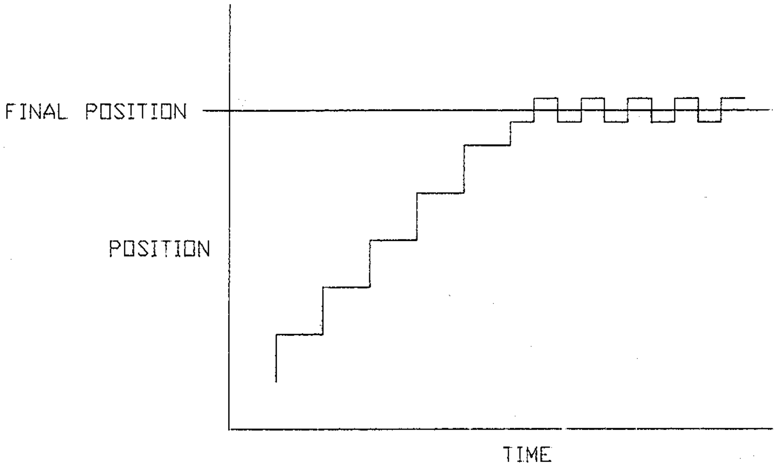
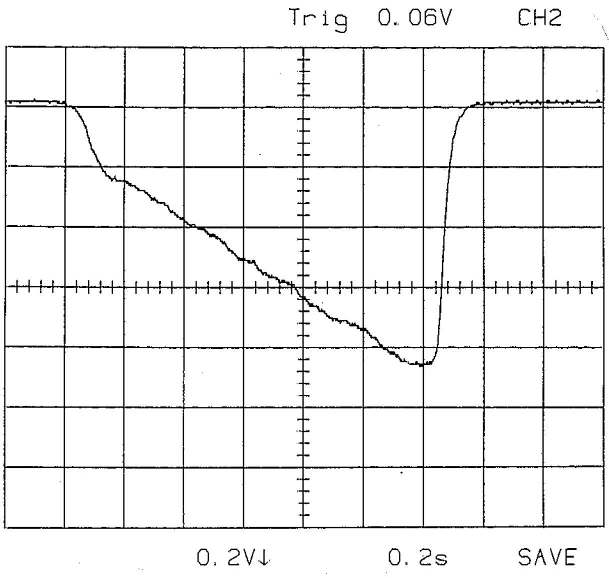


FIGURE 4.11 Settling Time: Quantization Error

Settling time showing velocity and position 'errors of quantization' at a very low axis velocity.



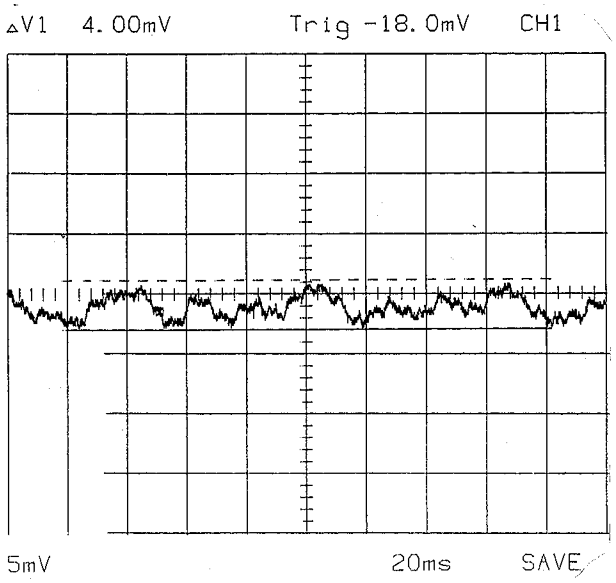
Plot 4.14 Stiction and "Stair Stepping"

This is a plain way slide commanded to move at a slow speed. The first few command pulses cause elastic windup of the leadscrew. Slide stiction prevents motion. When the elastic forces are large enough, the slide breaks away with a short high speed jump (indicated by the steep downward slope in the displacement signal). Once moving, the slide operates much better, but the digital motion of the slide/position feedback system is apparent in the trace. The subtle "staircase" effect in the position is due to the digital nature of the feedback and control system. During the retrace move both the slide and the control system operate better because of the higher velocity. The slide operates better because it flies higher on its hydrodynamic oil film, and the position control system operates better because of the higher rate of position feedback information. This allows the controller to calculate the actual velocity more accurately, resulting in better position loop damping and velocity control.

Section 4.5 Vibration

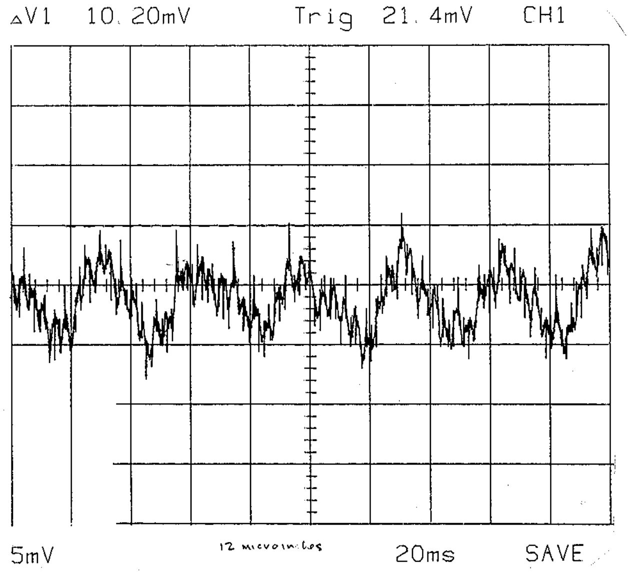
Vibration is the unwanted (generally) displacement of one machine element with respect to another. The Targa system with the TEK oscilloscope can give a general view of the nature of the vibrations if the signal is complex (i.e. made up of many frequencies). The system can give a reasonably good picture if the vibration is a relatively pure frequency such as might be encountered if one element in the machine tool were at resonance. The peak hold function on the Targa can indicate the maximum excursion over any time frame. If complex signals need to be analyzed there are two choices: use the TEK oscilloscope in the digital storage mode along with a PC and a PC based waveform analysis program and the TEK Grabber II waveform transfer software. In this system, the oscilloscope acquires a waveform and transfers it to the PC via the TEK software. Then the PC and a waveform analysis program break down the waveform into its spectral components and display them. The other choice is to route the output of the Targa directly into a real-time spectrum analyzer. The filter switch on the rear of the Targa should be set to “unfiltered” to take advantage of the full performance of the Targa system. Signals analyzed in this fashion can accommodate nearly any mechanical system including rolling bearing induced high frequency impulse signals. The use of a spectrum analyzer can also help to characterize noise (both mechanical and electrical) and vibration as to the source and its magnitude as a function of frequency. The ability to see the actual displacement between elements of interest as opposed to, for example, measuring the acceleration of one element with an accelerometer/charge amplifier combination, provides far deeper insight into machine tool dynamics.

The setup for vibration is similar to the other setups discussed in Section 4, the probe is mounted on one part of the machine tool and a target surface is mounted on another element. Generally, one is interested in the relative motion between the tool and the part so the probe might be mounted on the table and a target surface (e.g. a gage pin) would be mounted in the spindle. The oscilloscope should be connected and turned on. In this way, the amplitude of system noise (particularly electrical noise) can be immediately qualitatively assessed. Then simply turn on various machine tool subsystems like hydraulic pumps, axis servomotors, etc. one at a time to see their effect on the position of the tool with respect to the part. All of these subsystems contribute to the background noise or signature of the machine.



Plot 4.15 Grinding Machine, Coolant and Hydraulic Pumps Off

Wheel to workpiece vibration is 4 microinches. The source is ambient structural vibrations and acoustic noise.

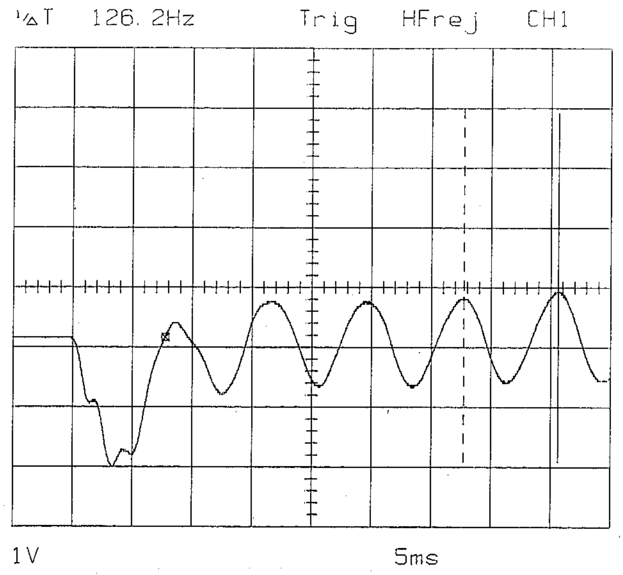


Plot 4.16 Grinding Machine, Coolant and Hydraulic Pumps On; Wheel to Workpiece Vibration is 10.2 Microinches

Wheel to workpiece displacement on a grinding machine with subsystems on and off, wheel is not rotating.

As a cautionary note, if high frequency signals are expected, probe mounting and target surface natural frequency are important considerations. See Section 2 for further information on probe holders. Also, the Targa/ Oscilloscope system can help to determine the natural frequency of the probe mount and the target surface. To do this, use the following steps:

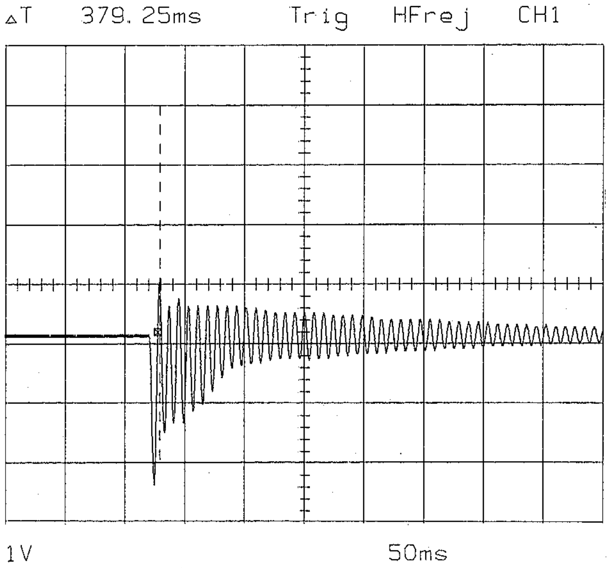
1) Set up the Targa and the Oscilloscope in the digital storage mode as described in steps 1-10 for settling time measurements (Section 4.4.3) except set the trace to the center of the CRT rather than in the middle of the upper half.
2) Arm the trigger by pushing the RESET button in the TRIGGER section. The READY LED should light.
3) With a small soft faced hammer, rap the probe mount or the target surface sharply.
4) Make adjustments to the CH1 VOLTS/ DIV and the SEC/DIV to display approximately 5 full cycles on the CRT, pushing the RESET button and striking the surface of interest each time an adjustment is made.
5) Ignoring the first cycle, use the cursors (See page 6-15 of the TEK 2211 manual) to measure the frequency of oscillation.



Plot 4.17 Natural Frequency of Probe Mount

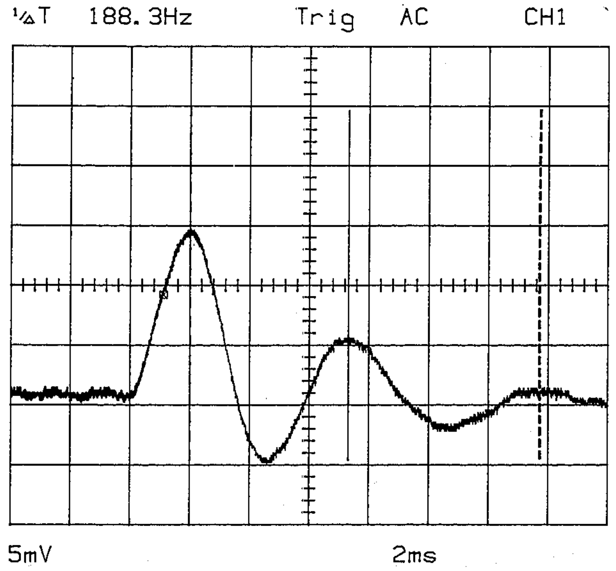
Natural frequency of a probe mount. Note the disturbed initial response due to higher order vibration from the impact process. It is difficult to store energy at high frequencies and such artifacts quickly disappear leaving only the lowest order, or fundamental frequency of the probe holder. The ΔT/ 1/Δ T cursors are used to measure the actual frequency.

The first cycle may contain high frequency artifacts from the impact process, but these should die quickly. The following excursions will be structural oscillations at the "natural frequency" or the lowest frequency at which the structure will resonate. The spacing between any two peaks should be the same. If not, there may be two or more elements in the structure whose natural frequencies are close together. The rate at which the amplitude decays is an indication of the amount of internal damping available. Things that oscillate for a long time (a la tuning forks) have either the capability to store a large amount of energy or have minimal internal damping, or both. Conversely, things that oscillate only a few cycles either cannot store much energy or have a large amount of internal damping. A good probe holder will oscillate with a small amplitude at a very high frequency for only a few cycles. Theoretically, measurements can be made when the structural vibrations in the system are close to the natural frequency of the probe holder and the workpiece as long as the damping of those elements is high. In practice, however, the probe/target natural frequencies should be at least twice as high as the highest structural vibration frequency applied to them and at least 5 times higher if high precision measurements are to be made. It should be noted that operation with a spectrum



Plot 4.18 Extended View of Probe Mount Response

This is an expanded view of the probe holder response to an impact. Even after nearly 400 milliseconds the peak to peak oscillation of the probe with respect to the target is still 200 microinches. The low natural frequency (126 Hz) and the long time to damp out indicate this is not a very good probe mount, especially for dynamic use.

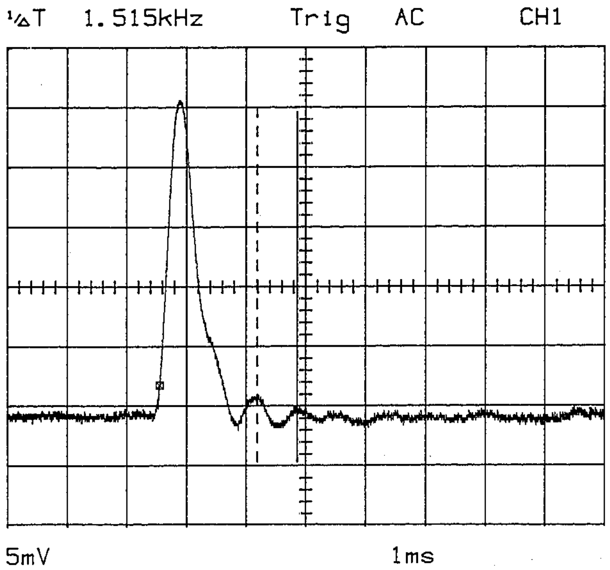


Plot 4.19 The Response of a Good Probe Mount

This probe mount is slightly better than the previous one from a natural frequency standpoint, but much better in terms of its damping; after only 1 cycle it is within 2 microinches of its initial position.

analyzer somewhat mitigates these requirements due to the analyzer's ability to discriminate exactly these sorts of signals; however, operation near resonance should be avoided altogether. Operation above resonance is possible, keeping in mind that the structure that resonates goes through a 180° phase shift and a large amplitude peak at resonance. This complicates measurements since the distance between the probe and the target may change significantly if measurements are made near resonance. If the driving frequency is high enough so the 180° phase shift is complete, the resonating structure begins to act as a mechanical filter. Finally, the probe holder will oscillate readily at exact integer multiples of the natural frequency and high frequency operation may excite vibrational modes other than the fundamental mode.

6) Curing probe holder problems such as described above is not a trivial task. In general, use short robust structures and design in some type of asymmetry like an off-axis hole. Symmetric structures resonate readily since their uniform geometric features facilitate the generation of standing waves. Also, use materials that have high internal damping. Cast iron is one of the best and some composite materials also exhibit this property. Also, pay attention to the other considerations mentioned in Section 2 such as electrical conductivity and good joint design.



Plot 4.20 The Response of a Very High Performance Probe Mount

A very high performance probe mount, in terms of both natural frequency and damping. A natural frequency of over 1500 Hz and very good damping allow the full performance of the Targa system to be used, even in mechanically noisy environments. Of particular note is the low amplitude of the natural frequency oscillation compared to the large amplitude of the impact. This mount is constructed of a short, thick-walled, ring structure with the joint surfaces ground flat to 10 microinches.

Plot 4.19 shows the response of a probe mount that is quite suitable for most situations. The mount has a reasonable natural frequency and very good damping. Plot 4.20 shows the response of a very high performance probe mount, suitable for the most demanding work.

Section 5.0

Dual Targa Applications

Section 5.0 Dual Targa Applications

The normal system described in Section 1 of this manual is a combination of 2 Targa capacitive sensor systems and a dual channel analog/digital storage oscilloscope. Such a combination can make many measurements a single channel system cannot make and the ability to process the sensor signals in unusual ways, such as a differential connection, further enhances the utility of this configuration.

Note: when using two Targas for combined measurements, both Targas must have the same sensor oscillator frequency. This is accomplished by connecting the "sync" signals together. See Figure 1.1, page 11.

Section 5.1 Axis of Rotation Applications

One of the major applications for this measurement system is the assessment of the quality of an axis of rotation. This is a very important parameter to be able to measure as civilization is intimately dependent on things that rotate. Some modern technologies such as machine tools, computer disk drives, jet engines, etc., are performance limited by the quality of their axes of rotation. With these considerations in mind, an American National Standard (ANSI/ASME B89.3.4m-1985) relating to axes of rotation has been developed and published. The standard contains a great deal of information and should be studied carefully. Some, but not all, of the information will be repeated here, but the emphasis of this manual will be on application of the Targa/Oscilloscope system to facilitate the measurements in the standard. The emphasis will be primarily on machine tool applications.

Section 5.1.1 Rotating Sensitive Direction Error Motion

An axis of rotation with a rotating sensitive direction is one where the tool rotates with the spindle as in a boring machine, a milling machine or a drilling machine. The dual Targa/Oscilloscope system can fully characterize both the synchronous and asynchronous error motions of such a spindle.

1) A probe holder is required that can mount the two probes in the same plane 90 degrees apart. All the usual considerations for probe holders still apply, and the 90 degree angle should be reasonably good, within 1 degree. The probe holder should be mounted right on the spindle housing if possible, otherwise one should strive for the shortest structural loop possible.

2) A "perfect workpiece" (usually a ball) should be mounted in the spindle. Some provision for adjusting the workpiece eccentricity with respect to the rotational axis should be made and this adjustment must have a rigid locking capability so as not to shift under rotational and vibrational influences. The geometry of the workpiece should be such that its errors are small compared to the expected measurements.

Fortunately, balls (grade 3) with errors in sphericity of less than 3 millionths of an inch are readily available.

3) Insure that the Targas have a common oscillator frequency. This is achieved by connecting the 'sync' terminals at the rear of the Targa. See Figure 1.1, page 11. Connect the output of one Targa to the CH1 input on the oscilloscope and the output of the other Targa to the CH2 input. Both oscilloscope inputs should be set to DC, the VERTICAL MODE switches should be set to BOTH, NORM, and CHOP.

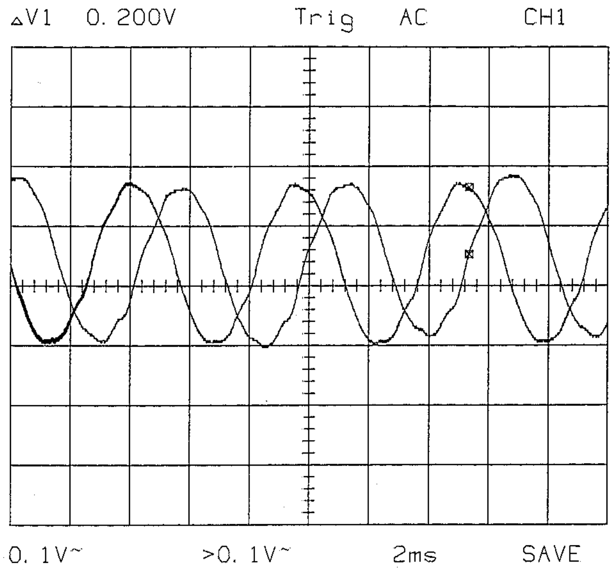
4) Turn on the system power by turning on the power strip switch. Insure that both Targas and the oscilloscope are turned on.

5) Using the digital meter on the Targa connected to CH1, bring the CH1 probe into the middle of the measurement range and adjust the eccentricity of the workpiece to a low value (i.e. center the workpiece reasonably well). The amount of eccentricity depends on the expected magnitude of the error motion and the system noise level and there is a trade-off between the two. If adjusted to a low value, error motion is magnified on the CRT but so is system noise. If set to a high value, the system noise is less apparent but the measurement sensitivity is low. A general rule of thumb would be to set the total indicated reading of the workpiece to about 4 times the expected measurement amplitude. In other words, if measurements on the order of 20 millionths of an inch are expected, adjust the eccentricity of the workpiece to about 80 microinches TIR. This allows a reasonable base circle to be displayed on the CRT while still retaining sufficient resolution to show the error motion. Then set the CH1 and CH2 VOLTS/DIV knobs so that 1 division is equal to the expected measurement value, which in this example, would be 20 mV/division (remember, the Targa transfer function is 1 microinch per millivolt). Also insure the eccentricity is symmetric about zero on the digital meter of the Targa. If not, reposition the probe so the middle LED on the linear range scale is lit and use the ZERO adjustment knob so the digital display indicates +/- 40 millionths at the extremes of the workpiece eccentricity.

6) Position the second probe so it is in the middle of the measurement range and use the ZERO knob to fine tune the output so the output is nominally zero with +/- 40 microinch excursions.

7) Rotate the spindle at the test velocity. The oscilloscope should display two waveforms on top of each other near the center of the CRT. See Plot 5.1. Use the VERTICAL POSITION KNOBS to separate the two waveforms. Each should be about 4 divisions peak to peak and one should lead the other by a quarter of a cycle. Adjust the SEC/DIV knob to display 1 or 2 cycles across the screen. Reversing the direction of rotation should cause the other waveform to lead by a quarter of a cycle. If no display is present, check to make sure the oscilloscope is triggering properly. The TRIGGER SLOPE should be _/¯ , the MODE should be P-P AUTO, the SOURCE should be CH1, and the COUPLING should be HF REJ.

8) Assuming the two sensors are producing traces on the CRT, turn the SEC/DIV knob to the extreme CCW position marked X-Y. The timebase sweep is



Plot 5.1 Plot of Two Probes, Mounted 90 Degrees Apart

disabled and the CH1 and CH2 input signals are routed, after amplification by the input amplifiers, to the horizontal and vertical deflection amplifiers for the CRT. A positive input to CH1 (X) will cause the electron beam that makes the CRT flouresce to move to the right (positive X direction in a normal Cartesian coordinate system); likewise a negative input to CH2 (Y) will cause the electron beam to deflect downward. The result of the changing sinusoidal waveforms being input to the X and Y channels is that the electron beam will trace out a roughly circular figure on the CRT. The degree of circularity depends on how close to a perfect sine and cosine the waveforms are. The 90 degree angle between the waveforms is established by the probe holder, and the workpiece form error is small compared to signals of interest. The Targa sensing is designed to reproduce these signals accurately and hopefully system noise (especially electrical noise) is low. The only remaining source to corrupt the perfect sine and cosine waves is the actual error motion of the workpiece i.e. it is not where it should be to produce perfect waves. The closed figure on the CRT is called a Lissajous pattern and the spindle error motion can be determined from it.

9) Once a Lissajous pattern is displayed on the CRT, use the CH2 VERTICAL POSITION and HORIZONTAL POSITION knobs to center it on the CRT. The CH1 and CH2 VOLTS/DIV knobs may be used to change the size of the Lissajous pattern but they should both be set to the same sensitivity. The spindle error motion value is equal to the difference in radii of two concentric circles that will just enclose the Lissajous pattern. The value obtained depends on the location of the common center of these two circles. There are 4 methods for locating the common center:

A) Minimum Radial Separation (MRS)
B) Least Squares Circle (LSC)
C) Maximum Inscribed Circle (MIC)
D) Minimum Circumscribed Circle (MCC)

The Axes of Rotation Standard (ANSI/ ASME B89.3.4M-1985) contains a complete section on each of these methods (Section A11, pages 28-31) and they will not be repeated here.

10) Once the center has been established, the CH1 and CH2 VOLTS/DIV settings determine the difference in radii of the two circles in millivolts. The error value is easily arrived at by remembering that the Targa transfer function is 1 microinch per millivolt.

11) Unfortunately, the Tektronix 2211 Oscilloscope cannot store in the X-Y mode. This means that the center must be established by one of the methods listed above and the error motion value estimated while the spindle is running.

12) There are many other artifacts of interest buried in the Lissajous pattern:

A) Transmission or gear noise: many machine tools have gearboxes to vary the speed and torque of the spindle over a wide range. These can affect the Lissajous pattern depending on what speed range the transmission is in. Gear mesh noise causes high frequency, low level signals to move around the main form of the pattern. If the numbers of teeth in mesh in the various speed ranges are known, a spectrum analyzer can look directly at the proper frequencies and measure their contribution to error motion. Also, gear mesh noise may exacerbated during acceleration and deceleration.

B) Spindle bearings: the rolling elements (balls, tapered, spherical or cylindrical rollers) rotate on their own axes as well as precess around the spindle axis at an angular velocity that is different than the spindle velocity. These effects are manifested in both high frequency signals (from rotation about element axes) and low frequency signals (from the elements precessing as a group) superimposed on the Lissajous pattern. These signals are less affected by spindle acceleration and deceleration than is the gear mesh signal. However, if angular acceleration is high enough, the rolling elements may skid or slide rather than roll, resulting in anomalous signals. Also, centrifugal loading in the bearings caused by very high speed might change the effective preload on the bearings and alter the error motion Lissajous pattern.

C) Imbalance: imbalance will cause a change in the size of the Lissajous pattern as a function of spindle speed. The pattern may get larger or smaller depending on where the imbalance is with respect to the line connecting the axis of rotation and the center of the workpiece. The amount that the size changes as a function of speed depends on how linear the stiffness of the spindle is. Rolling element spindles are not very linear; hydrostatic spindles are generally relatively linear.

Section 5.1.2 Fixed Sensitive Direction Error Motion

A machine tool with a fixed sensitive axis error motion is one where the tool is fixed or does not rotate with the rotational axis. An example of a fixed sensitive axis machine is a lathe or turning machine. In such a machine, only relative motion between the tool and the workpiece, in the direction of the tool, contributes significantly to part size or geometry error. Error motion of the spindle that is perpendicular to the tool has little effect on the size or geometry of the part. A computer disc drive, with its fixed head positioning mechanism, should be considered a fixed sensitive direction application. In general, the probe should replace the tool i.e. be mounted in the same position, for meaningful results to be obtained. A single probe at the tool position and some means for generating the base circle on the oscilloscope are required to make polar plots. However, the 2 channel Targa/Oscilloscope system cannot make fixed sensitive direction polar plots without some auxiliary equipment. Either a third channel, some base circle generating cams, and some additional analog electronics are required, or some sort of spindle position sensor (e.g. encoder or resolver) and a digital computer are required to achieve proper results. See ANSI/ASME B89.3.4M-1985 Sections A14 through A16, pages 32-35 for a more in-depth discussion of this situation. Also, see Addendum A (p. 83-89) for additional discussion.

Section 5.1.3 Asynchronous Error Motion

Asynchronous error motion is the deviation of the total error motion polar plot from the average error motion polar plot. In other words, it represents the revolution to revolution variance of the spindle from its position as determined by an average over many revolutions. To make asynchronous error motion value measurements, operate the spindle at the test velocity and set the oscilloscope to produce the Lissajous pattern. Then, draw an imaginary line from the center of the Lissajous pattern at any angle through the Lissajous pattern. Over many revolutions record the extreme values at this one angle. Do the same for several different angles. The maximum radial value minus the minimum radial value found at any angle represents the asynchronous error motion value. This value represents the peak to peak surface finish that the machine is capable of just as the error motion value represents the potential part geometry or roundness. See ANSI/ASME B89.3.4M-1985, Sections A7.2 and A7.3, pages 20-23, for additional information on the application of this information. Also, see Section A11.5, page 31 for information on choosing the correct center in the polar error motion plot for high accuracy measurements.

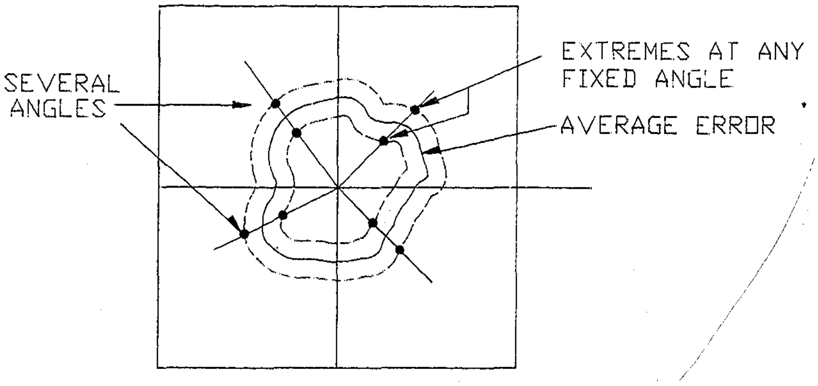
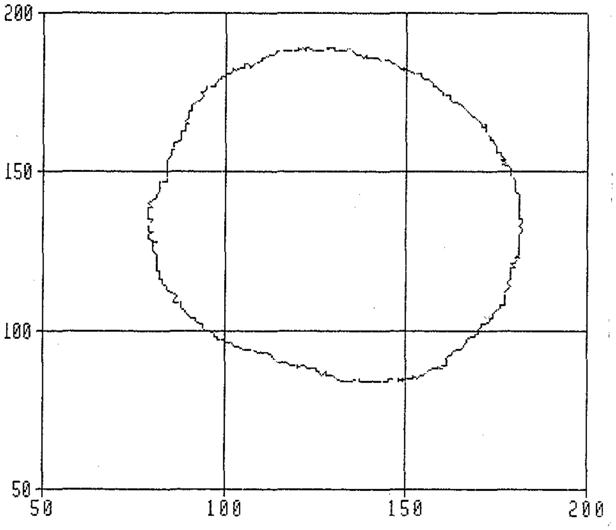


FIGURE 5.1 Asynchronous Motion Value Determination



PLOT 5.2 Typical Lissajous Pattern

Section 5.2 Quasi-Differential Measurement

The availability of two measurement channels from the Targa instruments combined with the ability of the oscilloscope to "subtract" CH2 from CH1, allows the possibility of making differential measurements. Differential measurements are measurements where one is interested in the difference only, and not the actual value of, two signals. The difference between the signals is usually small compared to the signals, or there may be noise or drift present. Processing signals this way yields many benefits, mostly in the areas of improved sensitivity (usually a factor of 2) and reduced influence of noise and drift. The drawbacks are the requirement of two sensors for a single measurement (although this is not always true) and more complicated electronics.

This section is titled `Quasi-' because while the oscilloscope can be configured to subtract one signal from another, it does not do a particularly good job of subtraction when compared to systems specifically designed for differential measurements. The term "true" differential system will be used for a system specifically designed to have excellent performance when making differential measurements. When making differential measurements, one is concerned with measuring only the difference between the signals, regardless of the actual value of the signals themselves. Thus, a true differential system with two inputs of 2.000 volts and 2.001 volts would have an output of either -0.001 volts or 0.001 volts (depending on which signal is subtracted). The same true differential system would have the same output if the inputs were 5.237 volts and 5.238 volts or -11.713 volts and -11.714 volts.

The output is the difference between the signals irrespective of the signals themselves. The (usually large compared to the difference) signal that accompanies the two signals, is called the common-mode signal or value. A true differential system has the property of eliminating or rejecting this common mode signal. No system is perfect and a small amount leaks through to corrupt the measurement slightly. A well designed differential system would reject or reduce the effect of the common mode signal by a factor of perhaps 100,000. This means that, in the original example above, the true difference would be 0.001 volts and the common-mode error would be 2 volts (the common-mode signal) divided by 100,000 (the common-mode rejection ratio) or 0.000020 volts. Therefore, the output of the differential system would be between 0.000980 volts and 0.001020 volts when the exact difference is 0.00100 volts, for an error of about 2% of the difference value. There is not enough range on the oscilloscope screen when the input signals are in the two volt range and the sensitivity (VOLTS/DIV) is set high enough to discriminate a 0.001 volt difference, or to even display the signals.

For all differential systems, the ability to reject a common mode signal is best at DC and low frequencies. The common-mode rejection ratio degrades as the common-mode signal frequency increases. This means that a differential system can reduce one of the most pervasive of system noises: 60 Hz powerline noise. This can be done because the 60 Hz signal generally appears in both sensors with approximately the same amplitude (if component layout is symmetric and antenna loop area is similar, etc.) and at the same time (because of the single source) so it is a common-mode signal and is rejected. If one were interested in a 15 millivolt differential signal where the 60 Hz noise on the two channels is 105 mV and 107 mV respectively, the 15 mV signal would have only 2 mV of 60 Hz noise when displayed differentially. The same signal would be unmeasureable if the 60 Hz noise was present during a single channel measurement. Any signal that affects both sensors simultaneously, even if it is not electrical in origin, such as thermal drift or vibration, is a common-mode signal and thus reduced by the common mode rejection ratio at the frequency of the signal. As was stated previously, the higher the frequency of the common signal, the lower the common-mode rejection ratio and the less effective the system is at reducing the signals effects.

Unfortunately, general purpose oscilloscopes are not designed to be "true" differential measuring systems. Such instruments have a low common-mode rejection ratio at DC and degrades rapidly as the common-mode signal frequency increases. In addition, if the common-mode voltage is high and the desired measurement sensitivity is high (e.g. measuring 0.001 volt difference with a 5 volt common-mode signal), the oscilloscope input amplifiers may saturate or operate in a nonlinear fashion, causing erroneous results. The moral here is to adjust the probes or the offset adjustment on the front panel of the Targa to keep the outputs near zero volts. This minimizes the common-mode signal. Also, don't depend on significant rejection of common-mode signals with frequencies above 150 Hz. The Tektronix 2211 oscilloscope used in this manual has a common mode rejection ratio of about 100:1 at 150 Hz for a 500 mV p-p sine wave input to both channels. Any significant common mode voltage (i.e. 100 mV) seriously compromises this value. Oscilloscope manufacturers do not generally specify the common mode rejection ratio of general purpose oscilloscopes. For these reasons, the oscilloscope may be considered a "quasi-differential" measuring device, unless fitted with special provisions for differential measurements. Technically, the oscilloscope can make the measurements but they are subject to relatively severe restrictions, and should be made with those restrictions firmly in mind.

Section 5.2.1 Tilt Error Motion of an Axis of Rotation

Tilt error motion of an axis of rotation is one of the most common measurements made using two probes in the differential mode. The measurement can be made by placing the probes so they measure on the face of a perfect workpiece or by placing the probes so they look at the radial motion at two locations along the axis of rotation. See Section A6 and Figure A8 in ANSI/ASME B89.3.4M-1985 for additional information on nomenclature and probe placement. In either case, the difference signal is displayed on the oscilloscope, and the value at any point must be divided by the distance between the probes. The result will be the instantaneous tilt error, given in radians. To convert radians to arcseconds, multiply the radian value by 206,265. Multiply the radian value by 57.296 to convert to decimal degrees. For example, if a differential signal at a particular spindle angle has a value of 410 microinches (.000410 inches) and the separation between the probes is 2.5 inches, the instantaneous tilt is .000410/2.5 = 164x10-6 radians or 164 microradians. This is equal to .00940 degrees or 33.8 arcseconds.

Obtaining a stable display when making differential tilt error measurements can be tricky. The most reasonable method is to adjust the time base until one full sweep across the oscilloscope screen is equal to one complete revolution. This can be done by using the SEC/DIV knob and the CAL knob that is coaxial with the SEC/DIV knob. The SEC/DIV knob sets discrete sweep rates and the CAL knob allows sweep rates between the discrete rates. Alternatively, an external trigger signal (from an index mark on an encoder or a reflective photosensor, for example) can be input into the EXT INPUT connector in the trigger section. The second method is superior to the first but requires additional hardware.

Section 5.2.2 Straightness

Two probe differential measurements for straightness are superior to single probe measurements (See Section 4.2.1) because differential measurements are sensitive to rotation (angular motion), but not to translation, of the instrumented axis. This allows separation of translation (seen with either of the two probes used as a single channel measurement) from angular error motion. The set-up is the same as a single channel straightness measurement except the second probe is mounted some distance from the first probe. Either probe is used to measure the translation and the two are used differentially to measure the angular motion. As in the previous section, a single value at any axial position of the axis will be obtained from the difference between the two probes; this value must be divided by the distance separating the probes to yield the angular motion in radians. The conversion factors listed in the previous section for conversion of radians to degrees or arc seconds also apply when measuring straightness.

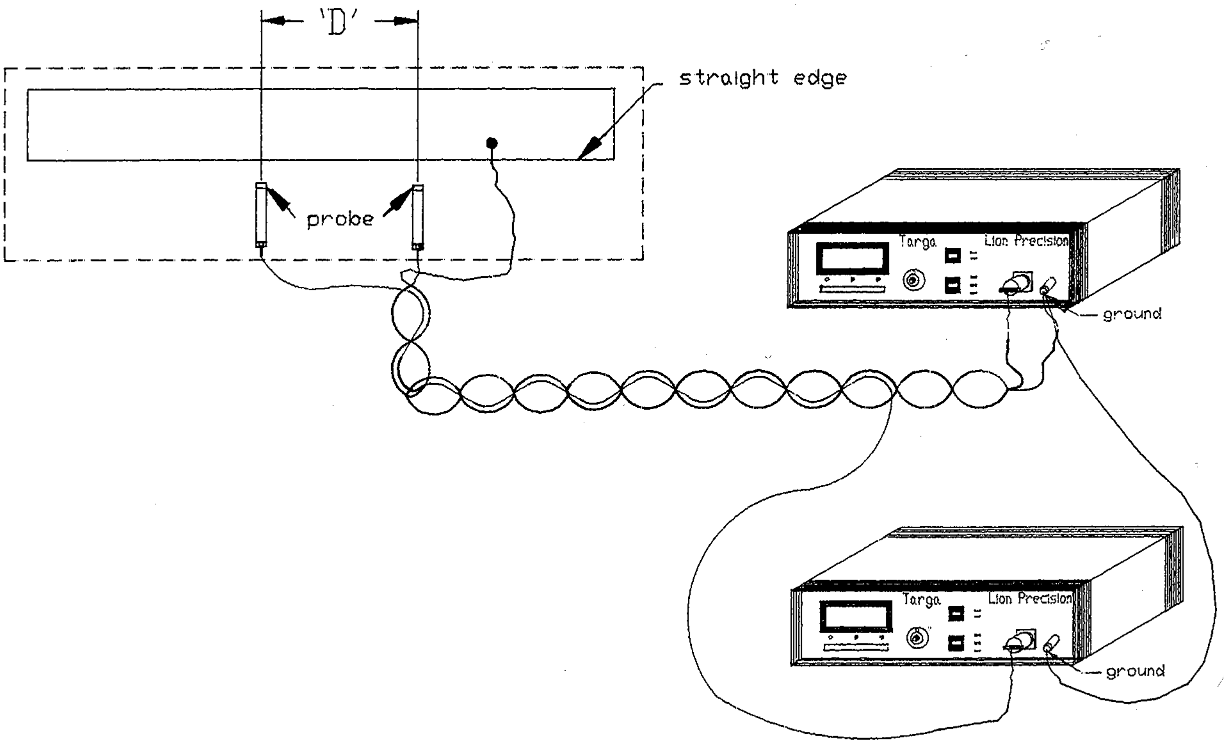


FIGURE 5.2 Straightness Measurement Using 2 Probes

Section 5.3 Multi-Axis Applications

Multi-axis applications of single channel measurements are possible because of the two probes, signal conditioning electronics, and oscilloscope with two input channels. The set-ups are identical to the single channel except that two probes are used and the measurement result in one direction is compared to the measurement result in the other direction. A typical application and some brief comments will be given in four different areas.

Section 5.3.1 Multi-Axis Position Repeatability

A typical application would be an X-Y machine tool slide such as a milling machine or a lathe. In these machines, one axis usually has quite a bit more travel than the other axis. The long travel axis has a long ballscrew and quite possibly more friction than the short axis. The lower torsional stiffness of the long ballscrew combined with the extra friction conspire to reduce the positioning performance of the long axis. This situation could be evaluated by making subsequent single channel measurements, but it is more time effective to make a single two-channel measurement. For the example of a milling machine, the two probes are mounted on the table in the directions of the two axes. A target (e.g. precision ball or gage pin) is mounted in the spindle and the spindle moved into position so the two probes sense the target. The probes are arranged so they are coplanar in the Z-axis and their axes intersect the spindle axis.

The spindle is moved away from the setup position and commanded to return to "home" or zero several times. The variations are recorded and analyzed as in the single channel method.

Section 5.3.2 Multi-Axis Settling Time

For the same reason as the previous section, (torsional stiffness and friction) the settling time of the short axis may be more rapid than the long axis. Also, since nearly all CNC controls are serial processors (i.e. doing all the calculations for one axis and updating it, then doing the same thing for the next axis, etc.) it might be possible for one axis to actually be commanded to stop before another, even though these events are thought to be simultaneous by the user. Knowledge about a machine tool in this regard might cause a user to orient a part in a particular way on the machine tool to take advantage of the higher performance axis.

The setup is exactly the same as in Section 5.3.1. The oscilloscope should be used in the digital storage mode and the trigger properly set (see Section 4.2.3). The spindle is moved away from the probes, the oscilloscope trigger is reset, and the machine tool is commanded to return to zero. This test might also be done with an application program rather than the instrinsic machine function. Swapping the X axis and Y axis command line positions in the application program should reveal the axis processing sequence.

Section 5.3.3 Multi-Axis Vibration

Multi-Axis vibration analysis is useful when there is the possibility of significant vibration in a particular direction and it is important to characterize the effect of this vibration on the system in a different direction. A useful example would be a machine with a hydraulic cylinder driving an axis where pressure pulsations from the hydraulic pump cause motion (vibration) along the axis of the cylinder. A user might wish to characterize the effect of this pulsation in the direction perpendicular to the cylinder, thereby establishing the effect on, for example, surface finish. One can set up two probes, one parallel to the axis, and the other normal to the axis and directly measure the motions in the two directions.

The component of the normal signal that is at the same frequency as the vibration signal on the other channel is the response in the normal direction to the parallel direction excitation. To get a reliable measurement, be sure the oscilloscope is triggering on the parallel axis vibration signal, which is roughly sinusoidal and uniform in frequency.

Many other set-ups are possible and of course the angle between the probes is not restricted to 90 degrees. For example, Section 5.7.3.2 of the B5.54 standard describes using five probes to characterize five of the six degrees of freedom of an axis of rotation.

Section 5.3.4 Multi-Axis Thermal Growth

Multi-Axis thermal growth or distortion is simply the set-up and use of two probes rather than one as in Section 4.3. The advantage of using two probes is the additional information gained from instrumenting two dimensions or axes simultaneously. Such a set-up can provide deeper insight to machine distortions during thermal transients or during warm-up. Combining 2-D thermal distortion data with a system assembly diagram may help point out asymmetric thermal paths, poor thermal joints, etc., that can contribute to machine tool performance variations.

Section 6.0

Capped Probe and Calibration Tests

Capped probe tests for noise and thermal stability demonstrate system performance under very closely controlled conditions. They are useful for determining the performance suitability of a capacitive position sensing system for a given measurement task, and can also be used to measure the influence of external noise sources on the measuring system.

Section 6.1.1 Capped Probe System Noise Test

The noise test is used for determining both the minimum noise level the system is capable of achieving and also to determine the susceptibility of the system to external noise. The external noise is usually electrical in nature and consists of both radiated and conducted noise. The test is quite simple in that the probe tip is covered with a cap that simulates a target but also shields the measurement electric field from any external sources. The cap must be a very low expansion metallic material like Invar. The engaged length of the cap on the sensing end of the probe should be as short as possible to minimize thermal growth. See Figure 6.1.

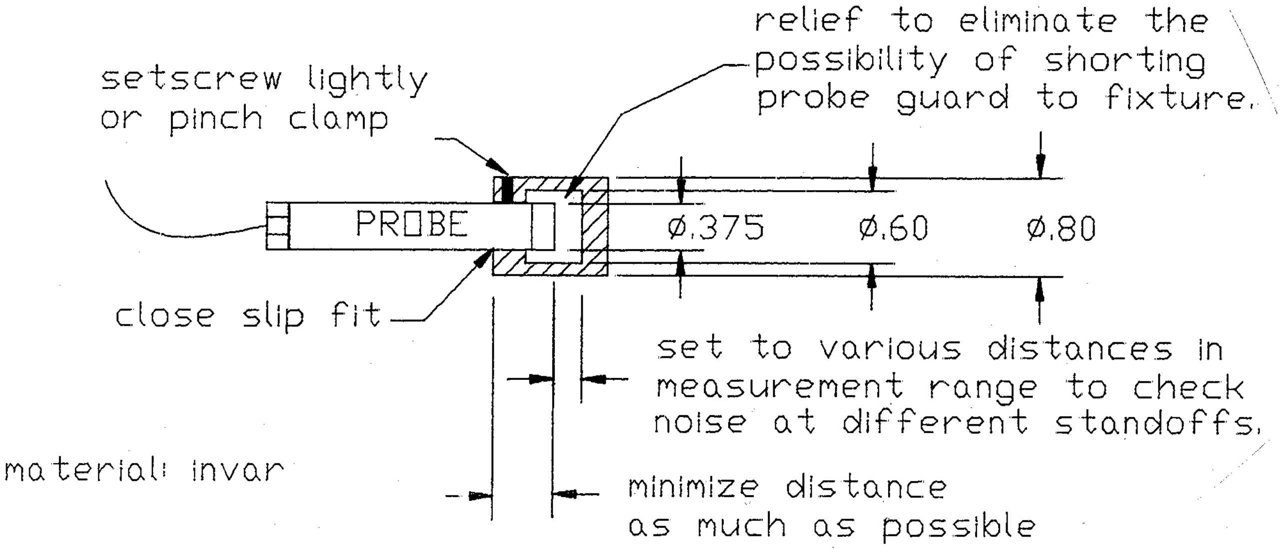


FIGURE 6.1 Probe Cap Fixture

Once the measurement electric field is fully contained by such a structure, the measurement can no longer be affected by any external influence and all remaining signal aberrations are either the result of noise in the system electronics that is independent of the measuring process or external noise that the system picks up. The oscilloscope sensitivity is then set to maximum by setting the CH1 and CH2 VOLTS/DIV knobs to 5 mV/ division and pulling out the 'CAL' knob. This increases the vertical sensitivity to 0.5 MV/ DIV or 0.5 millionths of an inch per vertical division on the oscilloscope CRT. The width of the trace indicates the system noise level. For reliable measurements, the actual signals must be at least 3 times (preferably 10 times) larger than the system noise level. Also, the influence of external electrical noise sources (motor controls, welders, 60 Hz noise, etc.) can now be determined by simply turning on the offending device and noting the change. 60 Hz noise can be examined by setting the TRIGGER SOURCE to LINE.

Note: The specified Targa/oscilloscope system noise level with capped probes in an electrically quiet area is 2 mV.

Section 6.1.2 Thermal Stability Test

The capped probe test can also be used for testing thermal stability of the probe, the Targa or the TEK 2211, or any to them in any combination. The probe, for example can be tested for thermal stability by capping it and placing it in an environmental chamber. The temperature of the probe is varied and the change in Targa readings is recorded as a function of temperature. The Targa or the oscilloscope can be subjected to the same test, provided the environmental limits of the instruments are not exceeded. Maximum operating temperatures are as follows:

Probe:	250 degree F
Targa:	110 degree F
TEK 2211:	93 degree F

Section 6.1.3 Probe Calibration Check

Occasionally, it is helpful to rapidly establish whether or not the Targa system is operating correctly and generally calibrated. A fixture is available in which the probe can be quickly mounted and its operating characteristics determined. See Figure 6.2.

The Calibration Check Procedure is as follows (NOTE: THIS IS <u>NOT</u> A CALIBRATION):

1) Set the fixture to zero.
2) Connect a digital voltmeter to the output coaxial cable from the back of the Targa using the BNC - double banana connector supplied with the calibration fixture. Insure the ground side of the connector (identified by the GND tab) goes in the LO or COM port on the voltmeter. Set the voltmeter to read DC volts.
3) Mount the probe and adjust it so the position indicator on the Targa front panel is in the mid range.

4) Adjust the Targa front panel ZERO knob so the Targa display reads 0.000.

5) Insure that the rear panel "scale" switch is set to "THOUS" and move the target toward the probe 0.002 inches by turning the spindle on the check fixture.

6) The front panel display should read approximately 2.000 and the digital voltmeter should read the same value as on the front panel display, within 1 mV.

7) Move the target .004 inches away from the probe by turning the check fixture spindle in the opposite direction.

8) The front panel display and the digital voltmeter should both read approximately -2.000.

9) Reset the check fixture to zero. Both the front panel display and the voltmeter should read about zero.

10) Successful completion of steps 5-9 indicates that the probe is operating correctly and is generally calibrated.

Note: The oscilloscope can be used in place of the digital voltmeter if the input channel connected to the system being checked has its coupling set to DC. The trigger source should be set to CH1 or CH2, corresponding to which Targa/probe is being checked, and best results will be obtained by setting the trigger MODE to P-P AUTO. As the target is moved with respect to the probe, the trace on the oscilloscope CRT should move up when the front panel display indicates positive values and down when the display indicates negative values.

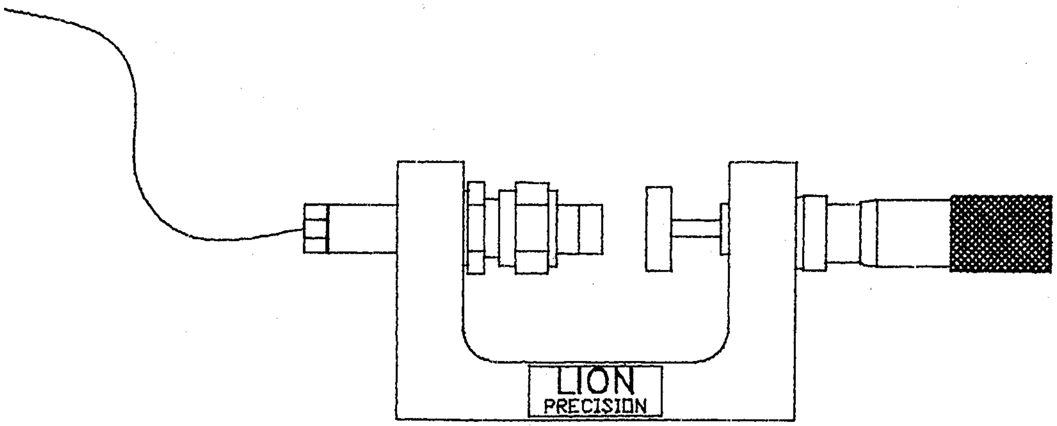


FIGURE 6.2 Probe Calibration Check Fixture

Section 7

Reversal Techniques for Separating Workpiece Form Error From Spindle or Slide Error Motion

Section 7 Reversal Techniques for Separating Workpiece Form Error From Spindle or Slide Error Motion

Occasionally, it might be necessary to characterize a spindle or a slide with a less than perfect workpiece. This is especially true for slides when their error motion is measured using a straightedge. High quality balls and pins with form errors approaching 1 microinch are readily available at a surprisingly modest cost. High precision straight edges, especially ones whose lengths are more than 12 inches, are another matter entirely. Fortunately, there is a technique that is applicable to both spindles and slides that allows the form error of the workpiece to be separated from the error motion of the spindle or slide. All that is required is two sets of data and some simple mathematics. This technique is called the Reversal Method and was described by Bob Donaldson of Livermore National Laboratory in 1972. This method is sometimes referred to as the "Donaldson Reversal Method."

Section 7.1 Reversal Method for an Axis of Rotation

The procedure is completely explained in Appendix B of ANSI/ASME B89.3.4M-1985. Please read Appendix B before proceeding with this section. In that explanation, the use of a polar chart for graphical interpretation of the data is used. Since the Targa system cannot make overlapping polar charts, the best that can be done is to collect the data at as many angular positions as is deemed reasonable for accuracy, do the calculations at each angular position, and hand plot if required. An example follows:

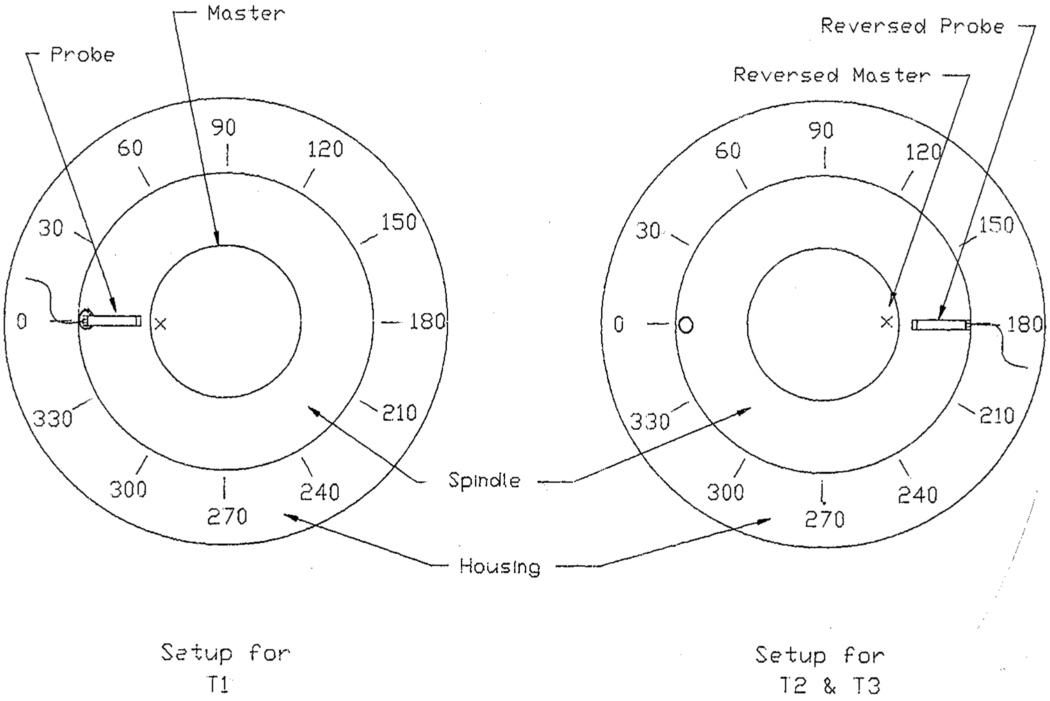


FIGURE 7.1 Reversal Method for a Rotary Axis

1) Mount the workpiece on the spindle and center it as close as possible. While it is not necessary to center the workpiece, it is good practice to do so because most transducers (whether they are capacitive in nature or use some other phenomenon to sense displacement) are not perfectly linear over large excursions. Reducing the transducer excursion to a minimum enhances the measurement reliability.

2) Mark the spindle, housing, and workpiece as shown in the setup for T1. (Different angular steps may be used if a different number of data points is desired).

3) Position the probe as shown in the setup for T1 and adjust it so the front panel bar graph is mid-range. Use the ZERO knob to set the front panel display to zero when the spindle position pointer is at zero.

4) Record the Targa front panel reading at each of the desired angular positions. Insure that the Targa reads zero or very close to it when the position pointer comes around to zero again. If it does not read zero, the spindle probably has some degree of asynchronous error motion. See Section B4, page 41, ANSI/ASME B89.3.4M-1985 for further information on this problem. The only solution is to record readings at each position over several (e.g. 10) revolutions and average them to get the calculation value (T1) at each position.

5) Rotate the workpiece 180 degrees on the spindle and recenter it. See setup for T2 and T3. Also move the probe 180 degrees so it still senses against the marked point on the workpiece when the position pointer is at zero. It is important that the probe be at the same height on the workpiece in both locations. The probe must sense the same circumferential track on the workpiece in order to produce good results.

6) Adjust the probe so the Targa front panel reads as close to zero as possible. This insures that the same region of the probe sensing range is used.

7) After adjusting the probe position to as close to zero as possible, use the front panel ZERO knob to set the display to zero when the position pointer is at zero.

8) Rotate the spindle and record the Targa display value at each angular position. This is the T2 value. Again, if the spindle exhibits asynchronous error motion (readings don't repeat over consecutive revolutions at any particular position) record values at each position over several revolutions and average them at each position to arrive at the calculation value for T2.

9) Construct another column with values identical to T2 but with the opposite sign and label the column T3.

10) The out of roundness (P) of the workpiece at any angular position is equal to 1/2(T1+T2) and the spindle error motion (S) at any position is 1/2 (T1+T3).

Example Data

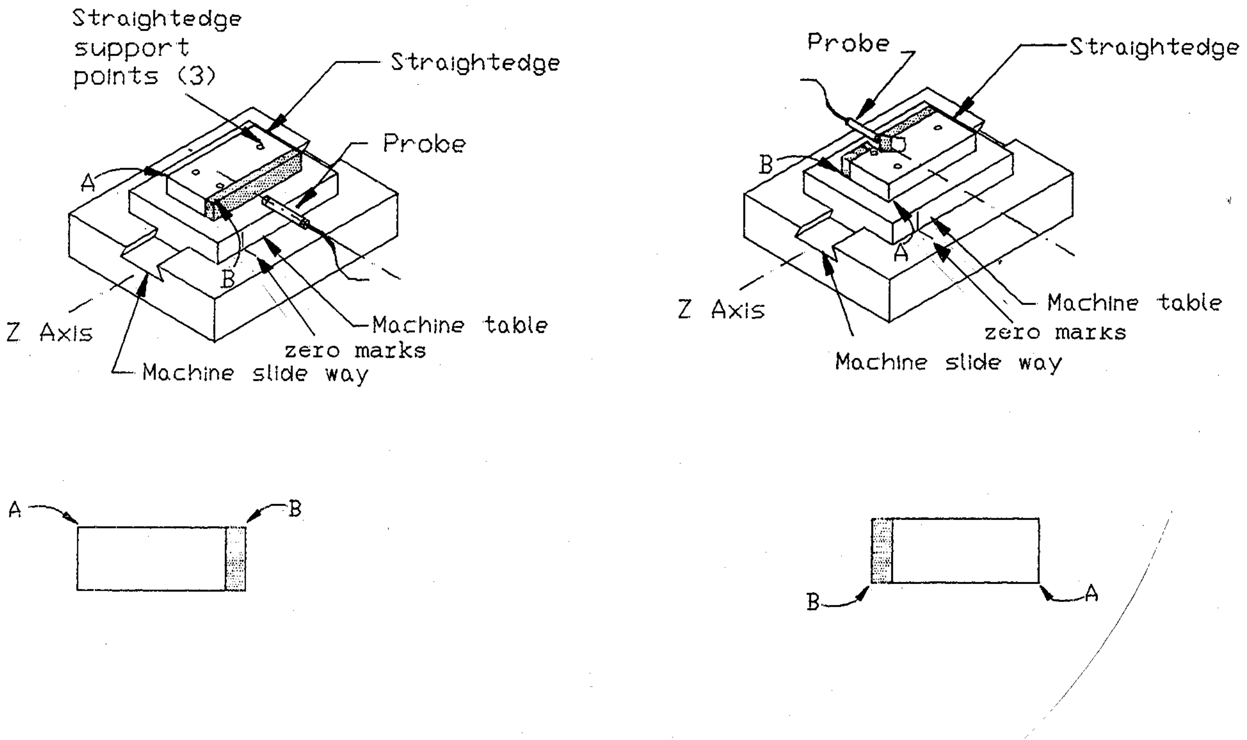
Position	T1	T2	T3	P	S
0	.000	.000	.000	0	0
30	.004	-.003	.003	.5	3.5
60	.006	-.007	.007	-.5	6.5
90	.007	-.002	.002	2.5	4.5
120	.005	.001	-.001	3.0	2.0
150	.008	.005	-.005	6.5	1.5
180	.009	.007	-.007	8.0	1.0
210	.011	.002	-.002	6.5	4.5
24	.007	-.003	.003	2.0	5.0
270	.006	-.004	.004	1.0	5.0
300	.004	-.003	.003	.5	3.5
330	.003	.002	-.002	2.5	.5

Note: The data (T1, T2,) are recorded directly from the Targa display, which displays millivolts when the rear panel scale switch is in the "THOUS" position. In this mode, 1 millivolt equals 1 microinch, so T1 and T2 are measurements in millionths of an inch. P and S are calculated directly in millionths with the decimal point and leading zeros that appear in T1, T2, and T3, removed.

11) The P and S data could be graphed in polar form similar to the diagrams shown on page 40, Figure B2, ANSI/ ASME B89.3.4m-1985. The individual data points from the data reduction chart would have to be connected by straight lines from consecutive angular positions on the polar chart. If a large number of points (e.g. 50) were taken, the hand plotted polar chars would look pretty reasonable.

Section 7.2 Reversal Method for a Linear Axis

Conceptually, the Reversal Method for slides is identical to the method for spindles. However, the fact that the straightedge does not close on itself like a circular workpiece does, and the possible error involved in positioning the probe when the straightedge is reversed require a slightly different procedure to obtain good results. As with the spindle procedure, two set-ups are required.



The probe must sense on exactly the same region of the straightedge, both vertically and along the axis of travel during both set-ups

FIGURE 7.2 Reversal Method for a Linear Axis

1) Mount the straightedge on the slide. While the straightedge reference surface does not have to be parallel to the axis of travel, it is good practice to adjust the straightedge so it is parallel to the axis of travel for the same reasons as stated in the previous section.

2) Mount the probe so the axis of the active area is at the vertical mid-point of the reference area on the straightedge. Adjust the probe stand off until the range bar graph on the Targa front panel is lit at the middle. Use the ZERO knob to set the Targa display to zero. Be sure the slide is at the "zero" position and the probe is at the zero on the straight edge.

3) Record zero at the zero slide position and record the Targa front panel reading as often as desired for as long a distance as desired. This data will be T1 for Trace 1. Several sets of data should be taken at each position to ascertain the repeatability of the slide. This is identical in principle to the problem caused by asynchronous error motion in spindles, although no equivalent term for slides exists. The actual recorded value at each position should be the average of all the data at that position. When returning the slide to the zero position to start a new trial, be sure and move the slide past zero, reverse it, and bring it back to zero, to take out any backlash in the drive system, unless, of course, the effect of backlash is being measured.

4) Turn the straightedge upside down on the slide by rotating the straightedge about its axis that is parallel to the axis of travel. The reference surface is now 180 degrees from where it was in step 3 but it is still parallel to the axis of travel.

5) Adjust the straightedge so it is parallel to the axis of travel. Insure that the slide position is at zero and move the probe to the opposite side of where it was mounted for step 3, so that the probe senses against the same straightedge reference surface.

6) Adjust the probe mount vertically so the probe senses the mid-point of the straightedge, and horizontally in the direction of travel so the probe lines up with the straightedge zero mark. It is critical to the Reversal Method that the probe sense exactly the same region in both set-ups.

7) Adjust the probe standoff to as close to zero as possible and use the ZERO knob on Targa to set the digital display to exactly zero.

8) Record zero at the slide position zero and then move the slide to the same positions as in step 3 and record the Targa display value at each position. Label this data T2.

9) Construct a third column of values for each position by using the same value as T2 but with opposite sign.

10) The straightedge error (P) and the slide error (S) are calculated at every position by the same equations as for spindles, i.e. P = 1/2(T1+T2) and S = 1/2 (T1+T3).

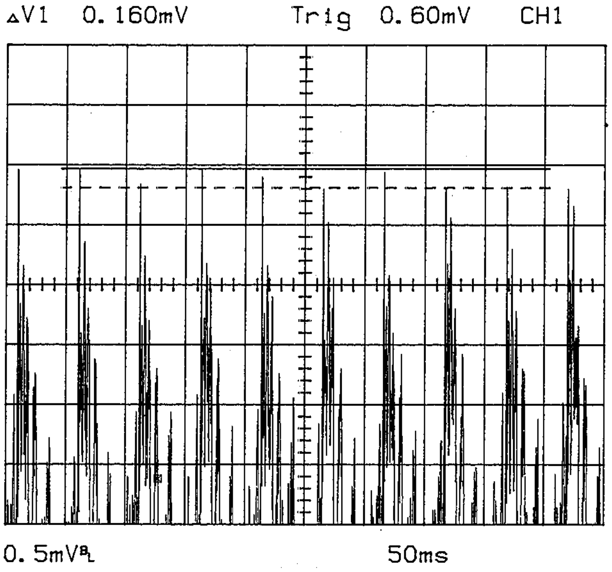
	T1	T2	T3	P	S
0	.000	.000	.000	0	0
1	.009	.006	-.006	7.5	1.5
2	.013	.002	-.002	7.5	5.5
3	.011	-.004	.004	3.5	7.5
4	.006	.001	-.001	3.5	2.5
5	.001	-.003	.003	-1.0	2.0
6	-.004	-.006	.006	-5.0	1.0
7	-.011	-.010	.010	-10.5	-.5
8	-.013	.003	-.003	-5.0	-8.0

Section 8

Epilogue

Epilogue

With a thorough understanding of the principles of probe mount design, grounding and shielding, electrical and structural noise, and the concepts and terminology of machine tool performance assessment, one can push the Targa system to its very limits. Plot 8.1 shows the asynchronous error motion of a 4 inch air bearing spindle at .16 microinches over 9 consecutive revolutions. The spindle performance is actually better than this since the signal on the plot is the sum of all the affects listed above. It is not possible to characterize the exact asynchronous error motion of the spindle but it can be confidently stated that the asynchronous error motion is less than .16 microinches. Capacitance sensing approaches the performance of the highest resolution devices available (tunneling and atomic force microscopes) at a fraction of the cost, with much greater potential utility (in the machine tool environment), and far less sensitivity to abuse and other environmental factors.



Plot 8.1 Asynchronous Error Motion of an Air Bearing Spindle

Asynchronous error motion of a Professional Instruments Model 4R Blockhead® Air Bearing Spindle. The oscilloscope vertical sensitivity is increased to .5 millivolts per division by pulling out the CAL knob on the CH1 VOLTS/DIV switch. The system sensitivity is then .5 millionths per division. The asynchronous error motion is .16 microinches.

Section 9

References, Associated Standards and Sources of Information

Section 9.1 Related Standards

Axes of Rotation Methods for Specifying and Testing	B89.3.4M-1985
Measurement of Out of Roundness	B89.3.1-1972(R1988)
Temperature and Humidity Environment for Dimensional Measurement	B89.6.2-1973(R1988)
Methods for Performance Evaluation of Computer Controlled Machining Centers and Work Centers	Draft ASME B5 TC52

Section 9.2 Related Books, Articles, and Information

Blaedel, K. and Bryan, J., "Tutorial on Thermal Effects," Presented at 1990 Annual Meeting of the American Society of Precision Engineering.

Bryan, J., and Carter, D., "How Straight is Straight," American Machinist, Vol. 133, No. 12, December, 1989.

Bryan, J., Clouser, R., Holland, E., "Spindle Accuracy," American Machinist Spec. Report No. 612, 1967.

Bryan, W.J. "Construction of a Diamond Turning Machine," 1978.

Donaldson, R., "A Simple Method for Seperating Spindle Error from Test Ball Roundness Error," CIRP Annals, Vol. 21 21/1, 1972.

Hocken, R. J., "Technology Machine Tools: A Survey of the State of the Art by the Machine Tool Task Force - Volume 5: Machine Tool Accuracy," October, 1980.

Lion, K. and Foldvari, T., "Capacitive Transducers," Instruments and Control Systems, November, 1964.

Martin, D., "Application of Precision Capacitive Displacement Sensors," Session 302A-1, Proceedings of the Sensors Expo, 1989.

Martin D. and Wilcox, R., "Spindle Runout Effects on Positional Accuracy," Presented at the University of Wisconsin 'Symposium on Small Hole Technology,' February 22, 1990.

Rolt, F. H., Gauges and Fine Measurements, Macmillan and Co., 1929.

Moore, W.R., Foundations of Mechanical Accuracy, Moore Special Tool Company, 1970.

Schlesinger, G., Testing Machine Tools, Machinery Publishing, 1938.

Tlusty, J., "System and Methods of Testing Machine Tools," Microtecnic, Vol. XIII, 1959.

Wilcox, R., "Dynamic Measurement of High Speed Spindle Runout," Printed Circuit Fabrication, Volume 12, No. 3, March 1989.

Wilcox, R., "New Developments in Dynamic Spindle Runout Measurement," IPC TP-844, Published by IPC, Institute for Interconnecting and Packaging Electronic Circuits, September, 1989.

Section 9.3 Organizations

American Society of Mechanical Engineers (ASME)
United Engineering Center
345 47th Street
New York, NY 10017

American National Standards Institute (ANSI)
105 - 111 South State Street
Hackensack, NJ 07601

American Society for Precision Engineering (ASPE)
401 Oberlin Road, Suite 108
P.O. Box 10826
Raleigh, NC 27605-0826

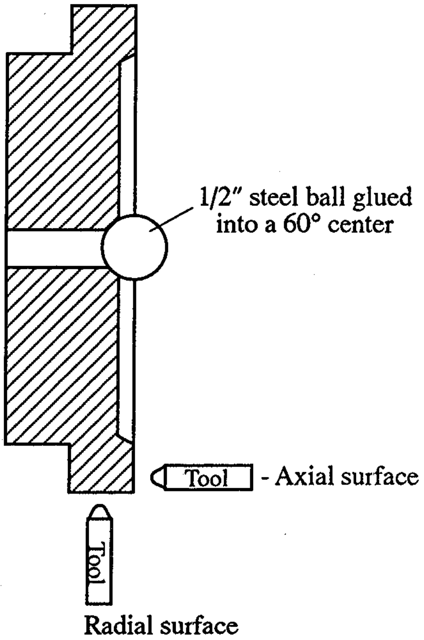
Addendum A

Fixed Sensitive Direction Error Motion

Addendum A Fixed Sensitive Direction Error Motion

As discussed in Section 5.1.2, a machine tool with a fixed sensitive axis error motion is one where the tool is fixed or does not rotate with the rotational axis. An example of a fixed sensitive axis machine is a lathe or turning machine. In such a machine, only relative motion between the tool and the workpiece, in the direction of the tool, contributes significantly to part size or geometry error. Error motion of the spindle that is perpendicular to the tool has little effect on the size or geometry of the part. A computer disc drive, with its fixed head positioning mechanism, should be considered a fixed sensitive direction application. In general, the probe should replace the tool i.e. be mounted in the same position, for meaningful results to be obtained. A single probe at the tool position and some means for generating the base circle on the oscilloscope are required to make polar plots. However, the 2 channel Targa/Oscilloscope system cannot make fixed sensitive direction polar plots without some auxiliary equipment. Either a third channel, some base circle generating cams, and some additional analog electronics are required, or some sort of spindle position sensor (e.g. encoder or resolver) and a digital computer are required to achieve proper results. See ANSI/ASME B89.3.4M-1985 Sections A14 through A16, pages 32-35 for a more in-depth discussion of this situation. Still, the two channel Targa system can provide a fair amount of information about the performance of a fixed sensitive direction spindle utilizing a "Test of Consequences." Jim Bryan coined this term to describe the well-known fact that an indicator measuring against a machined radial surface will read zero runout when located where the tool was, and twice the actual runout when located 180° from the tool, provided the workpiece is not disturbed when the indicator is moved. This concept can be used to get an estimate of radial error motion and can be extended to tilt error motion measurements when combined with the second probe and the ability of the oscilloscope to make differential measurements (see Section 5.2).

This technique involves machining an axial and a radial surface on a workpiece and then making several measurements on the machined surfaces without disturbing the workpiece. In addition, measurements on the axis must be made, so a reference surface must be produced on the axis of the machine. One possible arrangement for a workpiece with an axial reference is shown in Figure A1. The ball is the reference for axial measurements and should be centered as well as possible. The axial and radial surfaces are machined as smooth as possible. An aluminum workpiece machined with a large radius diamond tool with a slow feed rate will produce excellent results.



A possible workpiece design. The workpiece is mounted on the spindle and the ball centered as well as possible. The axial and radial surfaces are machined and the measurements made from these surfaces.

Figure A1

Once the ball is centered and the axial and radial surfaces are machined, measurements can be made according to the following procedure. Be sure to make all measurements at exactly the same speed that the machining was done at, as this technique is sensitive to imbalance induced errors. In addition, put a grease pencil mark on the axial and radial surfaces at the same angular location.

1) Replace the tool with a probe and measure the runout of the radial surface and the asynchronous motion of the radial grease pencil mark. See Figures A2 and A3.

   The value obtained in each of these measurements should be essentially the same and it is equal to the asynchronous radial error motion of the spindle. This is because the synchronous radial error (the motion

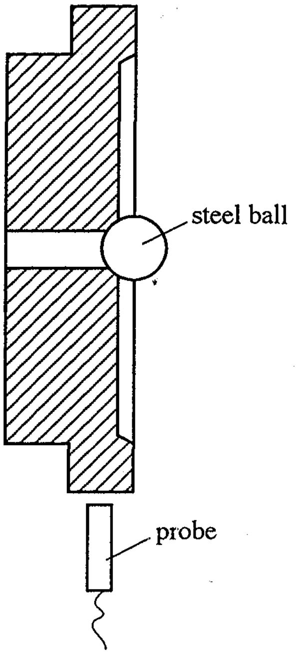
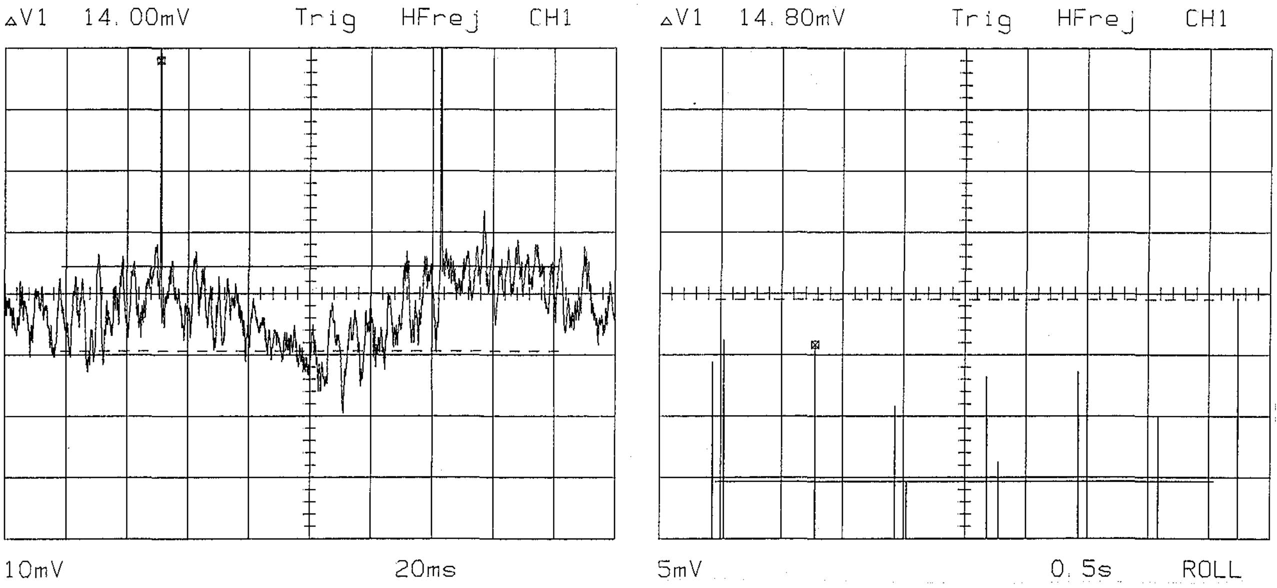


Figure A2 Probe Location



Runout of Machined Surface

Asynchronous Motion of Radial Grease Pencil Work

Figure A3

that is the same over many consecutive revolutions) and the fixed tool "machine out" the radial synchronous error motion when measured at the tool position. If these two values are not close (i.e., less than 10% difference), then something is wrong. The most likely culprit would be the machining process. A dull tool, insufficient coolant, built up edge, etc., can all conspire to increase the error in this measurement.

2) Move the probe 180° from where the radial tool machined the surface and measure the runout. See Figure A4 and A5.

At this location, the probe signal will be equal to the sum of the asynchronous radial error motion plus twice the synchronous radial error motion. However, the asynchronous radial error motion was already determined in the previous step so the radial synchronous error motion can be estimated by subtracting the asynchronous radial error motion value from the 180° runout value and dividing by 2 or:

$$\text{Radial Synchronous Error Motion} = \frac{30\text{mV} - 14\text{mV}}{2} = 8\text{mV} = 8 \text{ microinches}$$

This number can be used for comparison between spindles; however, it does not provide any information about the shape of the error, only about the value. Only the polor plot method specified in ANSI B89.3-4-1985 can fully characterize the value and the shape of the error motion, and this points out the inherent limitation of the test of the consequences.

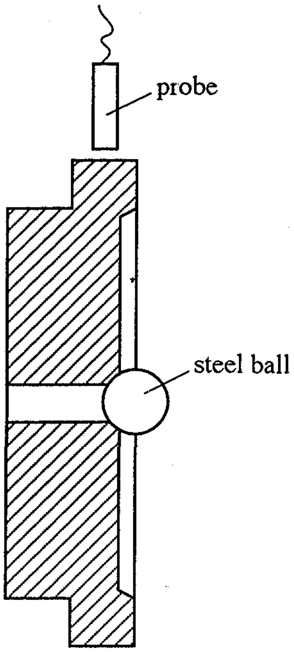


Figure A4 Probe Location

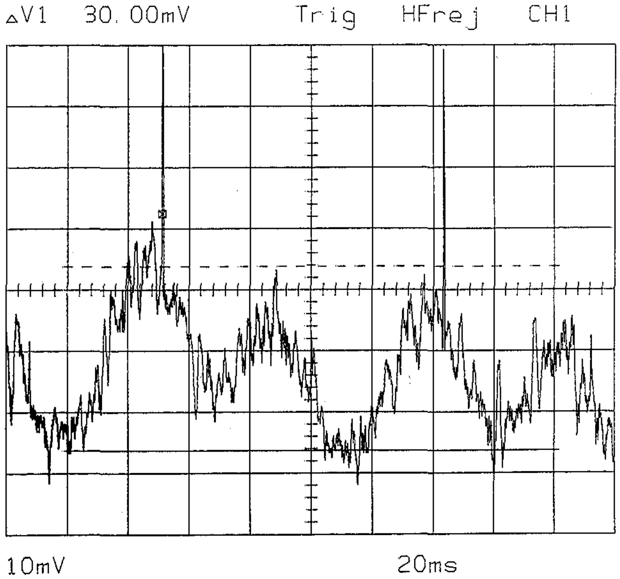


Figure A5
Radial Runout 180° from tool

3) The synchronous and asynchronous tilt error motions can be arrived at in a similar way, although the measurements are complicated by the fact that the axial measurements include components from both tilt and axial error motions simultaneously. The second probe is used to measure the axial error motions and can be subtracted electrically by the TEK 2211.

4) As with the radial measurements, a probe sensing against the axial surface where the tool actually machined the surface will measure only asynchronous effects. With the axial case both the tilt and the axial synchronous error motion are "machined" out simultaneously at the tool location and the probe should measure only the sum of the instantaneous tilt and axial asynchronous error motions. Therefore, whether the actual runout is measured or the asynchronous effects are measured by looking at the axial grease pencil mark, the values obtained should be similar. See Figures A6 and A7.

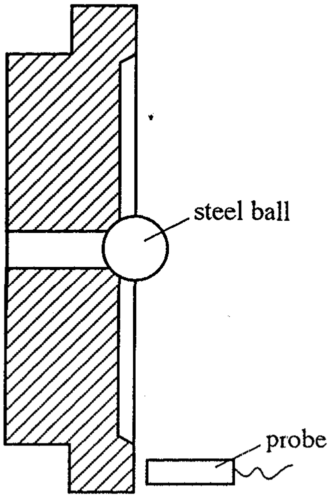
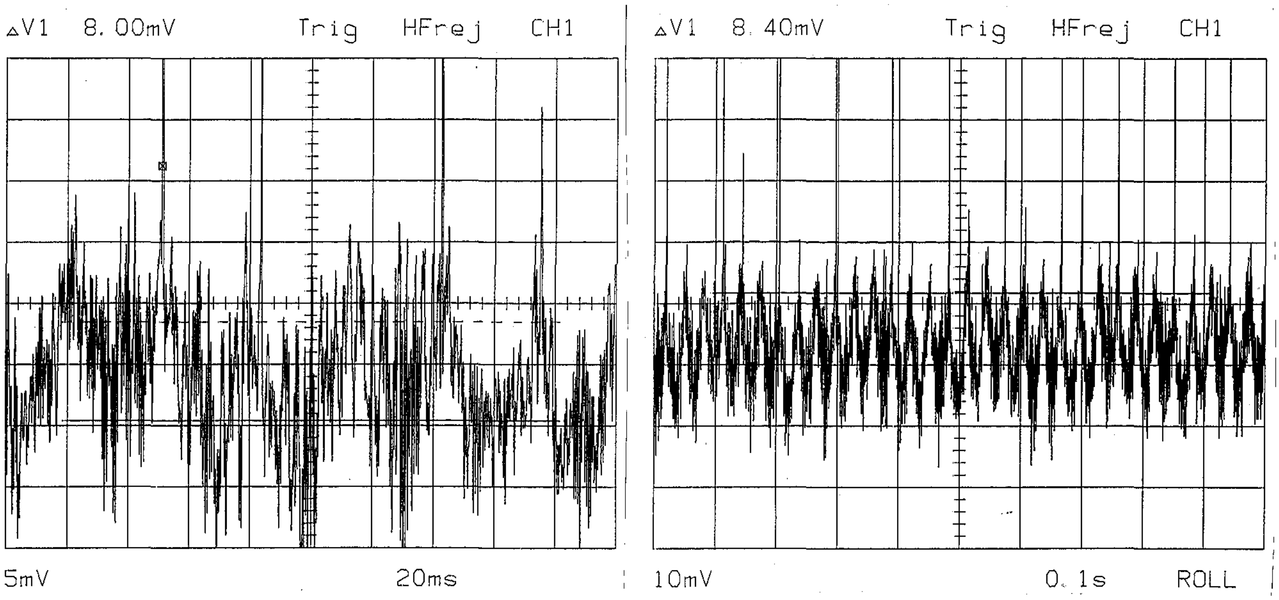


Figure A6 Probe at Tool Location



Axial Runout at Tool Location

Asynchronous Motion of Axial Grease Pencil Mark

Figure A7

5) The axial effects can be subtracted by setting the second probe on the ball on the axis and configuring the oscilloscope to subtract CH2 from CH1. The subtraction is done by setting the input mode switches on the TEK 2211 to BOTH, CH2 INV, and ADD. For subtraction, or "differential" measurements, measurement integrity is enhanced by having the average value of the signals as close to zero as possible. Once the spindle is rotating, use the offset knobs on the Targa instruments to set the digital to zero on both instruments. Also, record the distance "D" between the probes. See Figures A8 and A9.

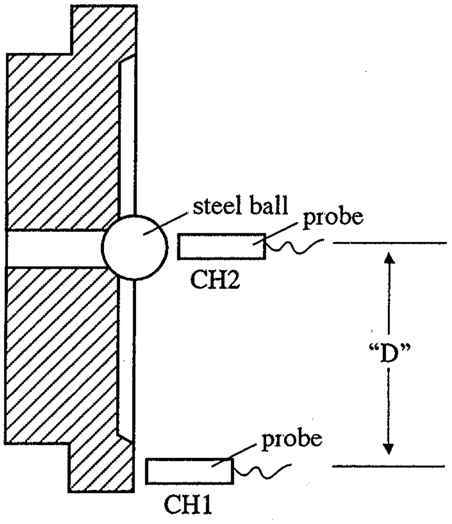


Figure A8 Probe Arrangement

6) The actual tilt value can be calculated by dividing the measured value by the probe separation (3.3 inches in this example):

Asynchronous Tilt Error Motion

$$= \frac{10.8\ \mu\text{in}}{3.3\ \text{in}} = 3.3\ \mu\text{radians}$$

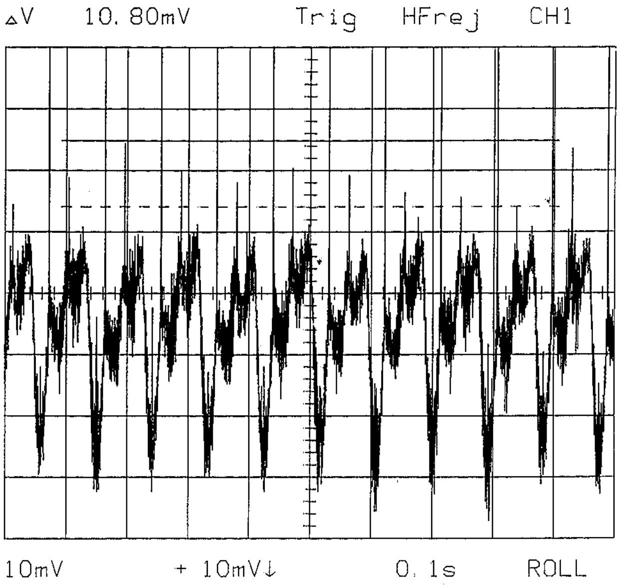


Figure A9 Asynchronous Tilt Error Motion Before Correction for Probe Spacing "D"

7) Similar to the technique for synchronous radial error motion, the synchronous tilt error motion is arrived at by moving the CH1 probe to a point 180° away from where the tool machined the axial surface. The axial reference probe is still used to remove both the synchronous and asynchronous axial error motions electrically. The resultant signal is the sum of the asynchronous tilt and twice the synchronous tilt error motions. Since the asynchronous tilt error motion value was measured in the previous step, it is subtracted away manually and the result divided by 2. This gives the synchronous tilt error motion at a specific radius, and the value must be divided by the radius to get an angular value. See Figures A10 and A11.

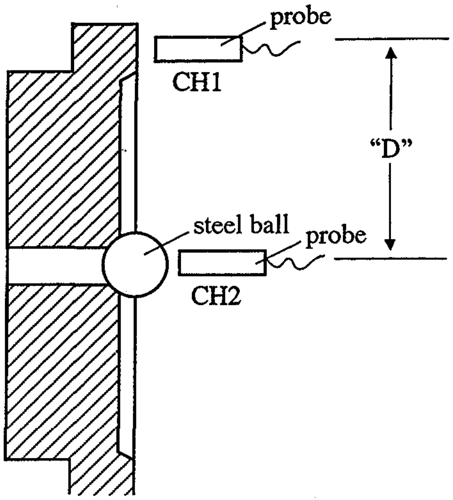


Figure A10 Probe Arrangement

8) The tilt synchronous error motion value is calculated as follows:

$$\frac{82.4\ \mu\text{in} - 10.8\ \mu\text{in}}{(2)\ (3.3\ \text{inches})} = 10.8\ \mu\text{radians}$$

Again, this value does not contain any information about the shape of the error curve, only a value.

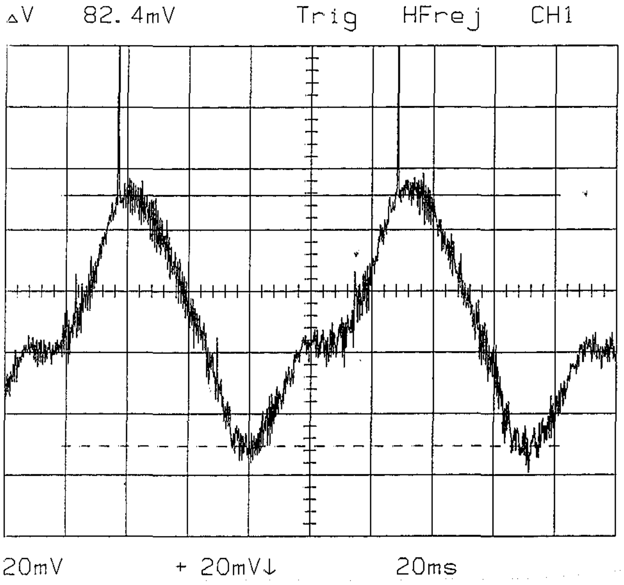


Figure A11 Runout of Axial Surface 180° from Tool Point with Axial Effects Subtracted

9) For completeness, the axial synchronous and asynchronous error motions, which are measured directly with the probe over the ball, are shown in Figure A12 and A13.

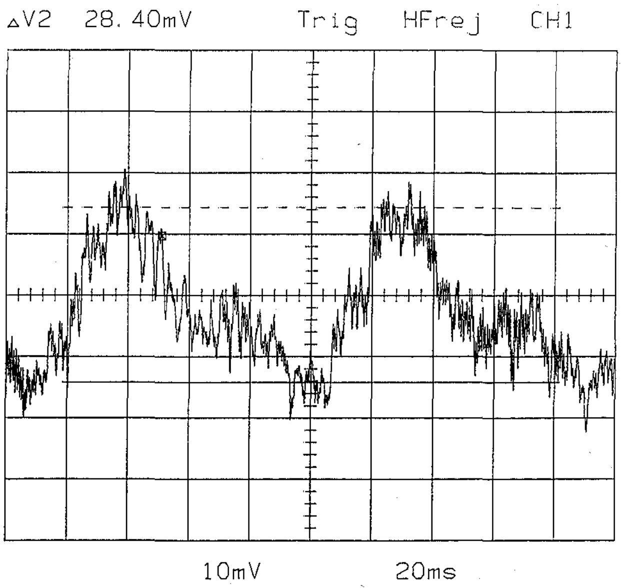


Figure A12 Axial Synchronous

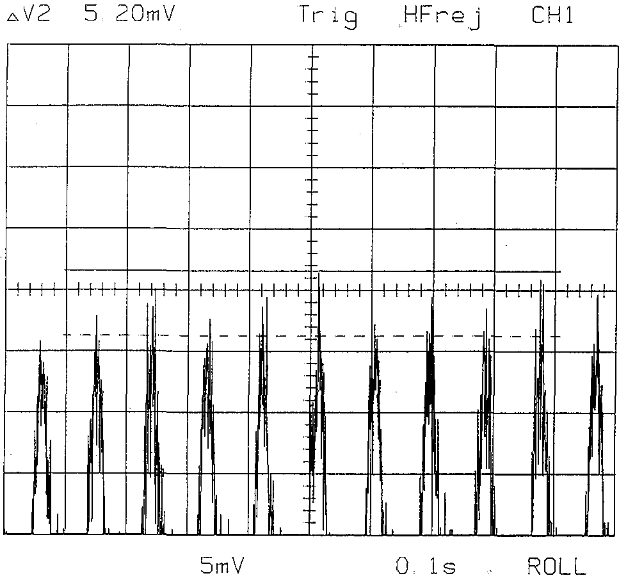


Figure A13 Axial Asynchronous