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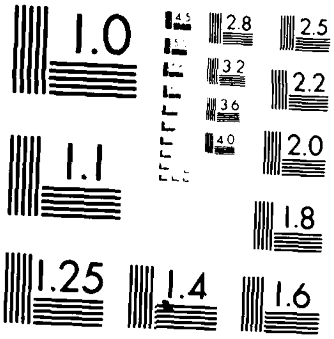

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

Final Report

ULTRA PRECISION MACHINING

submitted to

OFFICE OF NAVAL RESEARCH
Information Science Division
800 N. Quincy Avenue
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FINAL REPORT ON ONR CONTRACT

This final report summarizes the research activity at Stanford University during the past three years under ONR Contract N000-14-83-K-0053. Our work focuses on various aspects of ultra-precision manufacturing. The development of optical sensing techniques initially applied to the non-straightness of ways and the application of shear interferometry in measuring this characteristic machine tool imperfection. In actuation we have been principally interested in hydraulics. The ability of the working fluid to carry away the heat of inefficiency provides promise for improved thermal performance in actuation. Hydraulics, however, have historically operated in flow regimes which introduced vibration and seismic disturbances. So we have worked primarily on quiet hydraulics. Out of this some work on spindle metrology, vibration isolation evaluation, and some inovative techniques for machine tool operation have developed in addition to the actuation along the ways that were the initial thrust. Finally, the control environment for machines working at ultra high precision involves many considerations besides the immediate feedback control of axis motion. Imbedding this mixture of requirements in a computational environment provides a number of opportunities to improve the accessability and the friendliness of information to the operator. These areas are summarized below in this order with sensing, actuation, and computational environment as their subheadings.

1 - Sensing

Laser interferometry is an essential part of ultra precision machine tool feedback measurement. The dynamic range required for even relatively short stroke machines exceeds the ability of most sensing techniques. Based on the wave length of light the interferometric methods allow dynamic ranges in excess of a million and are essential if one is to maintain the precision and accuracy needed for ultra precision. Once a laser pathway has been dedicated on a machine to measure motions along the ways it would be convenient to make the straightness measurement that is motions perpendicular to the travel using the same laser pathway. By employing shear interferometry, this lateral displacement can be measured. During this contract experimental verification of the classical shear interferometry was carried out. In parallel, a thorough theoretical foundation was developed for the principles involved which provided an indication of design requirements and fundamental limits in the resolution that could be achieved. From this work indications of the engineering requirements for installing a shear interferometry straightness measuring system were developed. A visitor from Ching Hua University in Peking, Professor Yu, on a one-year exchange, has taken interest in this project and is working on the specifics of an engineering design.

A new area of research which has been developing since this summer is an anamorphic optical processor for readout of the speckle pattern. It should make possible the simultaneous measurement of the displacement vector along a line. If something deforms or doesn't move along a straight line, it should be possible to make this measurement using the new processor.

Participants: Prof. Hesselink, Prof. Yu, Steven Collicott, Robert Wentworth

2 - Actuation

We have been interested in the potential of hydraulic actuation because the working fluid carries away the heat of inefficiency and gives hope for improved thermal performance. To make this a reality we must redesign all of the hydraulic actuation techniques because conventional ones use a flow regime in which both seismic disturbance from flow accelerations and strain due to the constant displacement devices having fluctuating pressure would be unacceptable in a machine attempting to achieve optical quality performance. The devices we have developed are all laminar flow and involve continuous flow rather than trapping pockets of fluid in providing the transduction to mechanical work.

2a - Laminar Flow Motor

Chen has completed a thesis which was forwarded to ONR recently. He has successfully achieved an efficiency of 18% in the laminar flow motor. Compared to the theoretical maximum of 33% and expected reductions due to the flow past the lands that contain the flow, his results are extremely good. His theoretical calculations agree with the performance to within 1% of the input flow power.[1] Filtered passive fluctuations cause 0.2 μm

2b - Slideway actuation

A piston actuator without rubbing seals and a laminar flow control valve have been designed , constructed and testing is in progress. The control valve involves 4 laminar flow restrictors in a bridge configuration which provide the flow to the piston. A novel actuation scheme for the valve was developed using a commercially available Ledex solenoid. We modified it to replace the bushings with elastic support for the plunger. This technology has been made available to Ledex. The sensors are installed and working, the system has been operated open loop and closed loop performance is expected after the first of the year.

2c - Short Stroke Actuation and Sensing

A short stroke elastic actuator capable of a 0.010 inch (0.25 mm) stroke was designed and built. The actuator consists of a diaphragm assembly driven by a flapper valve, shown in Figure 1 . The diaghragm is constrained within a flexible tool post; when the flapper valve is activated, the diaphragm is pressurized and expands, pushing the tool forward. When deactivated, the spring forces in the tool post return the tool to its rest position. The actuator and tool post assembly is shown in Figure 2.

[1] Chien-Jen Chen, "A Laminar Flow Motor-Driven Machine Tool Spindle" Ph.D. Thesis, Stanford University, September, 1985

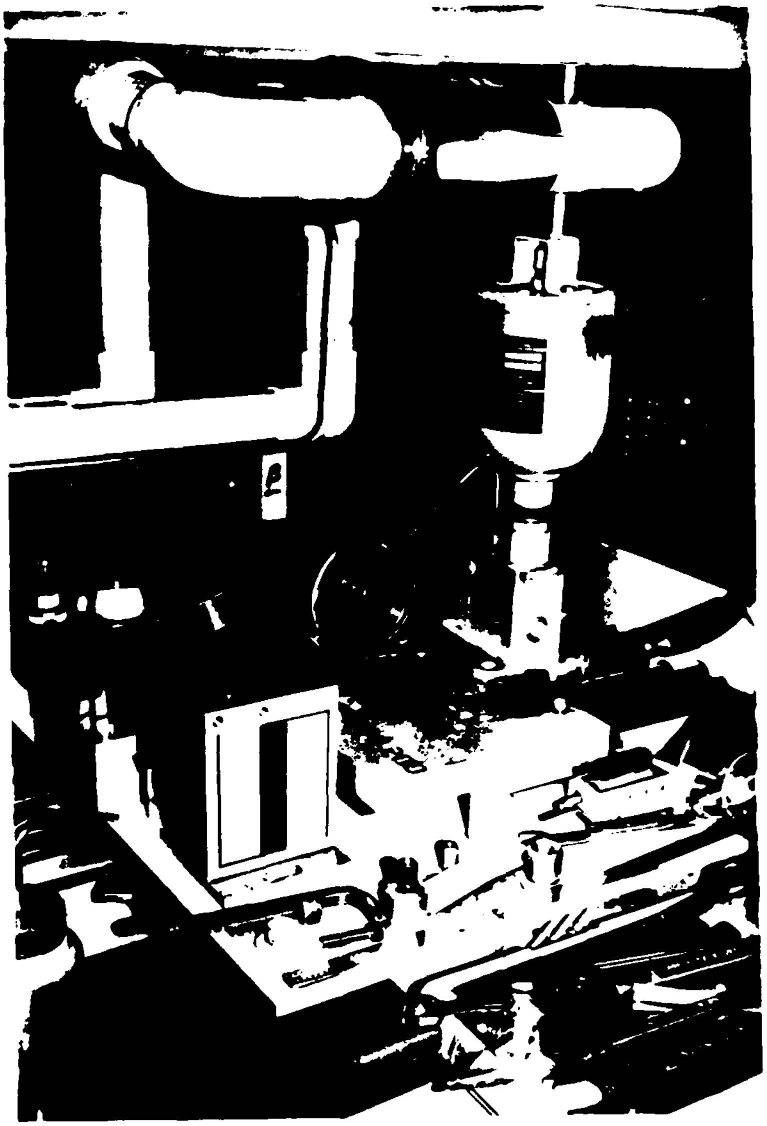

Figure 1

Short Stroke Actuator Diaphragm. The diaphragm is a hollow brazement of Graph-Air. When pressurized, the thin annular web undergoes plate stresses and the center sections deflect axially.

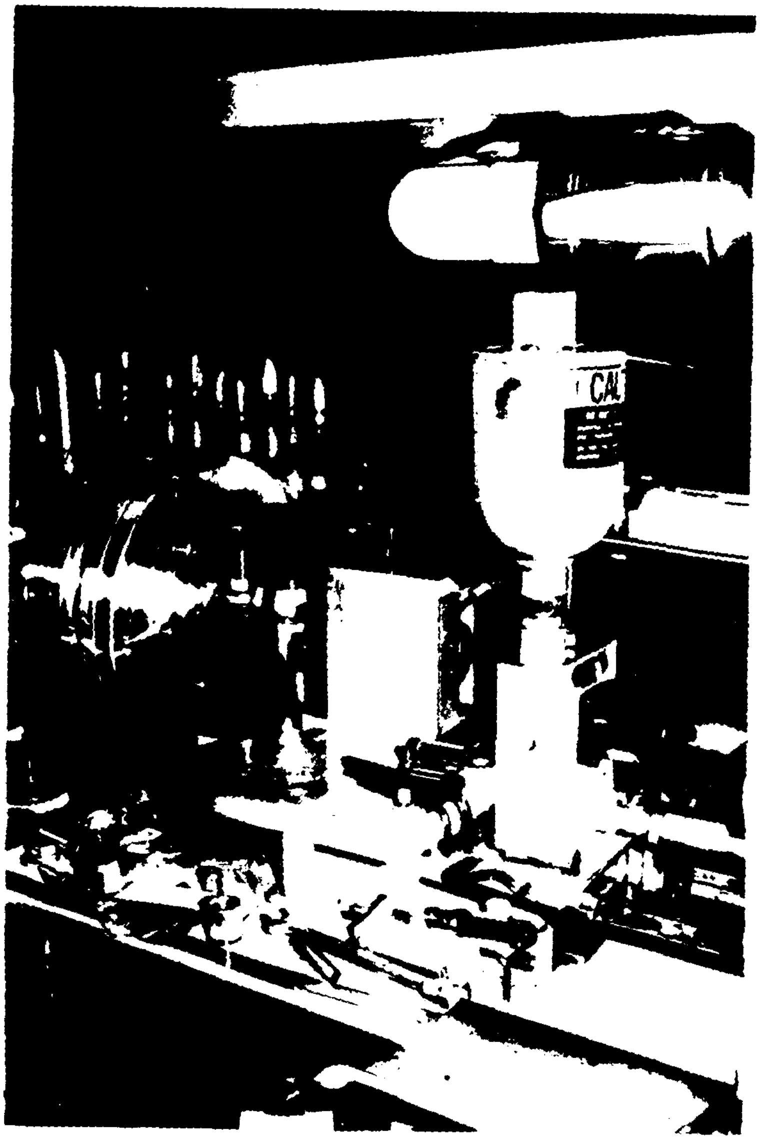

Figure 2

Short Stroke Actuator and Tool Post Assembly. A flapper valve modulates the pressure delivered to the diaphragm. When the diaphragm expands, the flexible tool post also bends, moving the tool forward, but maintaining rigidity in all other directions.

The material chosen for the diaphragm was Graph-Air, an air hardening tool steel which exhibits outstanding dimensional stability through heat-treatment. Although the manufacturer of Graph-Air recommended welding as an assembly method, Electron Beam Welding proved to be an unsatisfactory process due to the excessive thermal strains. An oven-brazing process, as suggested by Edwards Heat Treating Co, was used: After the individual conponents of the actuator were machined, they were fluxed and assembled. A silver solder was chosen with a melting point below the hardening temperature of Graph-Air, but above the tempering temperature. The actuator was then heat-treated and brazed at the same time. This is a novel process for this type of steel, and provides an excellent bond.

The actuator has a total travel of 0.010 inches, of which 0.007 inches are linear. Hysteresis is less than 100 uinches. The stiffness of the actuator is 40,000 lb/inch. When operating the actuator in the middle of its linear range, its dynamic behavior is that of a first order low pass filter, with a corner frequency of 31 radians/sec (5 Hz). This effect is due primarily to the hydraulic resistance of the tube connecting the flapper valve to the diaphragm; decreasing the hydraulic resistance between flapper valve and diaphragm will increase the open loop bandwith of the actuator.

Intel Corporation donated a System-310 microcomputer for controlling the various servo loops. This is an 8086/8087 based multibus computer, operating under Intel's iRMX multitasking system. With the addition of an SBC 732 A/D and D/A card, we have demonstrated control of various simulated plants. The computer will be used to control the short stroke actuator and the cross slide actuator.

2d - Straightness Correction

The nonstraightness of ways can be compensated for in several ways. The slide actuators can have a correction signal applied, the motion can be compensated with a short stroke actuator as described in the previous section, or one can modulate the slide motion itself to correct for non-straightness. This approach is taken on the DTM3 at Lawrence Livermore Laboratory. Separate elastic actuators were employed to correct slideway motion. In Japan a note appeared in a paper indicating that one had modulated the externally pressurized bearing to correct for non-straightness. It is this latter technique that we are interested in.

This study is intended to determine the characteristics and behavior of a caliper set of fluid bearings with the external restrictors being the two sides of an electrically controlled flapper valve. The purpose of this arrangement is to allow the lateral displacement of the caliper bearings and attached carriage with respect to the fixed guide rail. This movement, perpendicular to the direction of travel along the guide rail, permits compensation for nonlinearity of the guide rail which would otherwise induce lateral displacement and rotation about a vertical axis.

A literature review has turned up very little information. One citation (Nanometer Positioning Characteristics of Closed Looped Differential Hydro or Aerostatic Actuator; Kanai & Miyashita, submitted by Hoshi; Annals of the CIRP, vol.32/1/1983) claims to have built a system of this type, but reveals no detail of the design. Judging from the test results shown, it is a very low bandwidth device with a demonstrated range of .2 micrometers (8 microinch), a minimum controlled movement of .001 micrometers (39 nanoinch), and capable of a stiffness of 24 kN/micrometer (137 million lb/in.). It is not clear if their test rig is capable of achieving all of these capabilities simultaneously.

Mathematical models of the static and dynamic characteristics of a flapper valve controlled caliper bearing have been prepared and are currently being studied. A model of the closed loop system is being developed to evaluate compensation designs and system performance.

2e - Vibration Isolation Evaluation

As part of a class project (ME 119), the students undertook the design and construction of a pneumatic isolation system. One isolator consists of a small volume in a rubber bag, connected via laminar flow restrictors to a larger volume in a rigid container. The laminar flow restrictors provide a linear damping characteristic. Figure 3 shows the transient bahavior of a single isolator, while Figure 4 shows a typical response to the system of three isolators and the synthetic granite base.

To properly evaluate the vibration isolation, it is important to have the motion in all 6 degrees of freedom for both the grounded seismic behavior as well as the isolated behavior of the machine tool. We have been looking at the requirement for measuring instruments to determine residual motion on the machine and at the reduction techniques for evaluating the performance of the isolators.

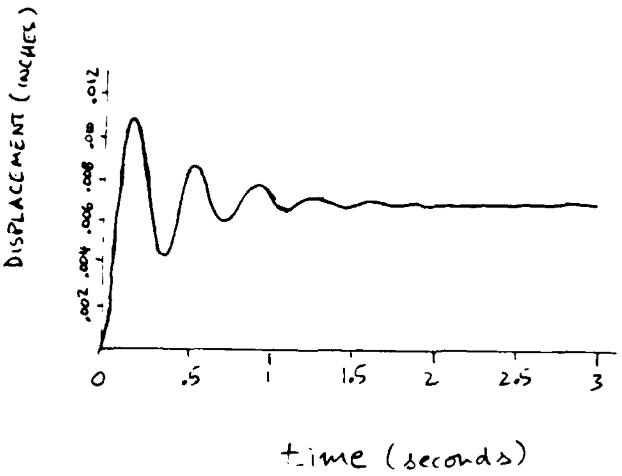

Figure 3

Transient response of one pneumatic isolator. Two of the three isolators were turned off. A weight was removed from above the active isolator; this chart shows the ensuing short term transient displacement. Eventually, the displacement would return to zero, due to the level control valve.

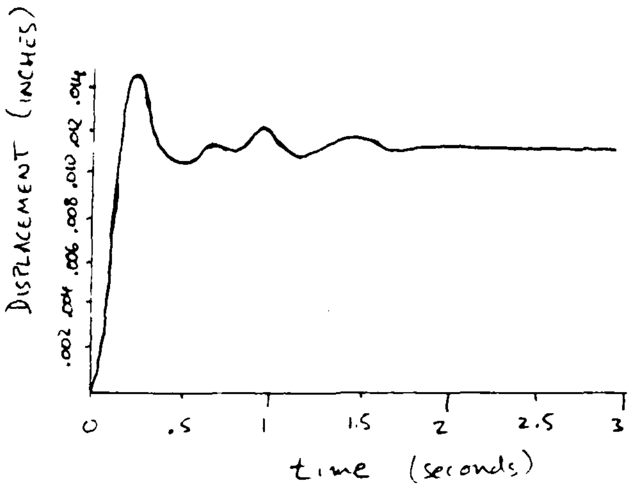

Figure 4

Transient response of the pneumatic isolation system. With all three isolators active, a weight was removed from the synthetic granite base. This excites two of the six modes of the base; a vertical motion, and a rotation about a horizontal axis. The transient displacement clearly illustrates the interaction between the two different natural frequencies of these modes. Again, the displacement will return to zero after several minutes due to the action of the level control valves.

2f -Spindle Motion Metrology

The laminar flow motor described first in this section was producing experimental results in the Winter of 1985. The need for spindle motion metrology was apparent. A course in precision engineering taught by Professor Beach and DeBra began in the Spring and this topic was suggested as a student project. It was too ambitious to be completed by the four students who undertook it during the Spring and some of the work continued with one of the students over the Summer and has been reported[2] and is reported here.

The spindle radial and axial movements are detected by a capacitive measuring device consisting of a circular metrology head and a detection circuit. The metrology head is made up of epoxy into which four pair of radial circular plates and one axial flat plate are embedded facing the surface of the proof cylinder. The proof cylinder is made of copper or aluminum and will be clamped, when in test, by a four-jaws chuck or a universal chuck of the machine to be tested. The radial motion of the spindle is, therefore, transmitted directly to the proof cylinder. The gap between the proof cylinder and plates represents the radial or the axial movement of the proof cylinder if the metrology head is held fixed. Every plate is excited by a constant magnitude 100kHz sinusoidal wave through a resistor. The voltage appeared between the plate and the proof cylinder indicates the magnitude of the capacitance between them. The relationship between the gap distance and the capacitance is given by Eq (1)

$$c = \frac{KeA}{d}$$

where

c = capacitance pF
K = 0.225 pF/in.
e = dielectric constant (e = 1 for air)
A = plate area, in.^{2}
d = gap between the plate and the proof cylinder

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[2] Chinglain Chou, Spindle Metrology Capacitance Detection Circuit September, 1985, Stanford University

Arrangement of plates and proof cylinder

Fig. 1 shows the arrangement and geometric configuration of the circular plate, the flat plate and the proof cylinder. The upper and lower circular plates constitute one pair of detecting device to measure the vertical movement. The left and right circular plate constitute another pair of detecting device measuring the horizontal movement.

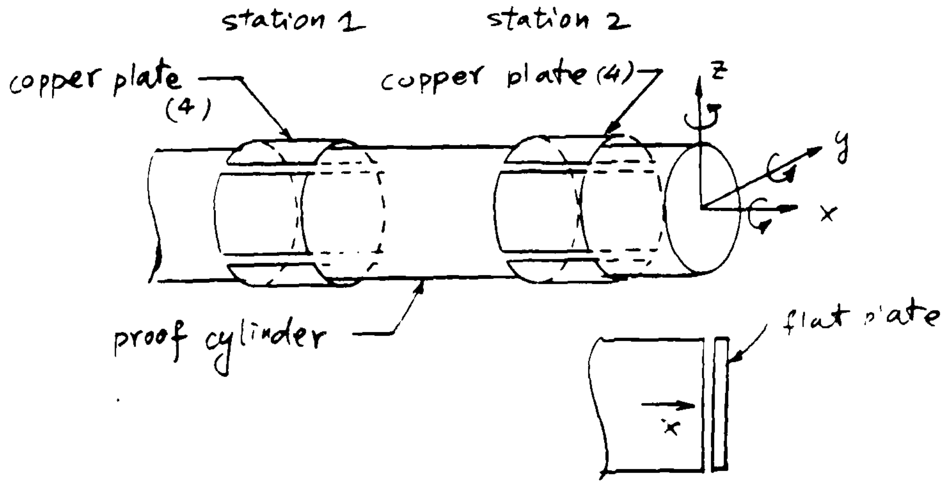

Fig 1. Arrangement of plates and proof cylinder

Radial Motion Detection Circuit

This circuit is composed of four identical channels of sub-circuit to measure the differential voltage between the plates that form pairs. The four channels of sub-circuit are named "outboard vertical," "outboard horizontal," "inboard vertical" and "inboard horizontal." The schematic diagram of this circuit is shown in Fig. 2. The complete circuit is shown in Fig. 3.

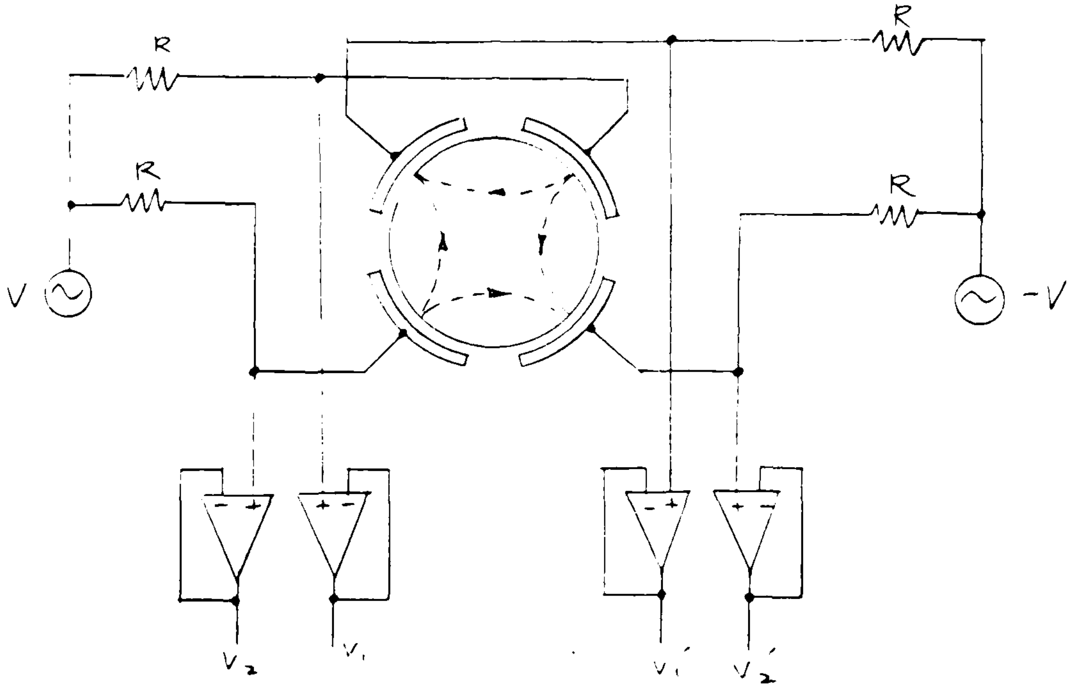

Fig 2. radial motion detection

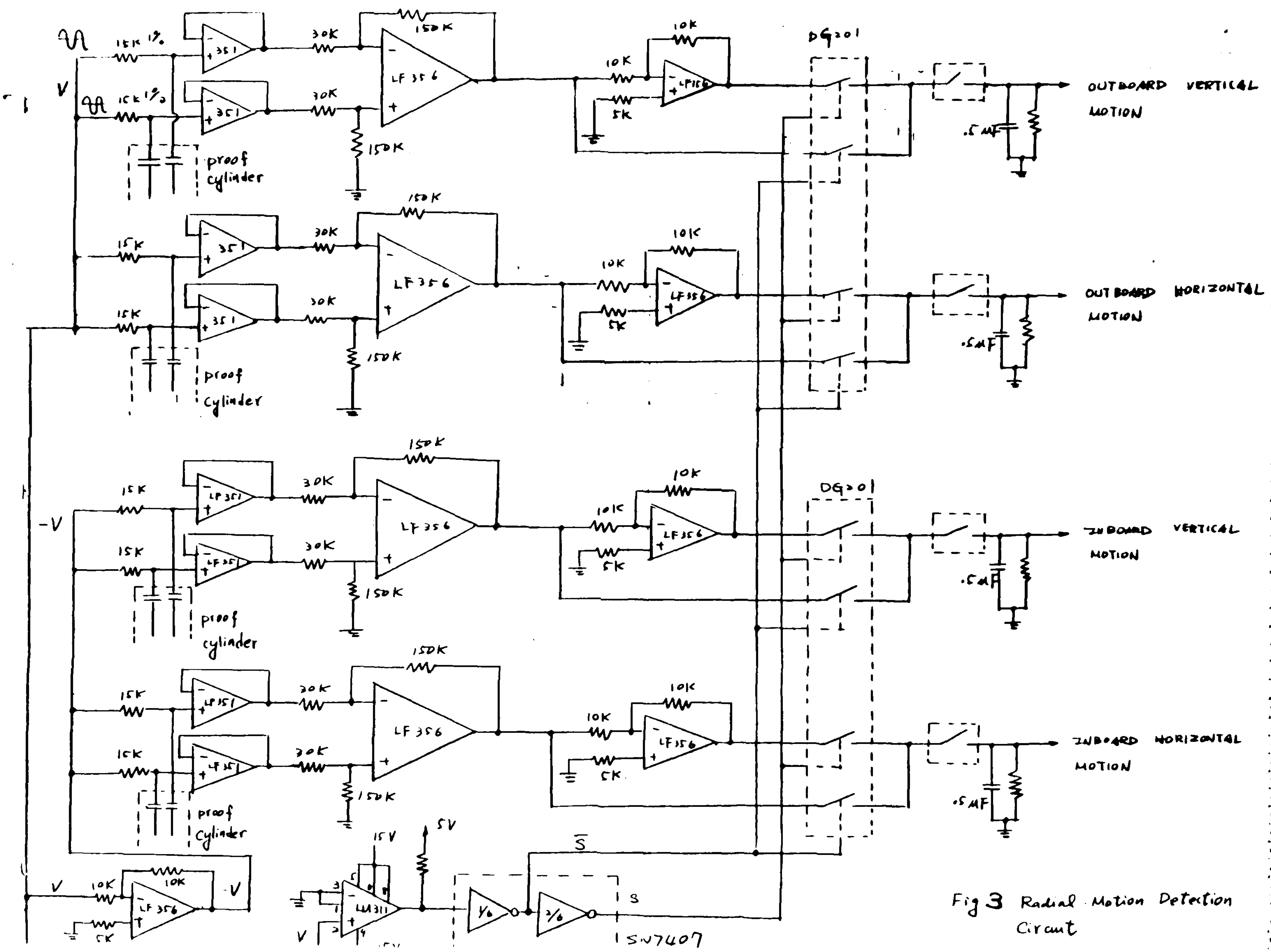

Fig 3 Radial Motion Detection Circuit

Axial Motion Detection Circuit

This circuit is used to measure the difference voltage between the real capacitor and the flat plate. Note that the proof cylinder is in the state of "virtual ground" so that it is not necessary to ground the proof cylinder. The schematic diagram revealing this measuring technique is shown in Fig. 4. The complete circuit is depicted in Fig. 5.

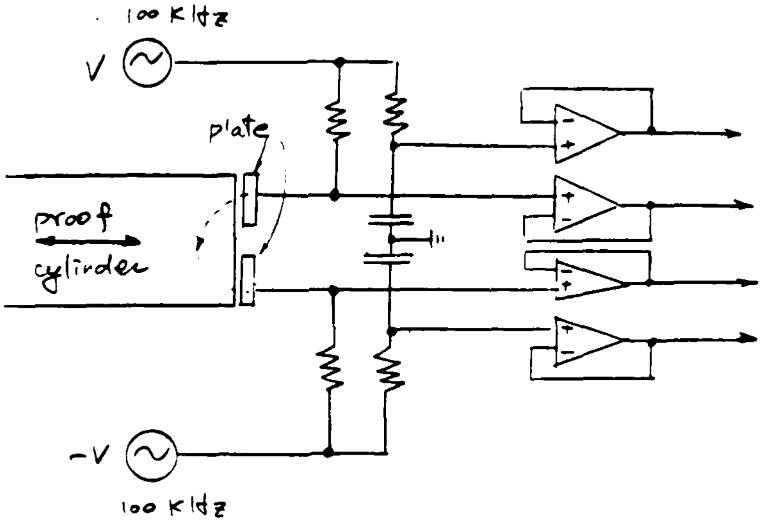

Fig 4. axial motion detection

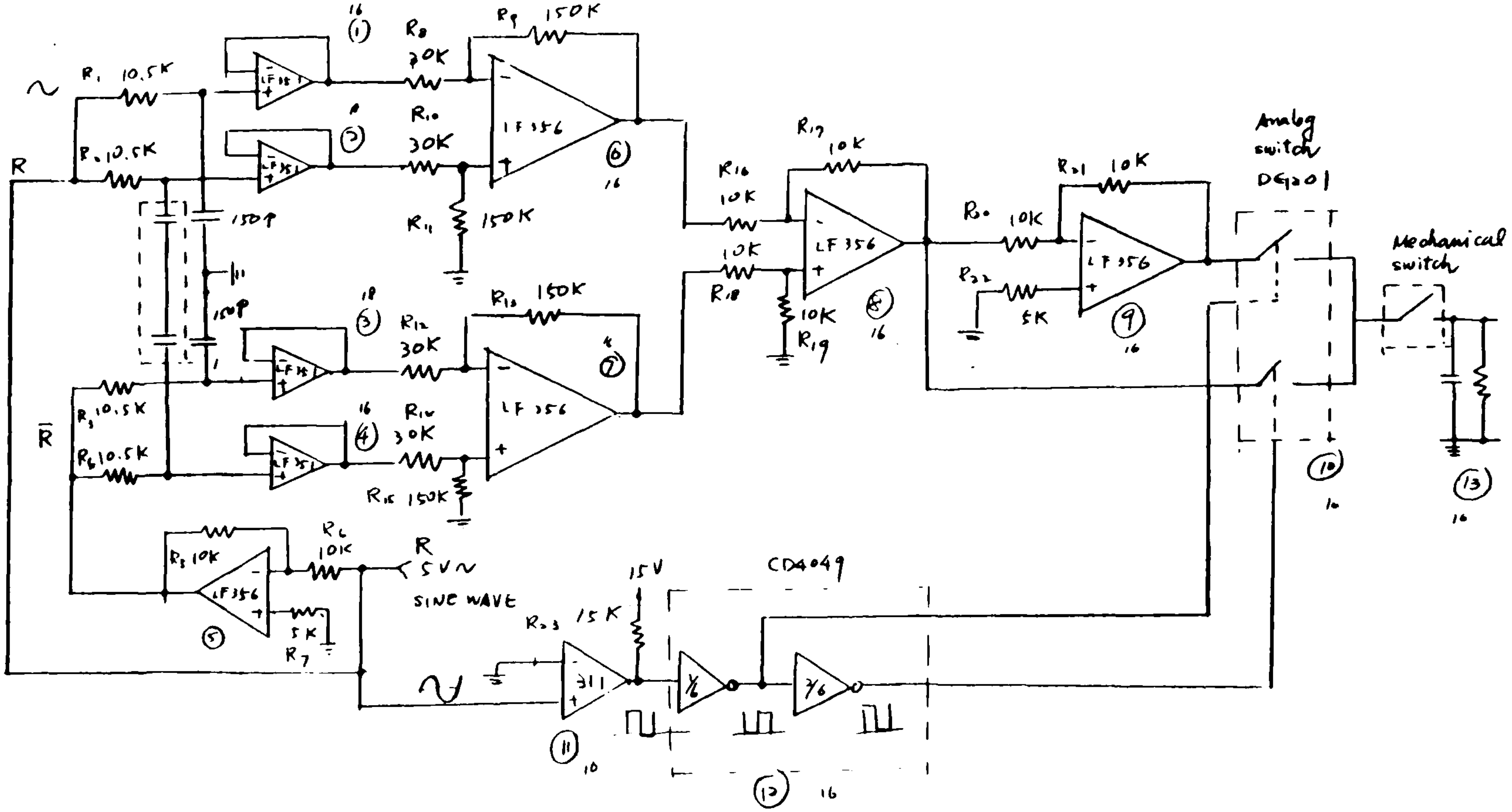

Fig. 5 Axial Motion Detection Circuit (Version 2)

Test Results of the Detection Circuit

The whole circuit is tested in the absence of proof cylinder and plates due to the incompletion of manufacturing. The capacitance between the plates and the proof cylinder is replaced by equivalent capacitors which are chosen as accurately as possible to represent the gap.

The test results of the radial and the axial motion detection circuit are shown in Fig. 5 and 6 respectively. The scale factor of asymmetry of the radial motion detection circuit is 2.6% which is due mainly to the mismatch of the resistors at the first and second stage. This problem can be solved in two ways. The first is to use more precise resistors at the locations mentioned above. This method necessitates a highly accurate resistor measuring device. The other is to calibrate the circuit and use a computer to compensate for the scale factor asymmetry.

The test results of the axial motion detection circuit deviates from the theoretical curve by an amount of ≈7.85 pF capacitance which is caused mainly by the stray capacitance between the wires, circuit board and the virtual ground.

So far the electronic circuit is complete. We only need to wait for the completion of the mechanical part. Then we can test this circuit in real world and evaluate the spindle runout.

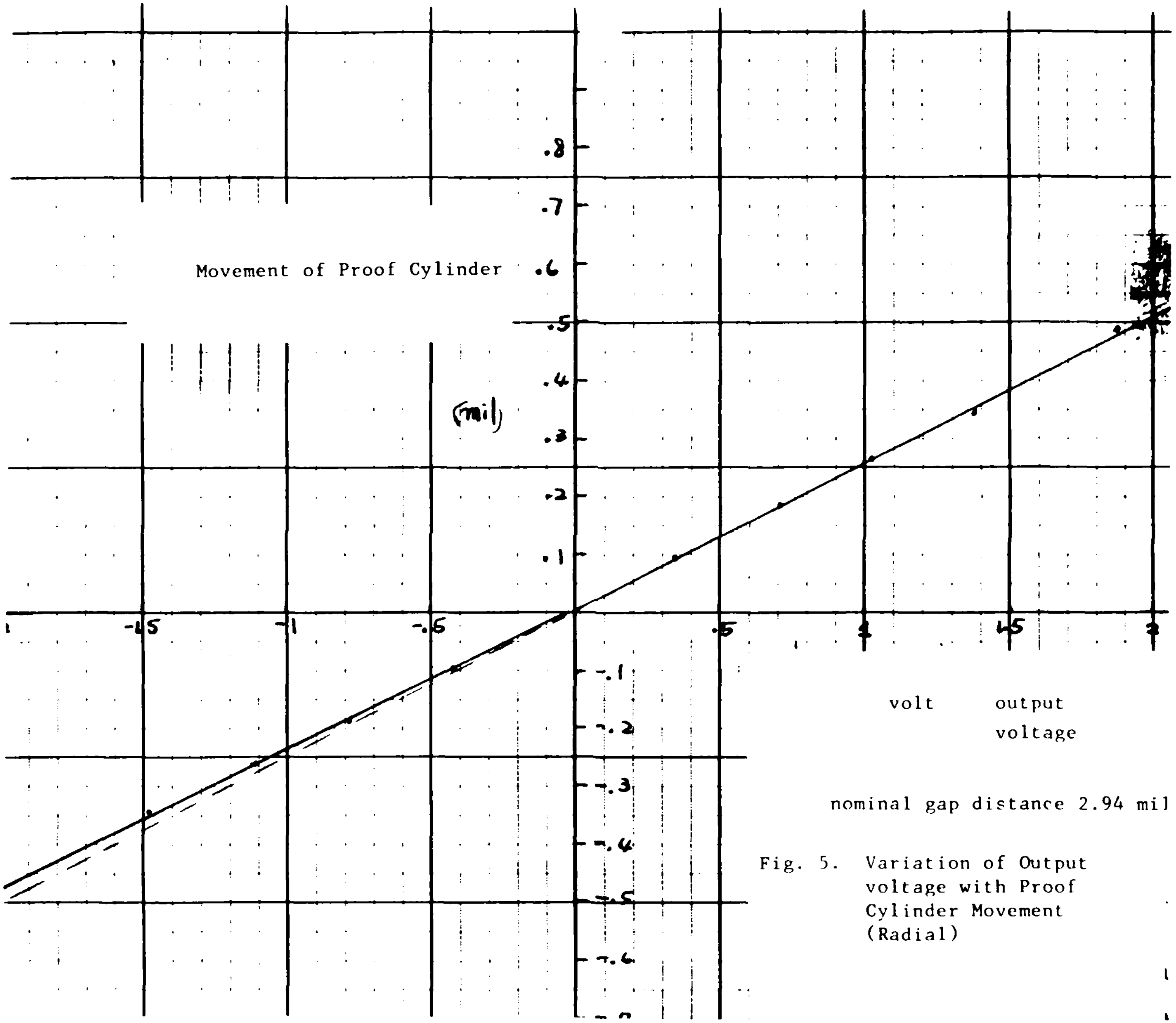

Fig. 5. Variation of Output voltage with Proof Cylinder Movement (Radial)

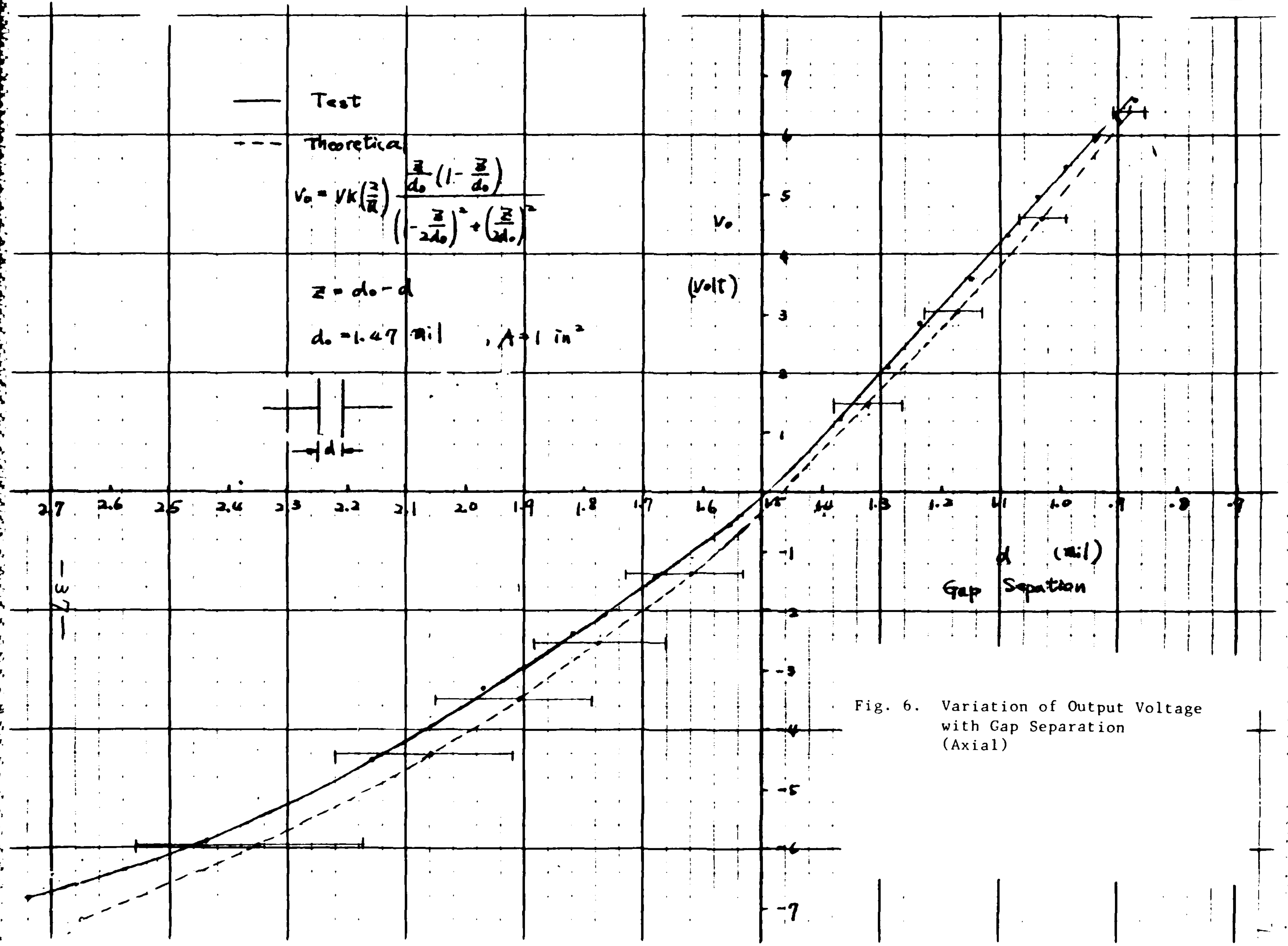

Fig. 6. Variation of Output Voltage with Gap Separation (Axial)

2g - Temperature Control

We have considered working on temperature control of shower oil and have had a number of students contribute to the project. Most recently a visitor from France, Karl Shubert, worked with us for three months on a project required for his degree from ENSAE in Toulouse, France. Karl developed a mathematical model and did some simulations as well as getting the HSC valve operating with the chiller. At the present time we have a greater heat load than can be handled by the control valve in series, so it is modulating the flow in parallel with a larger chill water flow when we are operating all of the hydraulics.

A student has become interested in pursuing this area for his research and I expect we will be doing more work in this area aggressively next year.

Participants: Professors DeBra and Beach; Ed Ditzen, Russ Hacker, Dick Van Patten, C. J. Chen, Cliff Oostman, Hy Tran, Chinglain Chou, Leslie Leland, Pat McCune, Karl Shubert, Graham Ross, Dan Blick, Norbert Wu, John Gill, Eric Siegler, Mark McCullough

3 - Computational Environment for Machine Tool Operation

The computational environment for ultra precision machine tools should include a variety of functions in addition to the low level ones of commanding the axes to reach appropriate positions for the machining process. There will be access to information on machine tool functions, operating instructions, data-gathering capability for machine tool metrology, and possible higher levels of contact with the computer-aided manufacturing data base source. To develop an understanding of these types of interactions with the machine, we have chosen to experiment with some machine tool metrology. Straightness measurement was chosen as a good candidate since it involves data taking and some processing to provide an indication of the condition of the machine. It is a task that cannot simply be done by manual data collection and inspection.

3a Straightness of the motion of a carriage could be checked against a perfect straight edge. However at the accuracies required in precision tools, no straight edge can be considered a perfect reference. Thus a technique which is limited only by resolution and repeatability must be applied. The use of a straight edge in two orientations provides two sets of data which can separate the straight edge figure from the straightness error of the ways. This is done by reversing the straight edge. Then the first trace represents the non-straightness plus the variations in the straight edge whereas the second trace represents the difference.

By adding and subtracting these two traces, one achieves a separation of the two figures.

The process requires gathering data and storing it for each run. A measuring device, in this case a stylus being read out by an LVDT, provides a signal which must be converted to digital form in order to be stored for later computation. The collection of data must be coordinated with the movement of the axes. The machine operation therefore becomes an integral part of the data gathering. This process has certain experimental limitations. The straight edge must be mounted in such a way that the LVDT stylus will track an identifiable portion of the straight edge so that when it is reversed the same path can be repeated.

It is fundamental to any precision data gathering process to get an indication of the reliability or the potential accuracy of the information. If the data are collected twice over the same surface the difference between the two traces is an indication of the repeatability of the measuring process. Thus in this relatively simple experiment we have an example of the kind of process that we would like to generalize for computational support in the machine tool environment.

Equipment

The machine tool on which the experiments were carried out is a machine of standard shop precision. However, the principles involved are unchanged. A

Bridgeport mill, retrofitted for numerical control using a Retroteck controller was chosen. The Retroteck controller was given its commands from a H-P 9836 computer. This computer is programmed in PASCAL and therefore provides an adequately flexible language for us to carry out these experiments. The straight edge was constructed by a student, J-K Chou, in an earlier project and its evaluation data were available. The LVDT used has a resolution of perhaps 2 - 3 μinches and a manufacture stated accuracy of 5 μinches. The fixturing for holding the straight edge and the LVDT were a combination of work by the earlier student project and an ad hoc setup for the current experiments. Some temperature observations were recorded but the variation was less than 1 °C during the measurements and played little role in this case on the determination of the results.

Data Gathered

The trace generated by the LVDT as the machine carriage moved was recorded. This trace was then repeated and the two sets of data differenced to obtain an indication of repeatability. By way of illustration a set of seven differences are given in Fig. 1 which indicates a repeatability of about 40 μinches. The uncertainty is contributed to by the play in the slides, the motion of the stylus over slightly different paths on the straight edge, and electronic instrumentation non-repeatability. The calibration bar on the right edge of the figure represents 100 μinches. The seven traces were gathered under automatic

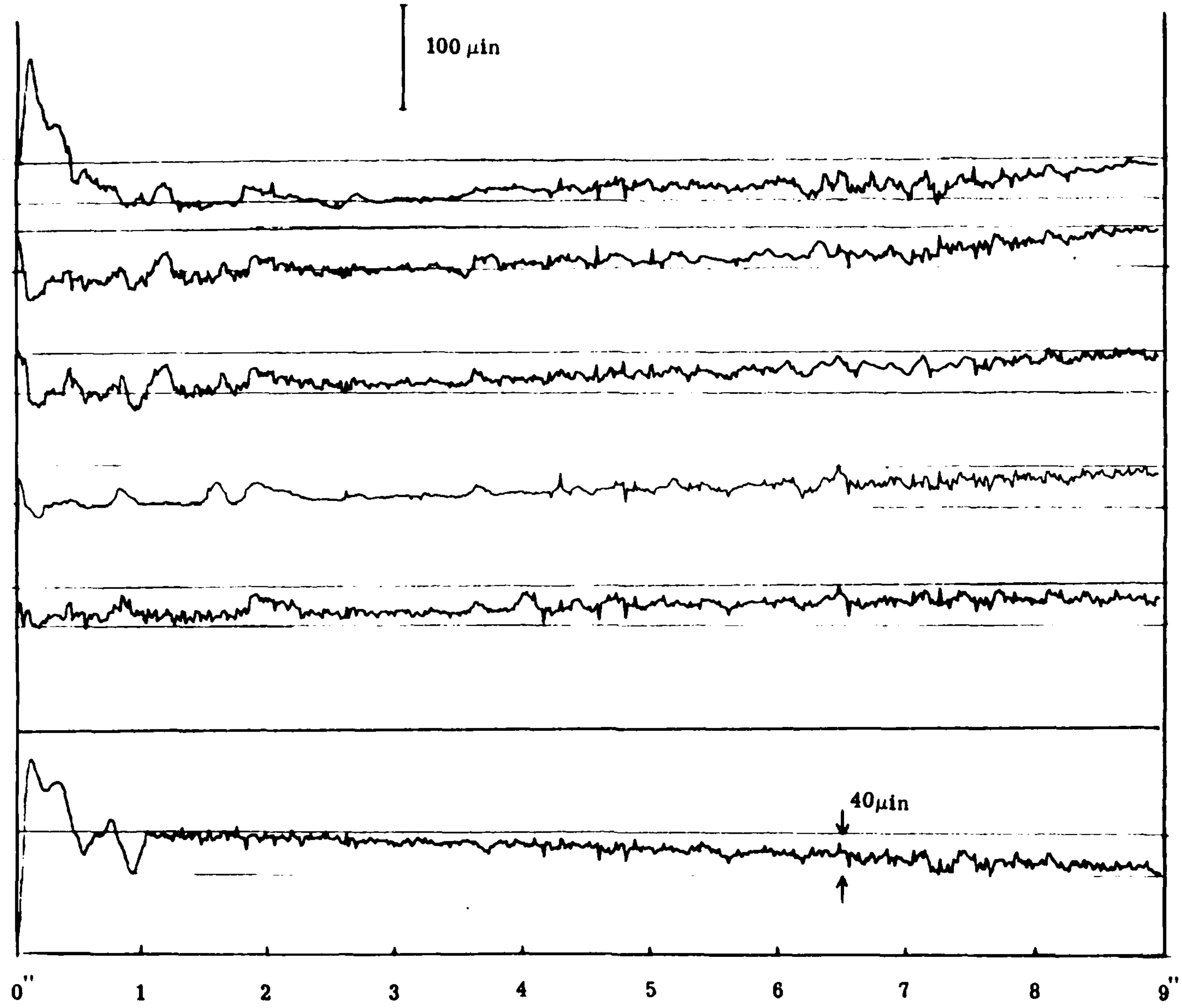

Fig. 1 Comparison of Measurements Over Traces of the Same Path, With the Second Measurement as Reference.

machine tool programming during a period of approximately one hour. Each trace was generated with the carriage moving slowly to a point approximately 1 cm beyond the end of where the data were recorded, stopping, then reversing back about 1 cm beyond the starting point at which point the carriage stopped for about one-half minute. On starting up it can be seen that either the fluid film or some readjustment for the direction of motion is not completed in the 1 cm of motion before the data begin to be collected. Thus the beginning of each trace on the left shows a somewhat different character depending upon how large this reversing transient is and how long it lasts beyond the point where the data starts being collected.

After the successive traces along the straight edge were completed to check repeatability, succeeding traces were taken with the straight edge reversed. The sum and difference were taken and the results plotted representing the straight edge contour or figure and the non-straightness of the motion of the ways. Figure 2 is an illustration of these results. The upper curve represents the straight edge and the lower curve the non-straightness of the carriage on its ways. The periodic behavior of the ways matches the pitch of the lead screw and is characteristic of ways driven by a lead screw in which the thread is not concentric with its bearings. The fact that this periodic behavior has been separated quite effectively from the straight edge figure by reversal is an indication of self consistency of the data taking and processing methods. Figure 3 shows a sequence of passes plotted together. The difference between these

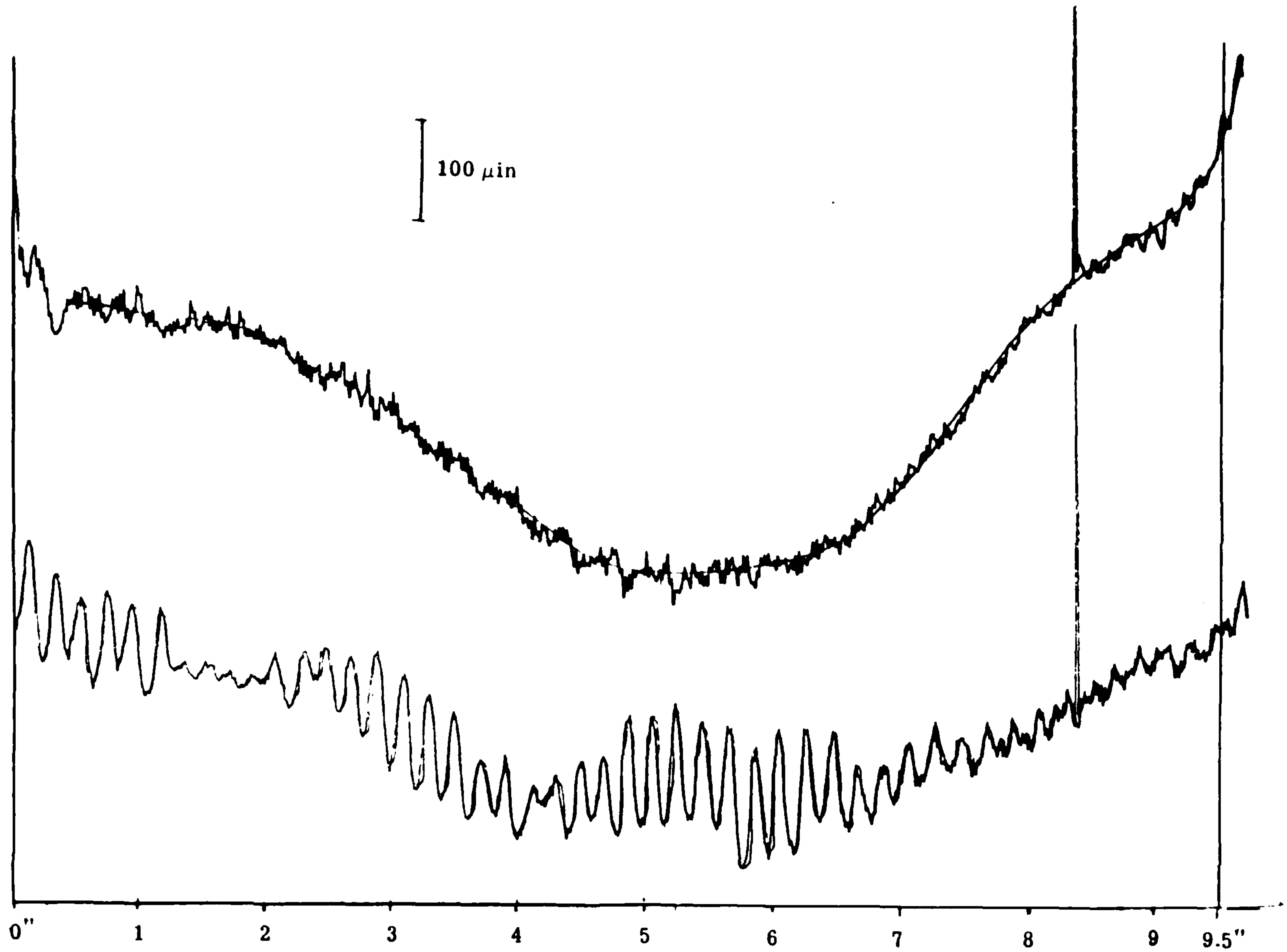

Fig. 2 Profiles of Straight Edge and Slide After Separation of Error by Straight Edge Reversal.

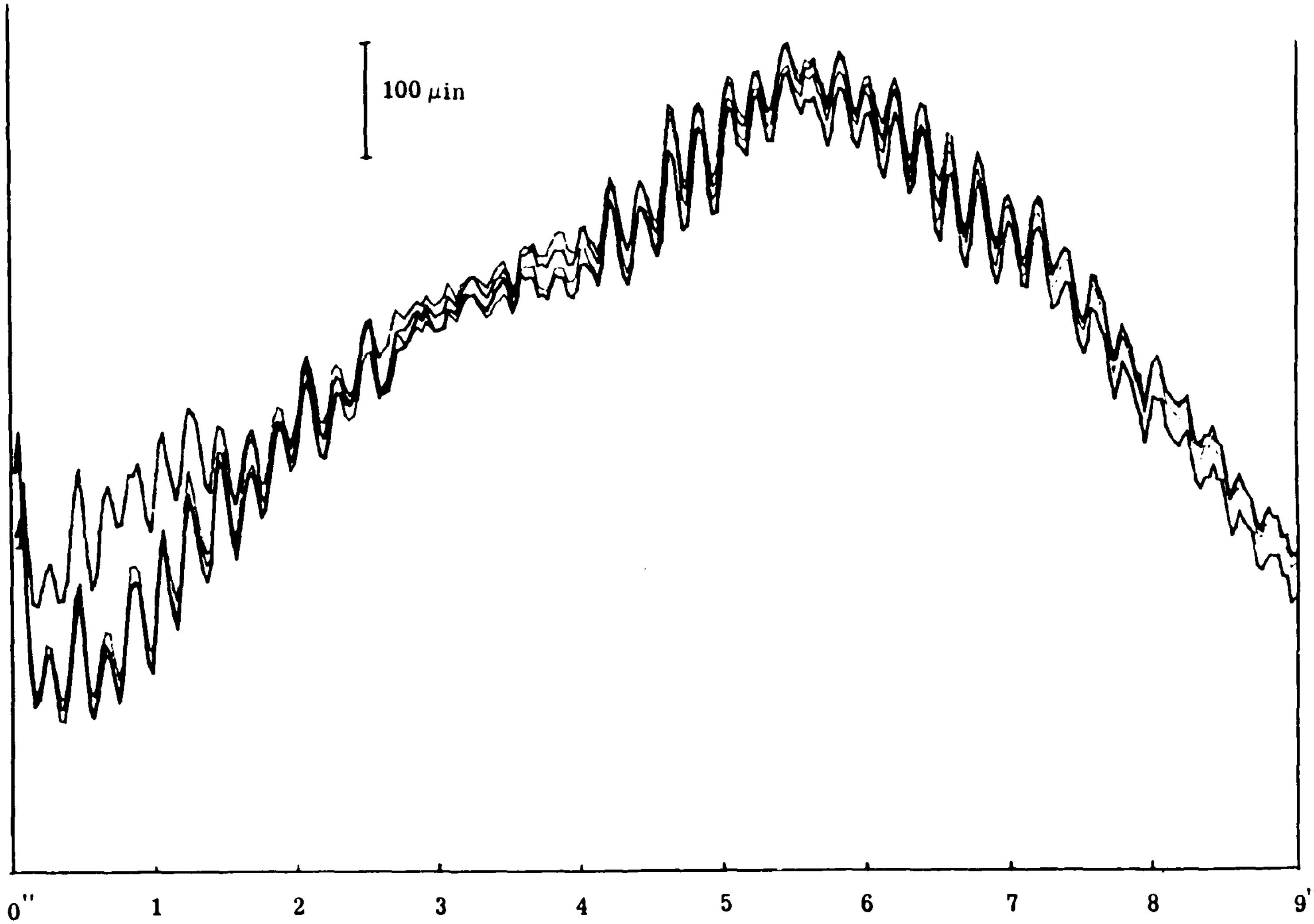

Fig. 3 **Profiles of Four Passes Over 9 Inches**

curves is the repeatability. Here one can see the distance required for a carriage to return to equilibrium after a reversal. Each of the traces is plotted from 300 data points which cover nine inches of travel and thus the data points are taken at 30 mil (0.75 mm) separation in this case. Figure 4 is another illustration covering six inches but with the same vertical scale. Figure 5 is a similar trace but with the initial point taken at the middle of the straight edge. This shows the initial transient is not a function of the location of the carriage on its ways but rather is associated with the reversing process.

Conclusions

Enough work was completed to see clearly some of the additional support desired from a computer environment. Instructions on how to set up the straightness measurement and indications of what to look for would be typical for a given machine. These data ought to become part of the information environment for each type of machine. The computer environment should exist early in the design phases of a machine and particularly be available as a repository for the machine tool metrology that is done during the development and checkout phases of a prototype.

For an ultra precision machine one would expect the repeatability to be the order of 1 μinch or less. Such a simple test as demonstrated here would be essential to establishing the health of a machine even if one didn't perform the reversal portion of the test. Suggestions of this type should be included in the

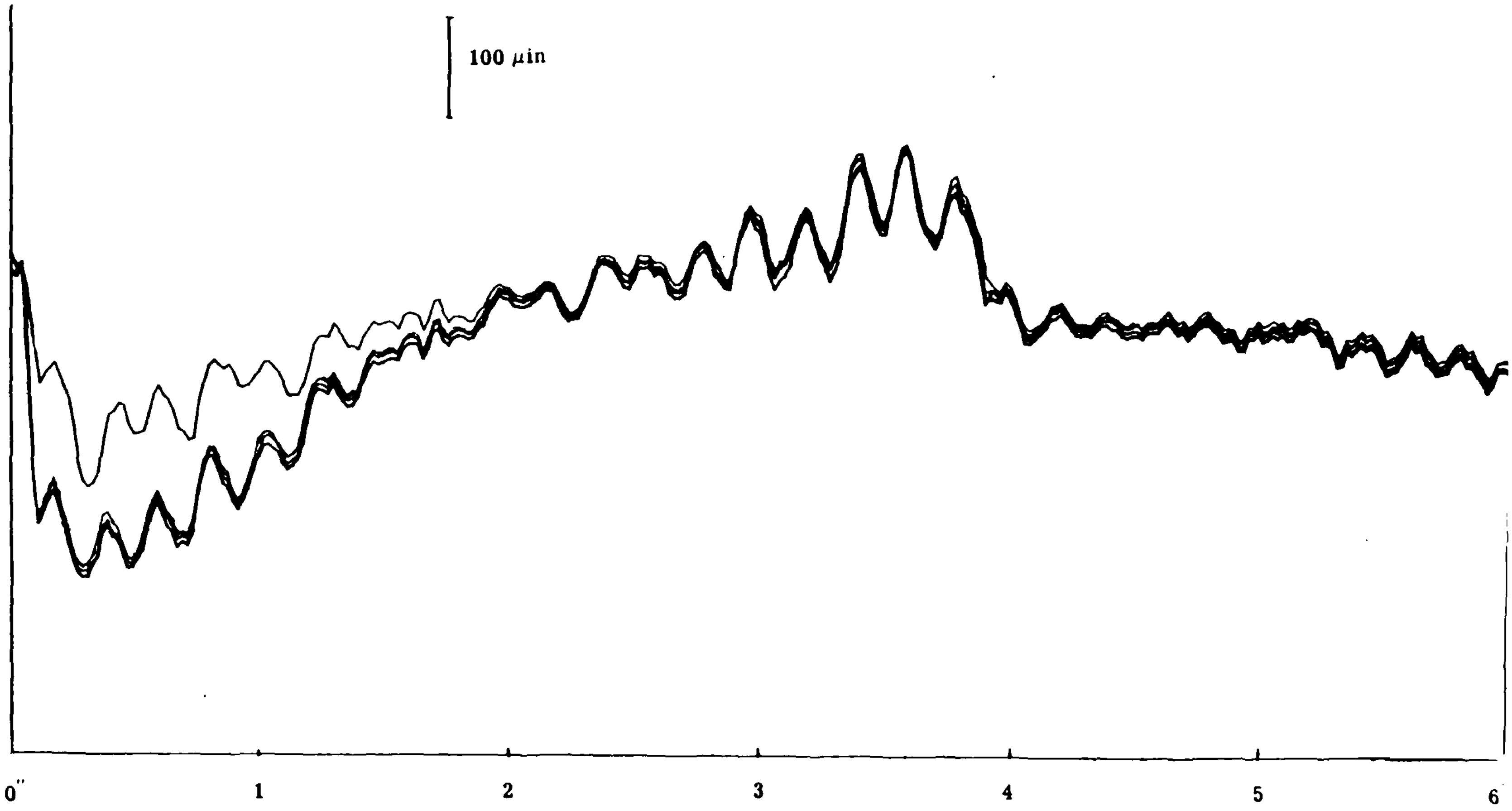

Fig. 4 Profiles of Four Passes Over 6 Inches With Straight Edge Located in a Different Position of Slide From Fig. 3.

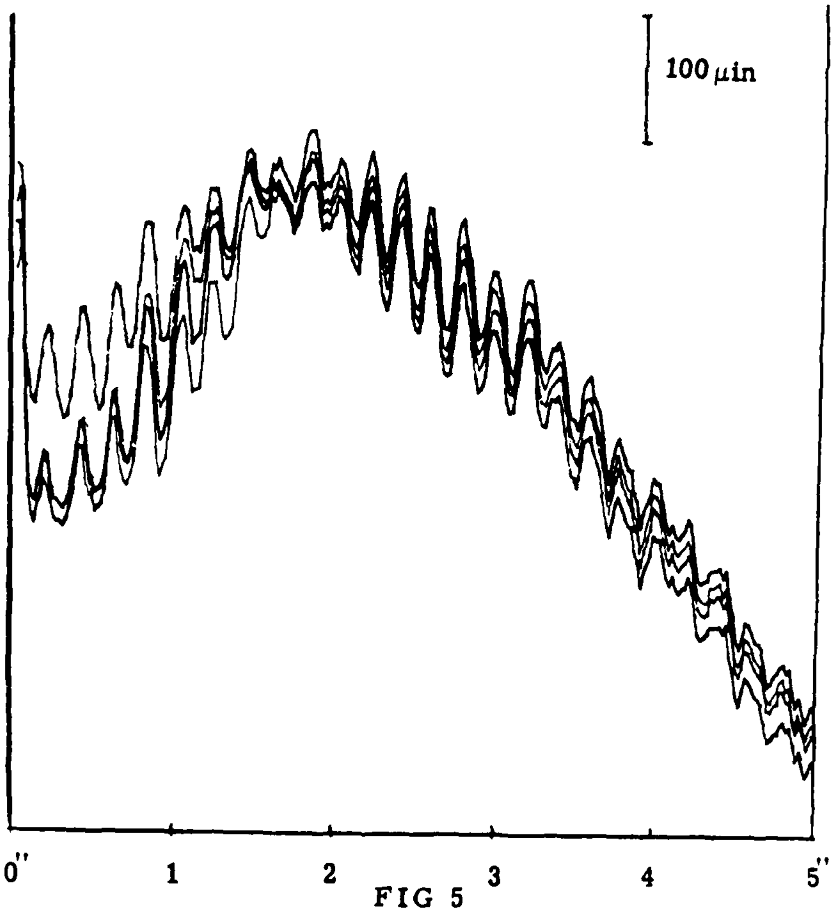

FIG 5

Fig. 5 **Profiles of Four Passes Over 5 Inches Starting From the Middle of the Straight Edge.**

supporting material associated with any machine tool metrology whether automated or just described by the supporting computer.

Additional tasks of this type will provide more insight into the methods of data collection and the types of data display that would be useful in addition to the obvious ones associated with a given test. This experiment has been a useful start in developing this type of approach.

1. Introduction

One of the basic methods available to a physician for diganosing a malfunction in the human body is to listen to its internal operation through a stethoscope. With recently available data acquisition and processing [15] technology it has become feasible to let a computer play the role of the caring physician to a machine, especially if downtime is very costly or reliability is crucial [14] [18].

The scope of this litterature survey is machine health monitoring by mechanical signature analysis with emphasis on processing methods and algorithms. In addition some references address the topics of data acquisition and human interfacing. It should be noted that machine health monitoring is an intersection of a number of well esteblished fields in engineering, each of which has a vast body of litterature.

2. Overview.

So far, machine health monitoring by mechanical signature analysis has been practised in a purely empirical fashion. A typical approach would be to attach an accelerometer to the machine or its part that is to be monitored and calculate the power spectrum (or other statistical parameters) of the vibrations. Then by observing how the spectrum changes as the machine begins to fail, a monitoring scheme would be designed to keep track of that particular feature. The tricky part is to come up with a statistical parameter (or a set of these) that will characterize some particular aspect of the machine's operation with good sensitivity to any changes and also with low variance so that the information given can be relied upon.

After having established a well confirmed suspicion that something is degrading in the machine, the cause and severity must be determined. In a complicated system where a failure can have multiple consequences and the diagnostic parameter is sensitive to more than one failure, the actual failure may have to be inferred from many observations, possibly making use of the machine's history. This function is normally provided by the experienced machine operator. Using expert systems for this is an increasingly feasible alternative although the high cost of developing such systems requires very high payoffs of the diagnostic system [26].

Another important aspect of diagnostic systems is the presentation of the machine's status to an attendant. This would normally involve a display, showing a schematic and numerical information as well as conclusions arrived at by an expert system.

Mechanical signature analysis is interdisciplinary by nature and involves applications of statistics, signal processing and system identification for processing data, using the techniques of dynamics and vibration theory for understanding the mechanism that generates the signal and also requires understanding of the properties of the instrumentation and measurement techniques used [4].

The references include some sources of general information. There are two books on the subject, one by Collacott [16] which covers causes, types and analysis of failures, sensors and monitoring schemes, with emphasis on vibration and contaminant analysis for diagnosis. The other book by Mitchell [27] is newer but narrower in scope. It treats only vibration analysis of rotating machinery with some discussion of the instrumentation needed and guidelines on how different failure modes are characterised in the spectrum of the machine's vibrations. Several case histories are given. Both books are aimed at maintenance engineers and do not assume real time processing and diagnosis. Consequently, discussion of processing methods is very limited.

Lyon and DeJong [24] have described the design and implementation of a high level diagnostic system, where combustion and gear mesh excitation of a diesel engine was monitored. Janisz and Brokenshire [21] reported recently on experimental use of a new system which employs a minicomputer with access to 300 transducers to monitor the healt of machinery in a large fossil fuel power plant.

Two litterature surveys have been given already on mechanical signature analysis. Volin [37] covered litterature up to and including 1979 and Hundal [20] from 1980 through 1982. These cover a little broader range of aspects than this one does.

3. Processing methods.

Several different methods have been applied to mechanical signature analysis. These range from simple level crossing detection to computationally intensive methods like multiple coherence calculations and cepstrum analysis. Although most methods are borrowed from statistics and system identification, some are designed specifically for diagnostics. They also differ in the amount of experience gained from their use.

Processing methods may be separated into three groups, in which processing is done either in the time, frequency or amplitude domain. Of the frequency domain methods, fast Fourier transforms (FFT) have enjoyed most popularity due to the common availability of spectrum analysers. Xistris et al. [39] have described a typical approach to using digital frequency domain techniques and Leon [23] provides some warnings and advice on how to perform the sampling for accurate representation. When diagnostic monitoring is automated using FFT the most easily implemented approach is to check if the spectrum or a certain part of it fits inside an envelope which represents limits of normal operation. However the FFT has leakage problems and limited resolution especially for short data records. Therefore alternative methods have been compared to the FFT. Romberg et al. [33] compared the performance of the FFT to the maximum entropy method in distinguishing two closely spaced vibration modes and Davies and Hammond [17] have compared it to three different parametric methods, namely Prony method, recursive least squares and the instrumental variable method as applied to structural system identification. A good tutorial of spectral analysis methods, including the above and others, has been written by Kay and Marple [22]. An interesting alternative to the FFT is provided by the fast Hartley transform which Bracewell [3] has developed.

Of the parametric frequency domain methods, ARMA (Autoregressive Moving Average) or AR seems to be gaining in popularity. Wu et al. [38] have performed ARMA identification on vibrations of a healthy electric motor to provide a reference filter which during monitoring cancelles the modelled dynamics and provides the residual (unmodelled) error sequence. A fault is diagnosed by comparing the power of this residual error to predetermined limits. Shuaib et al. [34] and Pandit et al. [28] [29] [30] [31] use the parameters of the model to calculate the characteristics of vibration modes which are found to change in accordance with the phenomenon being monitored. Bartelmus [1] has used the coherence function to indicate the quality of gear mesh.

Time domain methods are especially suitable to rotating machinery when the sampling is synchronized with the rotation in question and an integer number of rotations is analysed. This has the advantage of making FFT spectra of any signals that are coherent to the rotation free of leakage. Also, by adding sequences of synchronized data in the time domain, all noncoherent components of the signal will eventually cancel and the coherent component is left as if filtered out with an infinitely sharp comb filter with passbands at integer values of the fundamental rotation frequency. This procedure was developed by Braun [5] [6] [7].

When signals need to be separated into a primary component and delayed copies of the primary (e.g. due to reverberation) simple linear filtering may not suffice. This may then be done by cepstrum analysis, which is based on calculating the logarithm of the spectrum of a signal and then transform the result into a "time" domain, in which the two components will be more distinct than before in the original time domain. Lyon and Ordubadi [25] have described this procedure and its use in reconstructing the pressure profile of an internal combustion engine given measurements of engine block vibrations. Staufert and Tschudi [35] have used cepstral analysis for estimating the structural response of machine tools in operation.

Amplitude domain methods involve compilation of statistical parameters that are found to be sensitive to the machine's healt. Complexity of these methods ranges from detection of levels, such as in vibration severety measurements to forming combinations of statistical moments. The latter has been widely used in roller bearing condition monitoring where a dimensionless number called kurtosis which is the fourth moment of the variance of the acceleration record divided by the variance squered, is found to rise with the service life of the bearing. Cempel [11] [12] has described a set of such parameters and the determination of limits for these. These parameters have the important advantage of being independent of some variable properties of the machine, such as rotation speed. Other methods that have been presented are the compilation of density and amplitude statistics of peaks that appear in the time series [8] and estimation of the autocorrelation function using a technique called Random Decrement (Randomdec) [36] which is based on adding segments of the time series such that they begin at a certain trigger level. The autocorrelation is shown to be proportional to the expected value of the sum. Braun has described a method to keep track of changing variances [9].

Some methods are directly aimed at diagnostic systems with multiple simultaneous measurements. These systems provide information that allows sources to be distinguished and noise extracted from signals. The latter has been done by Chaturvedi and Thomas [13] in an experiment where the signal to noise ratio of a monitoring signal for a roller bearing was enhanced by attaching a sensor at a location where the primary signal was corrupted by noise and another one at a different location which measured noise which was in some unknown way related to the primary noise. Braun and Schulmann [10] have described a method for ranking the inputs by their monitoring effectiveness by using coherence matrices. Powell and Seering [32] have presented a method for estimating the input force time histories using the measured outputs and a stored matrix of frequency response functions. The method, wich uses pseudo inverses and singular value decomposition, is claimed to be able to separate multiple input force signals even when the vibration signals contain reverberated information from the inputs in overlapping frequency ranges. Gersch et al. [19] have described methods for source identification and power estimation using parametric methods (ARMA-AR).

Having now exhausted the list of references that give describtions of monitoring methods, it is interesting to note what is not reported. For example, there is not much said about the real time operation aspects of the monitoring process, such as computational requirements, how fast a failure is detected and how frequently the performance of the machine is checked. Only Braun [9] has presented a recursive method but these seem to be conceptually well suited for the task at hand because at every measurement an updated estimate of the machine's condition can be quickly calculated, whereas for batch processing sampling may have to be stopped while the data is being processed and new information is not available until the next data sequence has been collected and processed.

It is evident from this survey of methods that they represent a "bag of tricks" from which an appropriate method must be pulled for each application. As a final note, a good guide through this myriad of techniques is provided by Bendat and Piersol's book on correlation and spectral analysis [2] and the afore mentioned tutorial paper by Kay and Marple [22].

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3c - Realtime LISP Environment

A related research area is relating a realtime LISP environment. This work is currently funded by seed money from SIMA, the Stanford Institute for Manufacturing and Automation. Symbolics has indicated willingness to lend us a machine during the coming year on which John Bourg will be using some examples from our ultra precision machining to drive more practically the development of a realtime LISP environment in which to inbed the various considerations we have discussed earlier in surrounding the ultra precision machine with adequate computational, data and reference support.

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