Aerojet TechSystems

Orbital Transfer Rocket Engine Technology Program Integrated Control and Health Monitoring Capacitive Displacement Sensor Development

Task E.4 Final Report
Contract NAS 3-23772
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July 1989

Prepared for:
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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INTEGRATED CONTROL AND HEALTH MONITORING CAPACITIVE DISPLACEMENT SENSOR DEVELOPMENT FINAL REPORT

ORBIT TRANSFER ROCKET ENGINE TECHNOLOGY PROGRAM

Prepared For

National Aeronautics and Space Administration

By

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Aerojet TechSystems

NASA Lewis Research Center
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NASA LeRC Task Monitor was Marc G. Millis

16. Abstract

The development of a miniature multifunction turbomachinery shaft displacement sensor using state-of-the-art non-contract capacitive sensing technology is described. Axial displacement, radial displacement, and speed are sensed using a single probe within the envelope normally required for a single function. A survey of displacement sensing technology is summarized including inductive, capacitive, optical and ultrasonic techniques. The design and operation of an experimental triple function sensor is described. Test results are included showing calibration tests and simultaneous dynamic testing of multiple functions. Recommedations for design changes are made to improve low temperature performance, reliability, and for design of a flight type signal conditioning unit.

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FOREWORD

This document represents the final report to the National Aeronautics and Space Administration for work performed under Task Order E.4 to Contract NAS 3-23772. The task work span was from February 1987 through November 1988. This task addressed the Integrated Controls and Health Monitoring (ICHM) technology requirements for the Orbit Transfer Rocket Engine Technology Program. This is a summary report in that all material discussed herein was presented to the NASA program personnel at oral presentations or in the contractually required monthly program reports during active work on the task.

The principle investigator was Frank Collamore. The NASA LeRC Task Monitors were Richard Dewitt and Marc G. Millis. The prototype displacement sensors were manufactured by ADE Corporation.

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1.0 SUMMARY

This report describes the development of a miniature multi-function turbomachinery shaft displacement sensor using state-of-the-art non-contact capacitive sensing technology. Axial displacement, radial displacement, and speed are sensed using a single probe within the envelope normally required for a single function.

As part of this development an industry survey of over 150 manufacturers was made to select the technology best suited for the application. Included in this investigation were the following displacement sensing technologies:

1. Inductive
2. Capacitive
3. Optical
4. Ultrasonic

Non-contact capacitive sensing technology was selected for further development based on a superior combination of sensitivity, size, frequency response, and environmental tolerance.

The triple function capacitive sensor probe tip has three independent sensing electrodes which run in a groove in the shaft of the turbopump. The electrode on the tip measures the radial displacement of the shaft while the two side electrodes measure the axial displacement. One axial displacement sensor is used to measure speed by sensing a notch in the side of the groove facing one electrode. Sensors are excited from a high frequency oscillator. Diode assemblies in the probe tip create displacement signals as a direct current offset to the alternating current which is then measured and linearized by a signal conditioning unit.

Two experimental triple function sensor probes were fabricated along with a laboratory type signal conditioning console unit.

Performance tests are summarized as follows:

1. Room temperature calibration tests showed that each sensor error band was within ± 1.0 percent over its operating range of 0.005 inch to 0.015 inch.

1.0, Summary (cont.)

2. Rotating tests with a turbopump shaft simulator showed good dynamic response and simultaneous measurement of two variables. (The signal conditioning console had only two channels.)

3. Temperature compatibility tests were performed by immersing the sensor tip in liquid nitrogen (-320°F). These tests showed an indicated displacement shift greater than that expected from the change in dielectric constant between air and liquid nitrogen. Further investigations indicate that the potential causes for this shift are instability of the reference capacitors in the sensor tip, and changes in leakage capacitance of interconnections due to condensation or changes in material dielectric constants.

Conclusions reached from this special phase of the development program are:

1. Multi-function capacitive sensing is practical and provides an excellent means to reduce instrumentation penetration into turbomachinery housings.

2. Capacitive sensing meets resolution and response requirements for high speed turbopump shaft displacement measurements.

3. Additional development is needed to resolve the greater than expected low temperature shift. An improved design is defined herein.

4. Development of a small flight type conditioning unit is recommended to provide a flightweight sensor for rocket engine applications. A design is described herein.

2.0 INTRODUCTION

Aerojet has been investigating engine control and health monitoring technologies for the Orbit Transfer Vehicle Engine under NASA contracts starting in 1979. Over this period the emphasis has changed from strictly engine control to an integrated control and health monitoring system. This system requires a comprehensive stream of data supplied by sensors measuring important engine parameters.

Control and health monitoring system effectiveness is limited by the availability of suitable sensors.

One area of particular interest is the measurement of rocket engine turbomachinery internal dynamics. This task addresses this need.

The purpose of this task is to investigate and develop a sensor to measure axial and radial displacements of turbomachinery shafts. The task was divided into the two following subtasks.

1. Identify and evaluate approaches to measure the axial and radial displacement of turbomachinery shafts operating at high rotational speeds, and to select an approach which provides significant size reductions relative to currently available proximity probes. Provide a test plan for evaluating the most promising approach by means of suitable experiments or bench tests.

2. Fabricate or procure experimental probes of the design selected in the previous subtask and to perform the experimental evaluation. Perform experiments to determine the feasibility of the selected approach and identify any improvements or modifications necessary to provide a reliable sensor.

The multi-function capacitive displacement sensor developed as part of this task is an extension of the capacitive sensing technology developed by ADE Corporation using their active sensor probe technique. This technology was further developed during this program to incorporate three independent sensors into a single sensor probe and to adapt it to sensing relevant turbomachinery parameters. A

2.0, Introduction (cont.)

description of capacitive sensing and the active probe technology is included in Appendix B by David McRae of ADE Corporation.

3.0 EXPERIMENTAL MODEL DEVELOPMENT

The initial task was to review the state-of-the-art technology and select the approach which will result in the best overall sensor to measure both axial and radial displacement. A major objective was to reduce the sensor size for improved installation while maintaining the high reliability required for space based applications.

3.1 SENSOR REQUIREMENTS DEFINITION

A preliminary definition of sensor requirements was made in order to investigate and screen the various displacement sensor technologies that are currently available.

Table 1 lists requirements typical for a shaft displacement sensor to measure shaft deflections of a high speed cryogenic rocket engine turbopump.

TABLE 1

DISPLACEMENT SENSOR REQUIREMENTS

Range	0.005 to 0.015 inch
Resolution	0.00001 inch
Error Band	± 1.0% of range
Repeatability	± 0.25% of range
Thermal Sensitivity Shift	± 0.005% of range/°C
Temperature Range	-253°C to +100°C
Frequency Range	0-10 KHz (±5% displacement error)
Pressure Range	0-10,000 psia
Material Compatibility:	
Liquid and Gaseous	Oxygen
Liquid and Gaseous	Hydrogen
Liquid and Gaseous	Nitrogen

3.2 SURVEY OF AVAILABLE SENSOR TECHNOLOGY

A survey of available technology was undertaken to determine the current state-of-the-art for displacement sensors, their capabilities, and applicability to the OTV turbomachinery.

A library literature search was made yielding 122 items. The literature covered a wide range of transducer subjects including inductive, capacitive, ultrasonic, optical, and fiberoptic devices.

Profiles from 151 companies listed in the "Sensor and Transducer Directory" which included displacement or proximity sensors in their product line were reviewed. Inquiries were set to 42 companies from this list which appeared to have applicable technology. Most of the responses which were received described devices and technology that were for industrial applications and did not have the accuracy and resolution needed. Examples of some of the commercially available displacement measuring instruments which most nearly meet our requirements are shown on Table 2. Included in this investigation are the following displacement measuring technologies:

1. Inductive
2. Capacitive
3. Optical
4. Ultrasonic

The following assessments were made of the available technologies based on past experience combined with the results of this investigation:

Inductive:

Inductive displacement sensors measure the distance from the sensor to the target by generating a high frequency magnetic field. As the target moves toward the sensor coil eddy currents are generated in the target material which show up as losses in the oscillator bridge network. The variations in losses or distance are detected and used as a measurement of displacement. A typical block diagram of the sensor system is shown in Figure 1.

Table 2
Displacement Measurement Instruments

Type	Manufacturer	Range Mil	Resolution Mil	Accuracy	Size inches	Temp. Range °F	Output	Freq. Response	Comments
Inductive	Bently Nevada Corp. Minden, Nevada	70		± 1%	0.2 dia 0.8 Lg	-30 - +350	200 mv/mil	10kHz	Requires signal conditioner (proximitor) Size 2.0x2.4x3.1 in. Larger size probes avail.
Inductive	Metrix Instrument Co. Houston, TX	80			0.19 dia 1.26 Lg	-35°C - +175°C	200 mv/mil	3kHz	Requires signal conditionr. Used 1mHz excition to probe.
Inductive	Kaman Inst. Co. Colorado Springs, CO	10	0.004	± 1/2%	0.08 dia 0.81 Lg #10/32THD	-65°F - +300°F	100 mv/mil	50kHz	Requires signal conditioner. Several probe sizes available. Thermal sensitivity shift 0.008 mil/°F
Inductive	Scientific-Atlanta, Inc., Atlanta, GA	80			0.19 dia 0.75 Lg	-30 - +350°F	200 mv/mil	50kHz	Requires signal conditioner
Capacitive	ADE Corp. Newton, MA	3 to 9	1×10^{-3}	± 0.4%	0.10 dia Tip 0.280 x 1.0 lg overall		± 10 vdc Full Scale	40kHz	Probe contains 4 diodes and is excited from 3mHZ driver. External linearization circuits req'd. Min. electrode dia = 0.019 in.
Capacitive	MTI Inc. Latham, N.Y.	0.25 to 10	10×10^{-3}	± 0.4%	.25 x 2.5 in.	-200°F - +400°F	± 10 vdc	5kHz	Special coax cable req'd. No electronics in probe. Higher resolution for smaller range.
Fiberoptic (Lever)	MTI Latham, N.Y.	0.002 to 0.0055	1.4×10^{-3}	± 5%	0.063 in. x 3.0 in.	-100 - 300°F	6	60kHz	Probes available to .020" diam. with lesser performance
Fiberoptic (Lever)	EOTec Corp. West Haven, CT	≈.005	.06 min/mv		.285 dia x .95 in. lg		0-10 volts	5kHz	
Laser Triangulation	Diffracto, Ltd. Troy, MI	0.080	4×10^{-2}	±1... %	6 x 3.4 x 1 in.			200/sec	2 inch standoff distance required

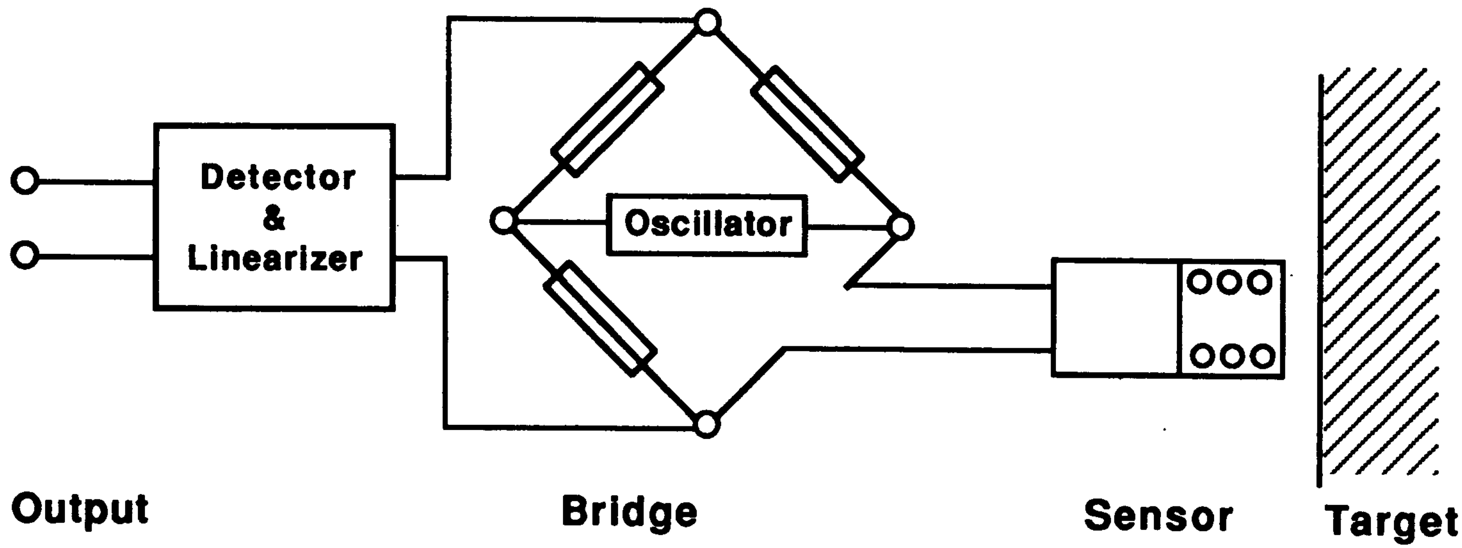

Figure 1. Inductive Displacement Sensor Schematic

Inductive sensors are widely used for displacement sensing in industrial applications and machinery. Aerojet has used them successfully in rocket engine turbomachinery for non-cryogenic applications. Sensors are available as small as 0.08 in. dia x 0.8 in. long. Larger diameter sensors measure larger displacements. Output is typically 200 mv per 0.001 inch. Frequency response is as high as 50KHz for some units.

Some of the factors affecting the indicated displacement are:

a. Target material resistivity and permeability
b. Proximity of sensing tip to conducting material
c. Temperature of sensor
d. Temperature of target

Multiple sensors in close proximity to each other can cause crosstalk and noise which will diminish their accuracy.

Our recent experience in using inductive sensors at liquid nitrogen temperatures (-320°F) has indicated erratic behavior with large signal changes under constant displacement conditions. In another case where sensors were designed specifically for use in liquid hydrogen the performance appears to be better. The initial calibration shows fairly good linearity from 0.005 to 0.015 inches. Zero shift is from zero to 0.003 inches from temperatures of -320°F to -411°F. To be useful the operating temperature must be known continuously and calibration curves at the appropriate temperature must be available or a temperature compensating signal conditioning unit is needed.

Factors affecting calibration are:

a. Coil resistance and temperature coefficient
b. Target material resistivity and temperature coefficient
c. Lead resistance variations

Capacitive

Capacitance displacement sensors use the capacitance between the sensor electrode and the target as an indication of distance. The circuit capacitance is inversely proportional to the distance between the sensor electrode and the target. Because the measured capacitance is very small (in the picofarad range) it is necessary to eliminate the effect of probe and lead leakage capacitance which can be many times the measured capacitance. Several signal conditioning approaches are used to try to meet this objective. Figures 2 and 3 show diagrams of two commercially available capacitive instruments capable of precision measurements. The ADE instrument excites the capacitive sensor with a high frequency (3mHz) driver to provide a signal proportional to the tip capacitance. A diode/capacitor circuit located in the sensor tip converts the alternating current to a direct current signal which may be transmitted to the signal conditioning unit unaffected by lead capacitances. Frequency response of 50KHz is claimed with resolution better than one microinch for sensor to target separation in the range of 0.010 inches. Standard sensor probe diameters as small as 0.280 inches are available. No cryogenic temperature performance is claimed; however, with diodes and a reference capacitor as the only temperature sensitive elements in the probe tips performance is expected to be as good.

The MTI instrument is an example of a passive capacitive displacement instrument. This instrument has no active electronics in the sensor tip. It uses a guarded circuit to eliminate the effects of stray and cable capacitance. The sensor configuration is shown in Figure 3.

Because of this configuration its excitation frequency is much lower resulting in a frequency response of 5KHZ maximum. The standard sensor tip is 0.25 inch diameter for a 0.010 inch range and has a resolution of 1×10^{-5} inches.

Optical

Optical displacement sensors use light reflected from the target as a means of measuring displacement. To obtain high resolution and accuracy special provisions are required. Some laser-based systems use triangulation to obtain displacement. These systems are usually bulky and not suitable for aerospace applications.

One unique system which takes advantage of fiberoptic technology is represented by an instrument manufactured by MTI. It measures light reflected from the target through a bundle of optical fibers. The arrangement is shown in Figure 4.

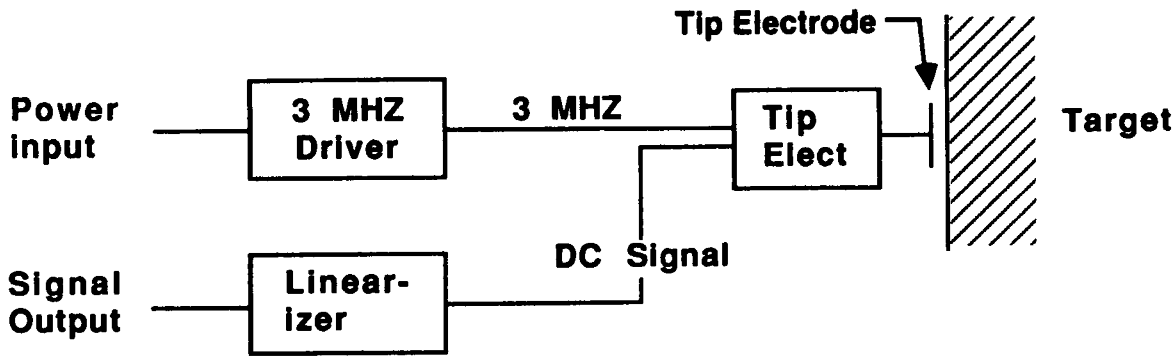

Figure 2. Block Diagram of ADE Capacitive Sensor

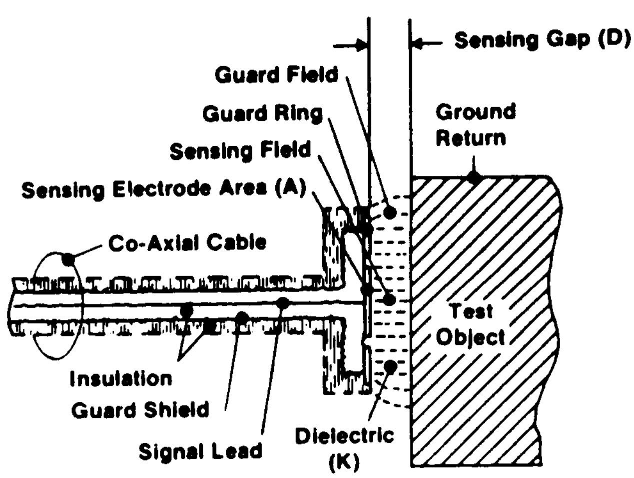

Figure 3. MTI Sensor Configuration

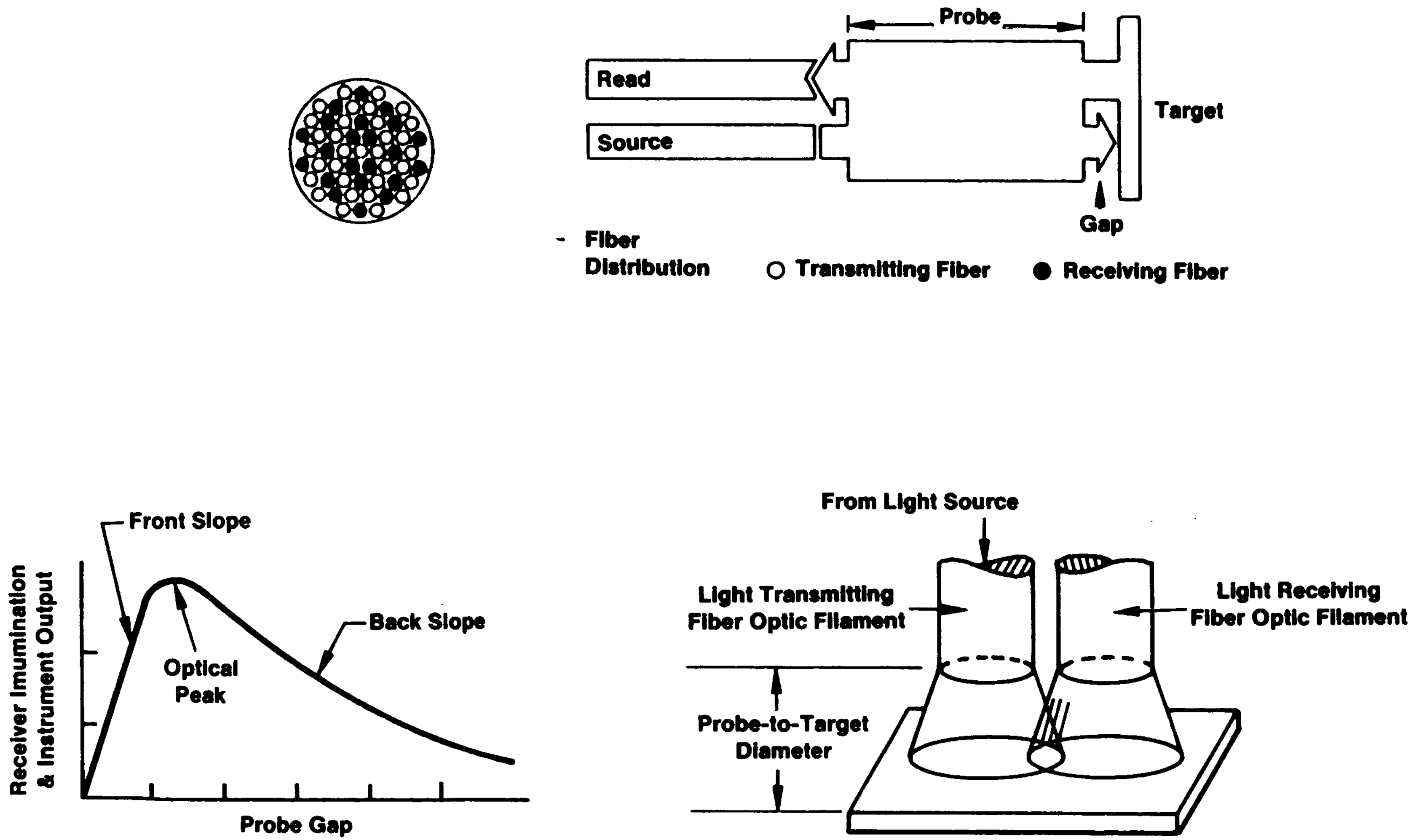

Figure 4. Fiberoptic Sensor Operation

3.2, Survey of Available Sensor Technology (cont.)

The sensor system utilizes adjacent pairs of light transmitting and light receiving fibers. The basis for the sensing mechanism is the interaction between the field of illumination of the transmitting fibers and the field of view of the receiving fibers. At contact with the target no light is provided to the receiving fibers. As the gap is increased a rapid increase in light to the receiving fibers is realized until an optical peak is reached. Beyond that gap the light reflected to the receiving fibers decreases according to a square function.

The system provides resolution in the microinch range with sensors as small as 0.063 diameter. Sensors have been made as small as 0.020 diameter with some loss in resolution. Problems due to differential expansion of the fiberoptic bundle and the metal sheath have occurred at cryogenic temperatures. Variations in surface reflectance and media opacity will result in measurement errors. In addition, accurate measurements are difficult to achieve without on-line gap adjustments.

Ultrasonic

Ultrasonic displacement transducers measure distance by reflecting high frequency acoustic energy from the surface of the target and measuring the transit time. These systems have a resolution capability in the range of 0.001 in. which is inadequate for measuring rotor dynamics of high speed turbomachinery. In addition, media temperature variations can introduce significant errors as sonic speed is a function of temperature.

3.3 EXPERIMENTAL EVALUATION OF A CAPACITIVE SENSOR

One of the most promising of the commercially available capacitive sensors found in the industry survey is the Microsense® system by ADE Corporation. Its advantages for our application are:

Sensitivity	2MV/μ inch
Standoff	0.010 inch
Range	± .005 inch
Frequency Response	40 kHZ

In as much as there was no experience or data on performance at temperatures below 40°F a test unit was provided by ADE for evaluation at cryogenic temperatures. The purpose of these tests were to determine if there were any functional problems in operating this type of capacitive sensor at liquid nitrogen temperatures. The experimental evaluation results are described in Appendix A.

The configuration of the test unit is shown in Figure 5. The tests were performed with fixed displacement sittings using a fixture and test setup as shown in Figure 6. The test specimen was immersed in liquid nitrogen and the indicated displacement was recorded. The indicated displacement was corrected for the change of dielectric constant from 1.00 for air to 1.433 for liquid nitrogen at -320°F.

A summary of the performance is shown in Table 3:

TABLE 3

CAPACITIVE SENSOR PERFORMANCE

Run Number	1	4	5
Displacement (mils)	11	15	11
Indicated Change (mils) (+70°F to -320°F)	-0.621	-1.782	-0.943
Error % of Setting	5.65	11.88	8.57
Thermal Shift %/°F	0.014	0.030	0.022

The results of these tests showed that the sensor operated over the temperature range of +70°F to -320°F with no apparent physical damage. The shift due to temperature change is within acceptable limits for measuring shaft dynamics of turbomachinery.

3.4 SELECTED TECHNICAL APPROACH

The various approaches which are available to measure axial and radial displacement of high speed turbomachinery shaft were identified and evaluated. Evaluation was based on the following criteria:

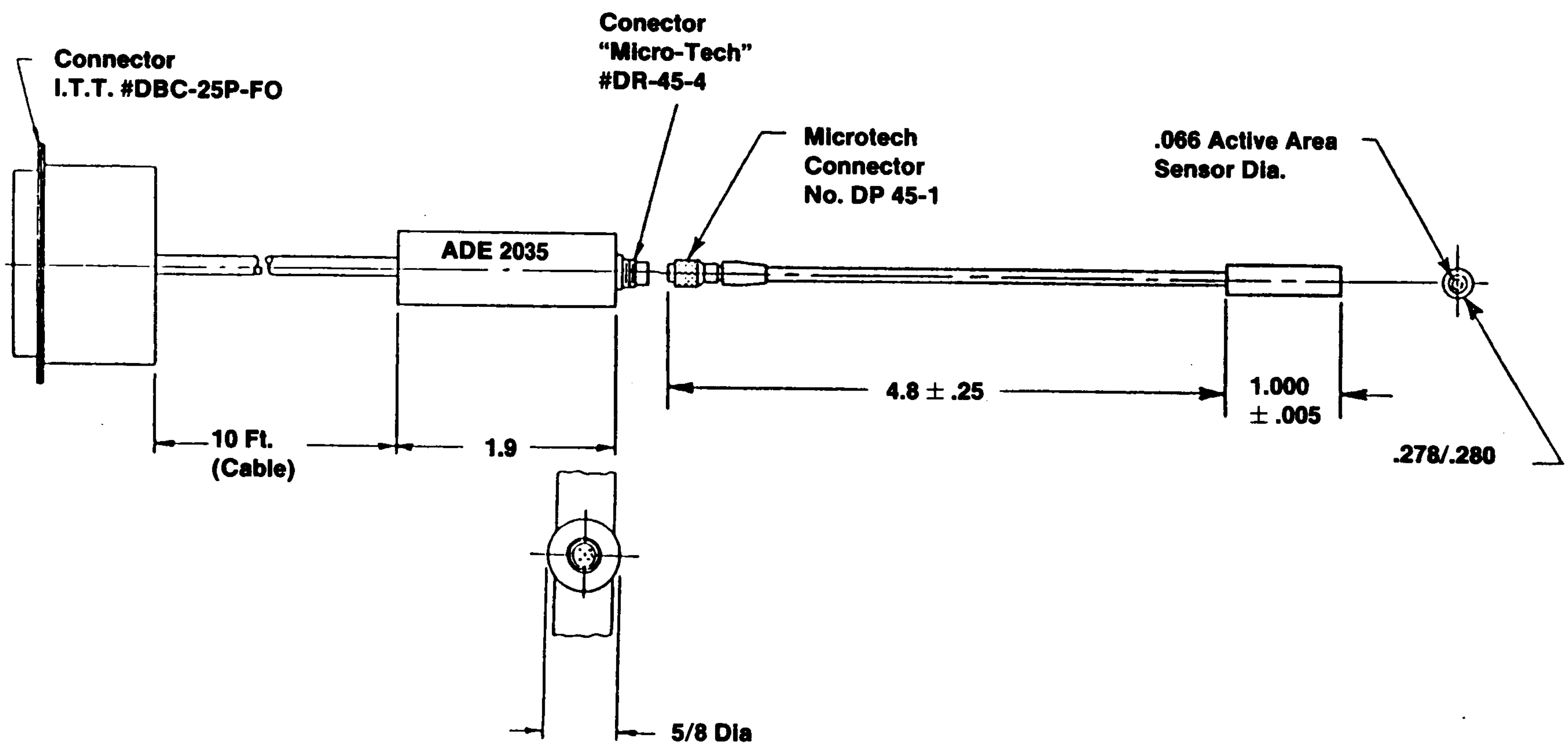

Figure 5. ADE Capacitive Sensor

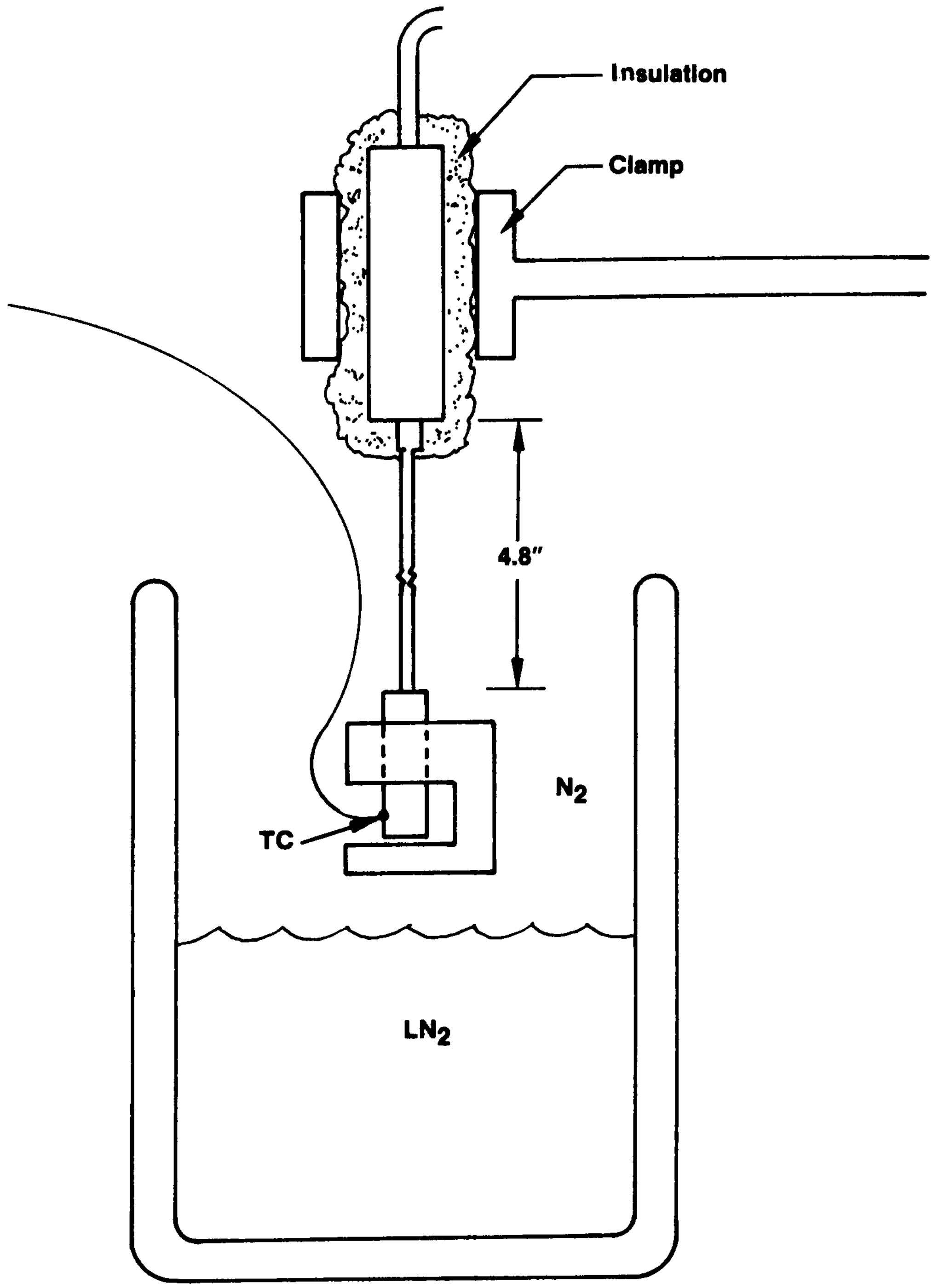

Figure 6. Cryogenic Test Setup

3.4, Selected Technical Approach (cont.)

a. size
b. Resolution
c. Displacement Measurement Range
d. Temperature Effects
e. Frequency Response
f. Environmental Compatibility

A subjective evaluation of the potential approaches is shown on Table 4. Of those listed, the capacitive technology offers the best potential for a miniature sensor compatible with the OTV environment. The capacitive transduction method appears to be the most stable under varying environmental conditions as capacitance is a function of the physical dimensions and dielectric constant of the media. A further advantage is that the capacitive sensor tip is the most adaptable to multiple function sensing.

There are two approaches which are used for capacitive displacement sensing. These are:

1. Passive sensing where the sensing probe contains only the sensing electrode and

2. Active sensing which have rectifier diodes and a reference capacitor in the sensor tip. A comparison of the attributes of the two systems is as follows:

	Passive	Active
Frequency Response	5KHZ	40KHZ
Resolution	0.01% of Range	-->
Linearity	0.2% of Range	-->
Temperature Stability	+	

As a result of this investigation capacitive transduction using active sensing technology was selected for the experimental evaluation phase of the program. The determining factors in making the selection were:

Table 4

NON CONTACT DEVELOPMENT TECHNOLOGY ASSESSMENT

Technology	Size	Resolution	Range	Temperature	Response	Environmental
Capacitance	3	5	4	4	4	4
Inductive	3	3	4	2	3	3
Fiberoptic/Lever	3	4	3	3	4	3
Optical Reflective	3	0	3	2	4	3
Optical Interference	0	5	1	1	1	1
Laser Triangulation	0	3	5	1	0	1
Ultrasonic	2	0	5	1	0	2

Ranking 0 (Unacceptable) to 5 (Excellent)

1. The higher frequency response of the active sensing technique is required for some turbopump applications.

2. The concept of a multi-function probe is easier to implement using active sensing technique. The shielded cables and guarded electrodes required for the passive system would be very difficult to implement.

3.5 CAPACITIVE SENSOR DESIGN

With the selection of non-contact capacitive sensing technology the design requirements for the experimental sensor were developed. These requirements are given on Table 5. Our approach to achieving the objective of providing a significant size reduction relative to currently available probes is to combine three sensors into a single probe of the size equal to that used by a single sensor currently available. This not only reduces the size required for a single sensor but also reduces the number of penetrations into the turbopump housing. The three functions sensed are axial displacement, radial displacement, and speed. Figure 7 shows how this concept works.

TABLE 5

DISPLACEMENT SENSOR REQUIREMENTS

Type	Capacitive
Range	0.005 to 0.015 inch
Resolution	0.00001 inch
Error Band*	± 1.0% of range
Repeatability*	± 0.25% of range
Thermal Sensitivity Shift*	±0.005% of range/°C
Temperature Range	-253°C to +100°C
Frequency Range	0-10 KHz (±5% displacement error)
Pressure Range	0-10,000 psia
Excitation	TBD
Signal	TBD
Material Compatibility:	
Liquid and Gaseous	Oxygen
Liquid and Gaseous	Hydrogen
Liquid and Gaseous	Nitrogen
Material:	
Body	Monel K-400
Electrodes	Silver, Nickel, Inconel

*Design Objective

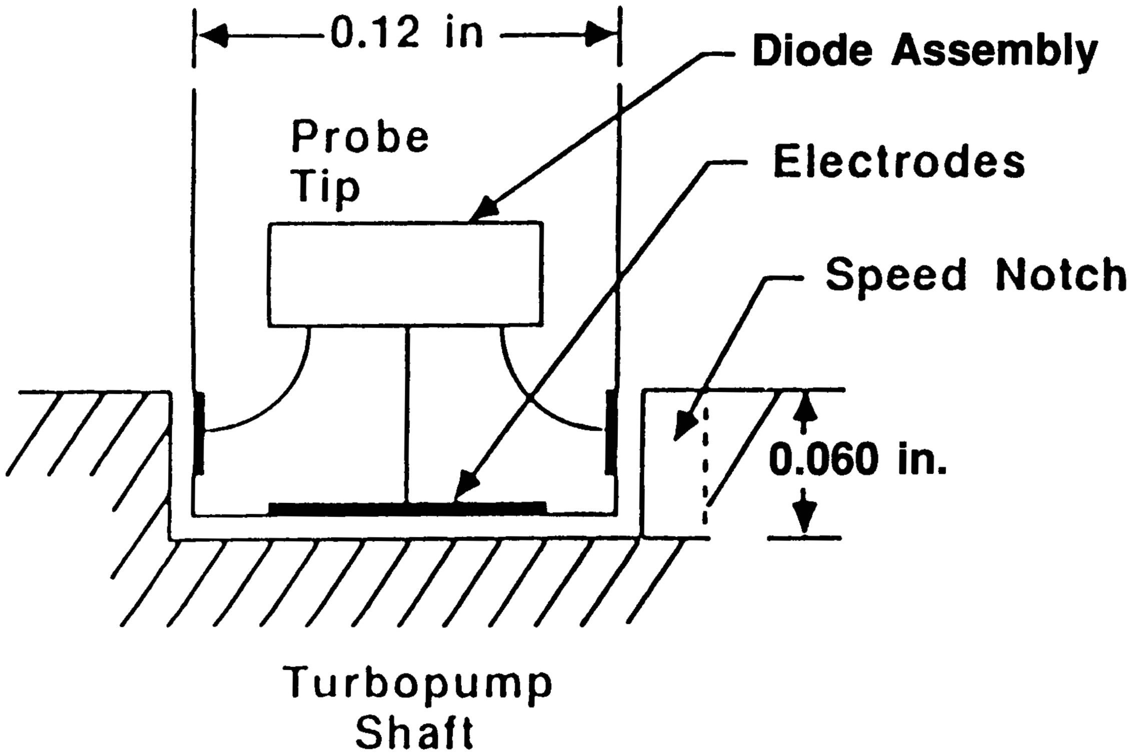

Figure 7. Triple Function Sensor Concept

3.5, Capacitive Sensor Design (cont.)

The probe tip has three independent sensing electrodes which run in a groove in the turbopump shaft. The tip electrode measures the radial displacement of the shaft while the two side electrodes each measure the axial displacement between the side of the groove and the probe. A notch in one side of the groove in the shaft generates a speed signal in one sensor. The sensors are excited from a high frequency oscillator. Diode assemblies in the probe tip convert the signals to direct current which is then linearized by the signal conditioning unit.

Figure 8 shows the envelope drawing of the triple function sensor. It is the same size as the miniature single function inductive probes currently used on the OTV oxygen turbopump. The sensing tip is 0.120 inch square by 0.080 inch long.

3.6 DESCRIPTION OF THE EXPERIMENTAL UNIT

The following experimental hardware was fabricated by ADE Corporation and delivered to Aerojet for testing and evaluation.

- (2) Three function capacitive displacement sensor probes
- (1) Oscillator-driven unit for one sensor probe
- (1) Set interconnecting cables
- (1) Model 3401 Microsense® 2 channel signal conditioning console

Figure 9 shows one sensor and its driver. Figure 10 shows the sensor tip detail. Figure 11 is a signal conditioning console unit similar to that used except a digital display with 0.00001 inch resolution was provided. It also has a ±10 volt dc analog output over its measurement range of 0.010 ±0.005 inches.

A block diagram of a single channel of the experimental sensor is shown in Figure 12. The amplifier/linearizer consists of current to voltage converters for both the positive and negative signals, a summing amplifier, a breakpoint stage to linearize the signal, and an output amplifier. The breakpoint stage is one method for linearizing the inverse characteristics of the capacitance vs distance produced by the sensor. It is a variable gain amplifier circuit which amplifies the signal by an amount dependent upon the magnitude of the signal itself. The result is to produce a linear output over the range of the sensor.

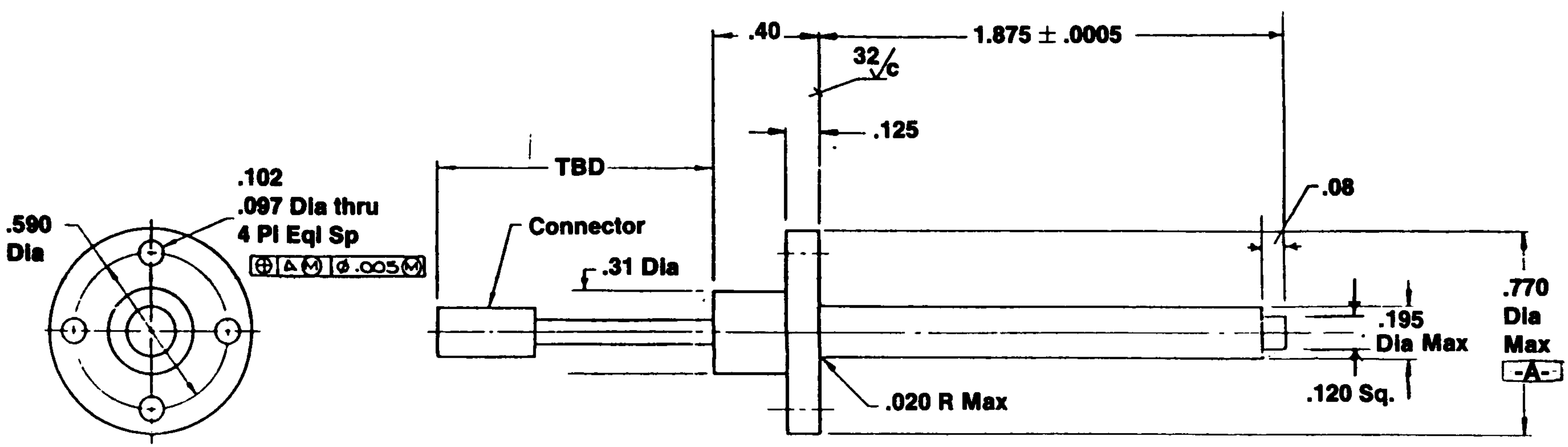

Figure 8. Triple Function Probe Envelope Drawing

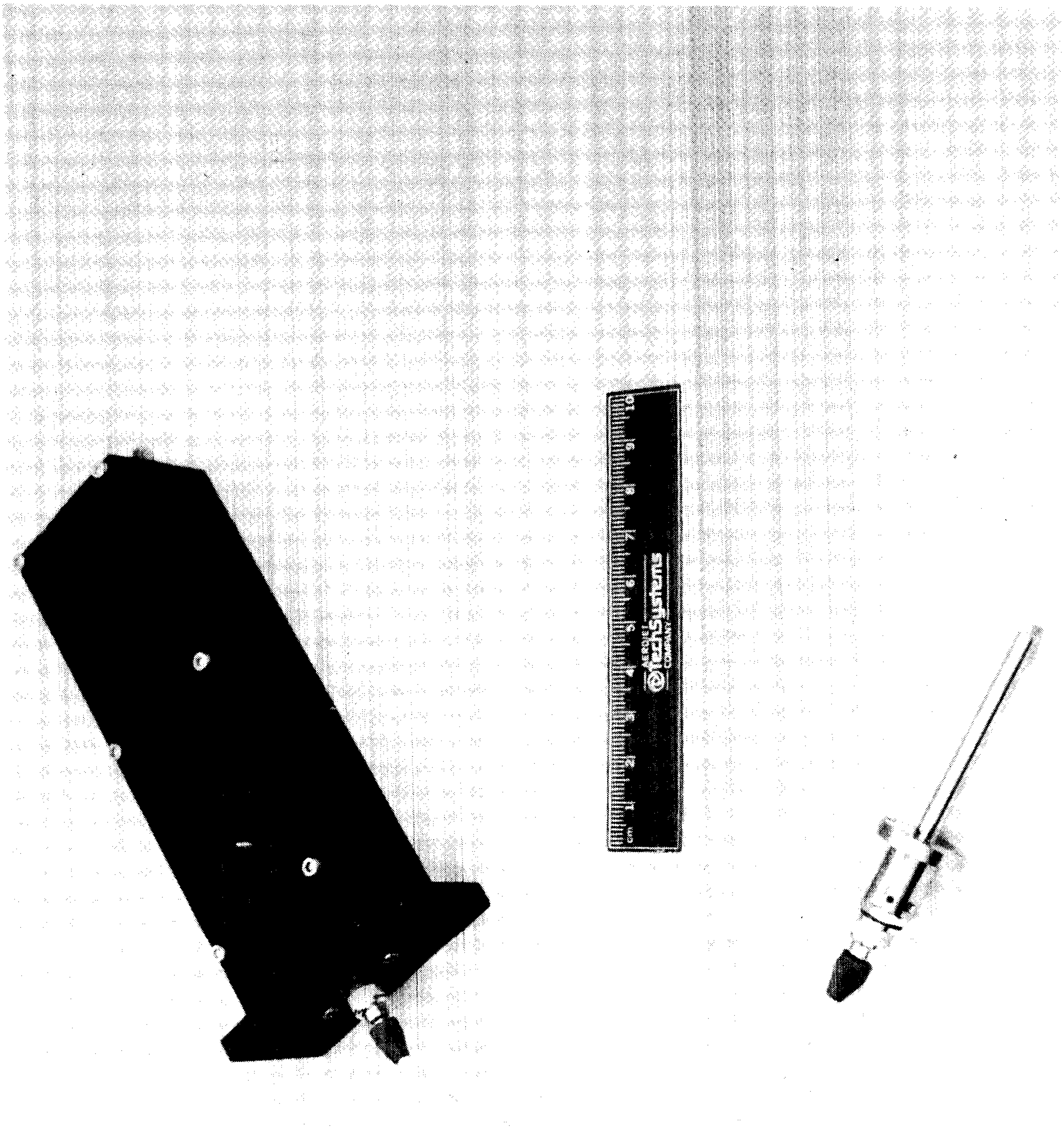

Figure 9. Triple Function Sensor and Driver

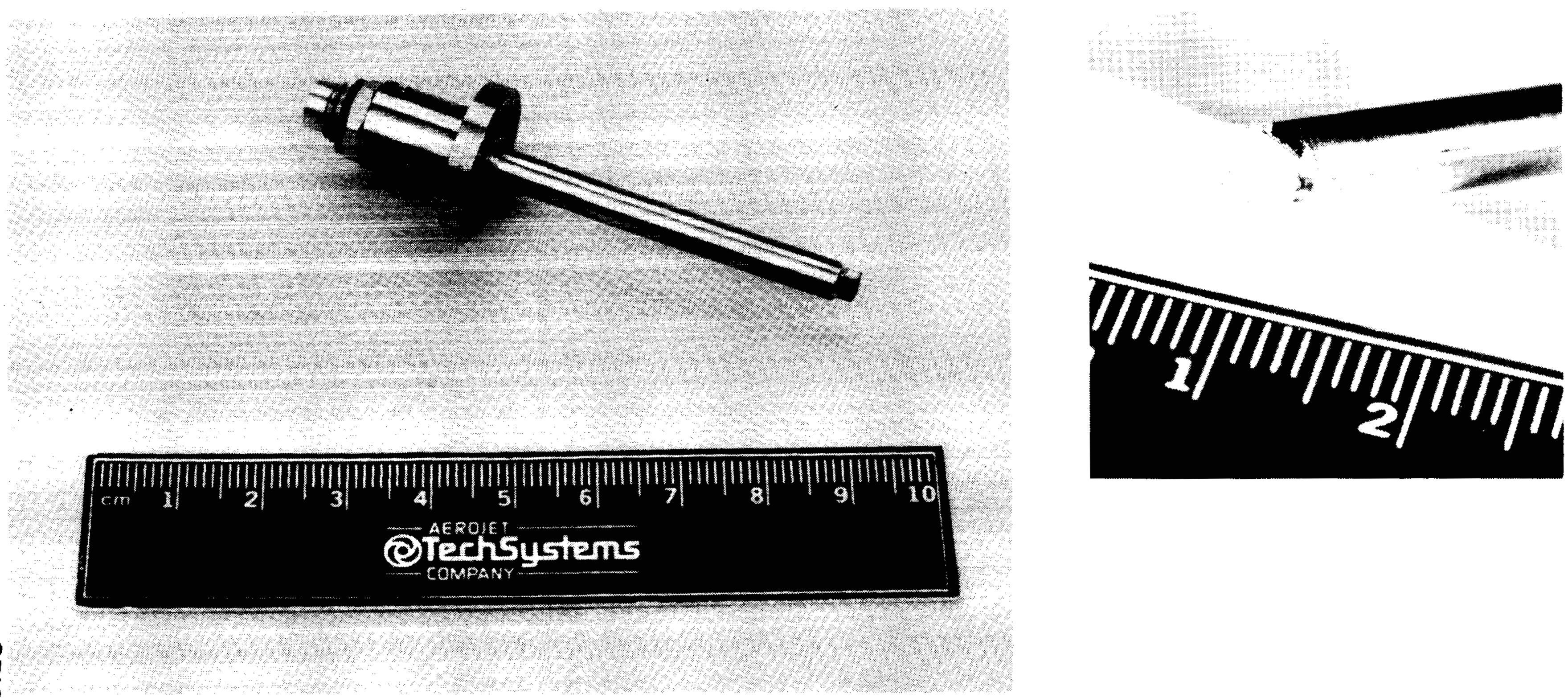

Figure 10. Triple Function Sensor

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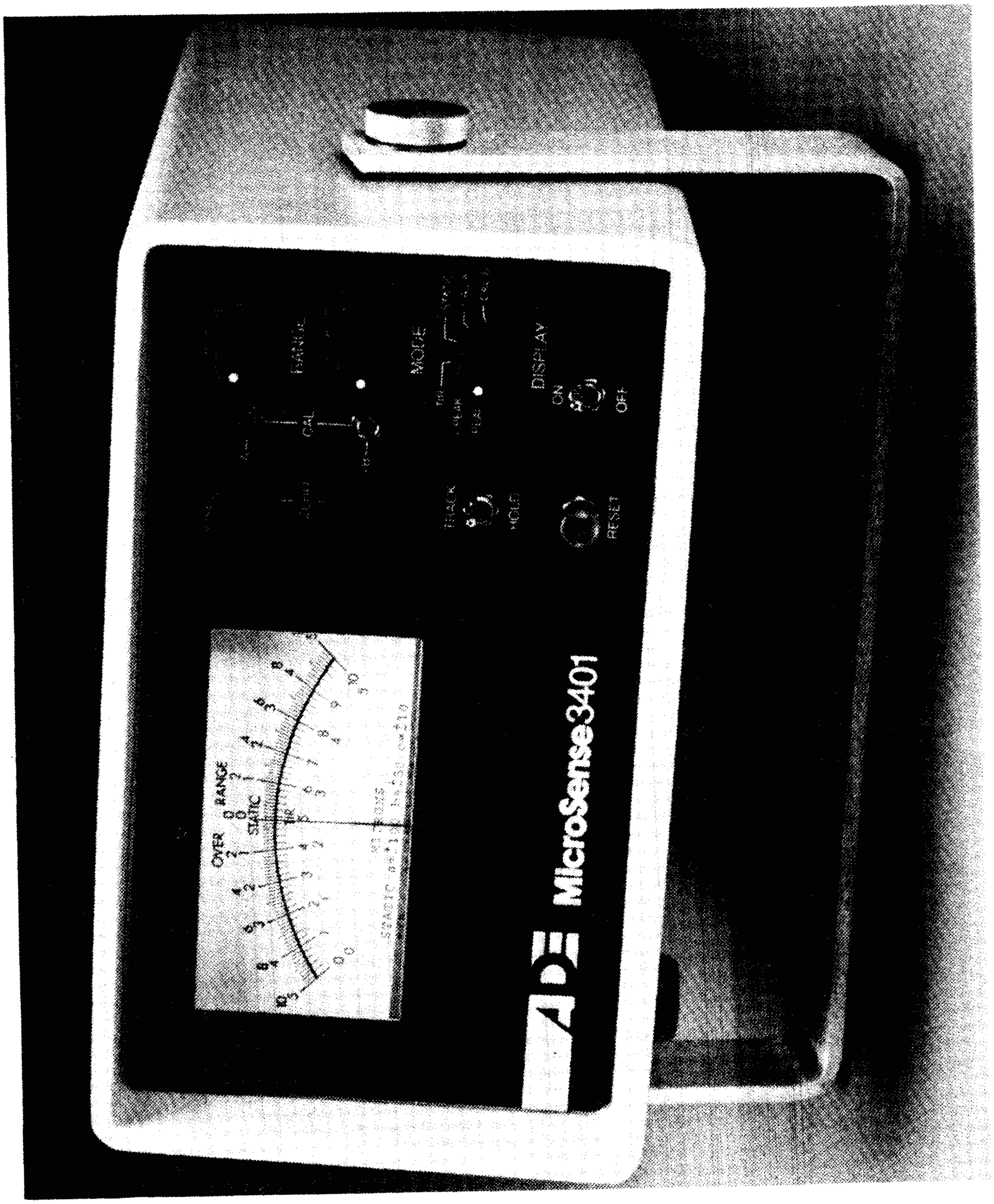

Figure 11. Signal Conditioning Console

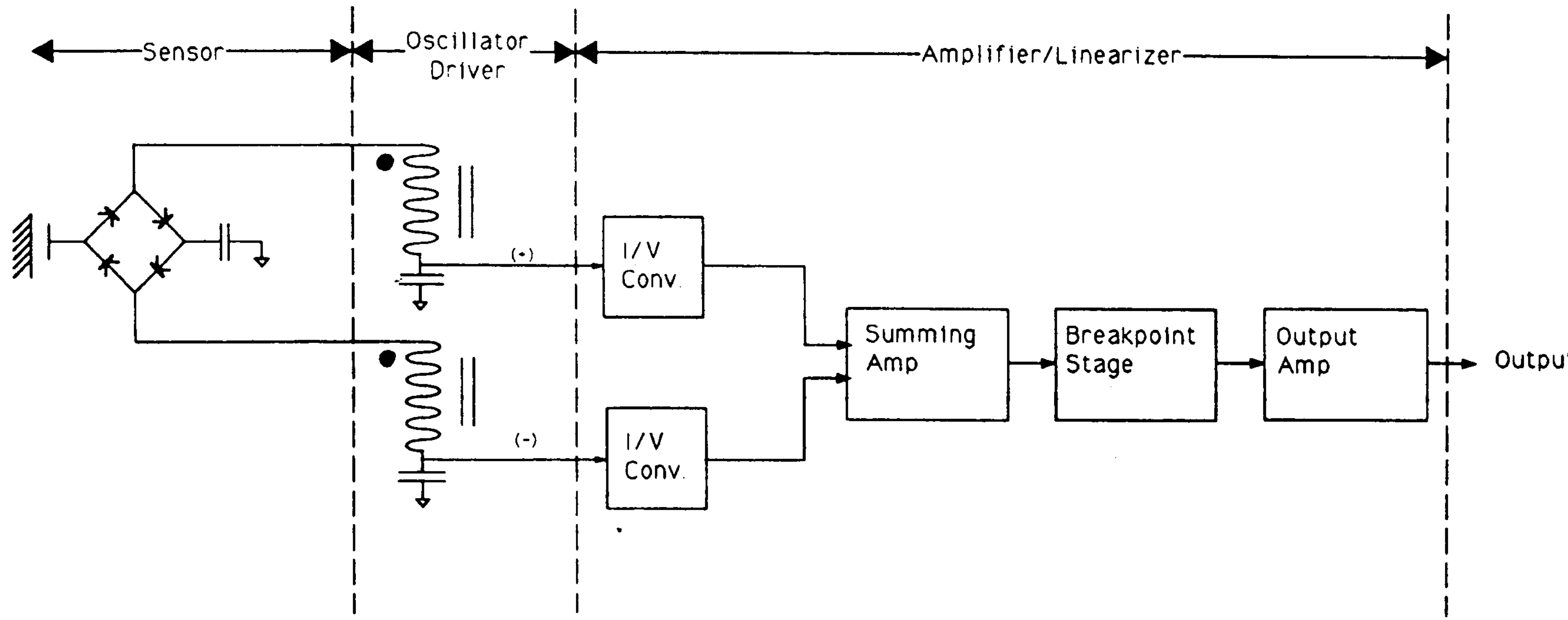

Figure 12. Capacitive Displacement Measurement System

3.6, Description of the Experimental Unit (cont.)

Figure 13 is the schematic diagram of the oscillator driver for the triple function sensor. A 3MHZ oscillator drives a transformer with multiple secondaries to excite the three sensors. Two corners of the diode ring are driven separately but in phase. The two resultant currents have equal, but opposite, non-zero mean values when the probe and reference capacitances are unequal. The dc component of the current to the probe is proportional to the difference between the sensing capacitor and the reference capacitor. This current has the inverse relationship of the sensor to target displacement which is then linearized by the amplifier-linearizer. A more detailed description of the capacitive sensing system is contained in Appendix B.

The following figures are design drawings which define the sensor.

Figure 14	Sensor Assembly
Figure 15	Sensor Housing
Figure 16	Sensor Electrode
Figure 17	Sensor Substrate

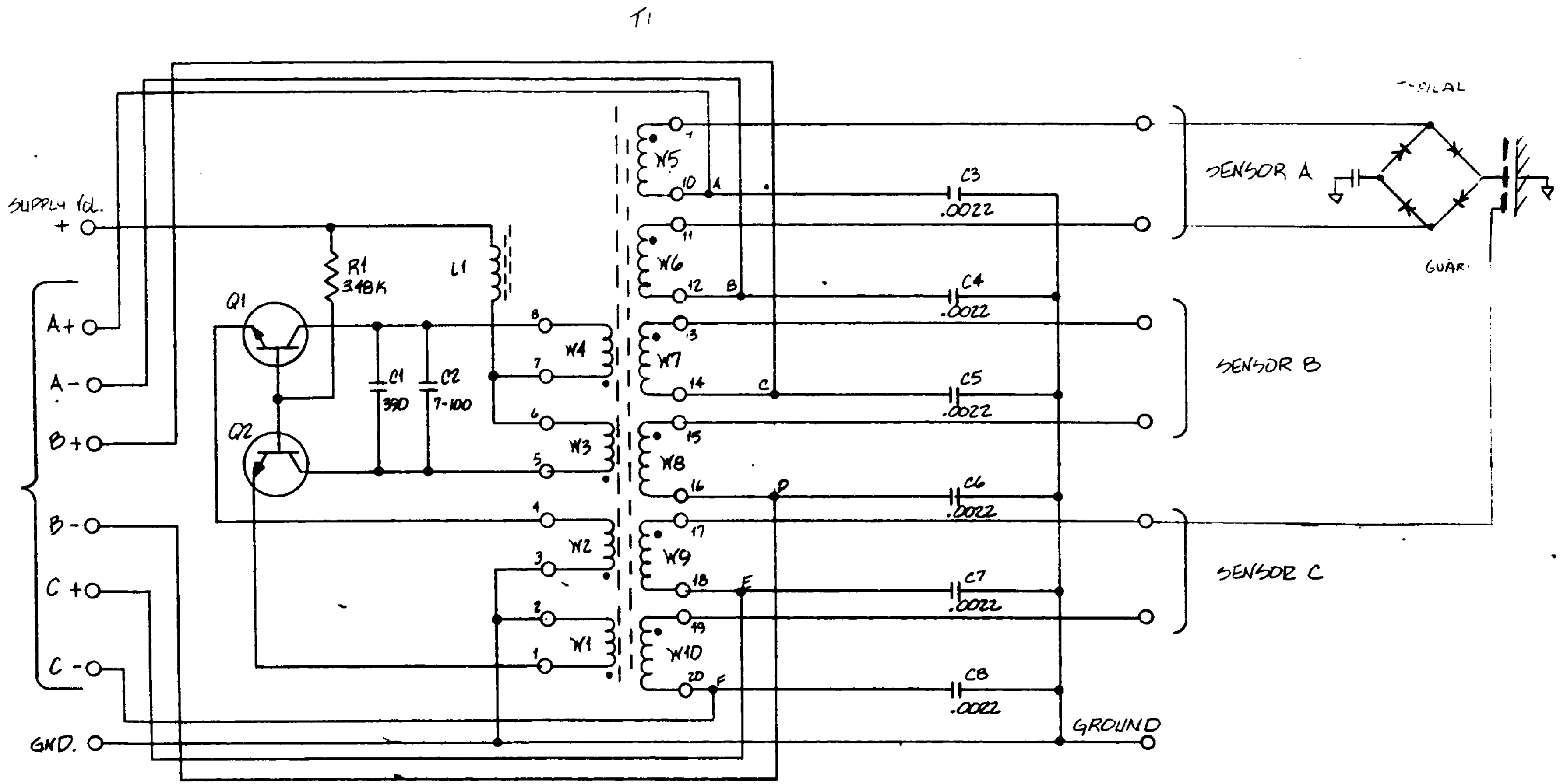

Figure 13. Electronic Driver for Triple Function Sensor

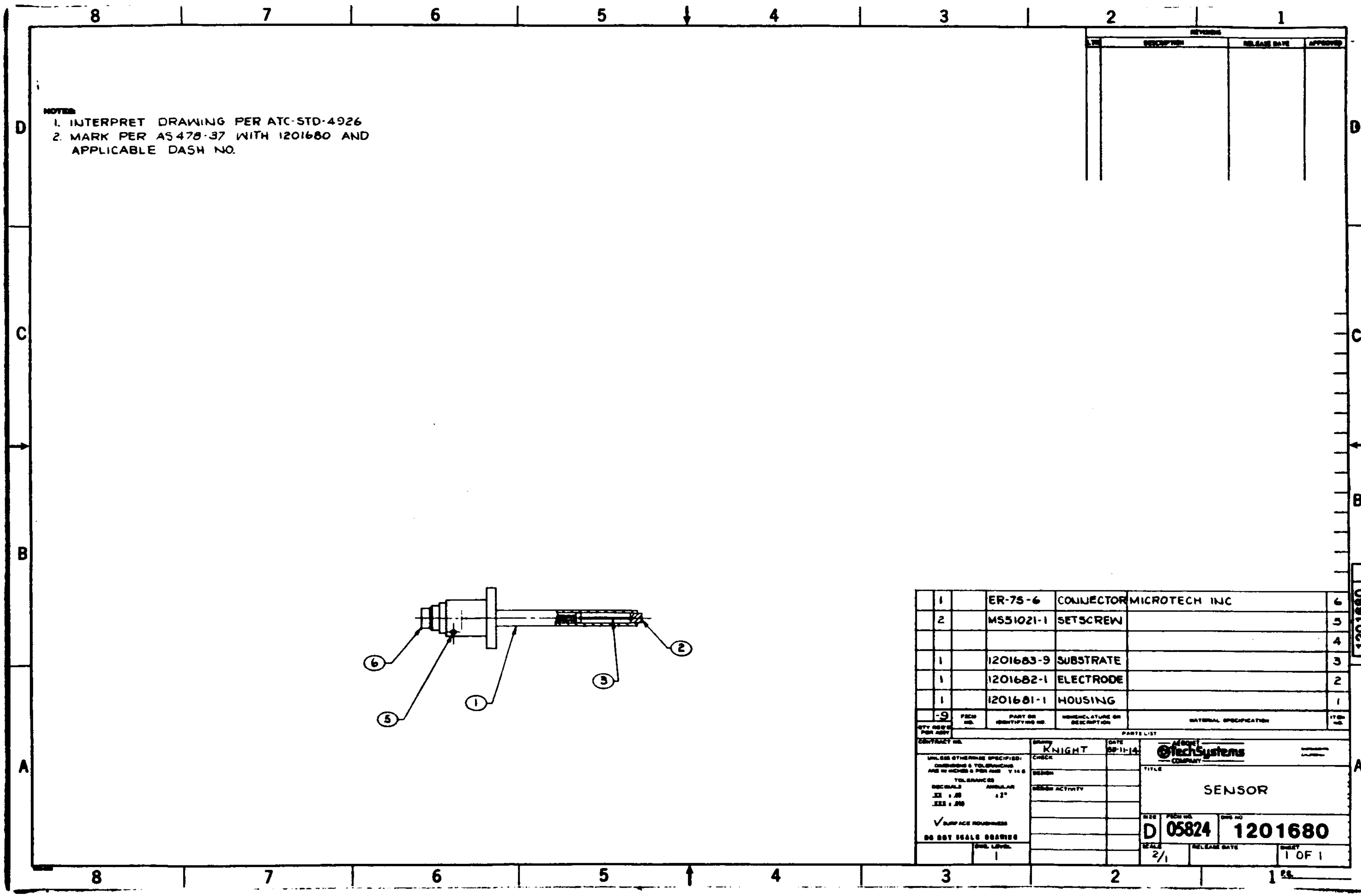

Figure 14. Sensor

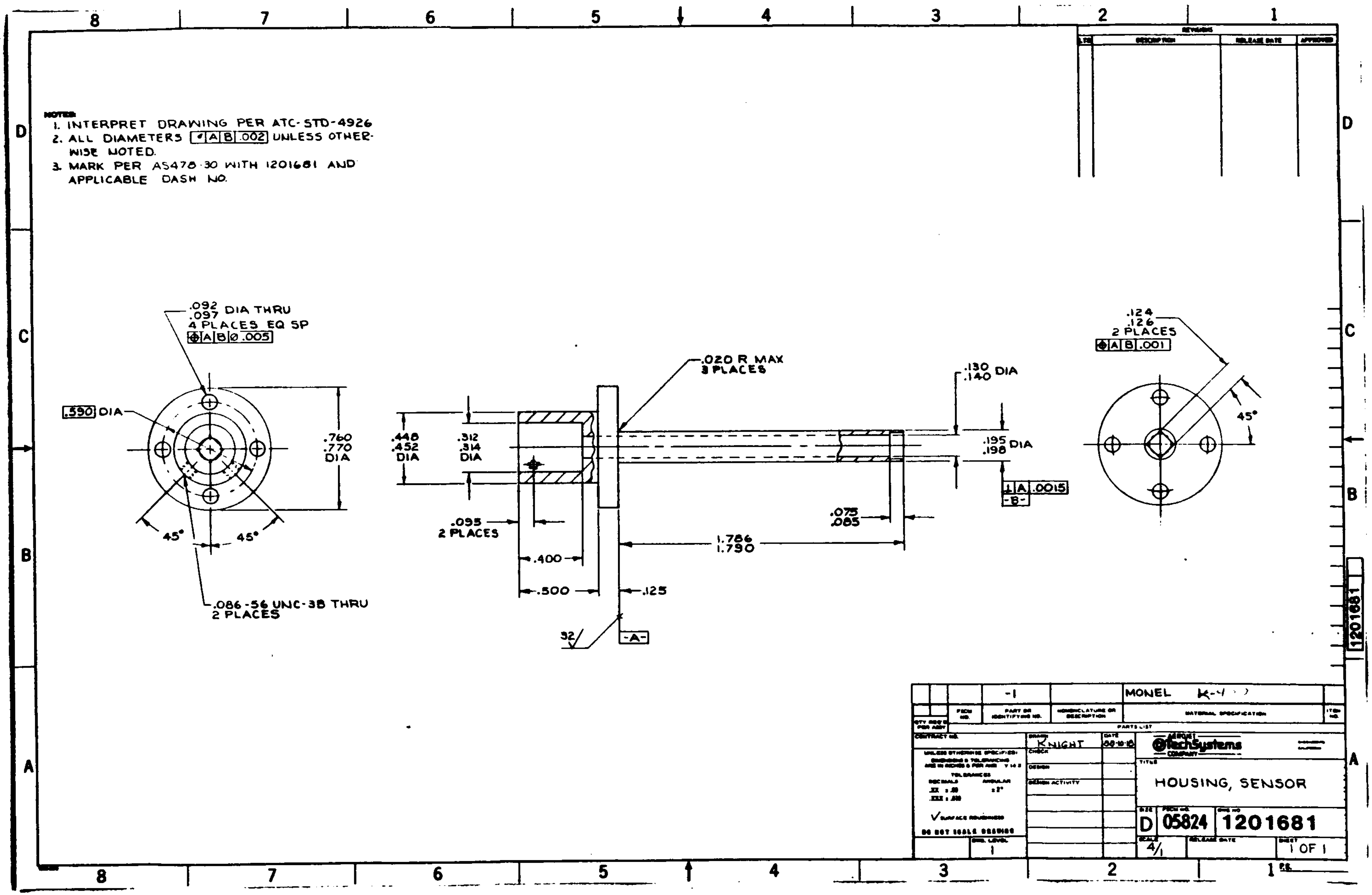

Figure 15. Housing Sensor

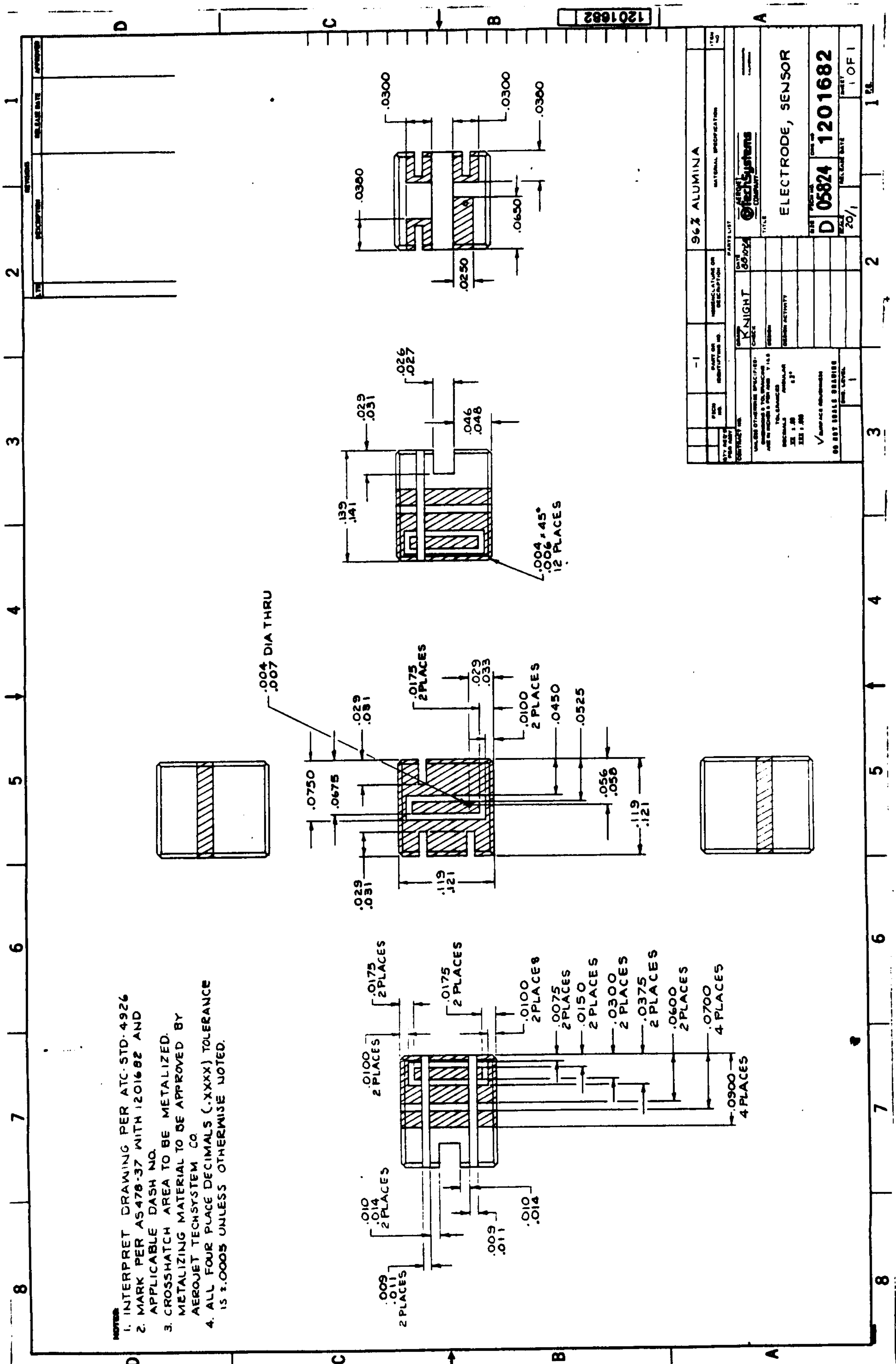

Figure 16. Electrode Sensor

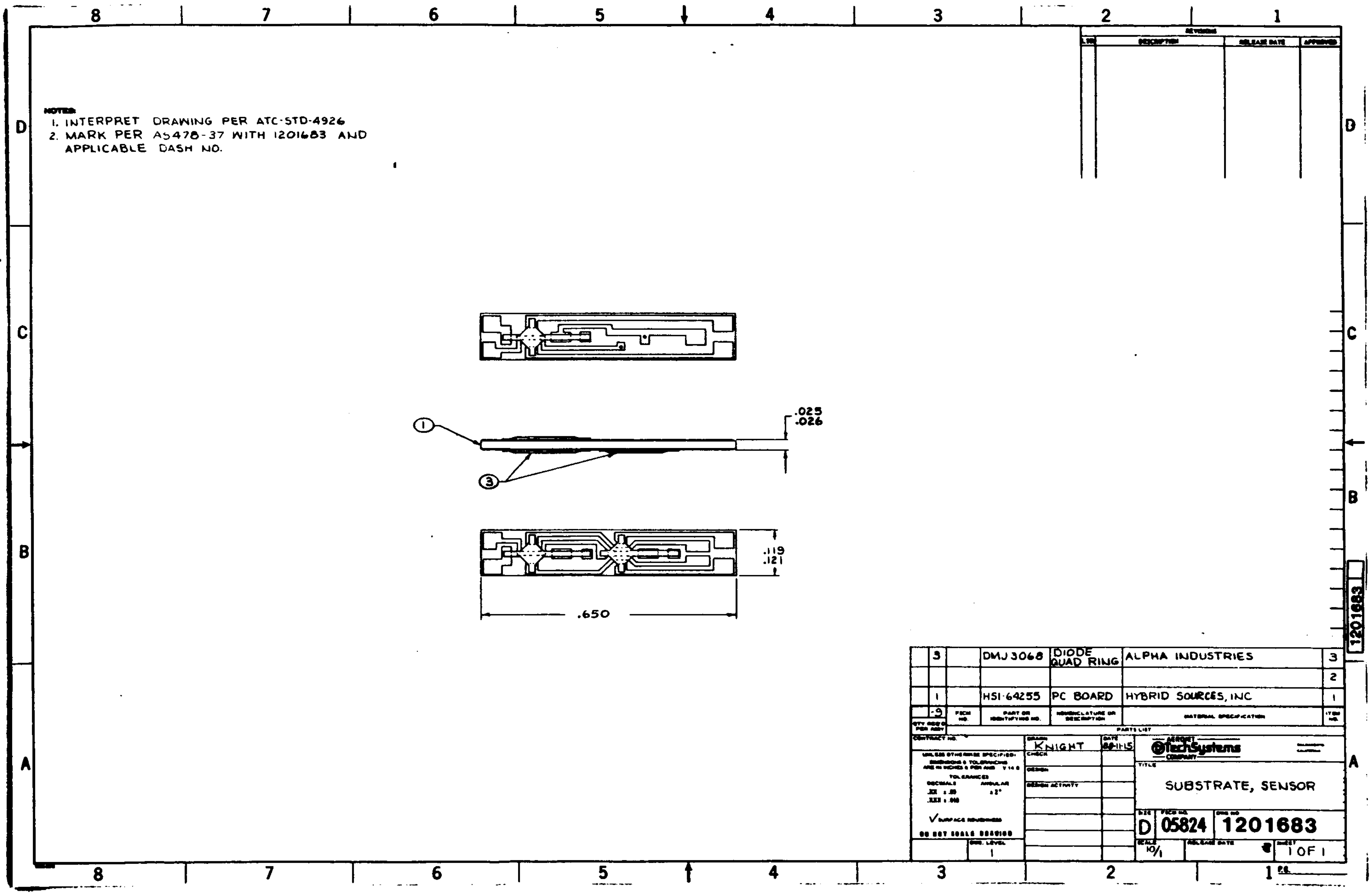

Figure 17. Substrate Sensor

4.0 RESULTS AND DISCUSSION

The experimental triple function sensors were fabricated by ADE Corporation according to the design requirements established in Section 3.5. Two units were delivered and experimental testing was performed to determine the feasibility of the approach and to identify improvements or modifications necessary to provide a reliable sensor.

This section describes the tests performed and the results achieved. The testing consisted of the following test series:

Room temperature calibration
Functional testing
Cryogenic testing
System characterization testing

4.1 ROOM TEMPERATURE CALIBRATION

The calibration tests were performed on each of the three sensors using a calibration test fixture as shown in Figures 18, 19, and 20. The calibration fixture uses differential screw translator with a non-rotating spindle and 5×10^{-5} inch graduations. The target has a 0.25 inch radius comparable to the OTV turbopump shaft. Figure 20 shows a fixture modification to calibrate the axial displacement sensors.

The tests were performed in one direction only to eliminate backlash effects in the translator mechanism.

The console contains calibration and zero adjustments to adjust sensor span and set zero position. The digital readout on the console has resolution to 0.00001 inches. An analog voltage output provides 2mV/microinch sensitivity. Range is from 0.005 inches to 0.015 inches.

Figures 21, 22, and 23 show the deviation of the indicated displacement from the measured displacement as a percent of full scale range. One percent equals a 0.001 inch.

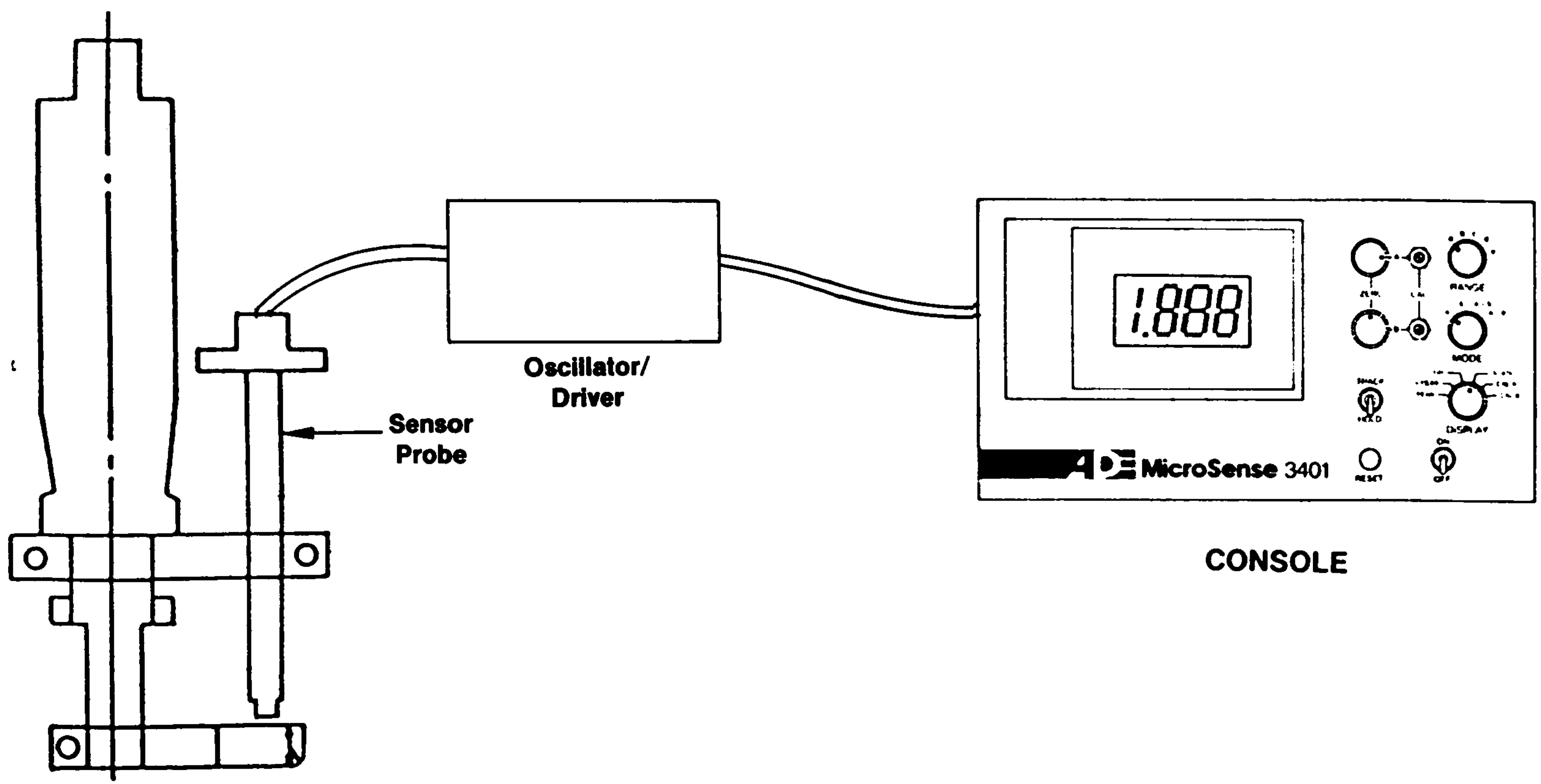

Figure 18. Setup for Sensor Calibration

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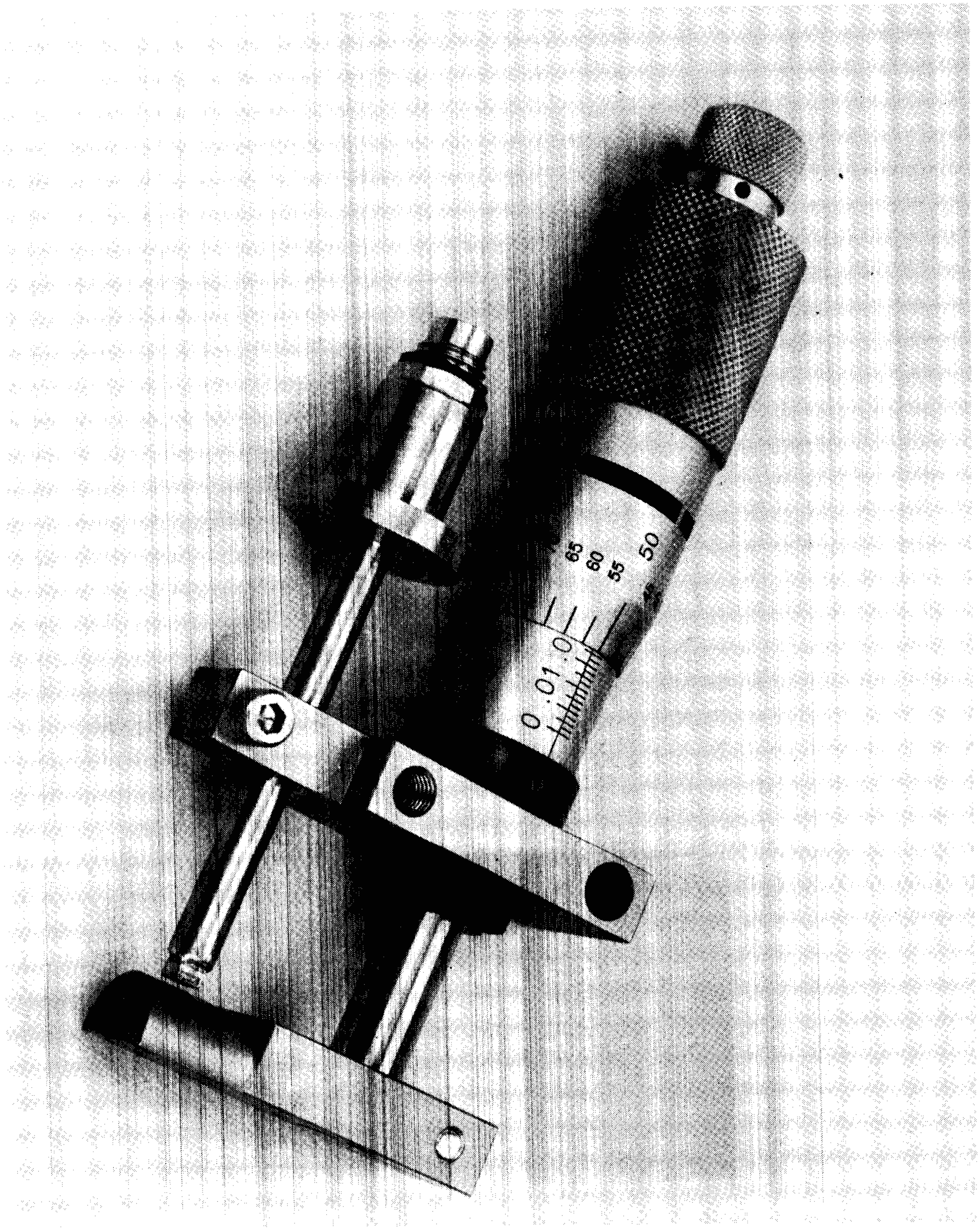

Figure 19. Calibration Fixture

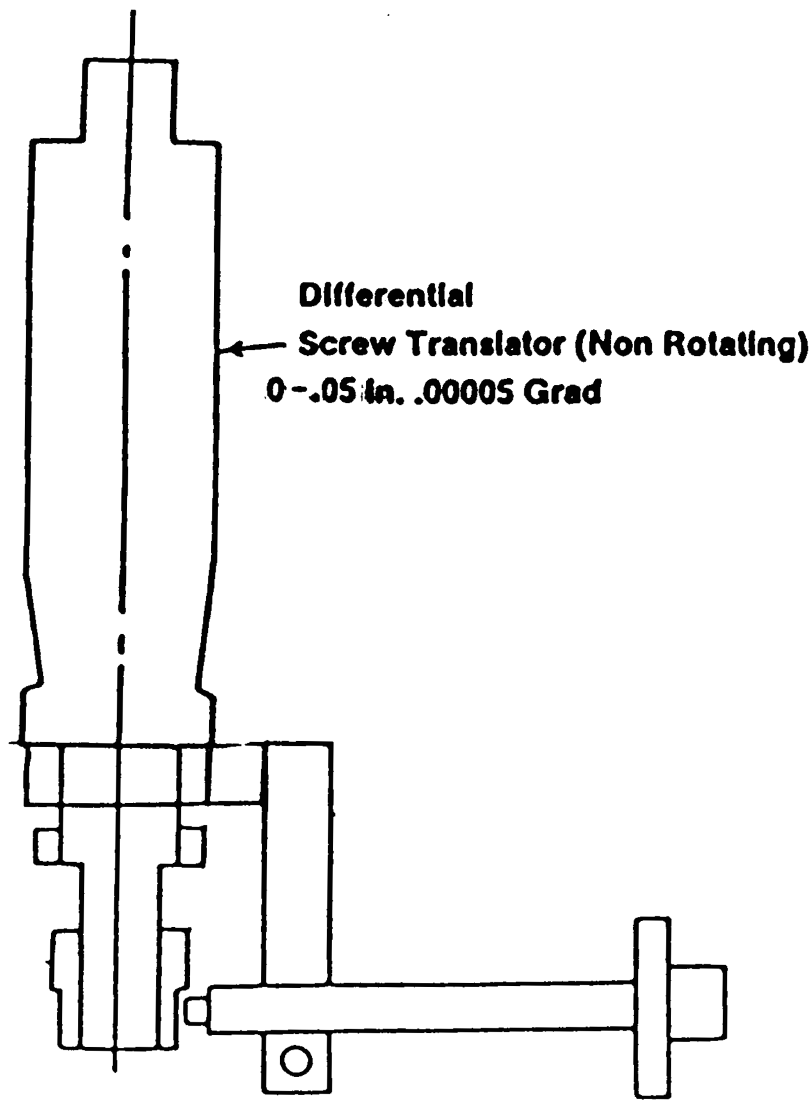

Figure 20. Axial Sensor Measurement Fixture

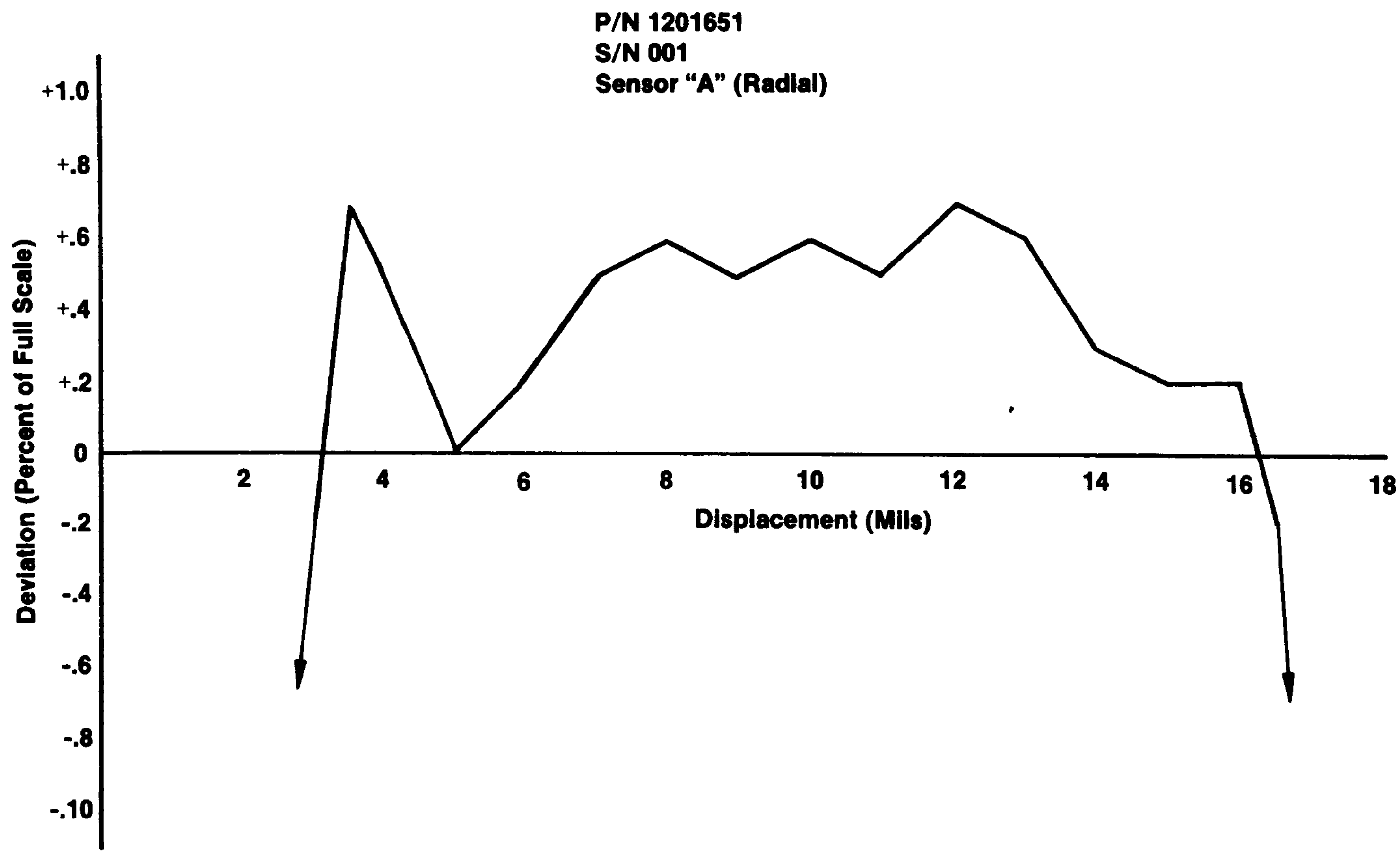

Figure 21. Deviation: Indicated vs. Measured Displacement

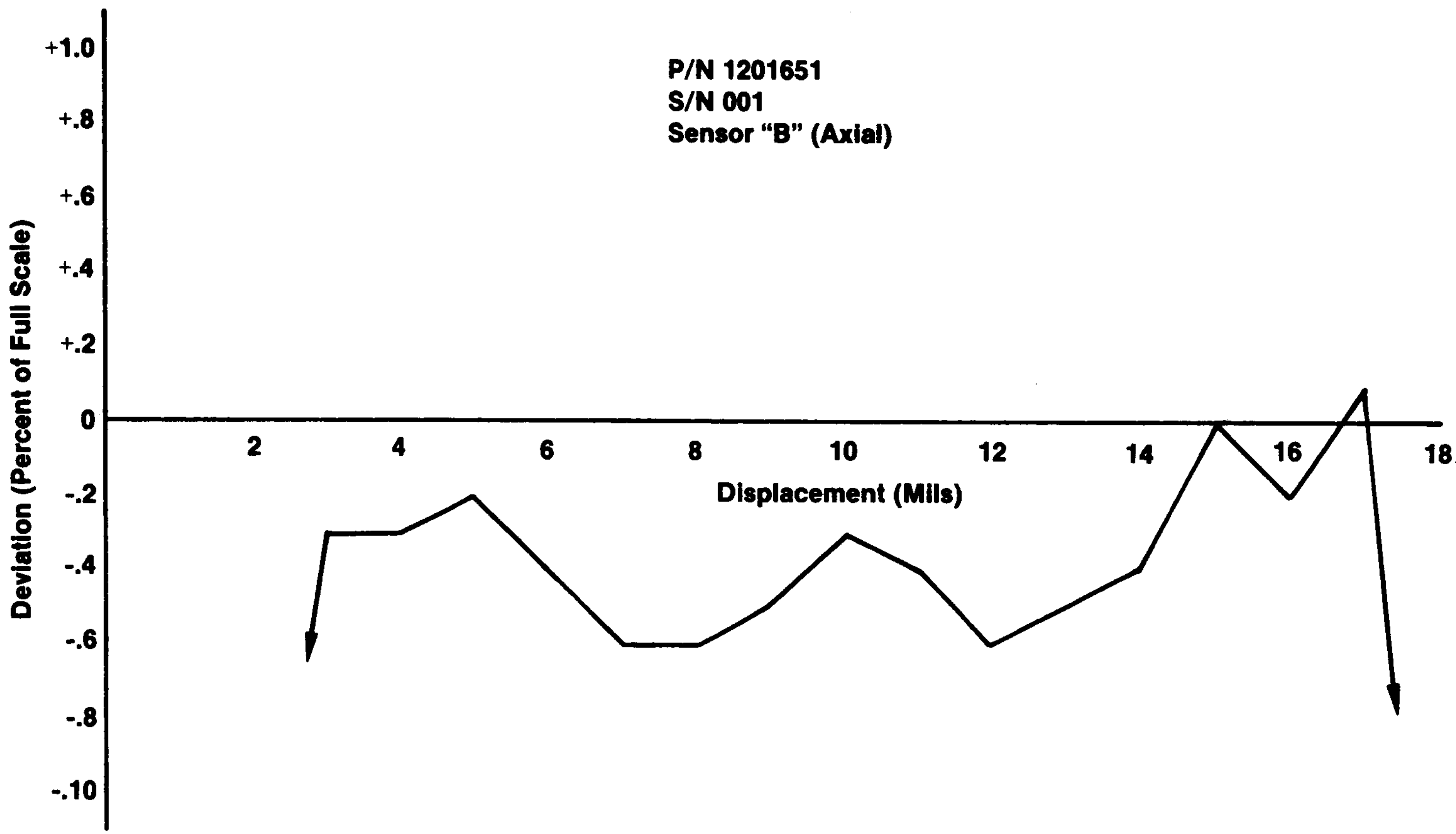

Figure 22. Deviation: Indicated vs. Measured Displacement

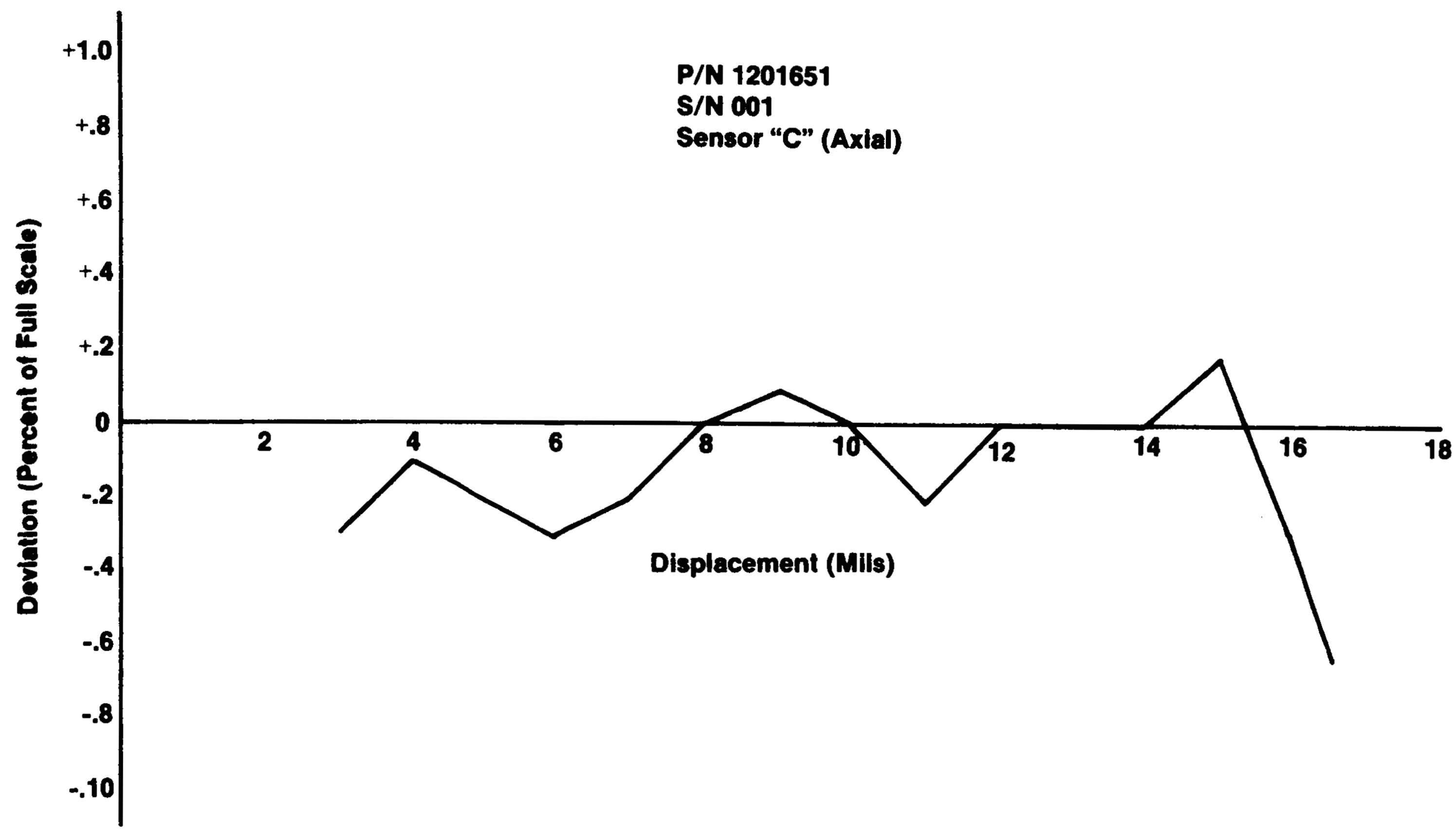

Figure 23. Deviation: Indicated vs. Measured Displacement

4.1, Room Temperature Calibration (cont.)

Axial displacement measurements of sensors "B" and "C" as shown in Figures 22 and 23 were made with the radial gap set at 0.010 inches. These measurements were repeated with the radial gap set at 0.005 and 0.015 inches to determine the effect of the radial gap and groove depth on the axial measurement. These results are shown on Figure 24.

The results of these tests show that each of the three sensors in the probe tip provides an accurate measurement over its measurement range. The slight effect on the axial measurements due to the radial depth setting was probably due to some fringing effect as the sensing electrode approached the top of the groove. This indicates that for most accurate measurements the axial sensors should be calibrated for the expected nominal radial displacement. Also, a slightly deeper groove would be expected to reduce the effect of these variations.

4.2 FUNCTIONAL TESTING

Functional testing was performed to evaluate the sensor performance under simulated turbopump operating conditions. The purpose of the tests were to demonstrate operation of the axial and radial sensors while making simultaneous measurements on a rotating shaft.

These tests were performed using a dynamic test fixture as shown in Figures 25 and 26.

The test fixture has a shaft simulator with a groove for the sensor tip and is driven at approximately 12,000 RPM by a dc motor. The shaft simulator was made with two groove configurations to test the sensor characteristics. Configuration(1) has a groove 0.140 inch wide and 0.060 inch deep. The bottom of the groove has a 0.003 inch steps at 90 degree increments around the circumference. Configuration(2) is similar except that it has 0.003 inch steps in the sides of the groove at 90 degree increments and the bottom of the groove is a constant depth. Figure 27 shows the sensor location in the groove in the shaft simulator. A dual beam digital oscilloscope was used to measure the outputs of two of the three sensors simultaneously.

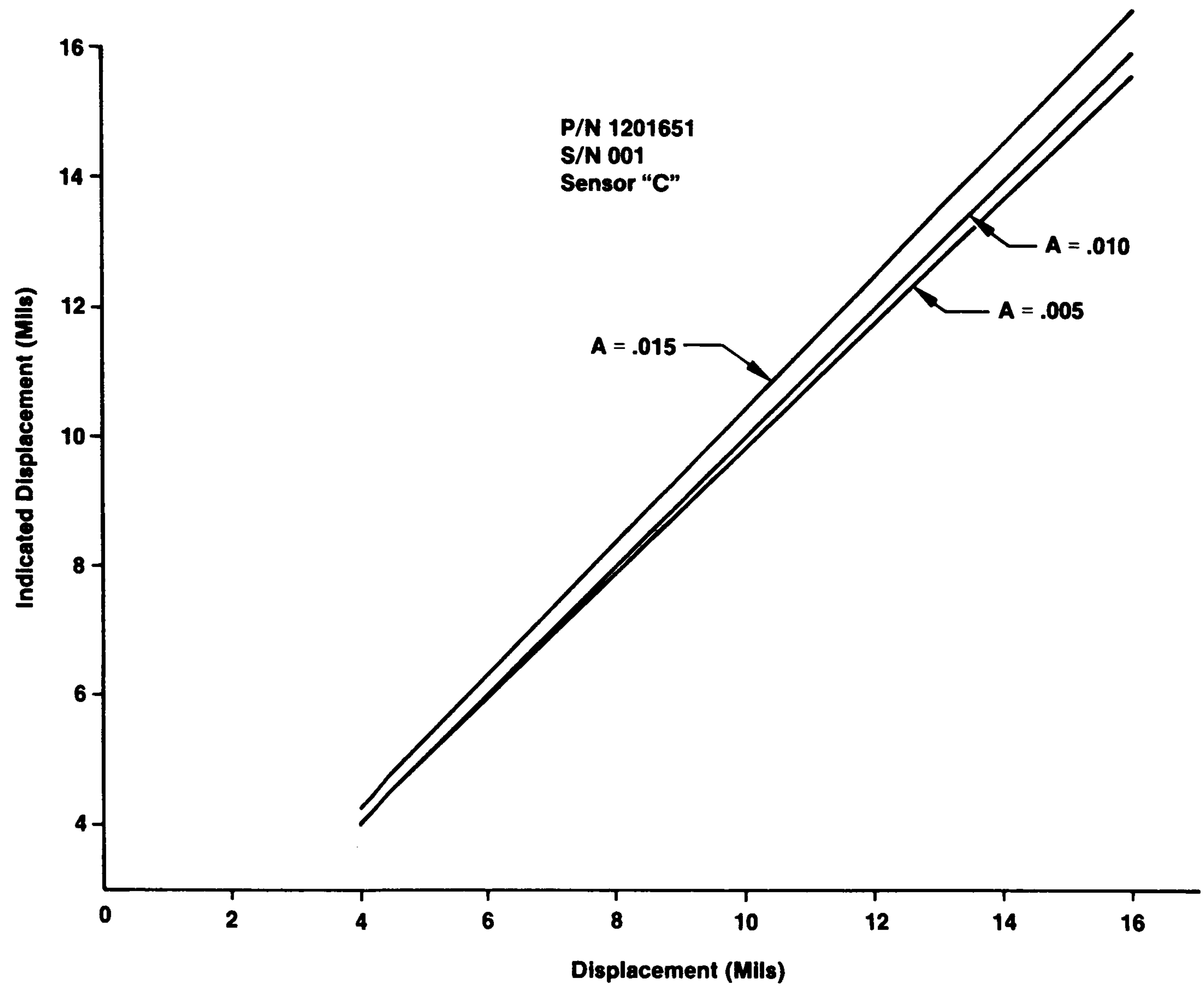

Figure 24. Effect of Radial Gap and Groove Depth

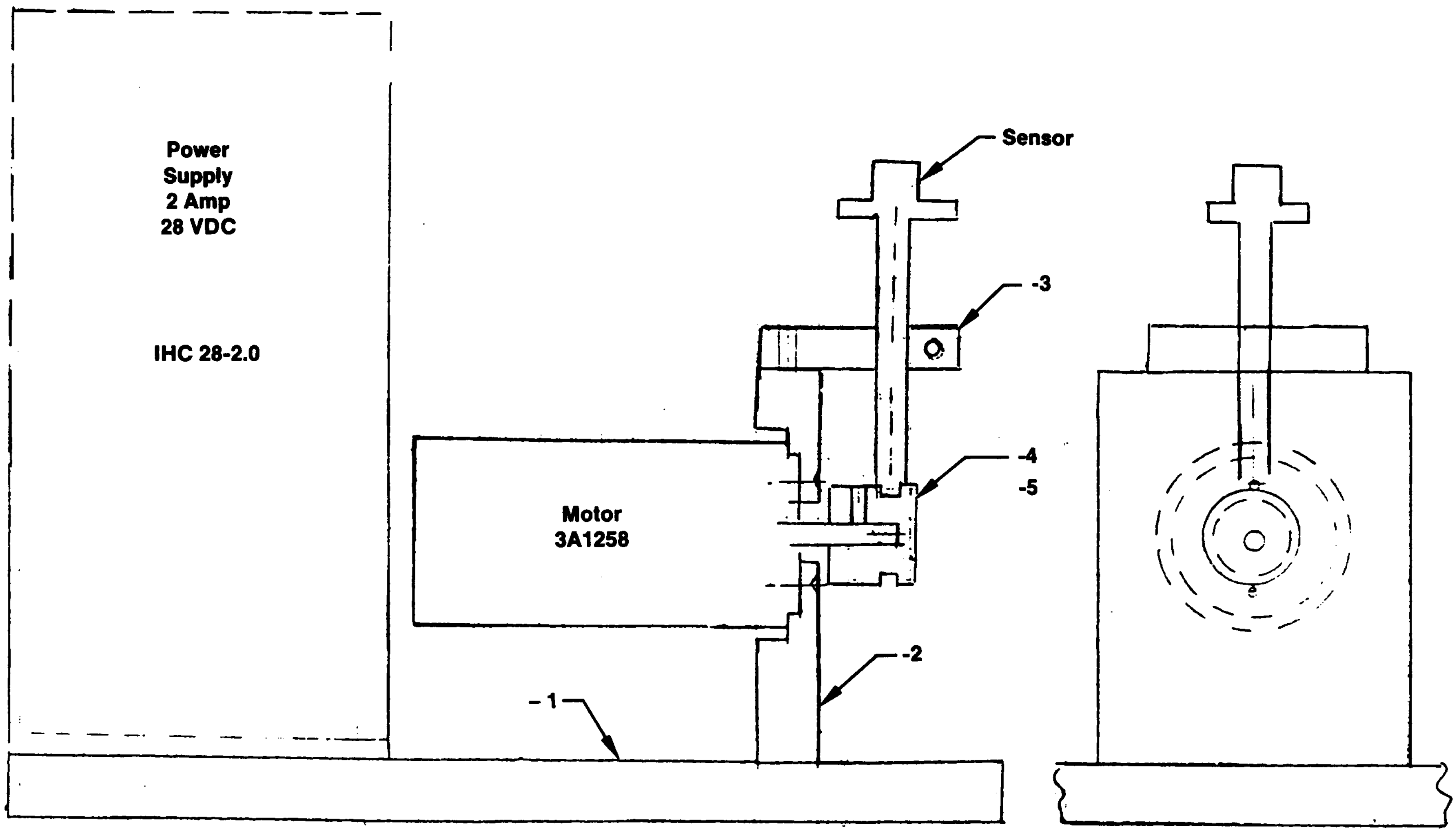

Figure 25. Dynamic Test Fixture

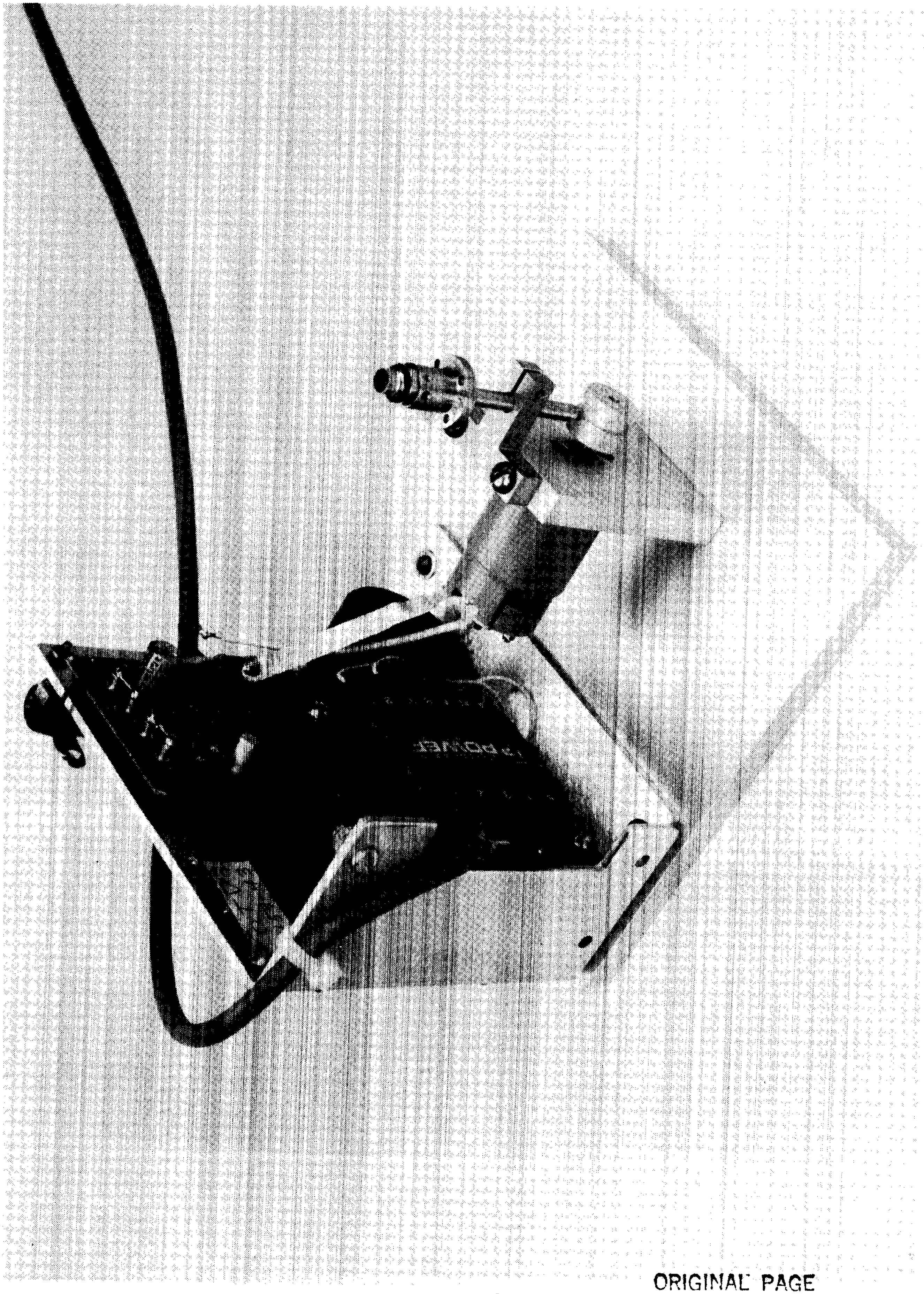

Figure 26. Dynamic Test Fixture

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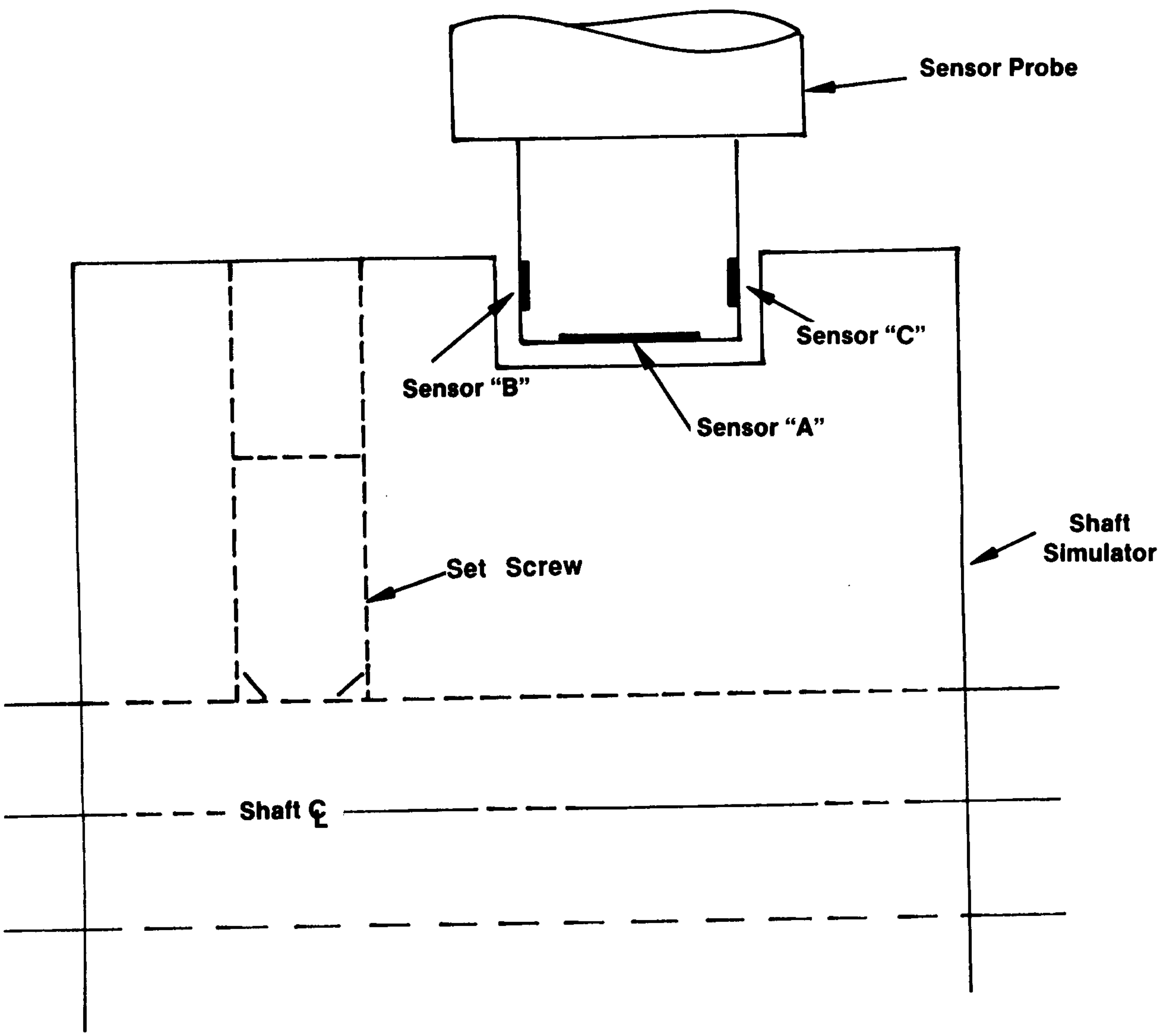


Figure 27. Sensor Location in Shaft Simulator

4.2, Functional Testing (cont.)

Figure 28 shows the sensor outputs using the configuration(1) shaft simulator. Channel 1, of both figures, is sensor "A" which measures the radial displacement of the bottom of the groove. The scale is 0.002 inches per division. This clearly shows the steps machined in the bottom of the groove.

Sensor "B" and "C" are the axial displacement sensors which measure the axial displacement of the sides of the groove. These are shown on channel 2 and are scaled at 0.001 inch per division. The variations in displacement shown are imperfections in the machining of the groove.

Figure 29 shows the results using the shaft simulator of the second configuration. All sensors ar scaled at 0.005 inch per division. Sensor "A" shows the radial runout of the bottom of the groove due to the offset caused by the set screw which clamps the simulator to the motor shaft. Sensor "B" and "C" shows the pattern of the steps in the sides of the groove. Sensors B and C measure the steps in opposite sides of the groove.

These tests demonstrate that a multi-function capacitive displacement sensor probe is practical and will make simultaneous measurements of radial and axial displacements of a rotating shaft. Speed measurements can be made by providing a notch in one axial groove surface. On line calibration can also be accomplished by using a known depth of the speed notch.

These tests demonstrated that the output of the sensors were repeatable and each sensor provided an independent measurement with no indication of cross talk between sensors.

4.3 CRYOGENIC TESTING

Following the successful testing of the three function sensor probes at room temperature testing was performed to evaluate performance at cryogenic temperatures. The purpose of these tests were to evaluate the sensor probe performance at temperatures expected in turbopump for liquid oxygen and liquid hydrogen. Liquid nitrogen at -320°F was used for these tests.

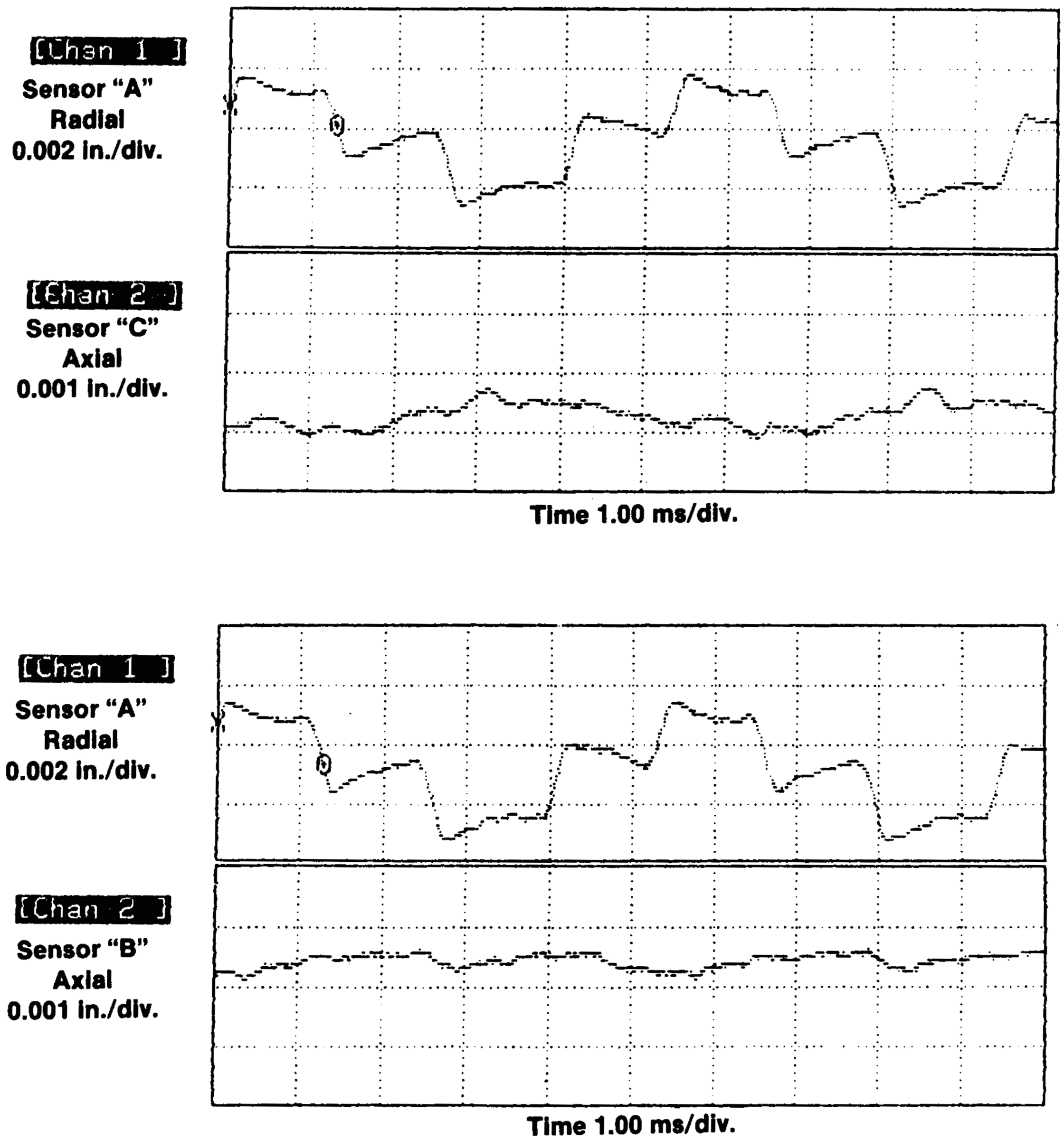


Figure 28. Functional Test Results

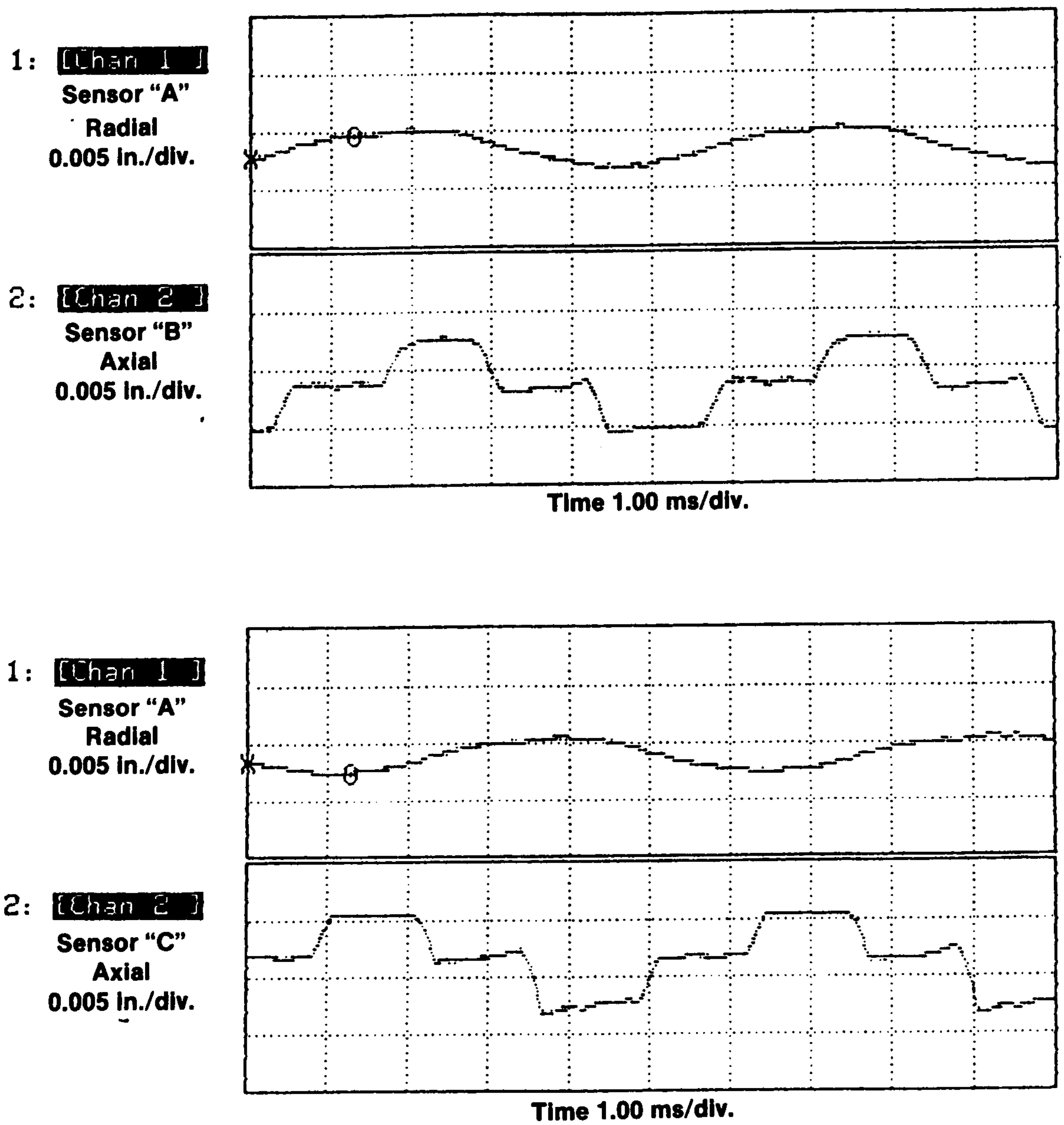


Figure 29. Functional Test Results

4.3, Cryogenic Testing (cont.)

The test setup is shown in Figure 30. The sensor was installed in the calibration test fixture using a 0.25 inch radius target to simulate the turbopump shaft. The sensor gap was set and a measurement made at room temperature. Then the sensor tip and target were immersed in liquid nitrogen. This test showed that as the sensor was immersed in liquid nitrogen there was a substantial shift in displacement reading which could not be accounted for by the difference in dielectric constant between air and liquid nitrogen or any differential thermal expansion of the test fixture. An example of these test results are shown in Table 6. It was noted that as the sensor was removed from the liquid nitrogen and the liquid in the sensing gap evaporated that the indicated displacement changed as would be expected due to the difference in dielectric constant from liquid to gas. Then as the temperature increased to room temperature the indicated displacement returned to near its original value.

These tests indicate that there is a component or components in the sensor tip that are changing with temperature. An examination of the design indicates that the potential problems may be:

1. An unstable reference capacitor. The reference capacitor consists of a lead from the diode assembly which is suspended above an electrode on the printed circuit board in the probe body to form an air dielectric capacitor. Differential expansion of the diode lead and the ceramic PC board could cause the gap between electrodes to change thus changing the reference capacitor value.

2. Condensation could take place within the probe body and on the PC board which could change the inter lead leakage capacitances of the probe circuit. Liquid oxygen condenses at liquid nitrogen temperatures.

It is noted that this problem did not occur during testing of the commercial version of the capacitive sensor described in Section 3.3.

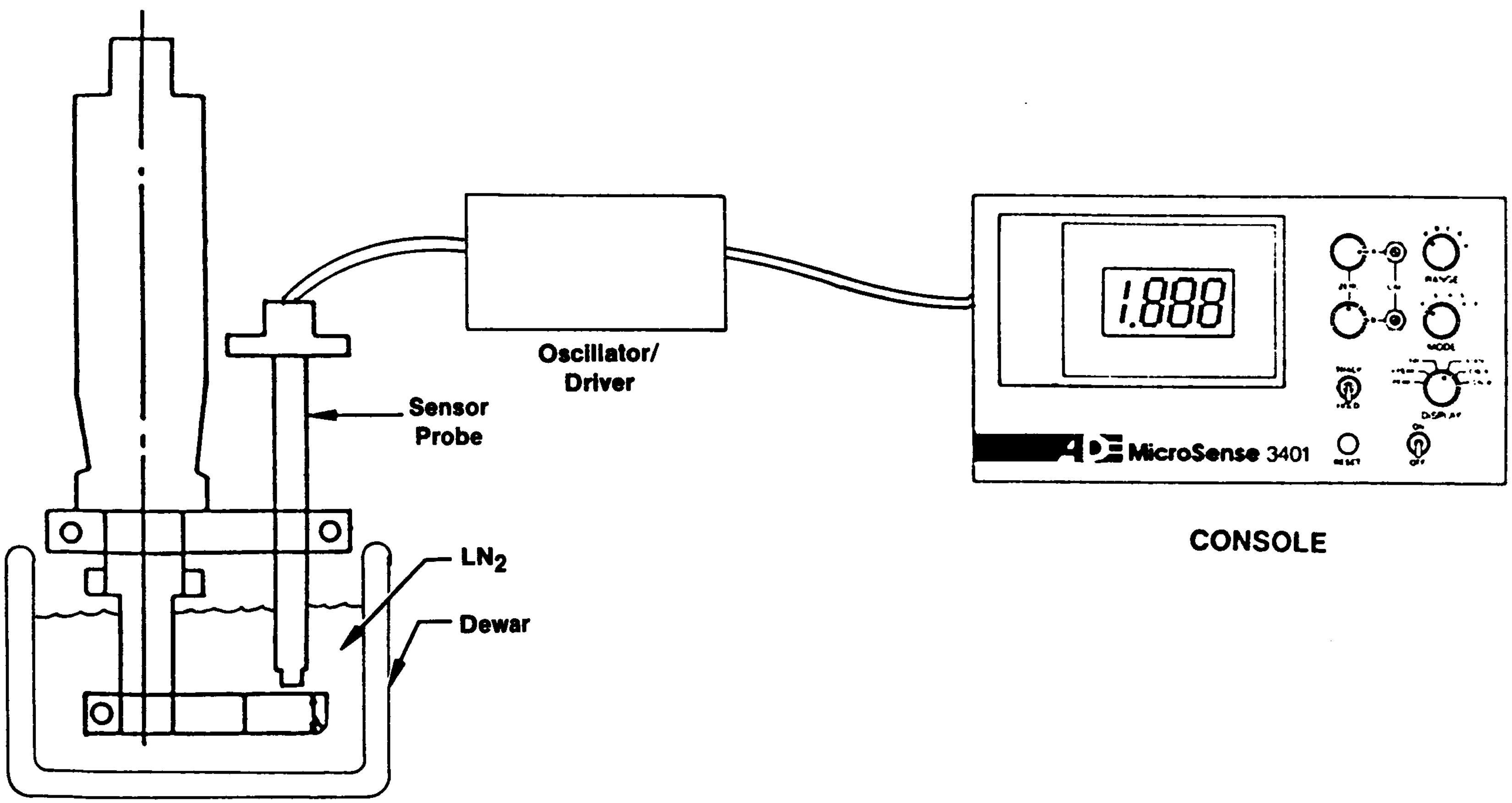


Figure 30. Test Setup for Liquid Nitrogen Tests

TABLE 6

CRYOGENIC TEST RESULTS

Condition	Indicated Gap (Mils)	
In Air at Ambient Temperature	10.63 (1)	15.54 (2)
Immersed in LN2	3.04 (3)	4.95
Removed from LN2, Gap Dry	4.20	7.20
After 1 Minute	5.00	8.60
After 2 Minutes	5.39	9.90
After 3 Minutes	5.78	10.90
After 4 Minutes	6.15	
Returned to Room Temp	10.84	15.44

(1) Test #1 gap set at 0.010 inches using a feeler gage
(2) Test #2 gap set at 0.015 inches using a feeler gage
(3) Instrument off scale

The construction of the commercial sensor tip differed from the triple function prototype unit in several respects. Its reference capacitor was of a similar configuration as the sensor capacitor and the tip electronics were encapsulated in epoxy. In the design of the triple function unit it was necessary to change components and component layout to accommodate three sensors in the smaller sensor probe. The electronics were assembled on a miniature printed circuit board which was located in the body of the probe. The assembly was not encapsulated. The effect of these differences may account for the poor performance at cryogenic temperatures.

4.4 SENSOR SYSTEM CHARACTERIZATION

The characterization of the sensor system was performed to provide a better understanding of the system operation and to provide a basis for recommending improvements to provide a reliable sensor. Tests were performed to measure the dc current to the signal conditioning console, the ac component of the signal, and supply voltages to the probe.

Figure 31 shows an electrical schematic of one sensor element of the probe and its drive unit. The drive unit has additional transformer secondaries for each of the other two sensors in the probe.

The excitation voltage applied to the sensor was measured and is 58.5 volts RMS at 2.9MHZ as shown on Figure 32. Equal, in phase, voltages are applied to the two opposite corners of the diode ring. As the sensor tip to target distance changes, an unbalance in the diode circuit occurs resulting in dc current flowing in the transformer windings and to the external signal conditioner.

The signal currents at the two output terminals of the probe circuit were measured using 1000 ohm resistors in series with the signal lines as shown in Figure 31. The signal current as a function of sensor tip gap is shown on Figure 33. It can be seen that after shifting the zero axis to account for a bias current, the signal current follows very closely to the inverse characteristics which is expected as the distance between the sensing capacitor electrodes are changed.

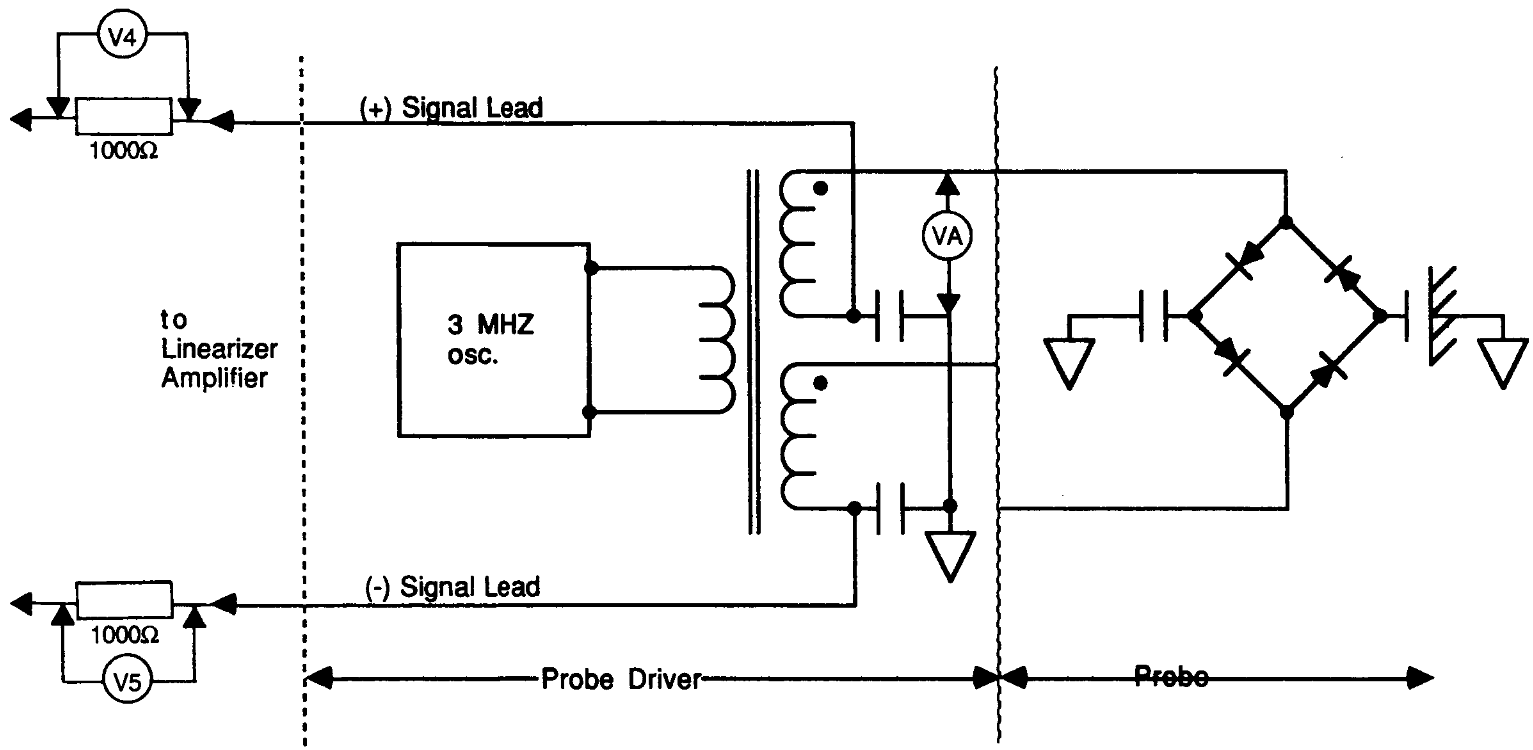


Figure 31. Sensor and Driven Schematic

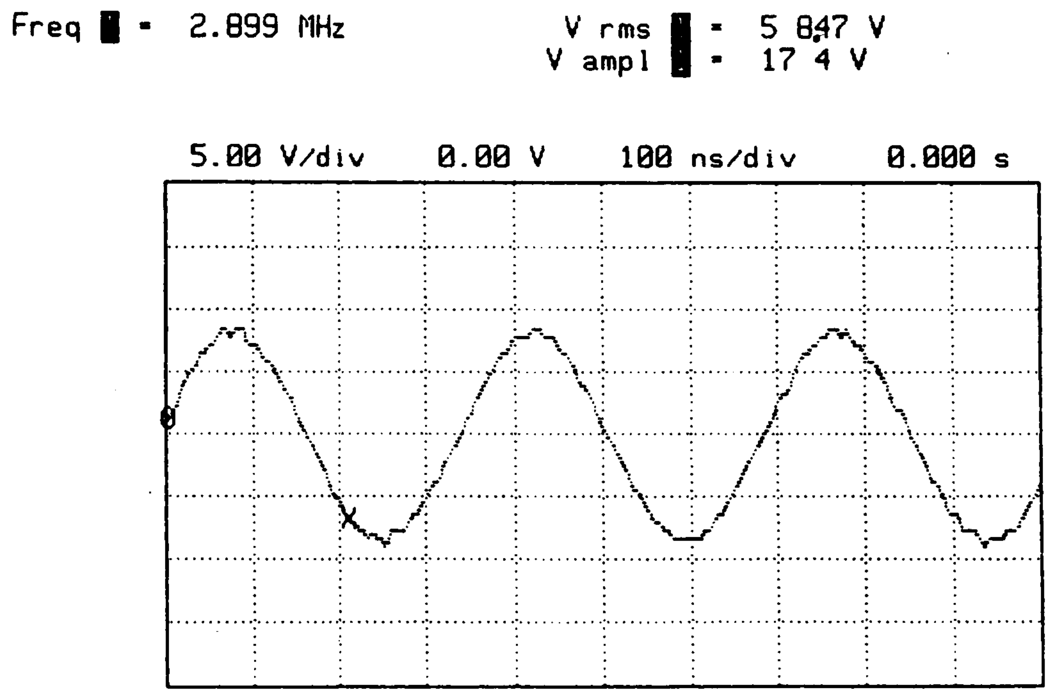


Figure 32. Sensor Input Voltage (V_A)

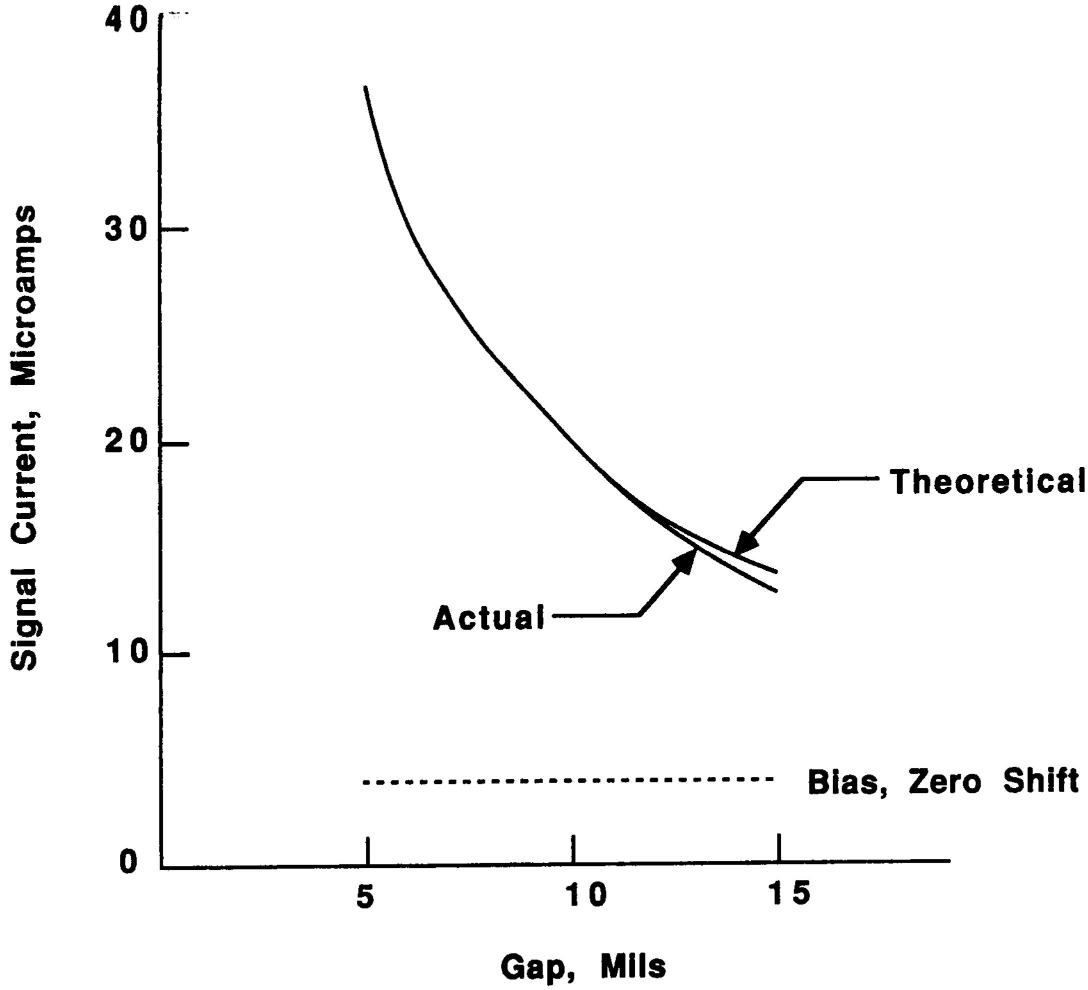


Figure 33. Sensor Signal Current

4.4, Sensor System Characterization (cont.)

Experiments were performed to measure the ac component (noise) of the output current signal from the sensor probe. Measurements were made across the 1000 ohm resistor in series with the output lead. Figure 34 is an oscilloscope trace of the ac component of the signal current. The ac component is filtered from the dc signal by the signal conditioning console. The sensor probe was then immersed in liquid nitrogen to determine if the low temperature affected the noise characteristics. No significant change in noise level was observed as shown in Figure 35. From these experiments it would appear that there was no significant change in noise generation as a result of operation at low temperature. However, the shift in displacement reading, as previously reported, was still present.

Tests were performed to measure the forward voltage of the diode assemblies at room temperature and -320°F. Three sample diode rings of four diodes each were tested at two current levels. The results are shown on Figure 36. A significant increase in forward voltage is evident at -320°F.

However, according to ADE Corporation, the change in diode forward voltage is not expected to cause a significant measurement error because of the relatively high voltage applied to the sensor tip. This is borne out by tests performed on their commercial unit with the results shown in Appendix A.

4.5 IDENTIFICATION OF IMPROVEMENTS

Triple function sensing of turbomachinery displacement and speed functions have been successfully demonstrated as part of this development program. A thermal shift problem was identified during cryogenic testing of the sensor probe with possible causes linked to instability of the reference capacitor and changes in capacitance leakage paths due to possible condensation and material dielectric constant changes.

The following improvements and modifications have been identified to overcome the deficiencies found in the experimental sensor probe and to provide a reliable displacement sensing system for rocket engine applications.

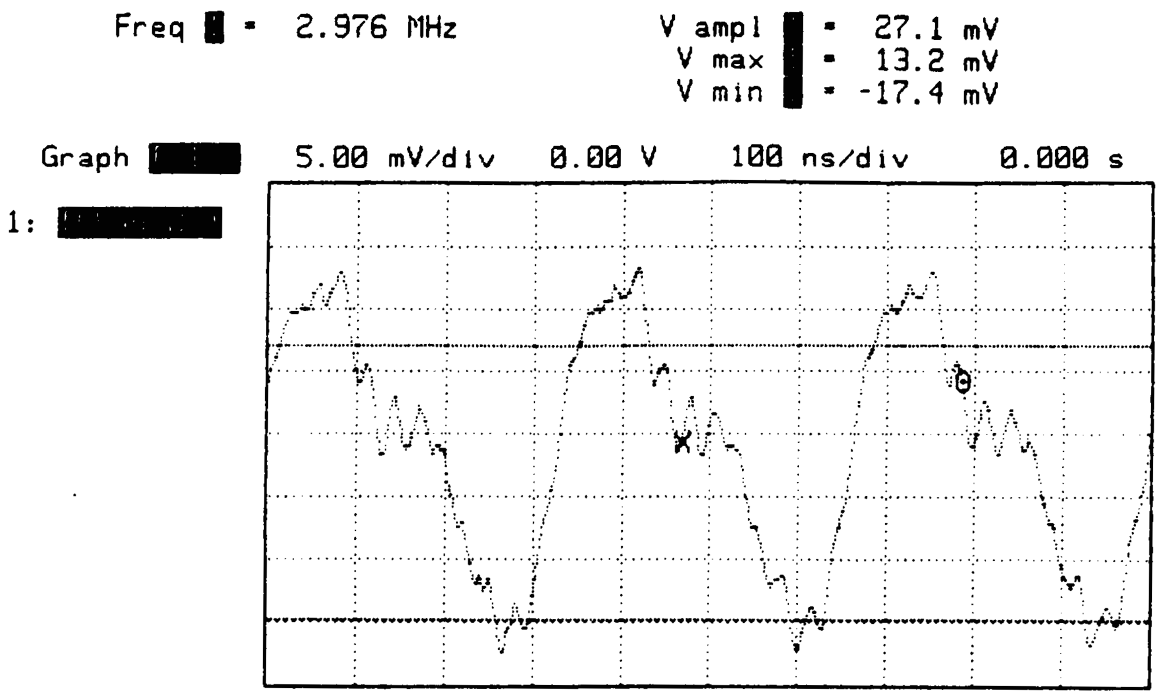


Figure 34. Signal Noise at Room Temp

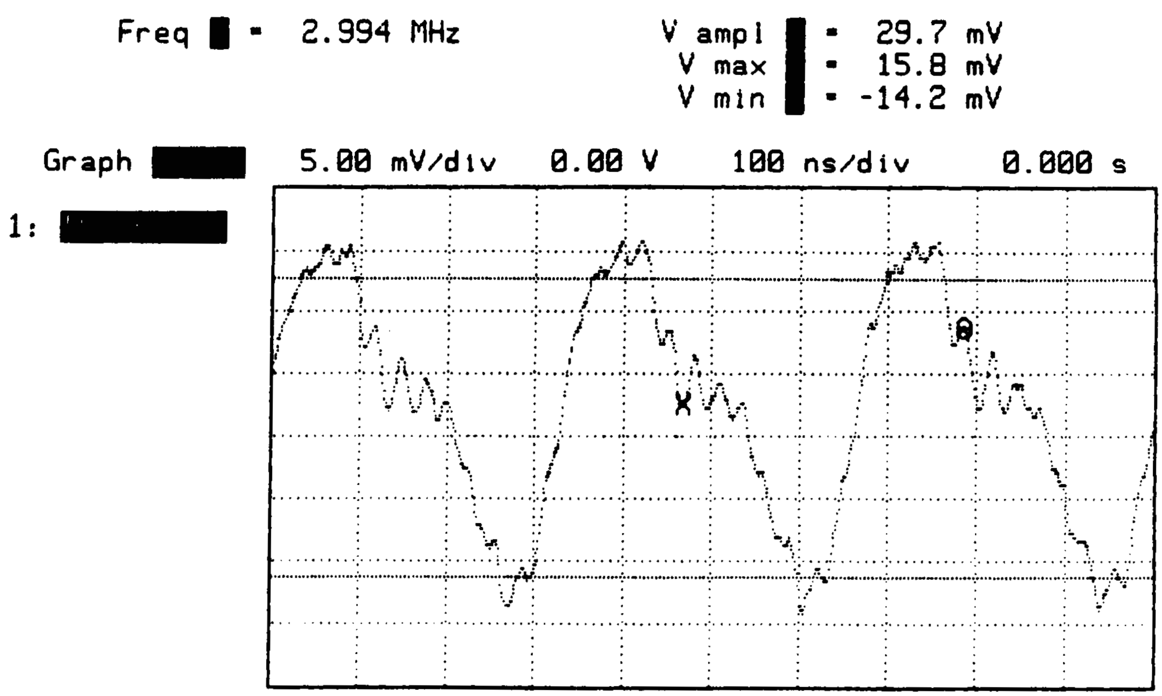
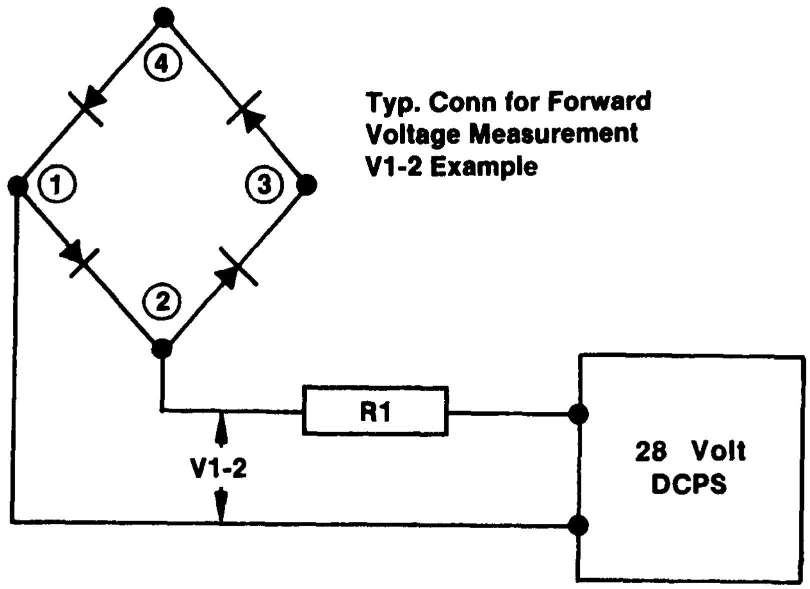


Figure 35. Signal Noise at -320°F



2MA R1 = 13.8 K OHM

0.2MA R1 = 132.3 K OHM

Sample	#1		#2		#3	
Temp	70°F	-320°F	70°F	-320°F	70°F	-320°F
2MA						
V1-2	.432	.652	.429	.650	.438	.659
V2-3	.429	.652	.432	.653	.438	.659
V3-4	.431	.652	.427	.650	.433	.654
V4-1	.428	.650	.430	.649	.434	.655
0.2MA						
V1-2	.317	.616	.315	.613	.323	.620
V2-3	.316	.614	.319	.613	.323	.619
V3-4	.317	.616	.315	.614	.320	.613
V4-1	.315	.613	.316	.610	.321	.617

Figure 36. Diode Forward Voltage Measurement

4.5, Identification of Improvements (cont.)

1. Improved Sensor Probe

An improved design incorporating the following features is proposed to eliminate these problems and provide a smaller and more reliable sensor.

- Temperature stable reference capacitors
- Miniature diode/capacitor assembly integrated into the sensor tip substrate using hybrid techniques
- Reduced stray capacitance in the sensor circuit
- Encapsulated sensor tip electronics to seal out condensation and stabilize interconnections

A sketch of the improved sensor tip with its integrated electronics are shown on Figure 37. The electronic assembly consists of 12 Schottky diodes and three capacitors connected as shown in Figure 38. The Schottky diodes are available in chip form size 0.015 inch square and are connected by a wire bonding process. The reference capacitors are three 0.1 pF MOS capacitors on a single 0.20x0.30 substrate. Their temperature coefficient of capacitance is specified at ±35 PPM/°C. The diodes and capacitors are assembled on the ceramic sensor tip and there encapsulated to seal out contaminants which could cause changes in interconnecting lead capacitances. The sensor tip is then installed into the sensor probe unit.

2. Compact Flight Type Signal Conditioner

The capacitive displacement sensing system requires an oscillator/driver to provide power to the sensing tip and a linearizing circuit to convert the inverse relationship between the signal and the sensor-to-target distance to a straight line function. The laboratory console units, because of their size and environmental considerations, are not suitable for rocket engines. A compact flight type unit is required for this system to be practical for engine applications.

Figure 39 shows the functional blocks of a Driver/Signal conditioner unit for the triple function capacitive sensor. A block diagram of a single channel of

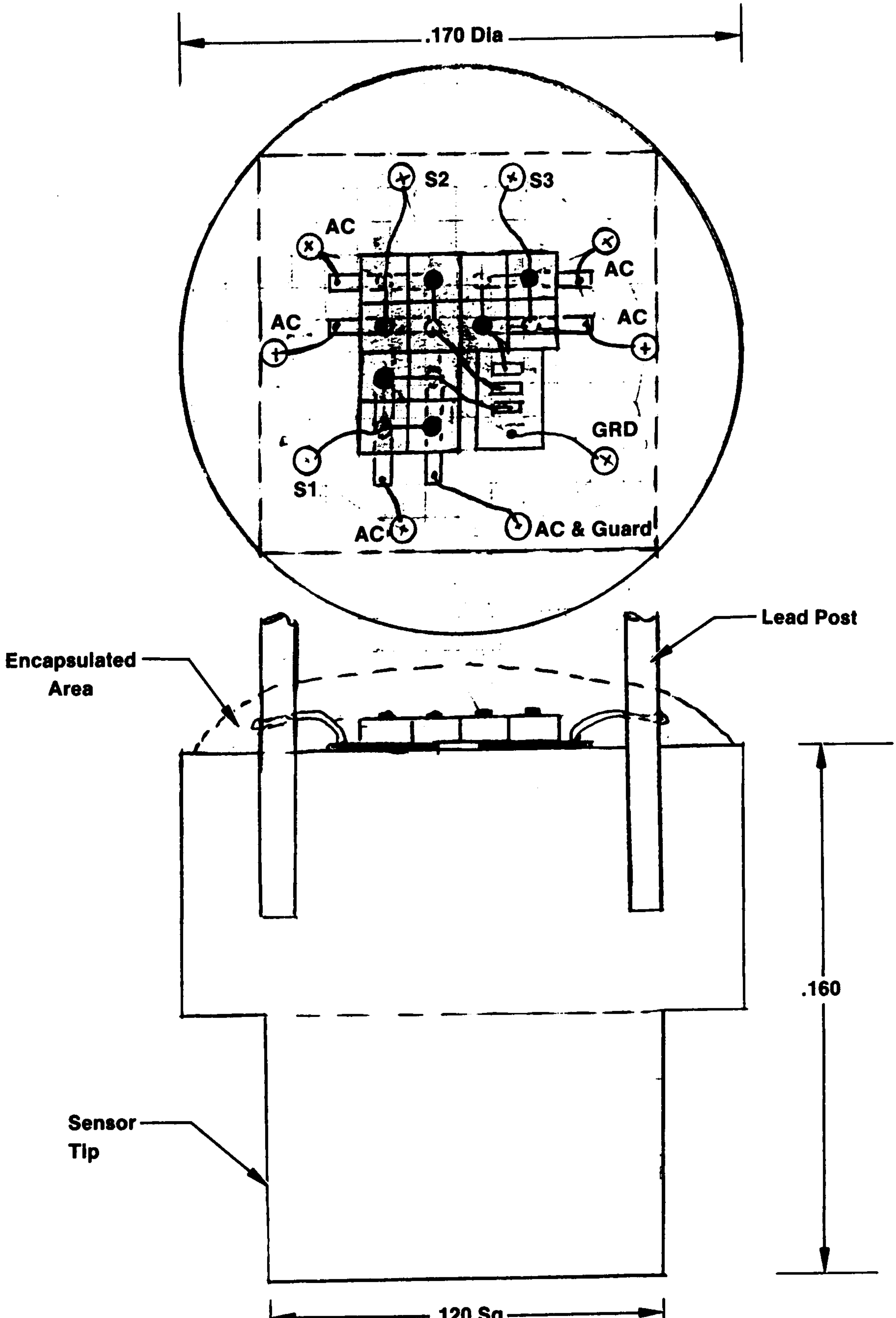


Figure 37. Sensor Tip/Electronics Subassembly

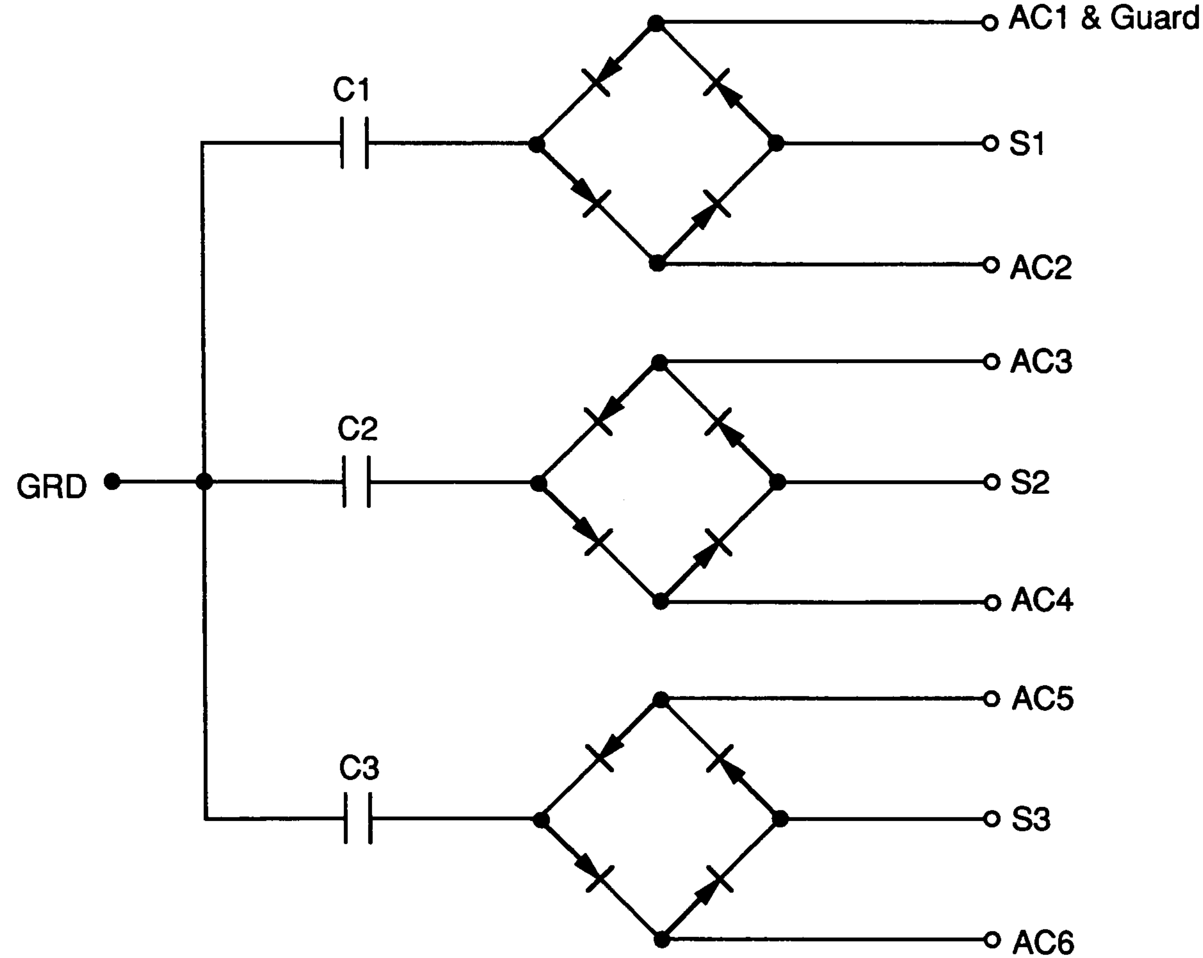


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Figure 38. Sensor Tip Schematic

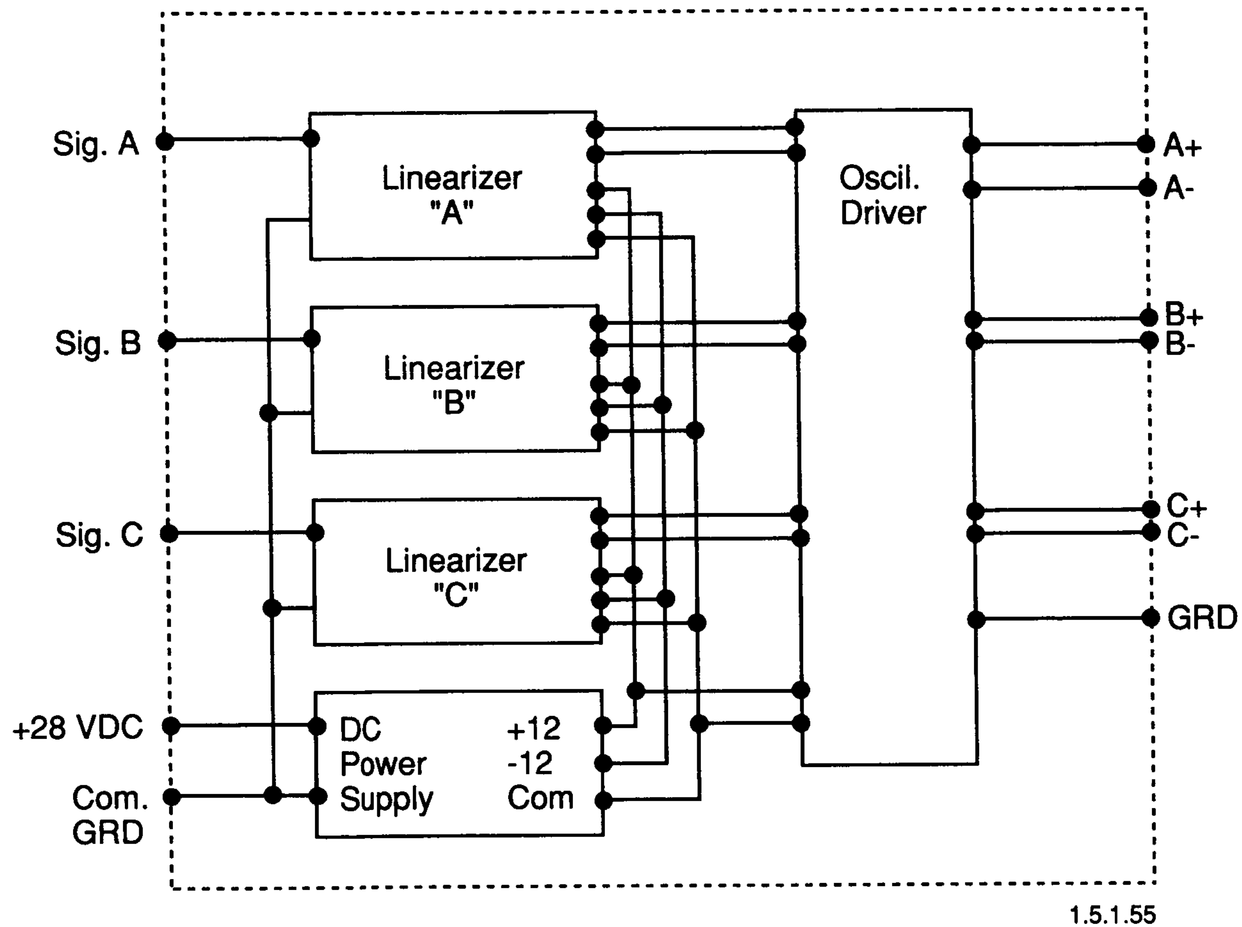

Figure 39. Signal Conditioning Module Block Diagram

the capacitive displacement measurement system is shown on Figure 40. A multiplier-divider linearizing technique which uses a single integrated circuit component is shown. The output of the multiplier-divider has the relationship of Vout=X(y)+Z where Z is the input from the sensor and X and Y are scaled constants. As the output (Z) from the sensor has an inverse relationship to distance of $Z=K1(^1/d)$ the output from the multiplier-divider is a linear function of Vout=K2(d).

By using integrated circuits and surface mount technology the driver-signal conditioner unit for the triple function sensor can be packaged on a small printed circuit board. A conceptual drawing for this unit is shown on Figure 41. The driver/signal conditioner unit is located within 8 inches of the sensor probe and must be designed to withstand the environments in close proximity of the components being monitored.

3. <u>Additional Sensor Approaches</u>

The multi-function capacitive displacement sensing technology provides a high degree of flexibility for sensing electrode configurations. The ceramic tip and electrode shapes may be custom designed for specific applications. Examples of future potential applications are:

- Value Position Sensor - Figure 42. The capacitive displacement sensor probe may be configured to provide a redundant valve position sensor by measuring radial displacement of a tapered hole in the valve pintle extension. It provides redundant capability in a much smaller size than an LVDT.

- Multi-Function Shaft Monitor - Figure 43. By modifying the sensor tip electrode configuration, three sensing elements can provide the following four measurements on a turbopump shaft:

  Radial displacement in 2 axes at 90 degrees
  Axial displacement
  Speed

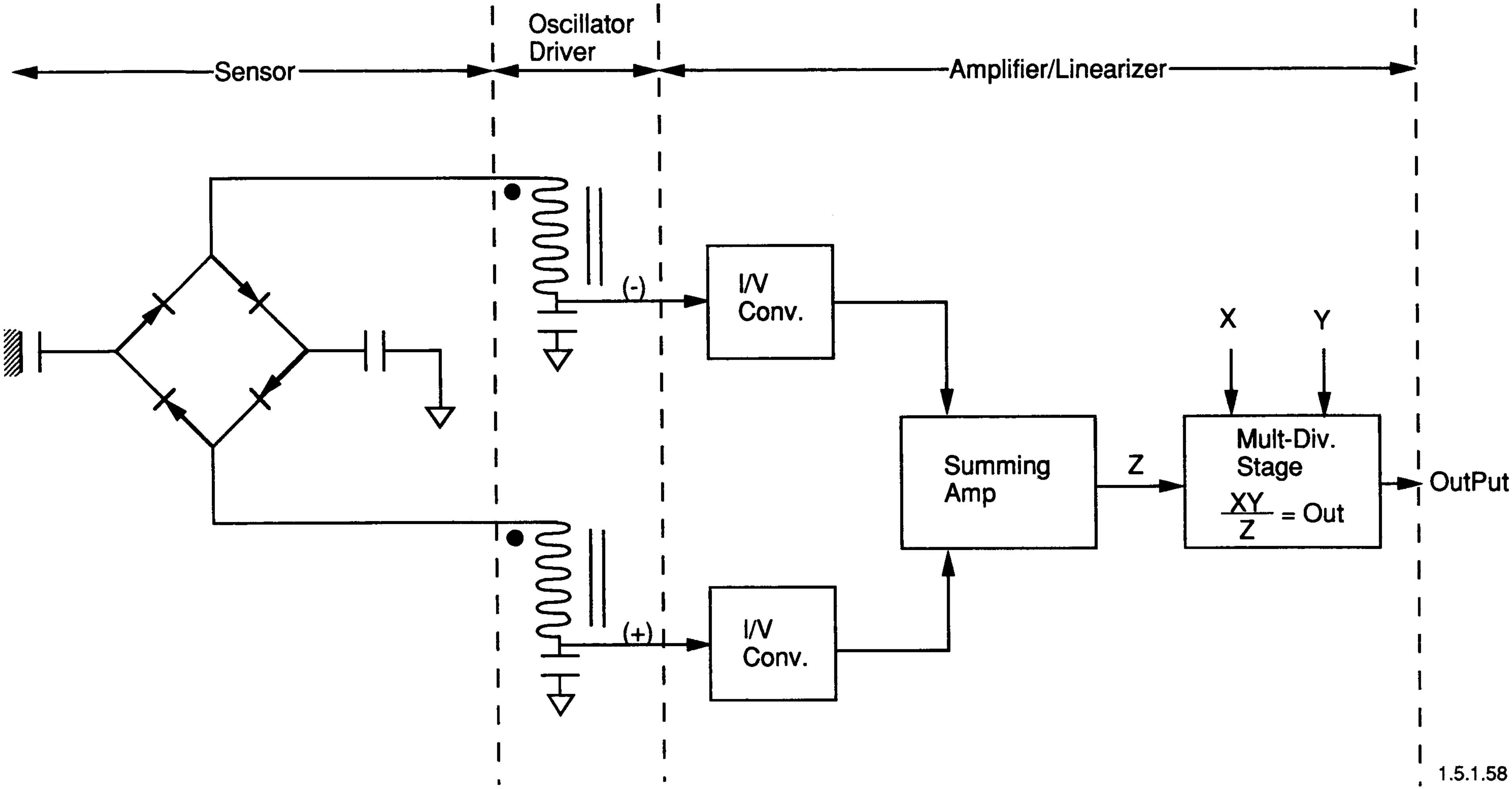

Figure 40. Capacitive Displacement Measurement System

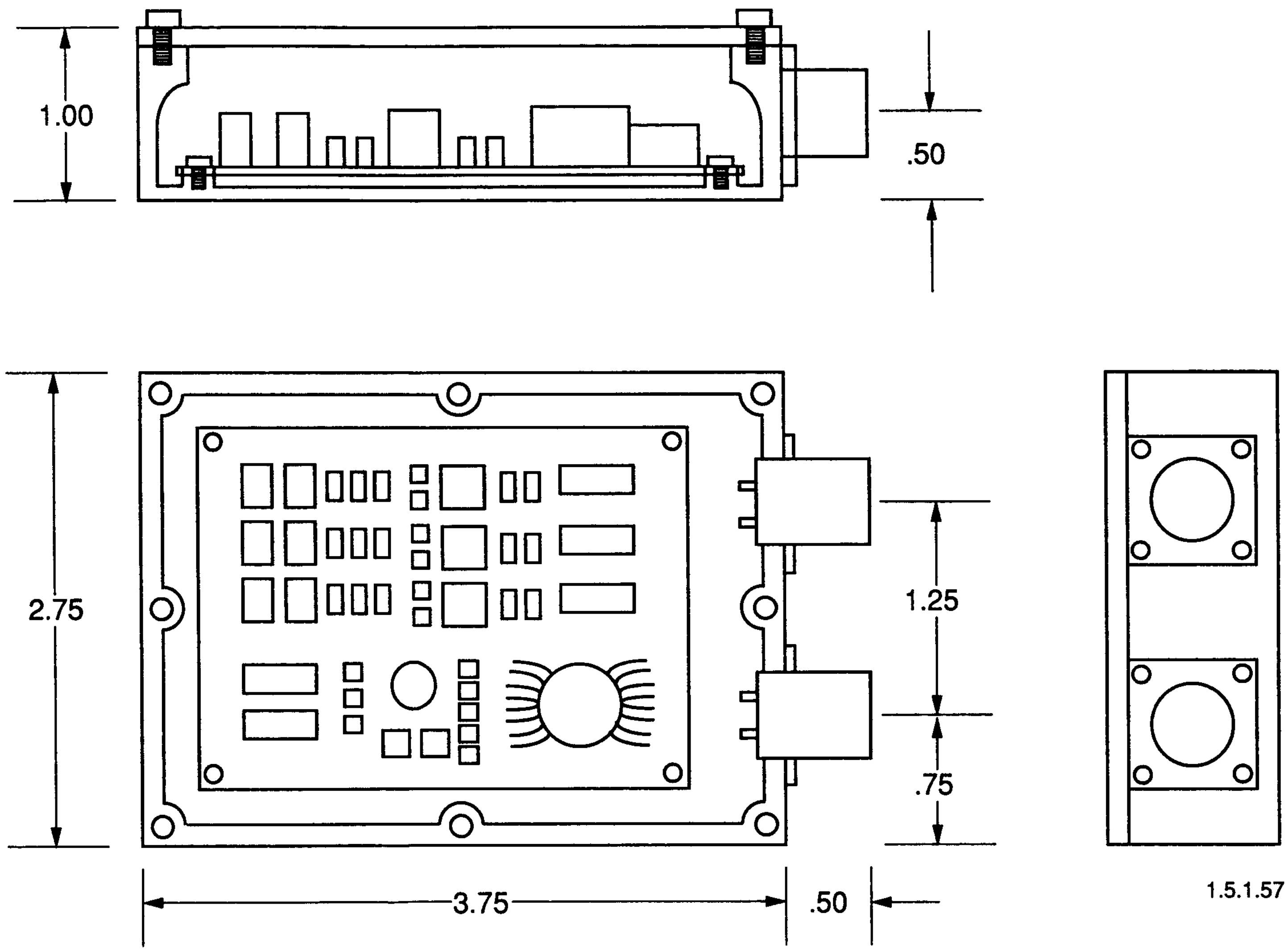

Figure 41. Signal Conditioning Module Assembly

Linear Displacement Sensor:

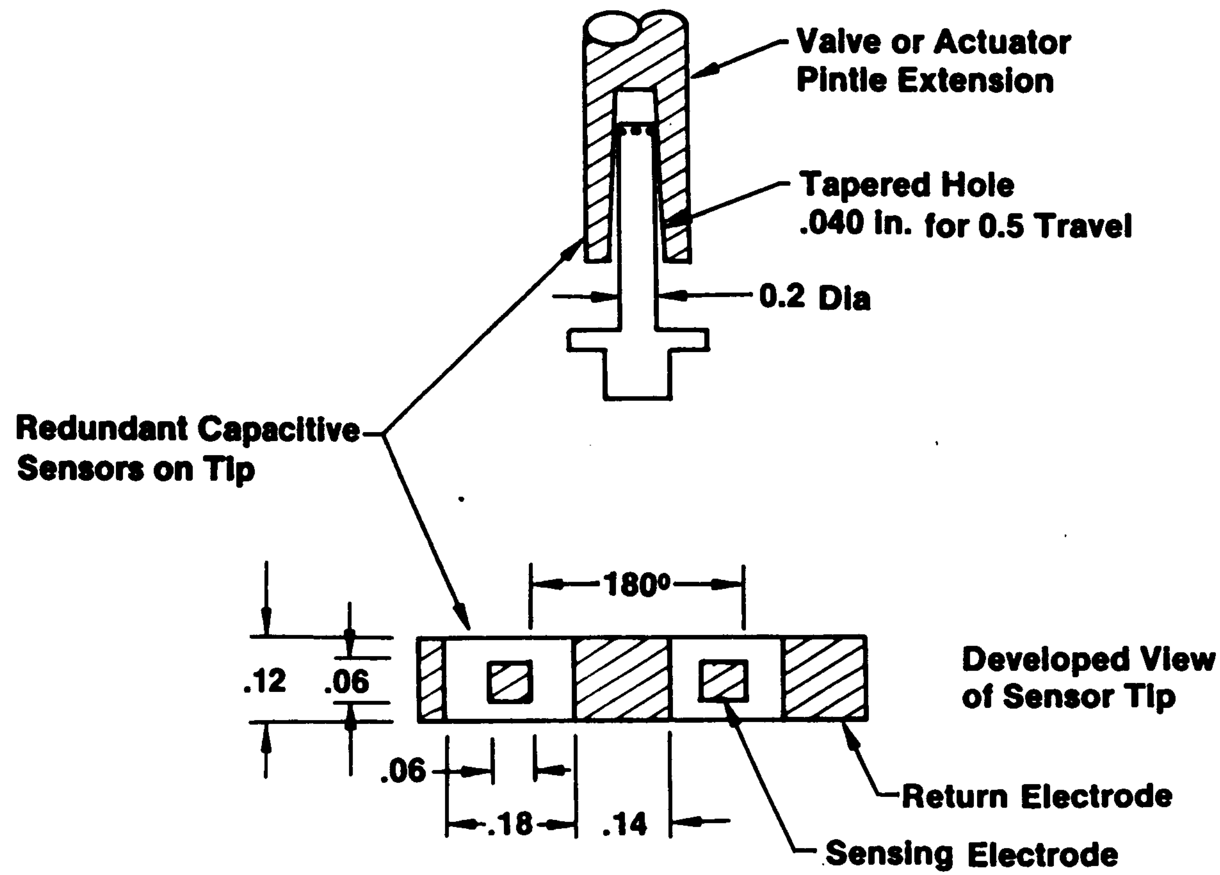

Figure 42. Redundant Valve Position Sensor

Multi-Function Displacement Sensor

- **Radial Displacement - 2 Axes**
- **Axial Displacement**
- **Speed**

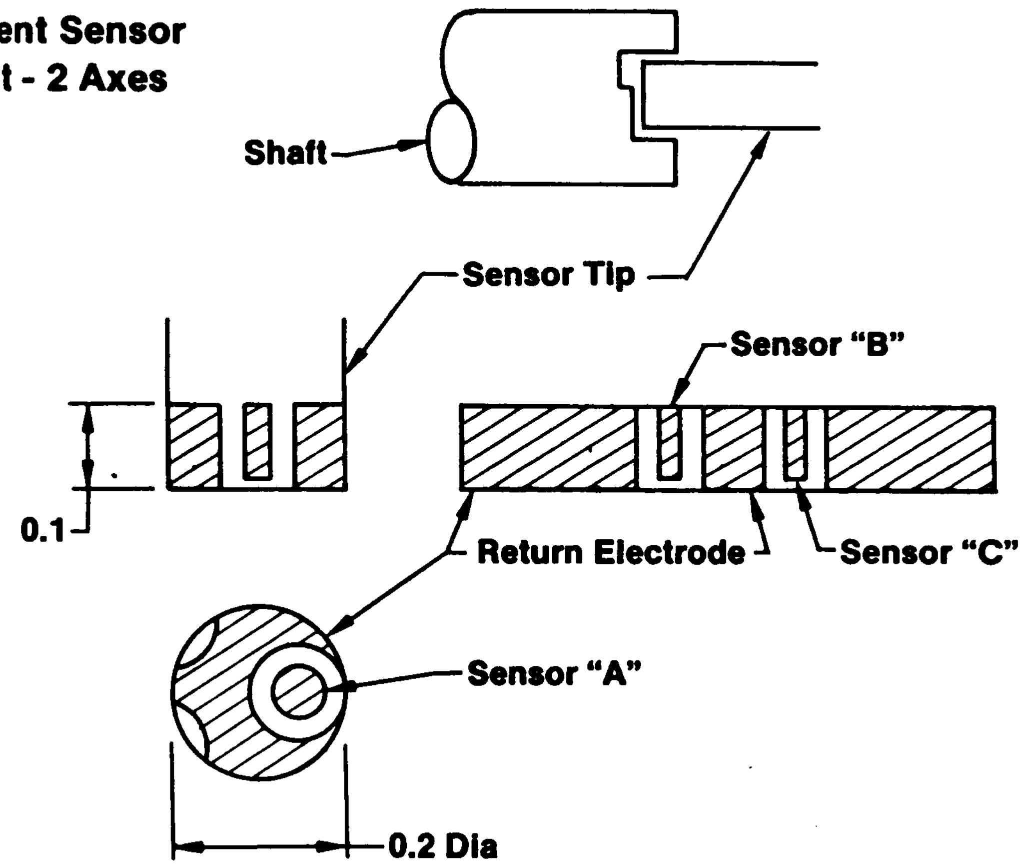

Figure 43. Multi-Function Shaft Monitor

4.5, Identification of Improvements (cont.)

- Rolling Contact Bearing Health Monitor. Miniature single function sensor may be using the same technology and could be used for applications such as bearing health monitoring using bearing outer race displacement techniques. These capacitive sensors have the frequency response and resolution required for this application. Multiple sensors can be accommodated by a single driver-signal conditioning module.

5.0 CONCLUSIONS

An experimental sensor was developed to measure axial and radial displacements of high speed turbomachinery shafts and to provide a significant size reduction relative to currently available proximity probes. Following an investigation of available technology, capacitive sensing was chosen as the best technology to achieve the task objectives. Capacitive sensing technology provides the small size, adequate sensing range, resolution and frequency response needed for sensing turbomachinery shaft dynamics at speeds exceeding 100K RPM.

Capacitive sensing was achieved using miniature sensing electrodes. A multifunction probe with advantages of small size and reduced number of penetrations through the turbomachinery housing was demonstrated with negligible fringing affects. Major accomplishments of this task were the development of an experimental three function displacement sensor probe and proof of the concept through testing. The experimental unit, which was built within the same envelope as a miniature single function inductive sensor probe, contained three independent sensors to simultaneously measure axial displacement, radial displacement, and speed. The following experiments were performed to evaluate the sensor's capabilities:

1. Room temperature calibration tests demonstrated that each sensor performed over its operating range of 0.005 inch to 0.015 inch with an error band of less than ± 1 percent of its range.

2. Functional testing using a dynamic test fixture to simulate a turbopump installation, demonstrated simultaneous axial and radial displacement measurements. Speed measurements can be made by providing a notch in one of the axial measurement surfaces.

The tests demonstrated that the output of the sensors were repeatable and each sensor provided an independent measurement with no indication of cross talk between sensors.

3. Temperature compatibility tests were performed by immersing the sensor probe in liquid nitrogen (-320°F). These tests showed an indicated displacement shift greater than that expected from the difference in the dielectric constant between air and liquid nitrogen. These tests indicated that there is a component or components in the sensor tip that are changing with temperature. Examination of the design indicates that the potential causes are instability of the reference capacitors in the sensor tip, and changes in leakage capacitance of interconnections due to condensation or material dielectric constant changes.

The following improvements and modifications have been identified to overcome the deficiencies found in the experimental sensor probe and to provide a reliable displacement sensing system for rocket engine applications.

1. An improved sensor probe design which incorporates hybrid techniques to provide a miniature diode/capacitor assembly mounted directly on the sensor tip. Encapsulated electronics are used to seal out condensation and stabilize interconnections.

2. A compact sensor driver and signal conditioning module which is suitable for rocket engine installation.

The multi-function capacitive displacement sensing technology provides a high degree of flexibility for aerospace applications. The ceramic sensor tip is amenable to custom electrode shapes for applications such as redundant valve position sensors, multi-function machinery shaft monitors and bearing health monitoring. This project has demonstrated that multi-function capacitive displacement sensing is practical and an excellent means to reduce the size and complication for monitoring turbomachinery shaft dynamics. Improvements have been identified to provide a useful and reliable sensing system.

APPENDIX A

EXPERIMENTAL EVALUATION OF CAPACITIVE SENSOR

1. PURPOSE OF EXPERIMENT. The purpose of this experiment was to evaluate the ADE Microsense capacitive displacement sensor at cryogenic temperatures. Our recently completed survey of displacement sensor technology indicated that capacitive transduction provides one of the best approaches available for measuring radial and axial displacement of high-speed turbomachinery shafts. One of the most promising of the commercially available capacitive sensors is the Microsense system by ADE Corporation. Its advantages for our application are:

Sensitivity	2 MV/μ inch
Standoff	0.010 inch
Range	± 0.005 inch
Frequency Response	40 KHz

The manufacturer has no experience or data on performance at temperatures below 40°F. This experiment is to provide information on sensor performance at temperatures to -320°F.

2. EQUIPMENT BEING EVALUATED.

- ADE Console Model 3401-R001, S/N 862712
- ADE Probe Model 2159, S/N T8565
- ADE Driver Model 2035, S/N D10146

See Figures 1 and 2 and Table 1.

3. EXPERIMENTAL SETUP. The experimental setup is shown on Figures 3 and 4. The sensor probe was mounted in a clamping fixture which allows the displacement to be set at a specified value. A Type T thermocouple is attached to the body of the sensor to measure sensor temperature. The sensor driver unit was clamped in a holding fixture to suspend the sensor assembly above a dewar filled with liquid nitrogen. Temperature is measured using an Omega Model 2168A digital thermometer. Displacement is measured using the ADE 3401 console and a FLUKE 8050A digital voltmeter. Displacement resolution is 0.5 microinch.

4. TEST PROCEDURE.

A. Adjust the sensor in the fixture to a displacement of 0.011 inch and clamp in position.

B. Record temperature and indicated displacement at room temperature.

C. Fill dewar with LN_2 to approximately 1 inch from the top.

D. Suspend sensor and fixture above the LN_2 surface.

E. Record temperature and indicated displacement as temperature decreases to approximately -200°F.

F. When temperature reaches approximately -200°F, immerse the fixture and sensor in LN_2 until the indicated displacement stabilizes. Record data.

G. Raise the sensor above the LN_2 and record data as the temperature increases.

H. Remove sensor from LN_2 environment and record data after temperature stabilizes at room temperature.

I. Repeat procedure with displacement set at 0.013 and 0.015 inch.

5. TEST RESULTS. The significant test results are shown in Figures 5, 6, and 7.

• Run Number	1	4	5
• Displacement (mils)	11	15	11
• Indicated Change (mils) (+70°F to -320°F)	-0.621	-1.782	-0.943
• Error % of Setting	5.65	11.88	8.57
• Thermal Shift %/°F	0.014	0.030	0.022

During testing, the time to reach ~-200°F was 30 to 40 minutes. As the temperature approached -200°F, the bottom of the test fixture contacted the LN_2 but the gap between the fixture and sensor was free of liquid. During immersion, the indicated displacement was corrected for the dielectric constant of LN_2 at -320°F=1.433.

Examination of the sensor following the tests in LN_2 disclosed no visible damage.

6. DISCUSSION OF TEST RESULTS. The purpose of these tests were to determine if there were any functional problems in operating the ADE capacitive sensors at liquid nitrogen temperatures. Potential problems were: (1) performance of the diodes in the sensor tip and (2) possible cracking of the glass insulation. There was no evidence of a problem in either case. The shift due to temperature change is well within acceptable limits for measuring shaft dynamics of turbo-machinery.

These tests were limited in scope and not considered to be calibration tests. Calibration under these test conditions would require a more extensive setup and fixturing.

A review of the equipment and test conditions indicates the following potential sources of errors and thermal shift.

A. Fixture Shift During Thermal Cycle

The fixture shift appeared to be minimal in the tests reported. The indicated shift in displacement when the unit was returned to room temperature was less than 0.0001 inch.

B. Variation in Dielectric Constant of LN_2

The indicated displacement of the sensor was corrected for the dielectric constant of LN_2 at -320°F (1.433). There is a possibility of contamination with water which could dissolve into the LN_2 from contact with air and has a high dielectric constant. It was noted that, as the testing progressed, the negative error increased. Note that

Run No. 5, which was taken two days later than run No. 1 showed a larger negative shift.

C. Differential Expansion of Materials

The test fixture was made of Kovar, while the body of the sensor was 303 stainless steel. (It was originally thought that the sensor was made of Kovar.) At -320°F, the differential expansion between Kovar and 303 SS would result in 0.001 inch increase in displacement. During the transient condition from room temperature to -200°F, the effects of differential expansion are unknown because the temperatures of the fixture and sensor are not the same. It is expected that the fixture is colder than the sensor during cooldown.

D. Increase in Diode Forward

Typically, the forward voltage of silicon diodes increases as the temperature decreases. This could result in a decrease in sensor current, causing an indicated increase in displacement.

E. Effect of Stray Capacitance at Sensor Tip

The indicated displacement in LN_2 was corrected for the change in dielectric constant between the sensor tip and target. However, there was also a change in leakage capacitance in the gap between the electrodes and the target. This effect could increase the measured capacitance and cause the sensor to indicate a shorter displacement than was calculated.

The following is an assessment of the previously noted error sources on typical turbomachinery installations.

1. Fixture Shaft

   Not applicable.

2. Variation in Dielectric Constant

Contamination is not likely to be a factor; however, temperature will cause a change in the dielectric constant of liquefied gas. Example for:

$$LO_2 \ \frac{-d\varepsilon}{dt} = 0.0024/^{\circ}C-$$

$$LH_2 \ \frac{-d\varepsilon}{dt} = 0.0034/^{\circ}C$$

3. Differential Expansion

This must be considered during the design.

4. Increase in Diode Forward Voltage

Probably not a significant error. Can be corrected by calibration at operating temperature.

5. Stray Capacitance

This may be a significant error factor. Can be corrected by calibration in the applicable media at operating conditions and the use of guarded electrodes.

TABLE 1. Displacement Sensor Requirements

Range	0.005 to 0.015 inch
Resolution	0.00001 inch
Error Band	± 1.0% of range
Repeatability	± 0.25% of range
Thermal Sensitivity Shift	± 0.005% of range/°C
Temperature Range	-253°C to + 100°C
Frequency Range	0-10 KHz (± 5% displacement error)
Pressure Range	0-10,000 psia
Material Compatibility:	
Liquid and Gaseous	Oxygen
Liquid and Gaseous	Hydrogen
Liquid and Gaseous	Nitrogen

TABLE A-1

ADE

SYSTEM SPECIFICATIONS 1.3

Probe Type:	2159/2035K
Probe Mounting:	Refer to Probe Drawing
Probe Cable Length:	Approx. 10 feet
Probe Active Area Diameter:	.066"
Minimum Distance from probe center line to target edge for accurate measurements:	Same as Active Area Diameter
Nominal Standoff (Probe-to-Target Spacing):	.0112"
Total Standoff Range:	.005" to .0175"
Gage Full Scale Display Range:	
DISP	TIR
a) ±.005"	0 to .005"
b) ±.001"	0 to .001"
c) ±.0005"	0 to .0005"
Rear-Panel Output Voltage:	
Displacement:	±10V = ±.005"
TIR:	0 to 10V = 0 to .005"
Linearity:	0.4% of Full Scale
Resolution:	As limited by noise
Operating Temperature Range:	40F (4C) to 130F (54C)
Temperature Stability:	5 microinches / degree F
Power Requirements:	115 VAC, 50/60 Hz

Frequency Response:
Displacement (3dB down): 40 kHz, typical

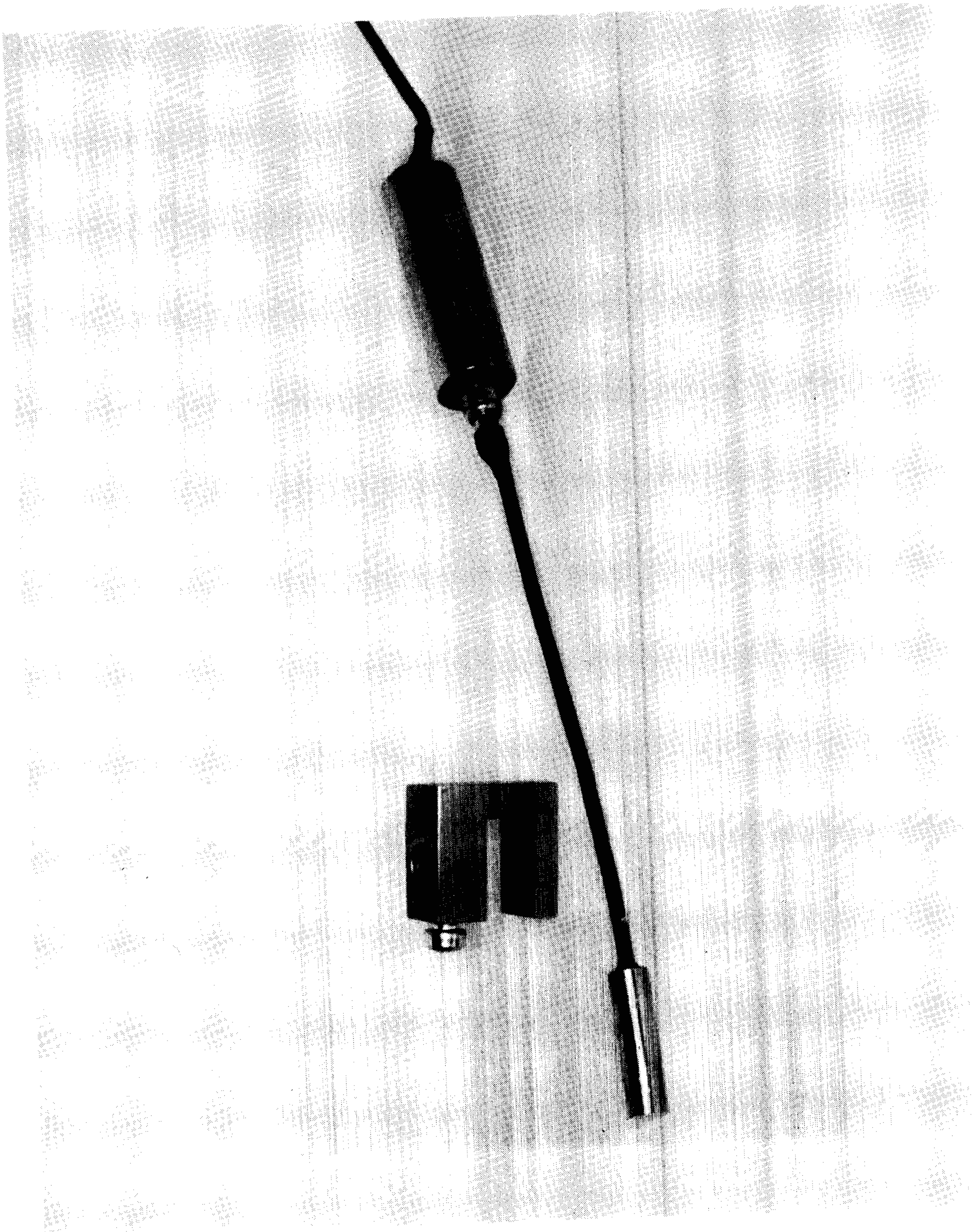

Figure A-1. Capacitive Sensor and Test Fixture

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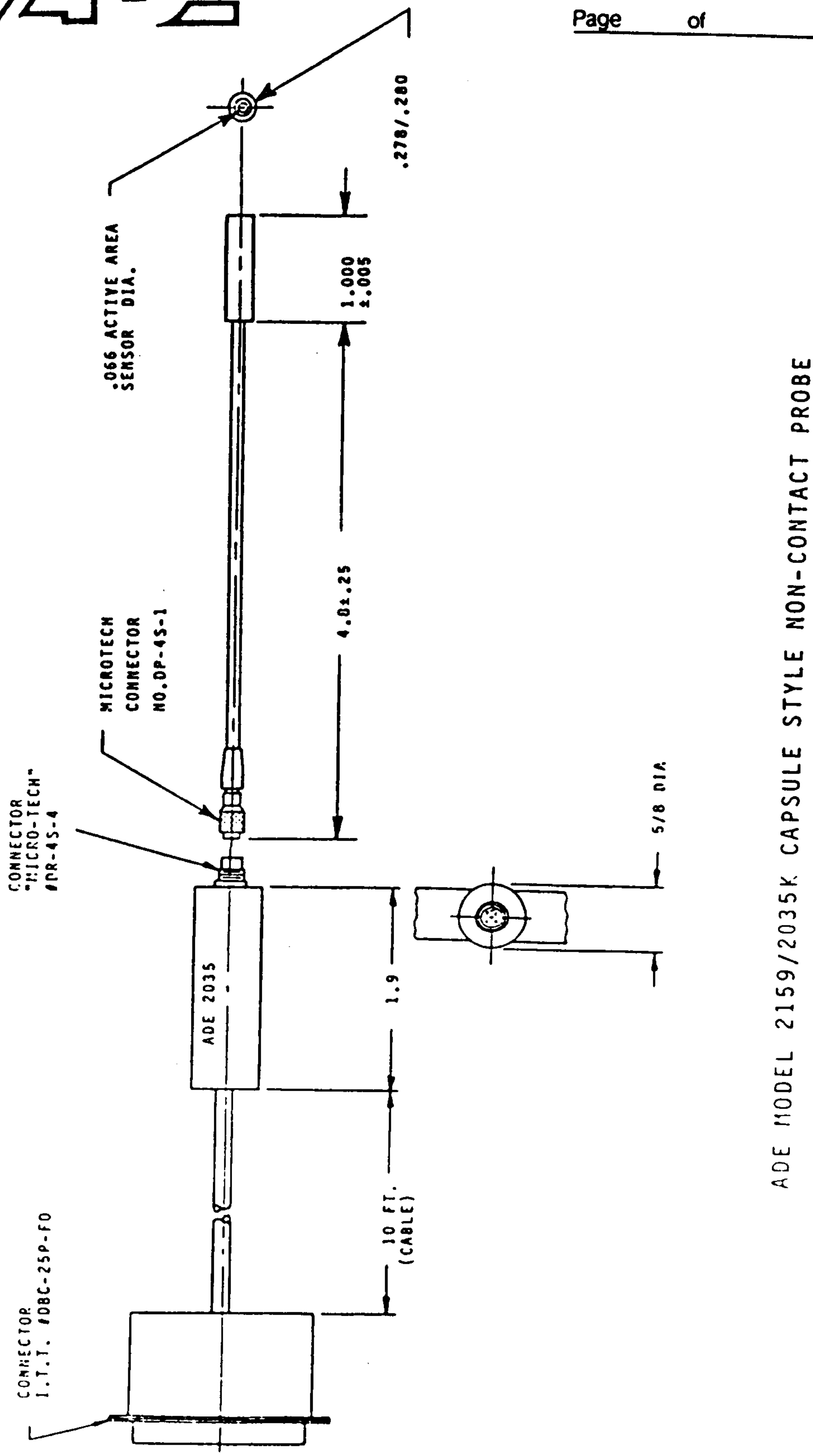

Figure A-2

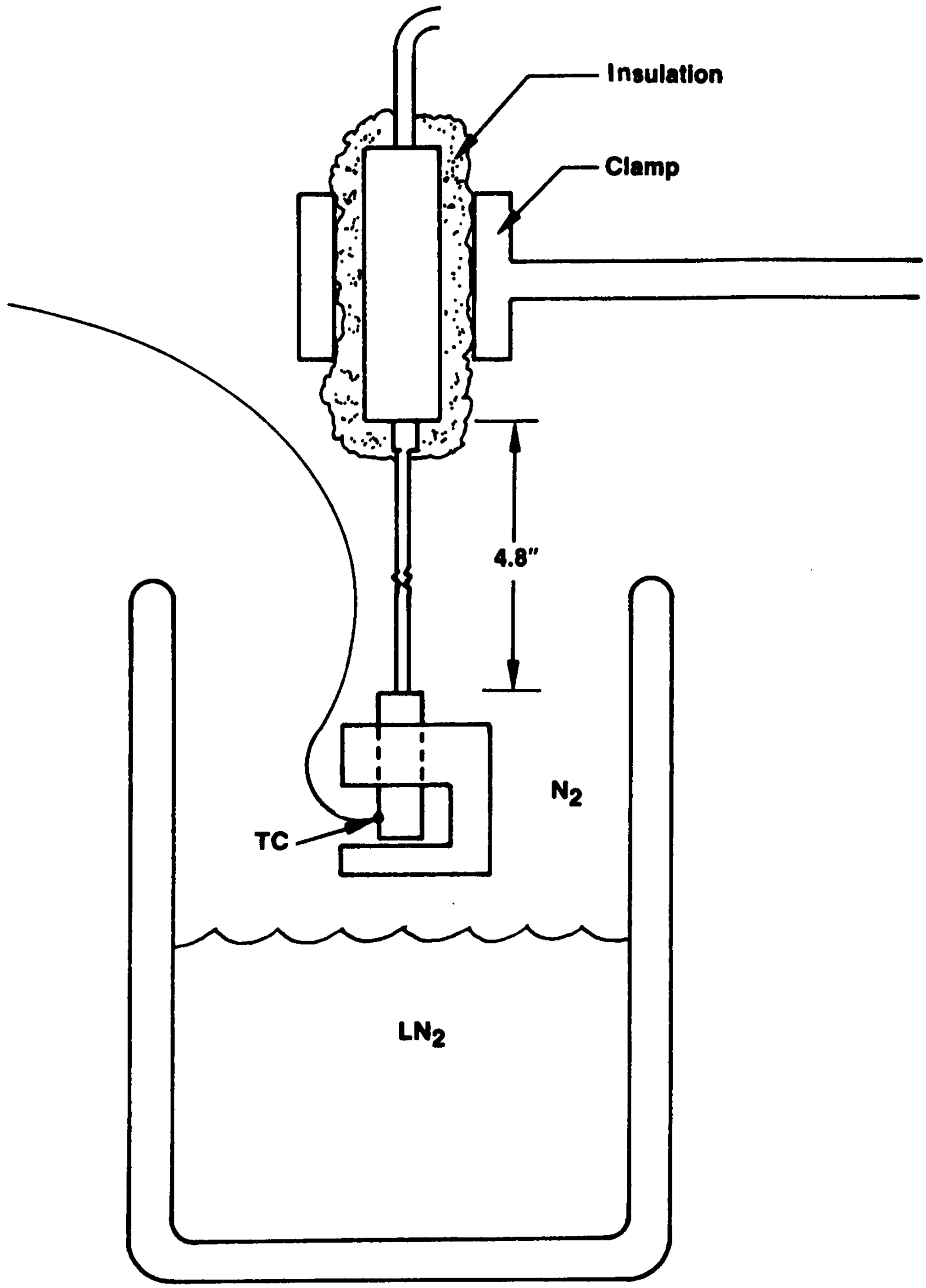

Figure A-3. Cryogenic Test Setup

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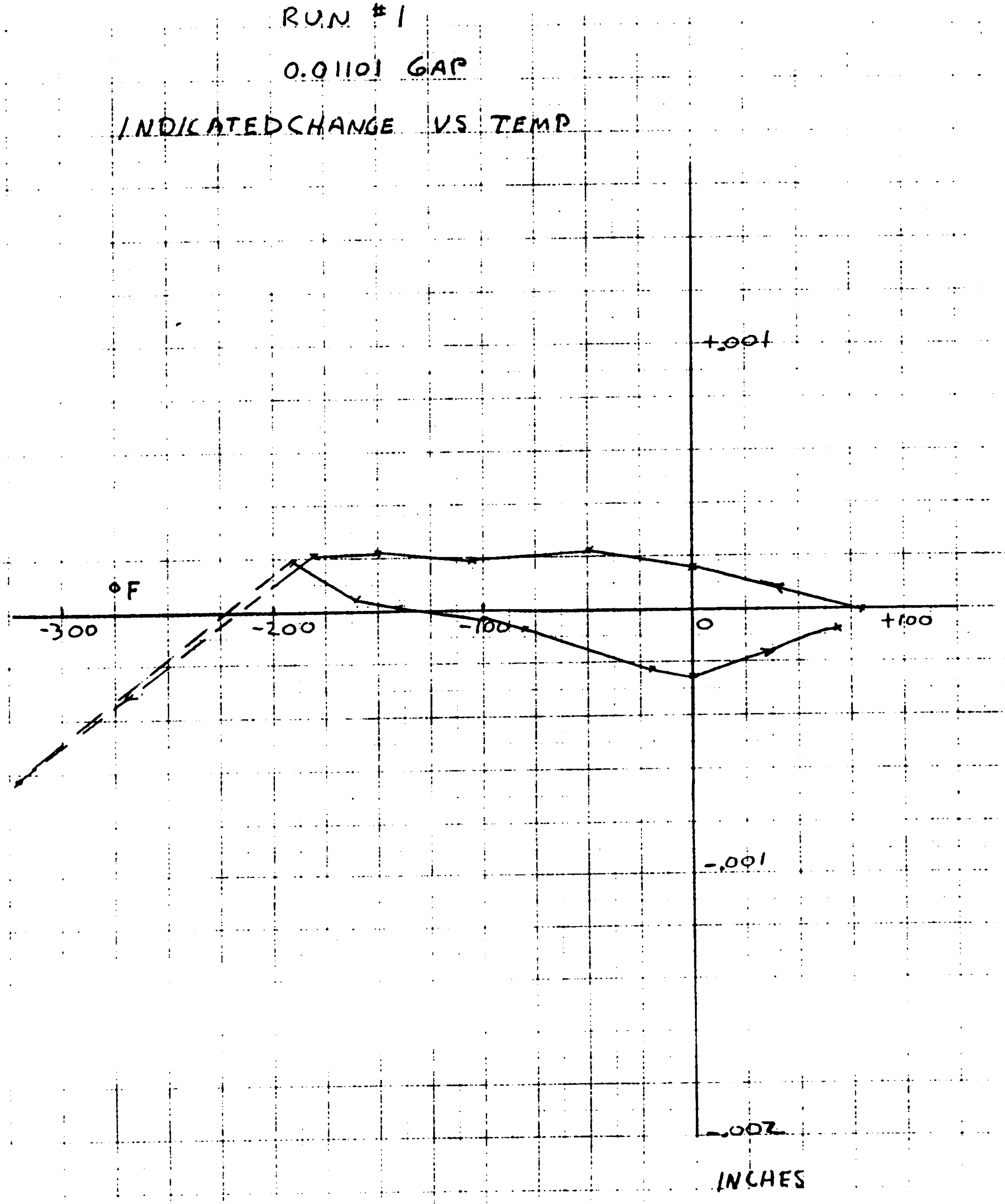
Figure A-4. Laboratory Set-Up for Sensor Testing



RUN #1
0.01101 GAP
INDICATEDCHANGE VS TEMP
+.001
°F
-300
-200
-100
0
+100
-.001
-.002
INCHES

Figure A-5

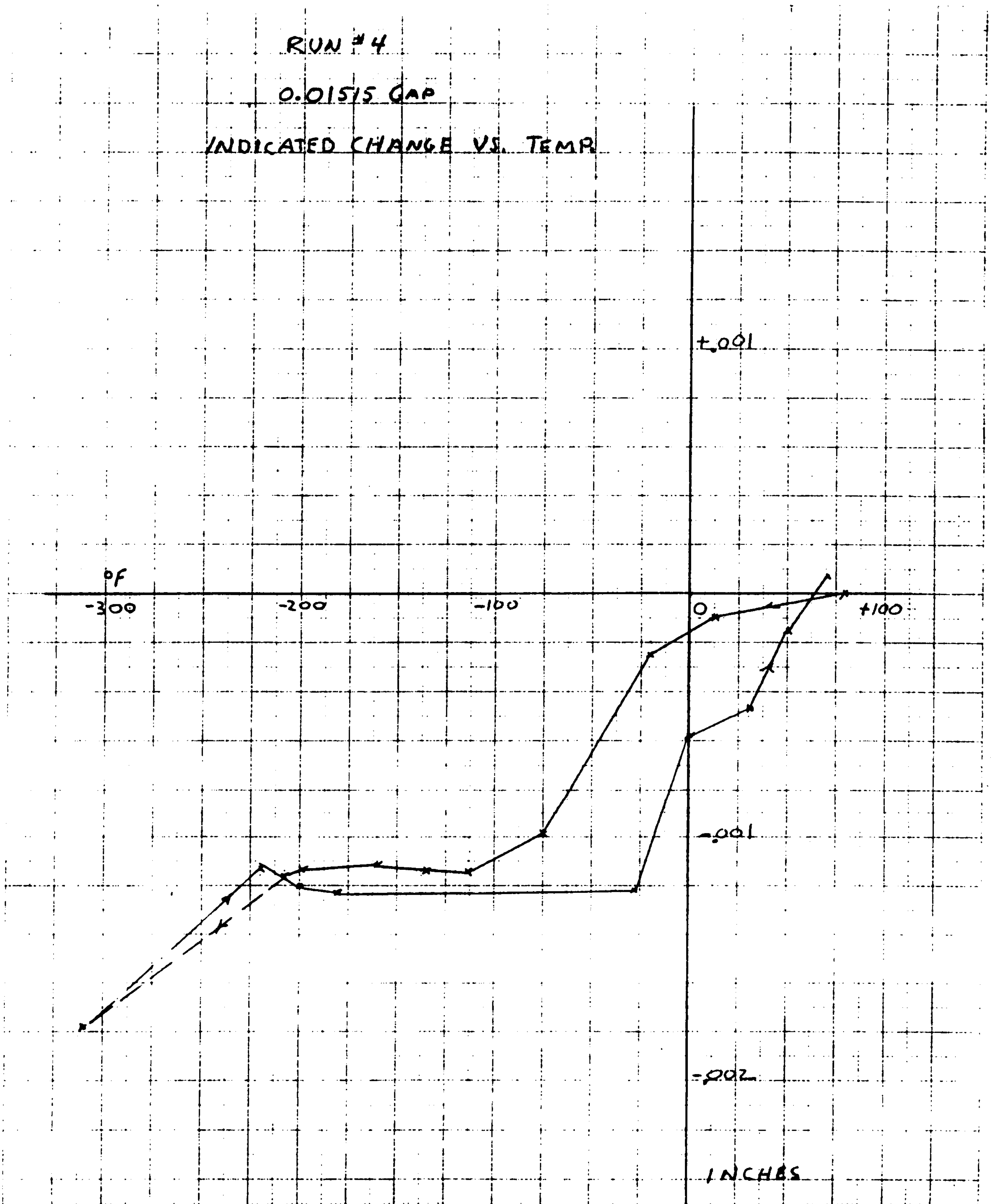

RUN #4
0.01515 GAP
INDICATED CHANGE VS. TEMP.
+.001
°F
-300
-200
-100
0
+100
-.001
-.002
INCHES

Figure A-6

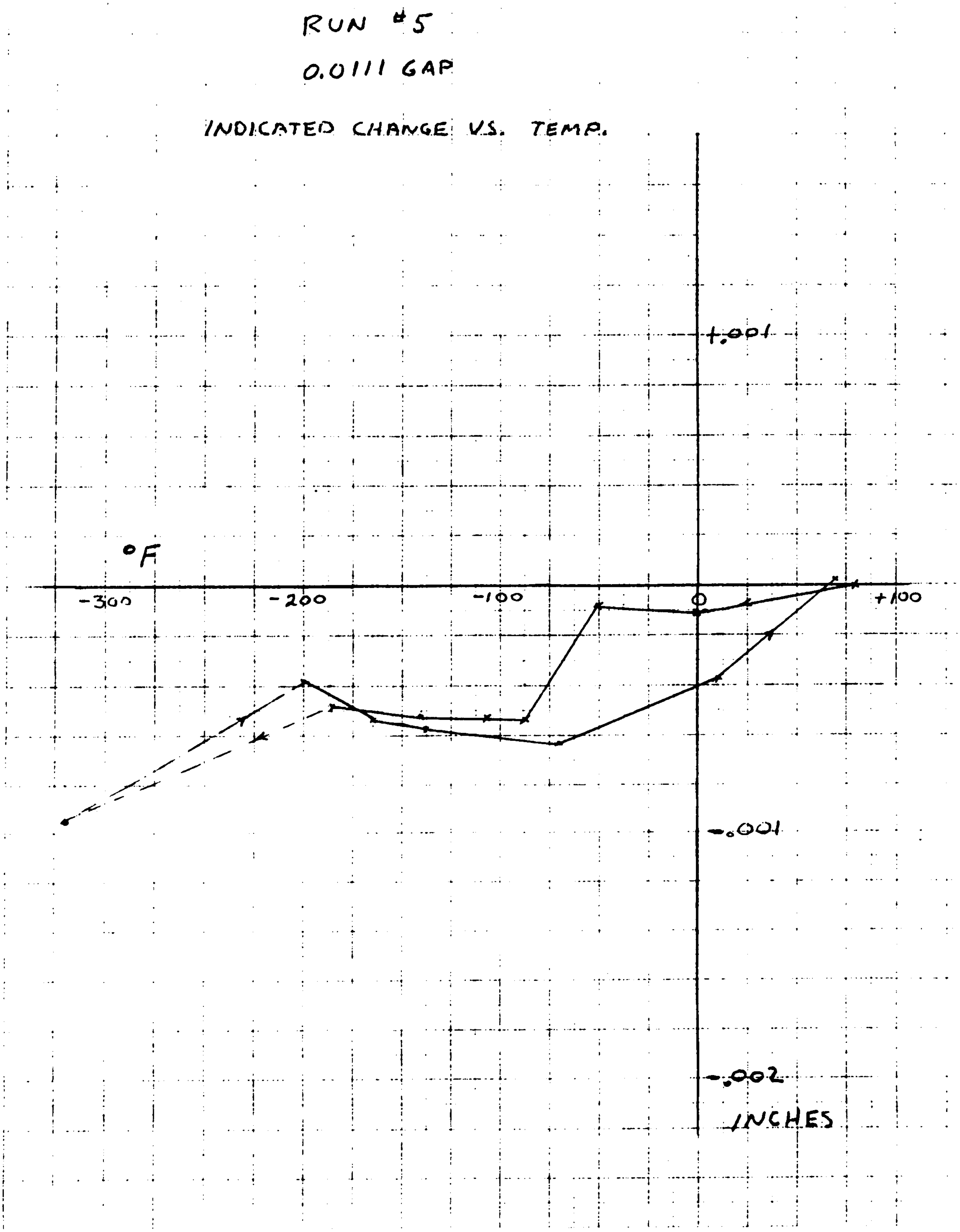

RUN #5
0.0111 GAP
INDICATED CHANGE VS. TEMP.
°F
-300
-200
-100
0
+100
+.001
-.001
-.002
INCHES

Figure A-7

APPENDIX B

NON-CONTACT DIMENSIONAL GAGING USING CAPACITIVE SENSING

NON-CONTACT DIMENSIONAL GAGING USING CAPACITIVE SENSING

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(This paper was originally presented at Sensors Expo 1987.)

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Non-Contact Dimensional Gaging Using Capacitive Sensing

1. NON-CONTACT DIMENSIONAL GAGING

1.1 INTRODUCTION

There are many instances where dimensional information is needed about an item which cannot, or should not, be touched. Runout of a machine spindle is to be measured as it rotates at thousands of RPM. The thickness of ceramic slurry needs to be controlled prior to baking. Flatness of silicon wafers must be determined in a "clean room" environment without scratching the highly polished wafer surface. These and many other problems may be solved using one of the non-contact, dimensional gaging techniques.

An array of products utilizing non-contact techniques are available. These products have been developed not for use as simple proximity sensors, but truly for precise dimensional gaging. The "contact analogue" is a micrometer rather than a limit switch. These products all share some advantages by virtue of their non-contact operation:

No surface damage. A non-contact technique will not scratch a shiny surface, indent a soft surface nor contaminate a pristine surface.

No part distortion. Contact gaging methods always generate forces on the measured part. To resist these forces the part is often clamped. The deflections resulting from these contact and clamping forces may seriously impair measurement accuracy on thin, soft or flexible items. There are no contact forces involved with non-contact techniques and often no need to clamp, so the part will not be in a distorted condition when measured.

No probe wear. Contact methods are subject to wear of the probe tip, particularly if abrasive materials are being measured or if the probe is being dragged across the measured surface. Additionally, a contact probe is often an assembly of bearings, springs and other mechanical components which are also subject to wear. Probe wear represents a source of error and also a maintenance concern. Most non-contact probes are all-electronic and they do not contact the measured surface, so there is no probe wear.

Faster Measurements. Although speed capabilities vary greatly, as a general rule the rate at which measurements are made with non-contact equipment is faster than with contact equipment. No time is expended bringing the probing surface(s) in contact with the measured part and frequency response of the gage is not limited by the inertia of any mechanical hardware.

In addition to those advantages listed above (which are generic to non-contact dimensional gaging techniques), each individual technique also has its own distinct advantages. These may make one technique a compelling choice over all others for a specific application. For instance, ultrasonic equipment has outstanding range capability (tens of feet) and eddy current equipment can accurately measure metallic objects under thick layers of oil or dirt.

Armed with an appreciation of the capabilities of these techniques, one can make an appropriate choice to solve the dimensional gaging problem at hand. This article will focus on just one of the non-contact options, the capacitive gaging method.

1.2 CAPACITIVE GAGING

"Capacitance varies with the distance between two conductive plates". This simple electrical effect was first harnessed as a displacement transduction technique at the beginning of this century. Today it is one of the prominent non-contact options for solving dimensional gaging problems. Driven largely by the challenging demands for better quality control in the semiconductor and computer industries, an array of capacitive gaging tools have evolved which are now used in a diverse range of manufacturing-related applications.

Capacitive gaging techniques share the advantages listed above which are generic to all non-contact methods; namely that measurements can be taken rapidly without damaging or distorting the surface of the measured part and without any probe wear. Additionally, capacitive gaging techniques have the following advantages and characteristics:

High Frequency Response. For the great majority of practical applications, frequency response is never a problem. Products are available with frequency response ranging up to 100 kHz or higher. This is an important characteristic to consider when making dynamic measurements.

High Resolution. Some capacitive gages are capable of measuring displacements of less than one microinch.

No Material Calibrations. Capacitive gages are insensitive to variations in resistivity of conductive materials, so there is no need to recalibrate when measuring different metals.

Can Measure Dielectrics. Some glass, plastic, rubber and ceramic parts can be measured, although dedicated calibrations are normally required.

Variety of Ranges. Capacitive gages can be configured to operate over a variety of ranges, from approx. one thousandth of an inch up to about one inch.

Easy to Use. Equipment setup is relatively easy. Most products are portable and modular in design. The same gage can be used for a variety of measurement tasks, static and dynamic.

Capacitive gaging will not meet the requirements of every dimensional gaging application, no single technique can. However its versatility makes it worthy of consideration whenever one is confronted with a challenging gaging problem.

2. SENSING TECHNOLOGY

2.1 INTRODUCTION

Many capacitive sensing techniques have been developed over the years for dimensional gaging usage. Today, two techniques predominate and they are the focus of this particular article.

The simplest capacitive gage consists of a probe, a cable and an electronics package. In some hardware configurations, the electronics is entirely separated from the probe by means of a long cable. This configuration is referred to as a "**passive probe**" design. In other hardware configurations, some electronics is placed in the probe housing, with more electronics at the end of a long cable. This configuration is referred to as an "**active probe**" design.

Regardless of the hardware configuration, the same transduction method applies. The probe tip incorporates a sensor which is positioned directly above the target surface. The sensor and the target surface may be considered as two plates of a capacitor; the air gap between the two as the capacitor dielectric. The "**driver**" portion of the electronics supplies excitation to the sensor, thereby setting up an electric field between sensor and target. The level of voltage or current in the transduction electronics is proportional to the capacitance of the tip/target combination. This, in turn, is a direct function of tip-to-target separation. Thus, by monitoring voltage applied to the sensor ("passive probe") or current flow to the sensor ("active probe"), the remote electronics can accurately determine the distance between tip and target.

In reviewing the elementary theory of the capacitive transduction method, let us assume that the target (item to be measured) is flat, conductive and grounded to the instrument electronics. (Later the implications of target shape, of imperfect grounding and of measuring non-conductive materials will be discussed). Placing a flat plate sensor in close proximity to such a target effectively creates a parallel plate capacitor (see Figure 1). The electrical capacitance of it is given by:

$$C = K*Eo*A/d \quad \text{... equation (i)}$$

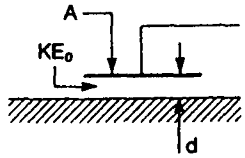
where: **C** is the capacitance.

K is the dielectric constant of the medium between the plates.

Eo is the permittivity of free space.

A is the plate area.

d is the distance between the plates.



$$C = \frac{KE_0A}{d}$$

FIGURE 1 CAPACITIVE SENSING MODEL

In most applications the sensor area is smaller than the target area, so sensor area is the appropriate substitution for 'A'. Furthermore, for a specific application, the sensor area was determined at manufacture and therefore may be considered a constant. In most applications, the dielectric medium between the plates is air. Air has a dielectric constant of 1.0006 and it varies little with temperature and humidity changes. Therefore it too may be considered a constant. Thus equation (i) reduces to the following for a *specific* application:

$C = \mathbf{k_1}/d$ ... equation (ii)

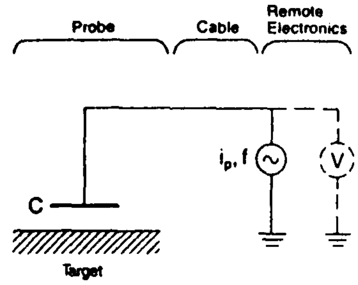
where: $\mathbf{k_1}$ is a constant (including E_o, K and A).

Equation (ii) suggests a classical transduction relationship exists here; namely that change in a mechanical parameter (distance, in this case) causes an electrical effect (change in capacitance).

2.2 PASSIVE PROBE TECHNOLOGY

2.2.1 Introduction

Many common hardware designs employing the capacitive sensor are "passive probe" based. As stated before, the name reflects the fact that the probe has no active (i.e. electronic) components. In its simplest form, the sensor plate is attached to the center core of a coaxial cable and the plate is encased in a *non-conductive* housing to electrically isolate the sensor from its clamp. (A *more* useful probe design will be discussed in Section 2.2.3). At the other end of the cable, the electronics package forces a constant amplitude, alternating current through the cable and sensor-target capacitance. A simplified schematic of this arrangement is shown in Figure 2.



$$V = \frac{i_p}{k_2 f C}$$

FIGURE 2 PASSIVE PROBE TRANSDUCTION SCHEME (SIMPLIFIED SCHEMATIC)

2.2.2 Basic Theory

Simple circuit theory applied to the scheme illustrated in Figure 2, yields the following equation:

$\mathbf{V = i_p/k_2 * f * C}$ ... equation (iii)

where: **V** is the voltage across the capacitance, (the measured output).

$\mathbf{i_p}$ is the amplitude of alternating current flowing, (maintained constant by the driver).

$\mathbf{k_2}$ is a constant involving conversion of the units of measure.

f is the frequency of alternating current flowing, (maintained constant by the driver).

C is the sensor-target capacitance, (if the cable capacitance is ignored, see Section 2.2.3).

For a specific application, we have already determined that $C = k_1/d$, (see equation (ii)). Substituting this into Equation (iii) and consolidating constants yields:

$\mathbf{V = k_3.d}$ ... equation (iv)

Equation (iv) conveys the attractive simplicity of the passive probe approach. The voltage resulting from the impressed current need only be appropriately scaled and biased to be a direct measurement of target position.

2.2.3 Practical Considerations

Two key assumptions were made in the simplified, theoretical model discussed above. One was that the cable capacitance could be ignored and the second was that the sensor-target combination is acting as a perfectly ideal, parallel plate capacitor.

In fact, the cable capacitance in this simple model is much larger than the sensor-target capacitance and appears in parallel with it. To prevent relatively minor shielding "leaks" or other seemingly small cable capacitance changes from dwarfing the capacitance changes at the sensor, the shield of the cable is also driven. It is driven separately, but at the same potential and in-phase with, the cable core and sensor. This is referred to as "**guarding**" the cable. By using good quality cable and driving its shield, cable runs of 10 feet or more are quite practical.

The second assumption, that the electric field between sensor and target is a perfect analog of an ideal parallel plate capacitor, can also be made true enough with slight modifications to the simple probe model described above. While the electric field lines may well be parallel near the center of the sensor, they are not near the edges. The field tends to 'spread out' from the small sensor to the large target (see Figure 3a). This phenomenon is called "**fringing**" and distorts the ideal transfer function ($C=k_1/d$) determined above. If left unchecked, it would result in non-linearity of the output signal, to a degree determined by the ratio of sensor size to separation gap (i.e. for a given sensor-to-target gap, smaller sensors would be less linear than larger sensors).

Fortunately, a relatively simple addition to the probe design successfully removes this potential problem. Another plate is added to the probe, concentric with the central sensor plate, and separated from it by a relatively thin insulator. This second plate is referred to as a "**guard**" or "**guard ring**". It is connected to the (driven) shield of the coaxial probe cable, so that it too is at the same potential and in-phase with the sensor. Therefore this guard ring also establishes an electric field with the target and, crucially, this field interracts with the sensor field. The net effect is to collimate the *sensor* field and move the fringing field to the extremities of the *guards'* field (see Figure 3b). Since the current in the guarding circuit is not the transducer output (see Figure 4), fringing of its field is of no consequence. Happily, with the sensors' field now virtually ideal, an inherently linear output is obtained.

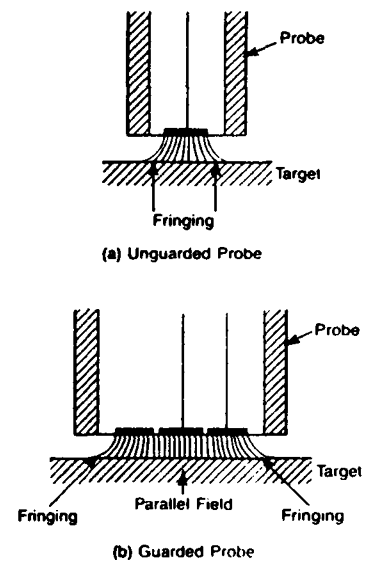


FIGURE 3 "FRINGING" EFFECTS

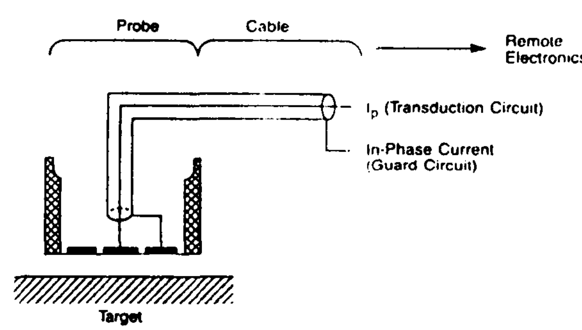


FIGURE 4 PASSIVE PROBE TRANSDUCTION (PRACTICAL DESIGN)

Guarding has two other benefits. Because the sensors' field does not fringe, a guarded probe can measure closer to the edge of a target than an unguarded probe (the size of the field at the target is effectively smaller). Also a guarded probe is much less sensitive to any leakage paths from sensor to probe housing. This leakage may be due to a contaminated probe face (e.g. oil on the tip) or a non-ideal insulator between the sensor and its housing. When a guard surrounds the sensor, the only difference in electrical potential across an insulator layer is between the guard and the probe housing, outside of the transduction circuit. On the negative side, adding the guard increases the probe housing size for a given sensor size and may increase the cost, depending on the manufacturing methods and materials used.

2.2.4 Linearizing Techniques

It is obvious from Equation (iv) that the output is inherently linear, so no "linearizer" as such is required. (Apart from some fine linearity adjustments made to the electronics when manufactured to compensate for slight imperfections in the assumed parallel field and also for non-ideal front end circuitry).

2.2.5 Probe Construction

Most common commercially available passive probes are constructed as an assembly of machined cylindrical and tubular parts. One face of the cylinder acts as the sensor, a larger diameter tube acts as the guard and a yet larger diameter tube acts as the probe housing. The cylinder and tubes are typically fabricated from stainless steel or aluminum. Between each of these metallic pieces is an insulator layer, quite often an epoxy compound that is potted in place (see Figure 5). For better stability at higher cost, glass preforms are used and the assembly is fired to create a fused seal at the glass-to-metal interfaces. Finally, the sensor end of the assembly is ground and polished and at the opposite end, a cable connector is attached.

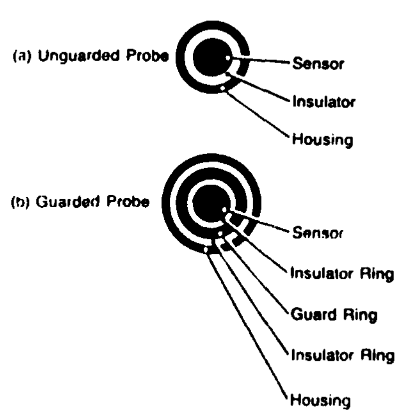


FIGURE 5 PROBE FACE OUTLINE

A more recent probe construction technique utilizes ceramic substrates with thick film electrodes plated on one face. This offers considerable design flexibility over the traditional probe construction method. A square or rectangular sensor is as easy to fabricate as a round one. The guard electrode can be located within a few thousandths of an inch of the sensor electrode, ensuring excellent sensor field collimation. The thickness of the plated ceramic piece is only about 0.020" which permits the manufacture of very thin probes (the size and shape of a tongue depressor, for instance). Plated-through holes allow for soldering of leads to both electrodes behind the sensor face. The ceramic piece is normally bonded into a metallic probe housing which shields the attachment leads, carries the BNC connector and allows for convenient fixturing.

2.2.6 Electronics Design

The driver electronics which drives the constant current through the sensor is an operational amplifier circuit. Excitation voltage and frequency is limited by amplifier bandwidth and dynamic range. voltages are typically up to 20 volts peak-to-peak, frequency is limited to about 15 kHz. Probe currents are on the order of nanoamperes. The raw output is an AC voltage and must be demodulated in order to separate the signal voltage from its carrier. A synchronous demodulator is typically used for this. Span and zero adjustment controls may also be provided.

Many designs are "zero-based": meaning the output signal is zero volts at "touch" and is +10 volts at its maximum range. In practice, operating at or near the point where the probe touches the target is undesirable, and runs counter to the intention of making *non-contact* measurements. In many cases the total measurement range cannot realistically be used because of this. Other designs avoid this situation by offsetting the operating range so that it exists about some nominal standoff.

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2.3 ACTIVE PROBE TECHNOLOGY

2.3.1 Introduction

By locating some driver circuitry in the probe itself and using more sophisticated electronics remotely, it becomes possible to meet more demanding measurement specifications.

In order to meet the individual measurement needs of a customer, capacitive gaging manufacturers routinely "juggle" parameters such as sensor size, operating range, nominal standoff (sensor-to-target gap) and bandwidth. It is fair to say that active probe technology affords greater flexibility in making those tradeoffs. It is also true that active probe technology can solve problems which cannot even be addressed with passive probe technology. Examples include measuring thick dielectric materials and measuring high frequency displacements (tens or hundreds of kilohertz).

In its simplest form, the sensor plate in an active probe design is attached to the center core of a shielded wire only a few inches long. At the other end of this wire a small electronics package drives the sensor with a constant amplitude, alternating *voltage*. The assembly is encased in a nonconductive housing to electrically isolate the sensor from its clamp. (A more useful and practical probe design will be discussed in Section 2.3.3). A long length of multi-wire cable runs from the probe driver package to the remote electronics. The remote electronics provides DC power to the driver and processes the probe signal, in this case the probe *current*.

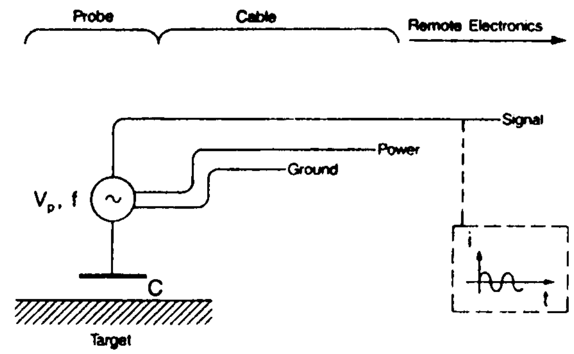
2.3.2 Basic Theory

A simplified schematic of the active probe arrangement is shown in Figure 6. Simple circuit theory applied to this scheme yields the following equation:

$$i = k_4 * V_p * f * C \quad \text{... equation (v)}$$

where: i is the resultant current flowing in the circuit, (the measured output).

k_4 is a constant involving conversion of the units of measure.



$i = k_4 V_p f C$

FIGURE 6 ACTIVE PROBE TRANSDUCTION (SIMPLIFIED SCHEMATIC)

V_p is the amplitude of alternating voltage applied to the circuit, (maintained constant by the driver).

f is the frequency of the applied voltage (maintained constant by the driver).

C is the sensor-target capacitance, (if the shielded wire capacitance is ignored, see Section 2.3.3).

For a specific application, we have already determined that $C = k_1/d$ (see equation (ii)). Substituting into equation (v) and consolidating the constants:

$$i = k_5/d \quad \text{... equation (vi)}$$

Equation (vi) shows that in the case of an active probe, the electrical output (current) is *inversely* related to the measured quantity (target position). Clearly, the remote electronics will need some linearizing capability to provide the desired result; output which is *linearly* related to target position. (Two methods used to accomplish this are explained in Section 2.3.4.)

2.3.3 Practical Considerations

The same assumptions made in the simplified theoretical model of a passive probe were also made above in the model for an active probe; namely that the capacitance of the cable between the sensor and its driver could be ignored, and that the sensor-target combination is acting as a perfectly ideal, parallel plate capacitor. An additional practical problem in this case is that the transduction output signal is a high frequency, ***alternating*** current with a mean value of zero, regardless of target position.

To combat the inevitable capacitance changes in the wire between the sensor and its driver and to produce outputs with a non-zero mean, a diode ring and a second driver-sensor-target combination is introduced (see Figure 7). The second sensor plate, called a "balance electrode" sets up an electric field with its own target, called a "tuning plate". Both of these plates are buried within the probe tip housing. The diode ring lies between the sensor-target capacitor and the balance capacitor. Two corners of the diode ring are driven separately but in-phase. The two resultant currents have equal but opposite, non-zero mean values when the two probe capacitances are unequal. Their RF components are filtered out in the driver electronics, leaving only the DC component (or signal frequency component in the case of oscillating targets). Therefore, a DC current proportional to the difference of the two probe capacitances is obtained. Since the balance electrode-to-target gap is fixed at initial manufacture, the DC probe current is directly related to sensor-to-target gap only.

The end result is that a current is generated which bears an inverse relationship to sensor-to-target gap, (per equation (vi) above). Despite the fact that the sensor is driven with a high frequency oscillator, the output is now an easily handled DC (or signal frequency) current. The symmetrical arrangement of a probe capacitor on each side of a diode ring, accounts for the excellent stability of the active probe. Any stray capacitance changes affecting both capacitors will tend to cancel.

The non-ideal fringing field between sensor and target can be made virtually ideal by using a guard ring to collimate the sensors' field, (as in the passive probe case). Alternatively, since its only effect is to slightly distort the resultant " $i = k_5/d$ " relationship, the distortion can be corrected by using an appropriate linearizing technique.

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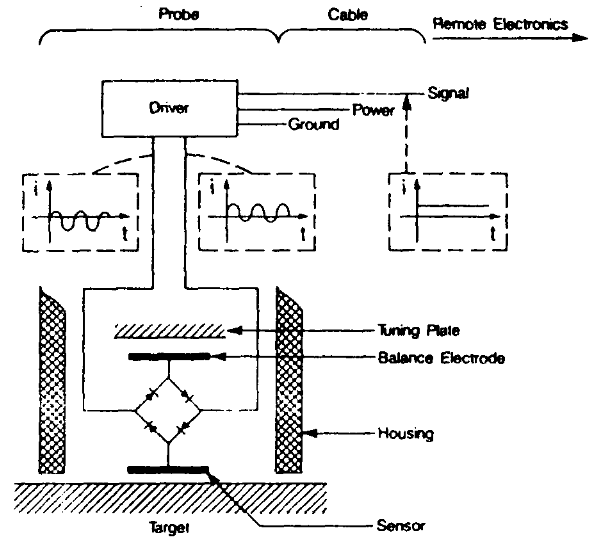


FIGURE 7 ACTIVE PROBE TRANSDUCTION (PRACTICAL DESIGN)

2.3.4 Linearizing Techniques

It is obvious from Equation (vi) that the transduction scheme is not yet complete. The desired output is a *voltage* which is *linearly* related to distance, rather than a *current* which is *inversely* related to distance. Several linearizing schemes are in use, the two most common being the "breakpoint" scheme and the "multiplier-divider" scheme. In either case, an op. amp stage in the front end circuit of the remote electronics first converts the incoming signal current into a voltage useful for further processing:

$$V_{fe} = k_6 * i$$
$$= k_7/d \quad \ldots \text{ equation (vii)}$$

where: V_{fe} is the front end amplifier output voltage.

k_6 & k_7 are constants.

A **breakpoint linearizer** is a piecewise-linear, variable gain amplifier circuit. The general form of its transfer function is shown in Figure 8. It amplifies the voltage from the front end circuit by an amount dependent upon the magnitude of the voltage itself. Large input voltages (resulting from large probe currents, in turn resulting from the target being close to the sensor) are amplified less than small input voltages. The net effect is to "pull" the larger voltages down.

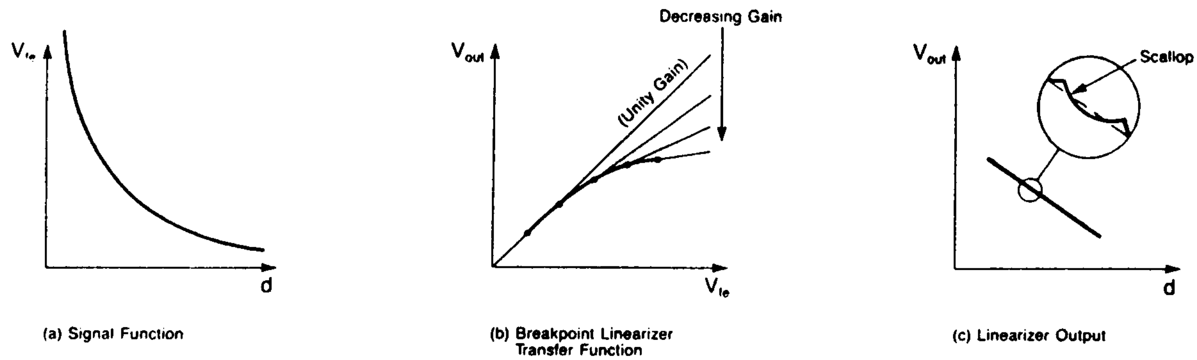


FIGURE 8 BREAKPOINT LINEARIZING SCHEME

This scheme works fine over the range of target position of greatest interest. However when the target gets extremely close to the sensor, the gradient of the signal increases at such a rapid rate that the number of discrete gain stages needed would likewise increase rapidly. This becomes burdensome in hardware and only serves to expand the operating range of the transducer into a region where contact between sensor and target is more likely. Therefore a minimum sensor-to-target distance is stipulated by the manufacturer, beyond which an "underrange" condition exists. This distance is referred to as "**near standoff**".

When the target is a long way from the sensor, the reverse condition exists; the output current varies very little with rather large changes in gap. To maintain good performance, this relatively invariant region is also excluded from linearization. A maximum sensor-to-target distance is stipulated by the manufacturer beyond which an "overrange" condition exists. This is referred to as "**far standoff**".

So the zone between near standoff and far standoff is linearized by the breakpoint scheme and this defines the operating range. After linearization, the output voltages are typically DC offset so that the output at near standoff is +10 volts and the output at far standoff is -10 volts. The transduction hardware is said to operate over plus and minus some distance about a "**nominal standoff**", where the output is zero volts (see Figure 9). For example a range of +/- 0.005" about a nominal standoff of 0.011" means that the hardware will produce a linearized output when the sensor-to-target gap is between 0.006" and 0.016".

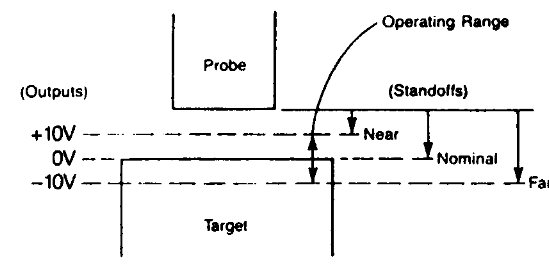


FIGURE 9 RANGE DEFINITIONS

The breakpoint linearizing scheme is very versatile but it's not perfect. Since the amplifier gain stages are discrete (10 breakpoints is typical), and the input to the breakpoint circuit is a smooth curve ($V_{fe} \propto ks/d$), the output is not a perfectly smooth straight line. The line is theoretically a series of shallow scallops, but in practice appears as a close approximation of a very shallow sinusoid. This deviation from a straight line is very minimal and determines the non-linearity of this transduction scheme, typically 0.1% to 0.2% of total operating range. This is quite comparable to that of passive probe hardware.

The versatility of the breakpoint method arises from the fact that **any** smooth, continuous curve may be linearized simply by adjusting the shape of the transfer function. A "perfect" inverse relationship is neither assumed nor needed. Signals from unguarded sensors are linearized as easily as those from guarded ones. Special calibrations can be generated for thick dielectric materials where, in the absence of any grounded target, the electric field lines loop around from sensor face to the grounded housing of the probe. Even though this case is difficult to model analytically, the relationship between probe current and dielectric target position may be found empirically. Then an appropriate set of breakpoints can be developed to linearize the output for this particular combination of sensor and dielectric material.

The second major linearizing technique for active probes is known as the **multiplier-divider** method. Here an IC called a logarithmic multiplier-divider chip is the critical component. This chip has the following characteristic; if three voltages X,Y and Z are applied to the three input pins of the chip, the following voltage appears on the output pin: $V_{out} = X*Y/Z$. Therefore if the signal voltage out of the front end amplifier ($V_{f.e.}$) is made "Z", and "X" and "Y" are properly scaled constant voltages, the output voltage from the chip will be linearly related to the sensor-to-target distance:

$$V_{out} = X*Y/V_{fe}$$

$$= k_7*d$$

Since the scheme clearly assumes an ideal inverse relationship between input signal and sensor-to-target distance, the multiplier-divider scheme works best with guarded probes. Non-linearity is typically in the 0.2% to 0.4% range. Unguarded probes can also be mated to these linearizers if greater non-linearity can be tolerated, or if secondary linearizing means are available. Operating range is usually defined about a nominal standoff in the same way as for a breakpoint linearizer and for similar reasons.

2.3.5 Probe Construction

Generally speaking, construction choices for active sensors are the same as for passive sensors. The sensor/insulator/(guard) assembly may either be an assembly of machined pieces or a thick film plated ceramic item.

However the probe is not as simple. A balance electrode (and its target) needs to be placed behind the sensor, and the diode ring wired to both. The other two corners of the diode ring are wired to the driver electronics a few inches away. These electronics are assembled on a small printed circuit board which is potted in place in the probe housing. A long multi-wire cable and connector is normally supplied as part of the probe.

Active probes are clearly more complex and costly to manufacture. However given their advantages, the extra effort and expense is often warranted.

2.3.6 Electronics Design

The driver electronics in the probe utilizes a simple two-transistor oscillator to excite the sensor. A nominal frequency of 3 MHz and voltage of 180 Volts peak-to-peak is used. (The drive frequency being about 200 times faster than for a passive probe accounts for the much higher frequency response of active probe designs). The probe cable carries DC voltage to power the driver and returns low-level (microamps), signal-frequency current to the remote electronics.

The remote electronics includes a regulated DC supply for the driver electronics, a front end amplifier and linearizer circuit, and calibration controls.

3. APPLICATION CONSIDERATIONS

3.1 INTRODUCTION

The previous section identified the two primary capacitive sensing technologies and highlighted circuit differences between them. When it comes time to select actual hardware to solve a particular measurement problem, more specific information and guidance is needed. This section offers some advice in that regard.

3.2 ACTIVE VERSUS PASSIVE

Part of the selection process will, no doubt, center on the relative merits of the active and passive technologies offered. Performance and characteristics of the two schemes are compared below:

Frequency Response. This is a measure of how faithfully displacement amplitudes are transduced as frequency of motion increases. It is an important specification to consider whenever target motion is to be measured, (e.g. vibrating, rotating or reciprocating parts). Active transducers are at least an order of magnitude better than passive transducers in this respect.

The fundamental limitation on frequency response is the sensor excitation frequency. As noted in Section 2.3.6, active sensors are driven at 3 MHz, passive sensors at 15 kHz (max.), a 200:1 advantage! Practical bandwidth of passive probe hardware is in the 3 kHz to 5 kHz range, standard active probe hardware is in the 40 kHz range. However the 40 kHz does not represent a design limit, but rather a judicious filtering choice (bandwidth is deliberately reduced to improve resolution). Instrumentation with 100 kHz response (and higher) is available but there is little market for it.

Measurement Resolution. This is a measure of the smallest increment of displacement which can be resolved. The ability to resolve signal change is limited by signal noise so this specification is normally quoted as the RMS value of noise on the displacement signal.

Signal noise is a system variable for both active and passive schemes. Active hardware noise decreases with larger sensors, smaller operating range closer standoffs and decreased bandwidth. Passive hardware noise is similarly affected, but also decreases with a shorter cable length. Until recently, active hardware was clearly lower in noise than a comparable passive hardware system, again by about an order of magnitude. It is therefore capable of much finer resolution. Recent R & D work at ADE Corporation has led to new designs which narrow that gap considerably.

Linearity. This is a measure of deviations from the ideal "straight line" relationship between target displacement and voltage output over the stated operating range. For comparable hardware, there is little difference in linearity between active and passive schemes, both are available in the 0.1% to 0.2% range. However the ultimate in linearity would be achieved with a large, well guarded, passive sensor.

Drift. This refers to the change in output due to time alone. It can be an important specification for applications involving long measurement cycles with no ability for drift compensation. With no electronic components in the probe, a well-designed passive probe will drift less.

Temperature Stability. This refers to the effect of temperature changes on the instrument output. Passive probe schemes are not only inherently less sensitive to temperature, but also can be more easily designed for temperature extremes at the probe.

Cable Length. Cable length between the probe and remote electronics is typically 8 to 10 feet on standard hardware of either design. Increasing cable length on passive designs increases noise and so degrades measurement resolution. Fifty feet represents a practical upper limit. This is not the case with active designs, cables are routinely supplied in lengths up to several hundred feet.

Cost. Certainly at probe and board level, active hardware can be several times more expensive than passive hardware. At instrument or system level this disparity is greatly reduced since other costs are generally insensitive to the active/passive decision.

3.3 SELECTING A SENSOR

Regardless of the outcome of the active/passive decision, a sensor will need to be chosen. The size and shape of the sensor are the critical decisions here. A few general guidelines follow:

Larger sensors can support larger operating ranges. If this is not intuitively obvious, refer to equation (i). This indicates that if the "Sensor Area/Standoff" ratio is kept constant, the resultant capacitance of the sensor/target combination is also kept constant. Some manufacturers use this to advantage by offering only one configuration of remote electronics. This one configuration can operate over any operating range (within reason), simply by switching to larger or smaller sensors.

While this approach clearly offers some flexibility, it also is rather limiting. There are many occasions when more range is needed, but a larger sensor is too big for the inspected part (refer to discussion of Spatial Resolution below). And conversely, there are many applications where the inspected part is large and extremely fine displacements need to be measured.

A larger sensor with the same operating range would offer better resolution and stability but cannot be supported by the remote electronics at that range.

So the alternative approach is to offer a family of front end/linearizer boards, each dedicated to a particular sensor size and operating range. This is the approach taken by ADE Corporation with their active probe products, (refer to Figure 10). By offering a variety of sensor sizes for any particular operating range, it is possible to make a more optimal choice.

Operating Range (Inches)	Sensor Sizes (Inches Dia.) .019	.066	.210	.360	.600
±.001	✓	✓			
±.002	✓	✓	✓		
±.005		✓	✓		
±.010		✓	✓	✓	
±.020			✓	✓	
±.050				✓	✓
±.100				✓	✓
±.200					✓
±.250					✓

FIGURE 10 AVAILABLE "SENSOR SIZE/OPERATING RANGE" COMBINATIONS (ADE ACTIVE PROBES)

Larger sensors have better resolution and stability (for a given operating range). If this is not obvious, refer to equations (i) & (v). These equations indicate that, all other parameters being equivalent, the transduction current from an active probe is proportional to sensor area. This implies that the signal-to-noise ratio improves with larger sensors, and this translates into finer measurement resolution and better signal stability. The same is true for passive probes.

Smaller sensors have better spatial resolution. The only advantages of a smaller sensor, other than it may mean a smaller probe package to fixture, is its ability to measure smaller parts, to measure closer to the edge of a part and to properly resolve smaller surface features. Recall from Section 2.1 that, for the parallel plate capacitor analogy to hold true, the sensor is normally smaller than the target. (If the sensor is larger, then the electric field distorts and this impacts linearity of the measurement. The sensor also becomes sensitive to lateral placement/movement of the target; both are usually unwanted effects). Fringing of the sensors' field must be considered too, as it also affects the size of the field at the target. The goal is to keep all of the electric field on the surface to be measured, not allowing it to stray onto adjacent surfaces or "go over the edge" of a part.

As a rule-of-thumb, the sensor dimension should be no greater than 60% of the adjacent flat target dimension for unguarded probes, and no greater than 80% for guarded probes. (For example, to measure thickness of a 1" wide steel strip, any unguarded sensor size up to 0.6" dia. or any guarded sensor size up to 0.8" dia., would be appropriate). For cylindrical and spherical surfaces, even tighter limitations are placed on sensor size, worst case being that sensor diameter should be no greater than 20% of target diameter. Provided these guidelines are followed, linearity deviations are minimal despite the surface curvature.

The second implication of better spatial resolution is that smaller sensors can more properly resolve small surface features on a part. Capacitive sensors, by virtue of their *field* sensing technique, inherently "average" the height of the sensor from the target surface. Therefore, if surface profile or flatness of a textured surface is being measured, smaller sensors may be preferred, (see Figure 11).

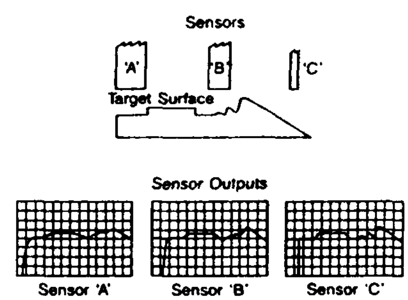


FIGURE 11 SPATIAL RESOLUTION

It should not be concluded from the preceding comments that this inherent surface averaging by capacitive sensors is always a negative characteristic. For instance, by excluding or "averaging out" the surface roughness of a part, a capacitive reading of dimension may sometimes be closer to the functional surface of a part than a contact reading.

One clever way of improving spatial resolution without reducing sensor size, is to use a rectangular-shaped, "stripe" sensor instead of the conventional round sensor. By aligning the stripe parallel to the direction of long features expected on an inspected part, better results are obtained. However since spatial resolution worsens in the orthogonal axis, this option only makes sense in certain applications.

Accuracy is better at smaller operating ranges. In this respect, capacitive gaging is no different from most instrumentation of any kind. There is typically an advantage in limiting the range of an instrument to almost the range you expect to measure. This is because some components of the ultimate "accuracy" specification are inevitably a certain *percentage* of range (linearity for instance).

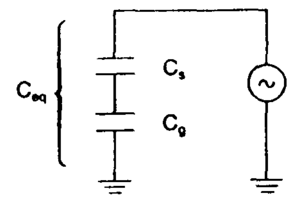
In summary then, the general approach to selecting an appropriate sensor size is this ... Select an operating range by determining the expected range of target motion (or height change or other dimensional variation). For this operating range, establish what sensor size options are available. Then select the largest size consistent with spatial resolution needs (size, shape and surface features of the item to be measured should be considered). This process may need to be iterated to arrive at an optimal solution.

3.4 TARGET GROUNDING

The capacitive probe theory developed in Section 2 assumed that the target was grounded to the remote electronics. In many applications this is, in fact, the case. In other applications it is easy to attach a ground return to the target. If so, then this is recommended for the best measurement stability and accuracy.

In a number of cases it is either undesirable, difficult or impossible to attach a ground return, especially for applications requiring an *entirely* non-contact solution. Fortunately, in most of these cases, the effects of an imperfect ground are negligible and capacitive gaging works reliably and well.

A non-ideal ground return may be represented in a circuit diagram (see Figure 12) by another capacitor (C_g) in series with the sensor/target capacitor (C_s). For the added capacitance to have negligible effect on the transduction scheme it should be *large* relative to the sensor/target capacitance. In applications where this is not the case and the added capacitance (C_g) is small enough to impact the measurement, it needs to be stable also, otherwise differences in capacitance to ground will appear as target movement on the gage.



$$\frac{1}{C_{eq}} = \frac{1}{C_s} + \frac{1}{C_g}$$

$$\Rightarrow \frac{C_{eq}}{C_s} = \frac{C_g}{C_g + C_s}$$

$$\Rightarrow 1 \text{ for } C_g \gg C_s$$

FIGURE 12 NON-IDEAL TARGET GROUNDING

To roughly estimate the importance of a *non*-ideal ground in a particular application, one can compute the ratio: C_g/C_s. If greater than 1000, then it can be ignored in most cases, as its effect will be less than that from other error sources such as nonlinearity. This is usually the case unless the measured part is particularly small and isolated, and/or rests on a thick dielectric material. Special hardware configurations are available for such cases.

3.5 DIELECTRIC APPLICATIONS

While the probe theory assumed that the part to be measured may be considered as one plate of a parallel plate capacitor, there are many applications where the measured part is made of dielectric material. Clearly, this may not be considered analogous to a conductive plate! Nevertheless, there are many applications involving dielectric materials which can be solved very well using capacitive techniques.

One common application involves thickness measurement of thin sheets of plastic, ceramic, glass and other dielectric materials. A typical approach here is to rigidly fixture a guarded probe over a grounded metallic backplane. This establishes a classic, parallel electric field in the gap. When dielectric material is inserted into the gap, the capacitance changes according to material thickness and dielectric constant. After appropriate scaling for the dielectric constant of the material, this capacitance change can be converted into a thickness signal. This scheme works best when the material thickness is much less than the sensor dimension and when its dielectric constant is moderate in value and very uniform.

Another common application is to measure the position of a dielectric surface, (this was discussed in Section 2.3.4). Here the appropriate hardware is an unguarded, active probe with a breakpoint linearizing scheme in the remote electronics. In this case, a grounded backplane is deliberately avoided, so that the electric field is established between the sensor face and its grounded probe housing. The dielectric material distorts the field in a repeatable manner which can be empirically determined and then linearized with appropriate breakpoints. This scheme works best when the material thickness is of the same order as the sensor dimension or greater and when its dielectric constant is high in value and very uniform.

3.6 ENVIRONMENTAL FACTORS

There are many industrial applications where gaging needs to be done in a wet, oily or dirty environment. Often the parts need to be inspected prior to cleaning operations, so an awareness of the issues involved with capacitive gaging is warranted.

Generally speaking, dirt, oil and water represent potential sources of error. They are dielectric materials and will be measured as such if they are present anywhere in the sensor/target gap. The magnitude of the error will depend on contaminant thickness and dielectric constant.

Specks of dirt on the probe face, on the target surface or in the air gap between will not be a problem. Even if the dielectric constant happens to be high, the "thickness" (if spread over the sensed area) is minute. *Layers* of oil, dirt or dust on either the probe face or the target surface will influence the measurement, making the target surface underneath appear closer to the probe than it really is. Depending on the application, adequate compensation for this effect may be possible. However even this becomes difficult if the layer of contaminant varies.

Droplets of water on either the probe face or the target surface beneath the sensor should be avoided. Water has a very high dielectric constant and results in major capacitance changes in the probe gap. For applications where water or coolant splashing is likely, a common remedy is to aim compressed air jets at the probe face and/or the target surface. (Normal atmospheric humidity variations are not a problem unless condensation occurs).

3.7 FIXTURING

For every application, some fixturing is required to position the probe(s) correctly with respect to the part(s) and feature(s) being measured. For some commonly encountered applications, dedicated fixturing products are available. For general purpose gaging, generic fixturing developed for contact gages (dial indicator stands, height gage stands, etc.) can be used, simply by substituting the capacitive probe for the contact probe. In many other applications, custom fixturing will be the best or only choice.

When considering fixture design, issues such as thermal stability, creep and vibration of the mechanical components need to be addressed. This is especially true for those applications where a great degree of precision is required. Given the capability of capacitive gaging equipment to resolve dimensions and displacements to a fraction of a microinch, the practical limitations of measurement in a high precision application may well be determined by the limitations of the mechanical fixturing used. (Clearly, thermal expansion and contraction of the measured part itself should also be minimized in these high precision applications, usually by controlling the ambient temperature).

3.8 PRODUCT ALTERNATIVES

A variety of product alternatives exist to meet different customer needs. Certainly a range of probes of different shapes and sizes have evolved over the years to fit various space limitations, part configurations and fixturing constraints that exist in the gaging world (see Figure 13). A range of different electronics packages is also available. A summary of the alternatives is presented below.

OEM Boards. These analog boards comprise front end electronics for the probe interface, linearizing circuitry and calibration controls. They require DC power input (typically +/- 15 Volts, regulated) and provide an analog output of displacement only (typically +/- 10 Volts DC). They have no display and no displacement output processing functions (peak capturing etc.). They are supplied as either bare boards or in an enclosure with input and output connectors. OEM boards and probes represent an inexpensive and convenient option for Original Equipment Manufacturers with a need for including non-contact gaging capability in their products.

Benchtop Instruments. Instrument consoles include not only the necessary probe front end/linearizing circuitry, but also a power transformer, display, console housing and convenient connections to the "outside world" (AC power cord, probe connector(s), analog output connectors, calibration/setup controls etc.). The consoles are usually of modular design, which allows for inclusion of a second channel and various displacement signal processing functions (peak holding, T.I.R. output, addition and subtraction of two channels, etc.). Benchtop instruments (see Figure 14), represent a very convenient, portable and easy-to-use option for a great variety of end-user applications, in inspection rooms, R & D work areas and on the factory floor.

Personal Computer Board. A new product release for 1987 is a Personal Computer-based capacitive gaging board, (see Figure 15). This board includes an analog front end and connectors for two probes, linearization circuitry, an analog-to-digital converter and a PC Bus interface. The board fills one vacant slot in a PC. The board generates displacement data in computer format so that manipulation of the data is more easily performed. This allows considerable flexibility in calculating complex parameters and also in handling, storing and analyzing measurement data. As a bare board and probes, this product will suit OEM needs, and when mated to a PC will perform as a powerful benchtop instrument.

Systems. Various turnkey systems are available, incorporating capacitive gaging hardware, for solving specific measurement problems. Some systems are manual, many are automated to various degrees. They address a particular industry need and include all necessary mechanical, electrical and electronic hardware necessary to meet the need. Examples include manual equipment for measuring thickness of computer hard disks at various stages of manufacture, and highly automated silicon wafer sorters which measure and sort more than a thousand wafers per hour.

4. APPLICATIONS

4.1 INTRODUCTION

Capacitive gaging equipment is used in a great variety of applications in many different industries. Several examples illustrative of this diversity are discussed below.

4.2 COMPUTER HARD DISK TESTING

Mechanical performance testing of hard disk drives for computers represents quite a challenge. The need is to qualify an assembly of a precision, motorized spindle and (at least) one plated aluminum disk which is clamped to it. Axial runout of the disk is critical since, in operation, a read/write head will index across the spinning disk only microinches above it. If the runout is too great, or its rate of change is too great, the head will not stay within its height limits and read/write errors will occur. In severe cases, the head may "crash" into the disk surface, resulting in permanent damage to disk &/or head. So dynamic testing of each assembly at rated speed (3600 RPM, typically) is the industry practice. Each recording surface is characterized prior to a head being installed.

What makes this measurement task so challenging? High frequency response is needed, since the higher frequency components of the runout waveform are potentially most troublesome. Microinch resolution is called for as the acceptable "window" of head-to-disk height is only a few microinches high. The disk has a mirror-finish and is assembled and tested in a clean room environment, so the measurement method needs to be both non-contact and non-contaminating. Material resistivity and thickness of the aluminum substrate and the plated layers will vary, so a method which is insensitive to these factors is preferred. Probes need to be small enough to fit within the confines of a hard disk housing.

Capacitive gaging is the only method capable of meeting all these requirements in a production setting. Not only is capacitive gaging used to test final assemblies, but also components; disks at various stages of manufacture, spindles and bearings. It is not surprising, therefore, that this represents one of the major markets for capacitive gaging products.

4.3 CERAMIC BLANKS

Ceramic substrates are used extensively in the electronics industry as carriers for integrated circuit devices. The raw material is a ceramic paste which is cast onto mylar film and dried. The sheets are cut into easily managed "blanks" approximately six inches square, and the mylar backing is removed. The blanks are measured for uniformity of thickness and then fired in an oven.

Contact measurement of thickness on the "green", or unfired, material is difficult. The material is quite soft, so micrometers tend to compress it. This leads to measurements which vary from operator to operator and may create areas of reduced section in the finished product. Manual measurement of a batch of blanks is also quite slow.

Specially calibrated capacitive gages are well suited here. A blank is simply inserted into the fixed gap between sensor and backplane and the thickness is displayed. There is no compression of material and sorting throughput is much improved.

4.4 RELAY SWITCHES

A relay switch is an intricate electro-mechanical assembly. Failures in service can be minimized by checking the initial mechanical performance of the switch. The crucial component is the return spring, which forcibly returns the relay contacts to an "open" position after the solenoid is de-energized. Should the "travel" or "throw" of the spring be too short, then the return force may not reliably change the switching state. If it is too long, then the spring stresses may lead to an early fatigue failure.

Attempts at using contact methods usually fail. Even the "light" contact force of a dial gage is sufficient to substantially counterract the travel of the leaf spring, which may be only a few thousandths of an inch thick. However a capacitive gage will measure the throw without intrusion. The electric field does not penetrate the spring surface, so the instrument response is totally unaffected by position or movement of adjacent components in the switch. Furthermore, the instrument generates a direct electrical output, allowing for automation of the testing process.

4.5 BRAKE PADS

Automotive brake pads are designed to have an "aggressive", high-friction surface. This makes them rather difficult to measure with contact methods, as abrasion and wear on the contact surfaces is substantial. This is especially true for on-line, thickness measurements where there is relative motion between pads and probe.

Capacitive gages can be used to advantage here. The measured surface is usually flat and inches wide. This permits the use of larger sensors which are much less sensitive to the usual inhomogeneity of the pad material (a mixture of metallic and organic substances). The probe can be fixtured well above the rough and "interrupted" surface which is presented by individual pads sliding by.

5. OUTLOOK

Making measurements and analyzing the results is the only way to quantify "Product Quality". Thus, manufacturing enterprises are making more measurements, on more products, at more stages in their processes than ever before. Many dimensional gaging applications and needs are surfacing which cannot be handled by traditional approaches, so interest in the non-contact technologies is particularly strong.

Capacitive gaging manufacturers are responding with new products which offer not only better transduction performance, but also an easier interface for adding automation and data analysis capability.

As the price of personal computers, with all their impressive data processing power, now approaches that of conventional benchtop instruments, the outlook seems clear. Computer-based "Quality Gages" will increasingly find their way into tomorrows' dimensional gaging world.

(The author gratefully acknowledges the assistance of Noel Poduje and Karen Willis of ADE Corp. in producing this article.)

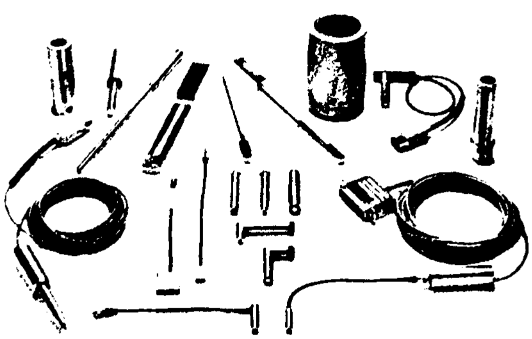


FIGURE 13 A VARIETY OF CAPACITIVE PROBES IS AVAILABLE

FIGURE 14 A BENCHTOP INSTRUMENT CONSOLE

FIGURE 15 A CAPACITIVE GAGING BOARD AND PROBES (FOREGROUND), FOR INSTALLATION INTO A PERSONAL COMPUTER (BACKGROUND)

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH