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Design and Implementation of a Transducer to Measure the Cross-sectional Dimensions of Bearing Raceways

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Kr'.stin Beth Zimmerman

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DESIGN AND IMPLEMENTATION OF A TRANSDUCER TO MEASURE THE CROSS-SECTIONAL DIMENSIONS OF BEARING RACEWAYS

By

Kristin Beth Zimmerman

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Metallurgy, Mechanics, and Material Science

1990

ABSTRACT

DESIGN AND IMPLEMENTATION OF TRANSDUCER TO MEASURE THE CROSS-SECTIONAL DIMENSIONS OF BEARING RACEWAYS

By

Kristin Beth Zimmerman

The cross-sectional dimensions of a 45" biangular roller bearing race cavity is measured to determine the proper roller size. Measurement is conducted by using a resistance strain gage based transducer. The transducer indicates the cross-sectional dimensions of the raceway, and this analog/digital information is fed into a computer program that generates the dimensions for a properly fitting roller for the bearing. The transducer uses the deflection of four cantilever beams to detect the cross-sectional dimensions of the bearing cavity. This transducer is capable of measuring dimensions on the order of one micro-inch or less.

This thesis is dedicated to my parents.

ACKNOWLEDGEMENTS

I would like to thank Kaydon Corporation for offering this very intrigueing research project and I owe my utmost gratitude and respect to my advisor, Dr. Gary Cloud, for his time, patience, and faith in me during this endeavor.

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CHAPTER 1

INTRODUCTION

I. THE PHYSICAL MEASUREMENT PROBLEM

During the evolution of roller and ball bearings, the necessity for accurately measuring the cross-sectional dimensions of bearing raceways to determine the proper roller/ball size has arisen. Many techniques to solve this problem have been developed in the past, but they were only able to measure, with 1/1000" precision, the raceway of bearings less than approximately 24 inches in diameter. Measuring larger bearings with 1/1000" precision has not yet been possible.

The manufacturing process for most large-diameter bearings is very labor/time intensive because of the precision required for close running tolerances between rolling elements and their matching inner and outer rings. Therefore, a method needs to be established to cut assembly time by at least a factor of two. This trial and error assembly-time problem can be solved by developing a measurement tool that indicates, exactly, the correct cross-sectional dimensions of the bearing race cavity. This dimensional measurement can then be used to determine the proper roller/ball size.

To begin, the project's design criteria must be established, and a measurement tool must then be designed to meet these criteria.

The design criteria for the measurement device were governed by the necessity for it to:

1. be a differential method of measurement;

2. be unaffected by the presence of the clearance groove machined into the raceway;

3. indicate small axial and radial misalignments between the two rings taken as a pair;

4. be user-friendly for appropriate use on the "shop floor" and require minimum time on any given set of rings;

5. yield a continuous record of measurement and indicate any deviations from raceway cross-section to give a first approximation to actual cross-section;

6. accommodate different raceway configurations, for example: (i) biangular roller, (ii) 4 point contact, (iii) angular contact thrust;

7. achieve the proper balance between sensitivity and range;

8. indicate on a read-out device, such as a computer, the proper roller and/or ball size for the particular bearing measured;

9. be cost effective.

These nine design criteria have been taken into account, and the solution lies in maintaining the aforementioned criteria in a measurement tool design.

Section II compares four potentially feasible techniques for measuring dimensional quantities.

II. METHODS EVALUATED FOR DISPLACEMENT MEASUREMENT

Experimentalists are always challenged to find simple but accurate techniques for dimensional measurement. Such techniques include optical and mechanical methods as well as resistance strain gage devices.

Some potentially suitable methods, such as optical, mechanical, and electrical measurement devices are described below; and they are evaluated against a few measurement techniques used in industry.

A. Optical Methods

For this particular problem, the optical methods considered were fiber optics and CCD (charged coupled device) arrays. In this application, the fiber optic measures dimensions by indicating the change in the fiber's radii as it traverses the surface being measured, while a CCD image sensor array measures displacement by indicating the variation in optical mismatch along a planar grid pattern [1]. Schematics of two such devices are shown in Fig. (1.1). Both of these methods are capable of measuring with considerable accuracy and sensitivity, but they have drawbacks in reproducibility of data. Many inconsistencies are incurred during the location of a datum or reference position for data collection. Therefore, both the fiber optic and CCD array fail items 1, 2 and 6 of the design

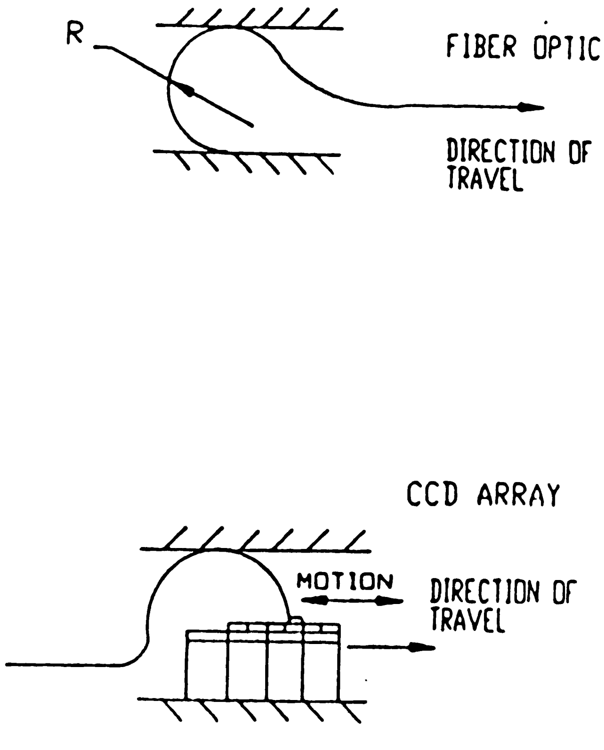


Figure 1.1: Schematic of optical measuring devices.

criteria. An optical method might work for this type of measurement problem, but with these drawbacks, attention was diverted to other methods.

B. Eddy Current Probe

The eddy current probe is another measuring device option. This probe emits a magnetic field which, when placed a nominal distance from the target, induces a current flow on the surface and within the target. Because this induced current creates a circular pattern, it is called an eddy current. It is this current that contains information about the contour of the target's surface and distance variations from the probe's reference position [2]. This device is unaffected by lubricants in the bearing raceway, but one drawback is that it is not easily adapted to analyzing different (ie. rounded or arched), raceway configurations. The eddy probe is capable of exibiting sufficient sensitivity and range for accurate measurement, but again, it would only be able to analyze the biangular race configuration. Therefore, the eddy probe fails items 2 and 6 of the design criteria.

C. Load Cell

Currently, a module housing a load cell is being created. The load cell is a force measuring device [3]. Each contact surface (in this case, the walls of the race cavity) creates different forces within the load cell; and any variances in force are recorded as displacement. A reference is established and successive readings are taken and compared differentially to that reference as the probe traverses the bearing raceway. This device has the potential of satisfying all but item 9 of the design criteria. Manufactured load cells cost approximately $400.00 each, and two would be needed for each transducer. Preliminary tests of a load cell device in the bearing cavity revealed sensitivities in a range from (0.30 to 0.35 mv/inch displacement). This approach was not pursued further as it seemed inferior to and much more expensive than the RSG transducer.

D. Electrical Resistance Strain Gages (RSG's)

An electrical resistance strain gage (RSG), in elementary terms, is a device containing a foil grid (resistor). When the surface that the strain gage is bonded to deforms, then a change in resistance is recorded. This is the basic idea behind the resistance strain gage. As to application, RSG's are frequently used to measure strain, and displacement, and are incorporated as sensors in transducers designed to measure such quantities as load, torque, pressure, and acceleration.

An RSG device, when properly designed, should satisfy all of the design criteria so attention was concentrated on this approach. Since an RSG transducer was designed to evaluate the bearing measurement problem, it is essential to describe how an RSG transducer works and why it was used. An in-depth description on the historical background of RSG's is contained in the Appendix A, along with an illustrative procedure on the definition of strain and how it relates to displacement.

E. Measurement Techniques Used in Industry

Among the reasons to create a means of accurately measuring bearing raceways is that both the inner and outer bearing rings need to match one another in tolerance so as to glide smoothly across the rollers or balls separating them. Currently, very accurate methods are being used to evaluate bearings that are less than 24 inches in diameter, but the problem lies in the eccentricities and out-of-roundness of larger bearings. Listed below are various methods used by industry to evaluate the measurement of large bearings [4].

Dimensional Measurement

1. Bendix Auto - DC Measuring Machine
   - diametral internal clearance
2. Bendix Cordax
   - deviation from true position or shape
3. Bendix Proficorder
4. Bendix Indicorder
5. Rank Tallycentric
   - deviation from true circle
6. Rank Precision Vertical Slide (with rotary surface plate)
   - deviation from squareness and cylindricity
7. Federal Comparator
   - 2-point size calibration, 32/1 scale (for master ring diameter calibration)
8. Rank Tallysurf
   - deviation from true radius (transverse surface finish)
9. Bendix Wavometer
   - raceway waviness (dynamic)

Note that even though these evaluation methods are used, there still exists a trial and error phase during the insertion of rollers/balls into the bearing raceway. This phase is very time consuming, since the procedure requires that the rolling elements and spacers (188 rollers and approx. 188 spacers in a 45" bearing) be inserted, one-by-one, through the bearing's loading plug until the bearing race is fully loaded. After the bearing is loaded, it is tested using the following criteria [4]:

Testing Criteria

1. The ring's diametral preload is recorded and the tolerance between mating rings is checked to match (+ 0.0001-0.0005 inches).

2. The breakaway torque, which is the force required to rotate the inner ring while the outer ring remains stationary, is measured. This measurement must yield 20-100 ft-lbs when checked at 6 equally spaced locations on the inner race, again, while the outer race is stationary. If this measurement is out-of-range, then an adjustment must be made by

changing either the roller size or spacer size.

3. If neither requirement is met, then the bearing must be either re-machined or scrapped.

The testing procedure, listed above for the 45" biangular roller bearing suggests that this process is extremely time intensive. Therefore, finding a means of expediting the "process" is critical.

III. SUMMARY

The purpose of this study is to determine whether or not a measurement tool can be designed to measure, with more precision than 1/1000", the cross-sectional dimensions of a bearing race cavity. This measurement is critical in determining the proper roller/ball size to use in each bearing assembly.

Now the discussion leads to the development of an actual displacement transducer design. Other methods were evaluated, and each had their own strengths, but the transducer satisfied more of the design criteria and became the chosen approach to solving this unique measurement problem.

CHAPTER 2

DESIGN AND RESULTS

I. FINAL DESIGN

The stages leading to the final design evolved from consideration of several potential models, some of which are featured in Fig. (2.1). Also, a large number of the design criteria previously mentioned in Chapter 1 were taken into consideration. Specifically, the transducer is designed with four cantilever beams (containing 2 resistance strain gages each) mounted onto a cube, Fig. (2.2), and the resistance strain gages respond to the deflection of the beams.

The following section outlines the experimental measurement setup and measurement scheme, while the remainder of the chapter discribes each component of the scheme.

II. EXPERIMENTAL SETUP

The experimental setup is shown, schematically, in Fig. (2.3). The transducer, which is located inside the bearing,

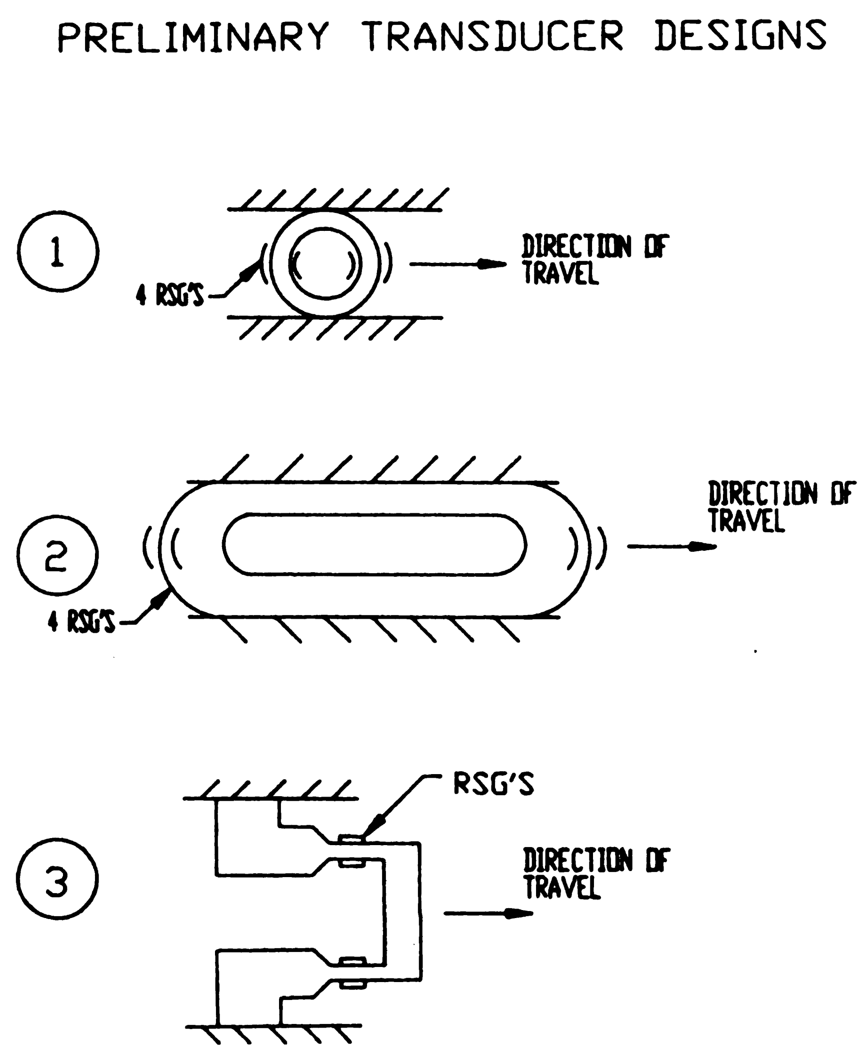


Figure 2.1: Preliminary designs after which the final prototype was modeled.

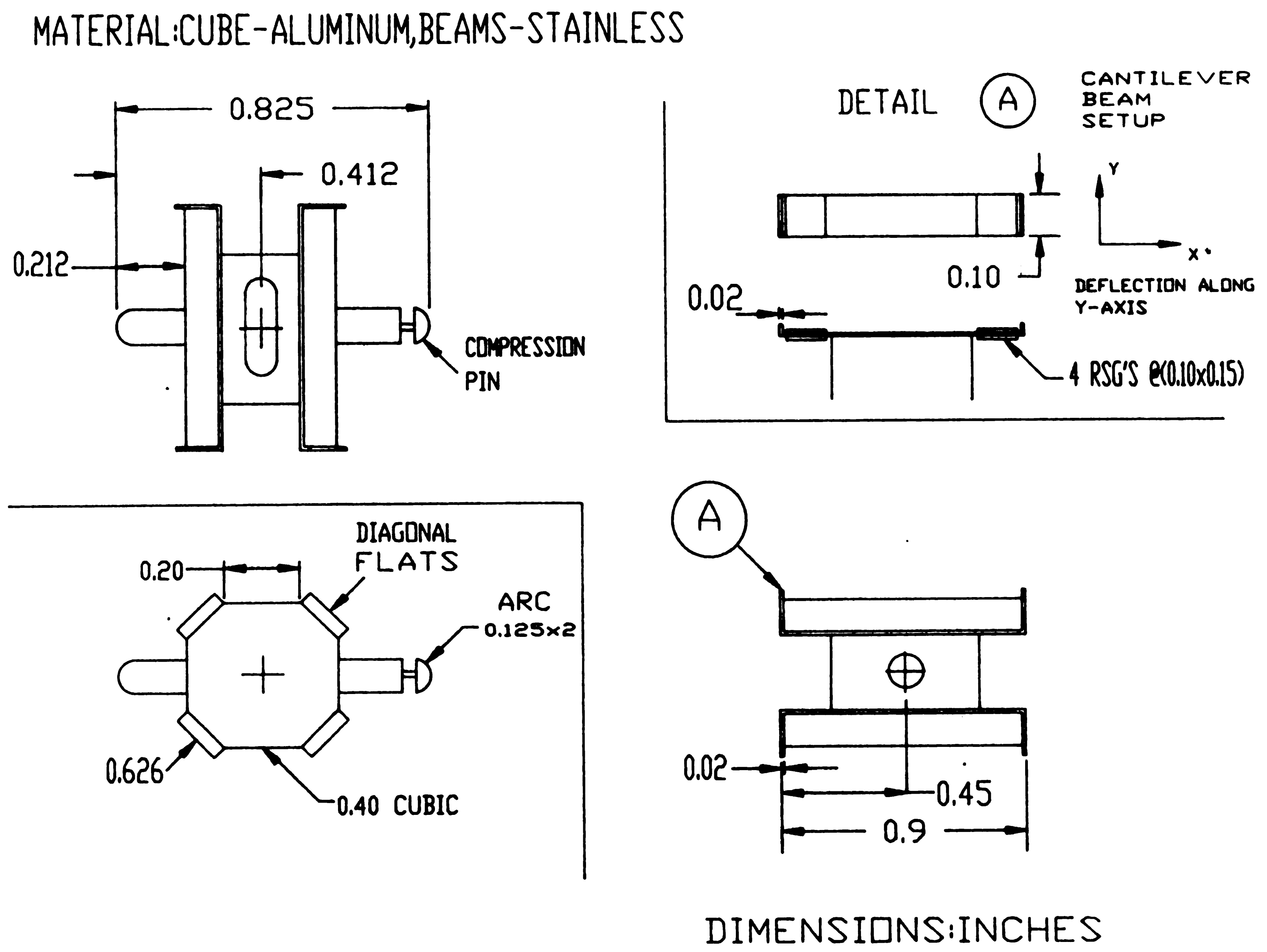


Figure 2.2: Final design of the transducer.

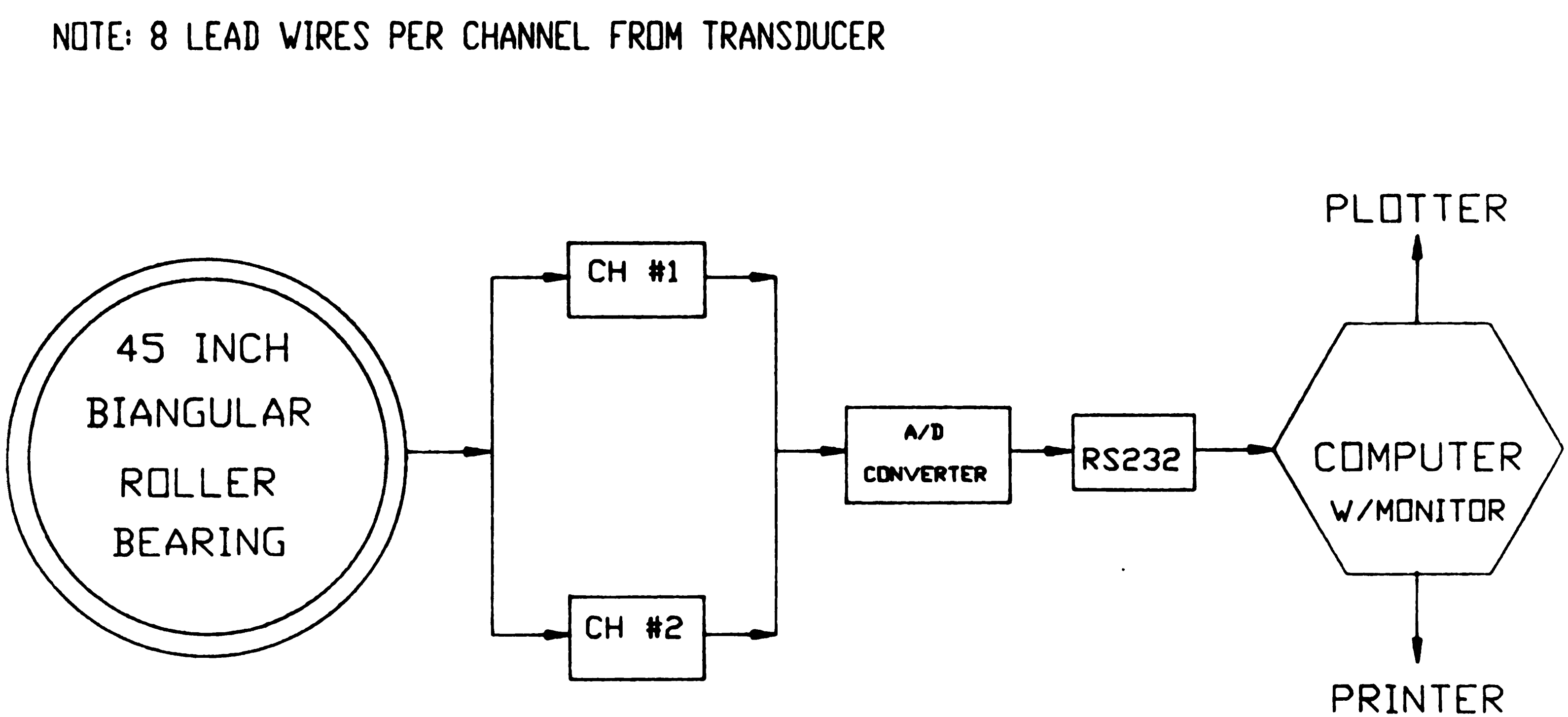


Figure 2.3: Schematic showing experimental set-up.

generates a measured value of distance across each diagonal flat of the raceway cavity. This dimension is sent directly to two strain conditioners/indicators via 16 lead wires from the RSG's. The final output is a digital display of the deflection in each individual set of beams. This digital output is then fed into an A-D converter and is assimilated by a computer program which reduces the data via software written in Atari Basic (Appendix B). An Atari Computer was chosen because a useful data acquisition program had already been prepared and was readily available for a feasibility study. Also, the Atari system can handle data character strings of great length (48K less committed memory) quickly and efficiently.

The computer program is written to read the values from the strain gages on the tranducer, calculate the cross-sectional dimensions of the race, plot the average dimensions, and finally, indicate the correct roller and/or ball size for each bearing configuration. This procedure of implementing the transducer to accumulate valuable cross-sectional dimensions is a very simple procedure that will expedite assembly time for each bearing.

III. TRANSDUCER CONSTRUCTION

Critical elements of the transducer design, including the placement and wire hookup of each RSG, are outlined in this section. The procedure in assembling the RSG transducer is quite methodical and begins by applying eight RSG'S to each set of cantilever beams, Fig. (2.4). Two lead wires (approx. 30 gage) are soldered to each gage and then woven through the cube's clearance hole enroute to two strain indicators/conditioners. Eight wires (wires 1-8) represent channel #1, while the remaining eight wires (wires 9-16) hook into channel #2. Each channel has its respective indicator. The indicators were set-up in a Wheatstone bridge circuit configuration with four active gages to alleviate temperature drift in the circuit. The gages themselves were compensated, but the circuit also had to be compensated to minimize errors. See Fig. (2.5).

With the transducer design complete, the next step was to verify the target of 10-20 micro-strain sensitivity with a theoretical calculation.

The next section illustrates a sample theoretical calculation.

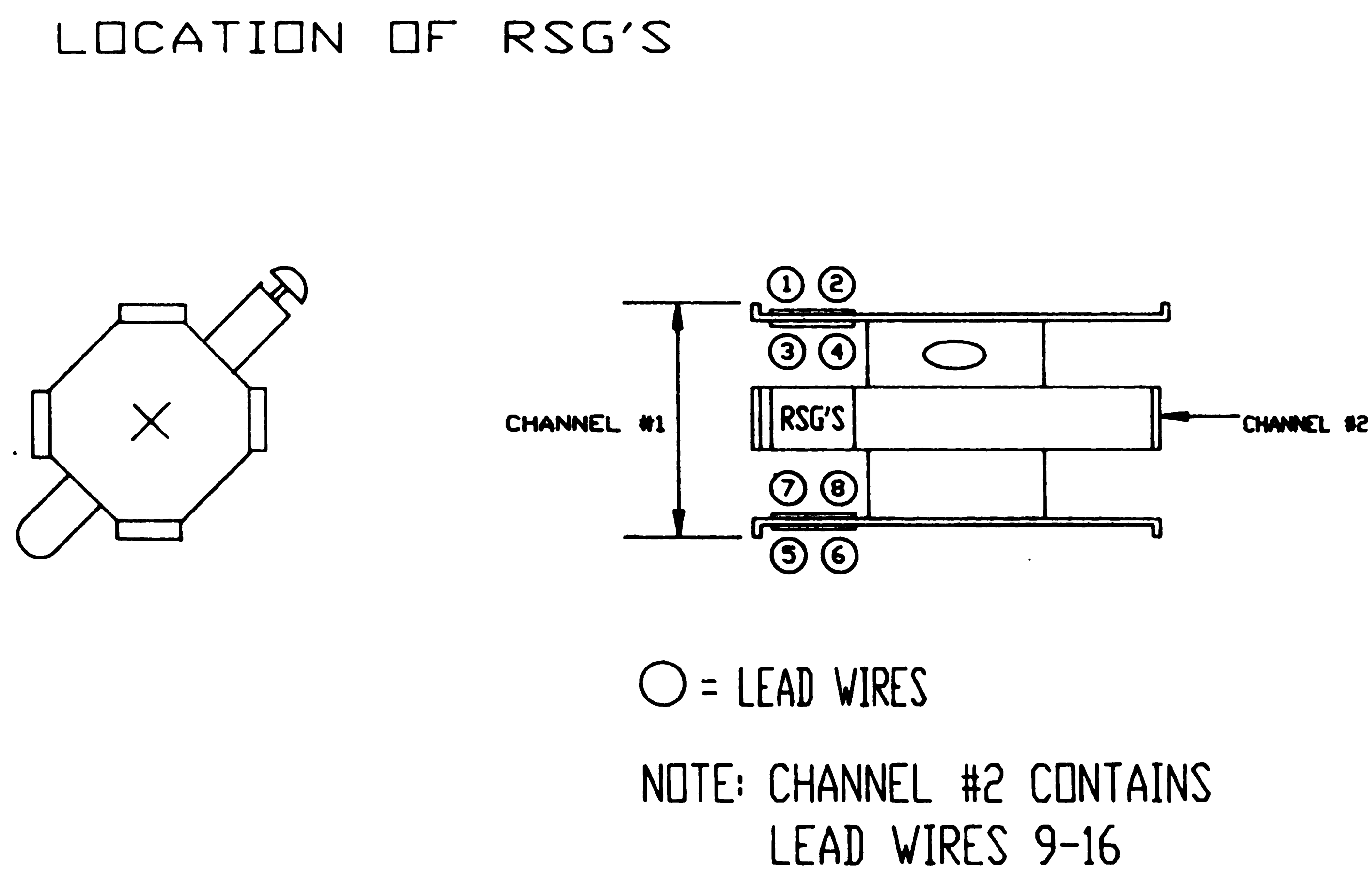


Figure 2.4: Placement of 1000 ohm RSG's on the two sets of cantilever beams.

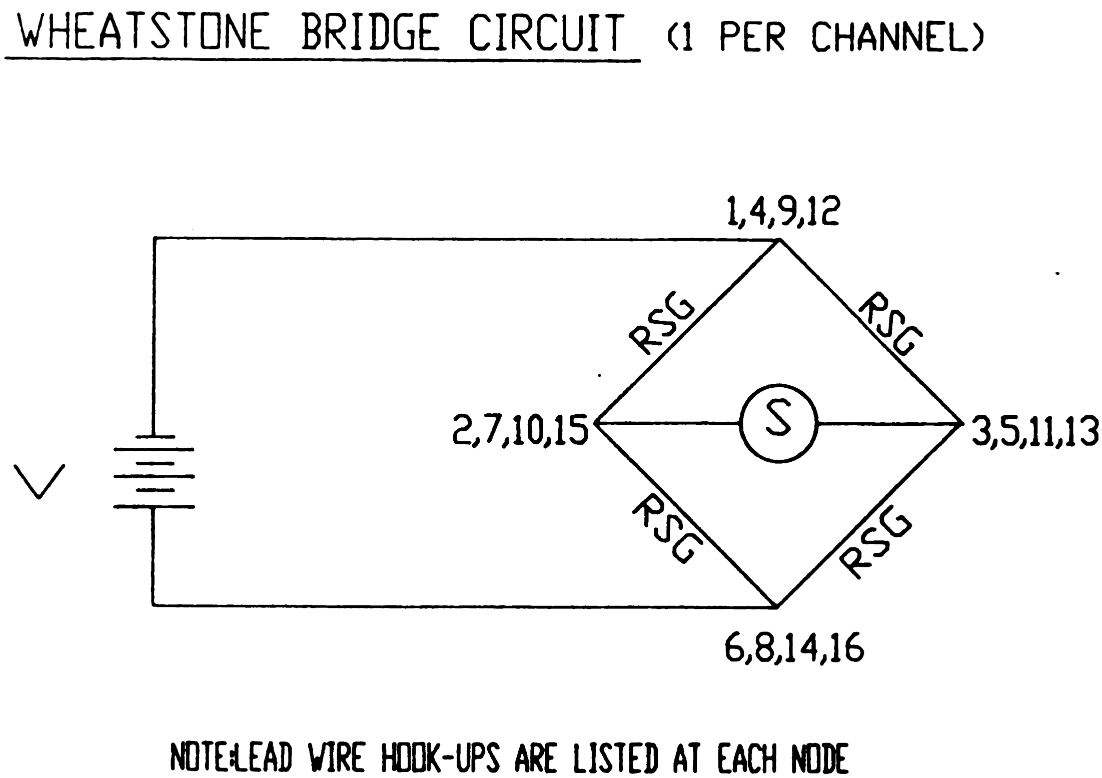


Figure 2.5: Wheatstone bridge circuit with compensating wire hook-up scheme.

IV. THEORETICAL STRAIN CALCULATION

Verification of the target sensitivity begins with the calculation of strain (based on beam theory) and by the equation:

$$\epsilon = My/EI \tag{2.1}$$

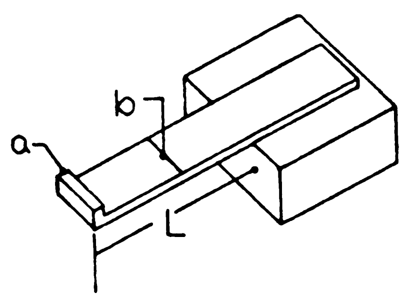
where: I - moment of inertia ($bh^3/12$)

y - distance from centroid (0.5 * a)

M - moment arm (force * distance)

E - Young's Modulus (28 x 10E6 psi) stainless steel

The cantilever beam parameters are found in the Fig.(2.6) below:



Values for a, b, h, and L are:

$$b = 0.10 \text{ inch}$$

$$a,h = 0.020 \text{ inch}$$

$$L = 0.225 \text{ inch}$$

To calculate I and y let:

$$I = bh^3/12 = (0.10)(0.02)^3/12 = 6.67 \times 10E\text{-}8 \text{ in}^4$$

$$y = 0.5\ (0.02) = 0.01 \text{ in}$$

Now that each component is calculated, strain can be determined as:

$$\epsilon = My/EI = \text{Force } [(0.225)\ (0.01)]/[(6.67 \times 10E\text{-}8) * (28 \times 10E6)]$$

$$= 1205\ \mu \text{ strain} * \text{Force} \qquad (2.2)$$

The calculation for displacement can now be determined.

Let displacement $Y_{max} = -FL^3/ 3EI$

$$(2.3)$$

where: F = load (pounds)

L = lever arm

In this sample calculation let F = 0.008299 pounds, so:

$$Y_{max} = -(0.008299)\ (0.225)/3(EI) = 17\ \mu\ \text{inch}$$

This calculation demonstrates that the amount of maximum deflection (Y_{max}) at the end of one cantilever beam equals 17 micro-inch at a load of 0.0083 lbs. This deflection value falls into the strain range of 10-20 micro-strain and verifies that by using RSG's in a cantilever beam configuration ample sensitivity is achieved. Table (2.1) shows how the 10-20 micro-strain sensitivity might be achieved by inserting particular values of force (column 1, Table (2.1)) into equation (2.3).

Theoretically, the sensitivity was proven to fall in a range from 10-20 micro-strain. It now remains essential to calibrate and verify, experimentally, that the RSG transducer achieves a calibrated sensitivity comparable to

SENSITIVITY FROM 10-20 MICROSTRAIN RELATIVE TO DISPLACEMENT

(F) LOAD lbs	DISPLACEMENTS micro-inch	STRAIN microns
.008299	17	10
.009129	19	11
.009959	20	12
.010788	22	13
.011618	24	14
.012448	25	15
.013278	27	16
.014108	29	17
.014938	30	18
.015768	32	19
.016598	34	20

Table 2.1: Sensitivity calibration.

the theoretical sensitivity. The next section describes this calibration procedure.

V. CALIBRATION PROCEDURE

To determine, experimentally, the sensitivity of the RSG transducer, a calibration scheme was established by inserting the transducer into an X-Y micrometer apparatus that separately induced compressive loads onto each set of cantilever beams, Fig. (2.7). As each set of beams was deflected along both the X and Y axes, the displacement in the beams was recorded in terms of a voltage difference across each set of RSG hookup wires. Therefore, two corresponding values of voltage and displacment were recorded. These two corresponding values establish points on a calibration curve, and the slope of the curve indicates the sensitivity of the system.

The preceding calibration also includes calibrating each channel. The calibration constant to convert the micro-strain or milli-voltage readings to readings of displacement was simply adjusted on each indicator by rotating the span dial. Utilization of the calibration constants will be outlined further in section IV.

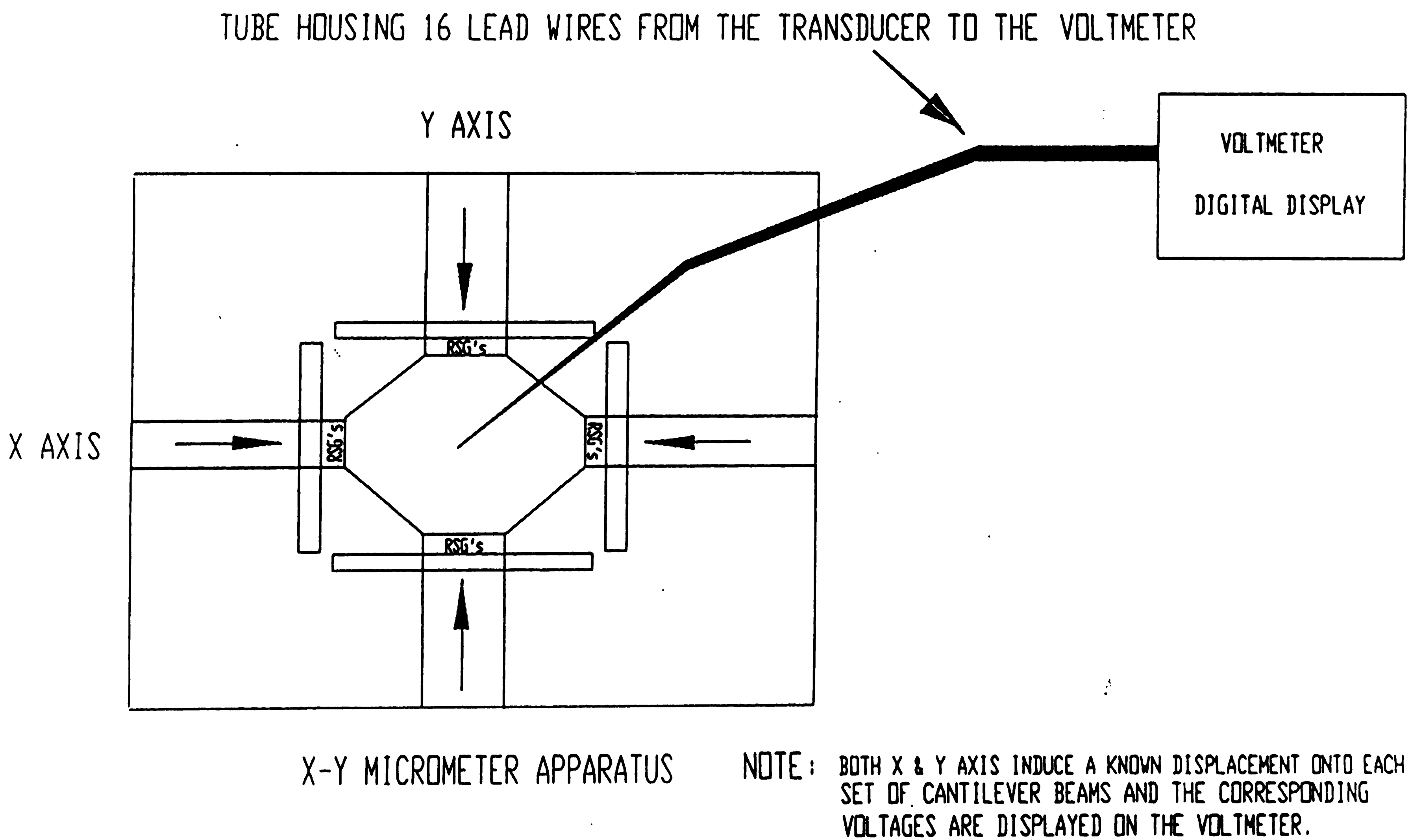


Figure 2.7: Micrometer/Calibration apparatus.

The transducer was now calibrated for differential measurement, but it still remained necessary to develop a means for obtaining the absolute calibration measurement of the bearing cavity. This can be done in any number of ways. The most effective approach is to machine at least two different biangular cavity configurations with dimensions varying slightly above and below the known range of the machined cavity size. For example, the bearing cavity is nominally machined with a cross-sectional dimension of (0.625 +/- 0.0002) inches; it is necessary to machine two other cavity configurations with dimensions of (0.625 + 0.0002 and 0.625 - 0.0002) inches, respectively. An Optical Comparator or Jo-Blocks can be used to verify the two dimensions. Note that the precision of Jo-Blocks is on the order of one micro-inch, while the Optical Comparator can achieve only 0.0001" precision.

Now plot the two cavity configurations. This results in a calibration curve evaluating displacement and voltage. The slope of the calibration curve is then used as the zero reference calibration constant. This zero reference is used in determining the absolute bearing cavity dimension. Note that the transducer must remain linear within this calibration range. A sample case is illustrated in

Table (2.2) and Fig (2.8). The sensitivity of the system is found to be 6.1 mv/0.0001" displacement for channel #1 and 2.5 mv/0.0001" displacement for channel #2. The difference between these two sensitivity values is caused by the dissimilar placement of each RSG on the top and bottom sides of the cantilever beams.

This calibration technique establishes the absolute size of the bearing cavity. Now the deflection values recorded off the transducer's two sets of cantilever beams, as the transducer traverses the race cavity, can be subtracted from the absolute cross-section of the cavity. As a check, this calibration test should be done both before and after the actual measurement has taken place.

A computer subroutine was written to handle the calibration measurements for absolute dimensions, as well as to compare the incoming measurements from the transducer. An average of the two sets of measurements is calculated, separated from the absolute cavity size, and this determines the correct roller/ball size to be used. Ultimately, a roller size with a clearance fit throughout the circumference of the bearing is sought.

CALIBRATION TABLE

Reference Temperature	:	72 F
Excitation Voltage	:	5 volts dc
RSG ID	:	SK-09-060CD-10C
gage factor	:	2.11+/- 0.3% at 24 degrees C
Ohms per RSG	:	1000 =/- 0.3% at 24 C
Transducer sensitivity	:	
channel #1	:	6.1 mv per 0.0001 inch disp.
channel #2	:	2.5 mv per 0.0001 inch disp.
Range	:	0-0.004 inches displ.

TABLE 2.2: Sensitivity Calibration

CHANNEL #1 SENSITIVITY = 6.1 mv/0.0001 INCH DISPLACEMENT
CHANNEL #2 SENSITIVITY = 2.5 mv/0.0001 INCH DISPLACEMENT

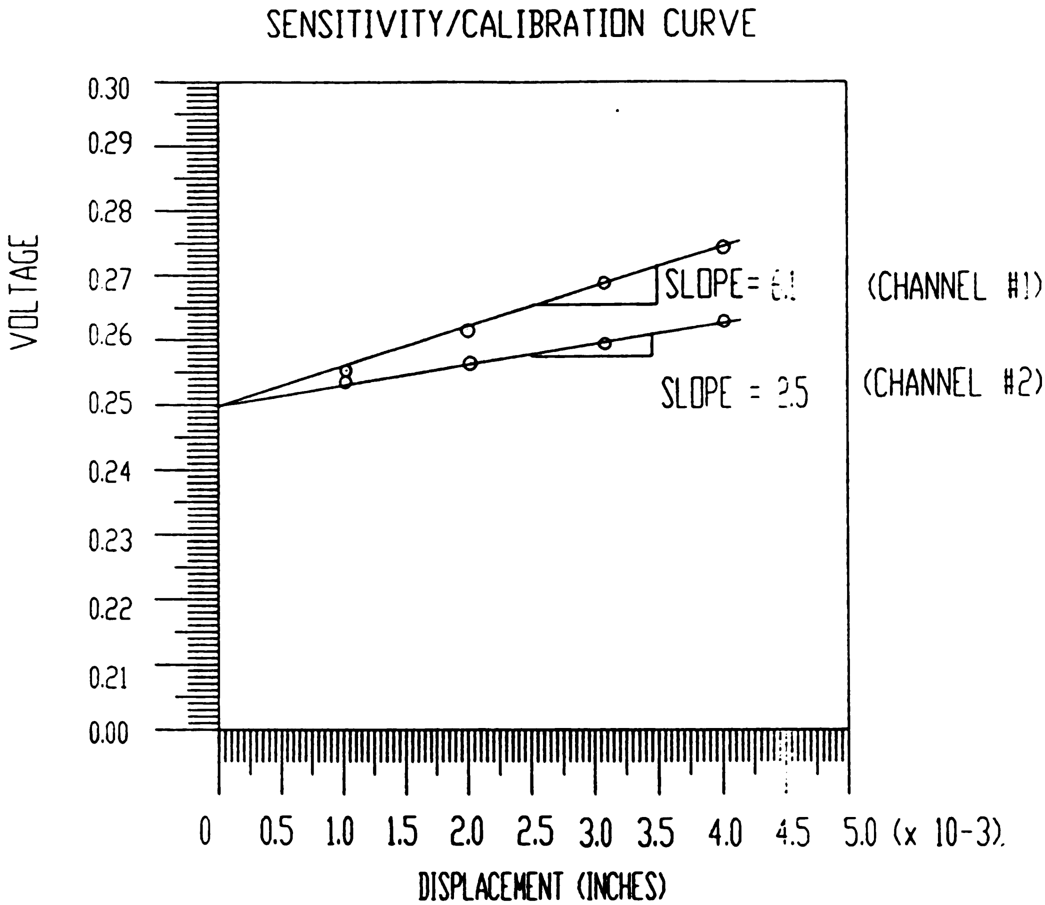


FIGURE 2.8: Calibration Curve

The following section outlines the physical setup of the computer program and describes the communication process between the transducer and the computer.

VI. COMPUTER PROGRAM PHYSICAL SETUP

The computer program is listed in Appendix B, but an explanation of the physical set-up is pertinent.

The strain indicators displayed displacement in each set of beams, via channels #1 and #2, therefore an interface was necessary to relay this information to the computer. This communication was achieved by hooking two cables (positive and negative) into each indicator's voltage output jack and connecting them to a Starbuck A/D converter [7]. Two channels were evaluated, so two separate channels were used on the A/D converter. The voltage was checked during the calibration process and was offset by a factor of 1 (volt) to insure a positive voltage reading for all displacements. The Starbuck A/D converter required positive voltage inputs.

Next, a single hook-up was made from the A/D converter to an RS232 interface (port 1). This hook-up enabled communication between computer, A/D converter, plotter, and printer. Only one communication port was used, and the two channels remained as separate strings of information; so a comparison between the two sets of beams could be made throughout the investigation. As the voltage information was read into the computer it became necessary to convert this number to a tangible displacement and ultimately into the actual cross-sectional dimension of the bearing raceway. This was done using the calibration factors and can be seen in the program as, "indicated voltage input converted to:"

1. indicated displacement
2. indicated diagonal channel size
3. actual diagonal channel size

* 4. correct roller/ball size to use in the bearing.

The analog input of voltage to the converter is computer keyboard activated, and up to 100 data points along the bearing circumference can be analyzed in a single run. As a recommendation for further study, it would be advantageous to create a randomized continuous sampling of points along 360 degrees of the bearing.

VII. COMPUTER CALIBRATION SUBROUTINE

To expand on the computer's contribution to the calibration calculation, an example procedure follows:

Step 1 - record dimensions and voltages for each calibration cavity. Disks 1,2 refer to calibration cavity disks of a particular size, while voltages 1,2 refer to the corresponding voltages created by inserting the transducer into both disk 1 and 2; i.e.

disk 1 = 0.624" [CD1]

disk 2 = 0.626" [CD2]

voltage 1 = 0.392 volts [CV1]

voltage 2 = 0.267 volts [CV2]

Step 2 - calculate the slope of the voltage vs displacement curve; i.e.

$$\text{slope} = \frac{CV2 - CV1}{CD2 - CD1} = 62.5 \text{ v/inch}$$

Step 3 - insert the transducer into the bearing and take a voltage reading; i.e.

average voltage [AV] = 0.331 v

Step 4 - calculate the interpolation increment; i.e.

increment [INC] = AV - CV2 = 0.064

Step 5 - calculate the absolute dimension of the cavity; i.e.

absolute dimension [AD] = disk2 - (inc/slope) = 0.624976"

This procedure is incorporated into the computer program listed in Appendix B.

Section VIII describes the experimental procedure and illustrates how the design criteria is satisfied by the RSG transducer.

VIII. EXPERIMENTAL PROCEDURE

Before the transducer is inserted into the bearing, the geometry of the bearing cavity must be established. This is done by inserting three balls, via the loading plug hole, into the gap between the bearing's mating rings. Each ball is then positioned every 120 degrees to allow the inner ring to rotate freely with respect to the outer ring. At this stage, the bearing cavity is ready to receive the transducer.

The transducer is inserted, via the loading plug hole, into the bearing. After insertion, the transducer traverses the bearing raceway, via rotating the inner race manually with respect to the outer race, and measures the cross-sectional variation within the dimensions of the cavity by indicating deflection in each set of cantilever beams. It is worth noting again that the cantilever beams located on the transducer were preloaded by the walls of the race cavity to ensure measuring contact at all times. An illustration of the preload configuration is found in Fig. (2.9). The sixteen wires from the transducer's RSG's were then fed through the clearance gap at the top of the race cavity and were hooked into their respective channel indicators.

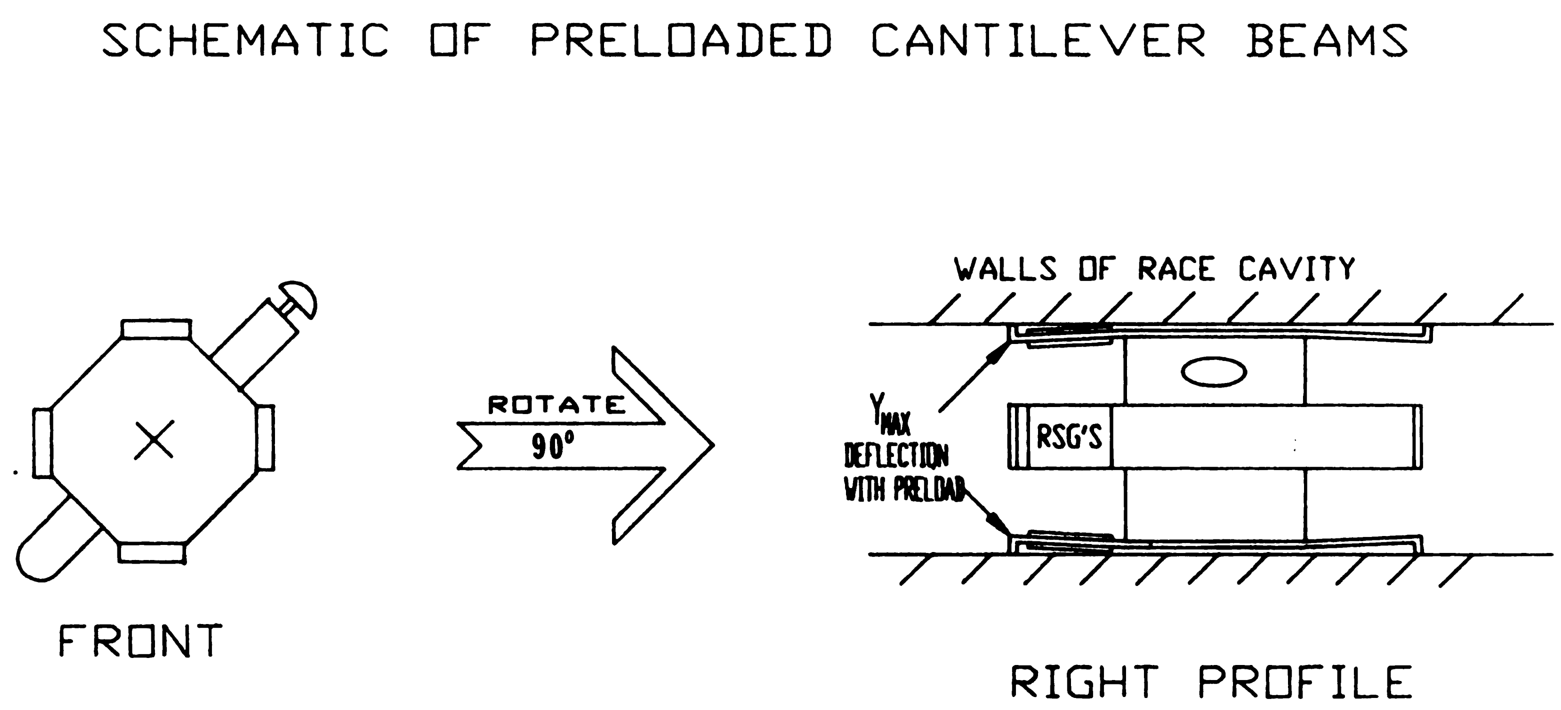


Figure 2.9: Y_{max} deflection shown for pre-loaded cantilever beams.

As the transducer accumulated dimensional readings along the bearing's circumference, there was an indication that some sagging or misalignment was occurring between the mating rings. This sagging was probably the result of the outer ring being stationary, while the inner ring was suspended by the three balls located 120 degrees apart. Again, implementing the three balls was essential to the rotation of the inner ring with respect to the outer ring. Transducer readings were taken at locations near each of the three balls, as well as at varying distances between each ball. It became apparent that the balls alleviated most of the sag between rings.

A complete description of how the transducer satisfies the design criteria follows.

The transducer is:

A. Unaffected by the clearance groove in the raceway. In fact, the clearance groove, which is located in the center of both the inner and outer ring, is used as a guide for the transducer's positioning (compression) pin as it traverses the circumference of the raceway, Fig. (2.10).

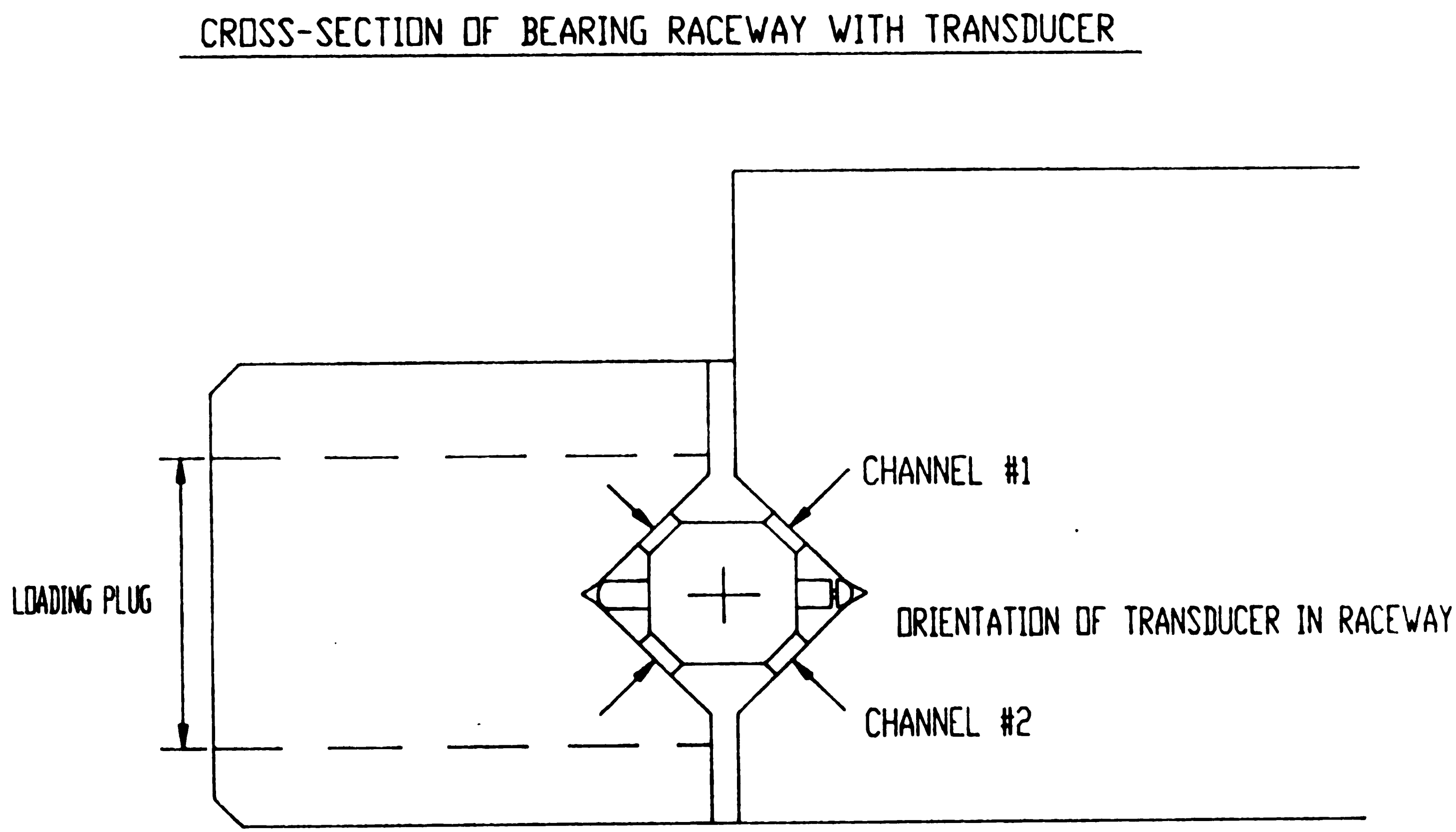


Figure 2.10: Transducer placement along centerline of bearing raceway cavity.

B. Able to measure relative out-of-roundness for the rings as well as radial and axial misalignment between the two rings. In preliminary readings from the transducer, it became apparent that if a reading was taken directly next to one of the three balls, located every 120 degrees, then misalignment between rings virtually cancelled. This must mean that the 5/8" + 0.001 size and tolerance on each ball is sufficient to take up most of the slack or gap (misalignment) existing in the bearing race cavity. Misalignment/out-of-roundness was apparent at arbitrary distances from each of the raceway balls.

C. Able to accommodate different raceway configurations (i) biangular roller, (ii) 4 point contact, and (iii) angular contact thrust. This feature is built into the transducer design and is located at the end of each of the cantilever beams, Fig. (2.11). Each beam achieves a preloaded (raceway flat) contact, at the extreme ends of the beams. Kel-F (a common flourocarbon) was selected as the material used at the contact surface because of its very low friction factor. Kel-F insured an easy, gliding, measuring surface between the bearing race and the transducer.

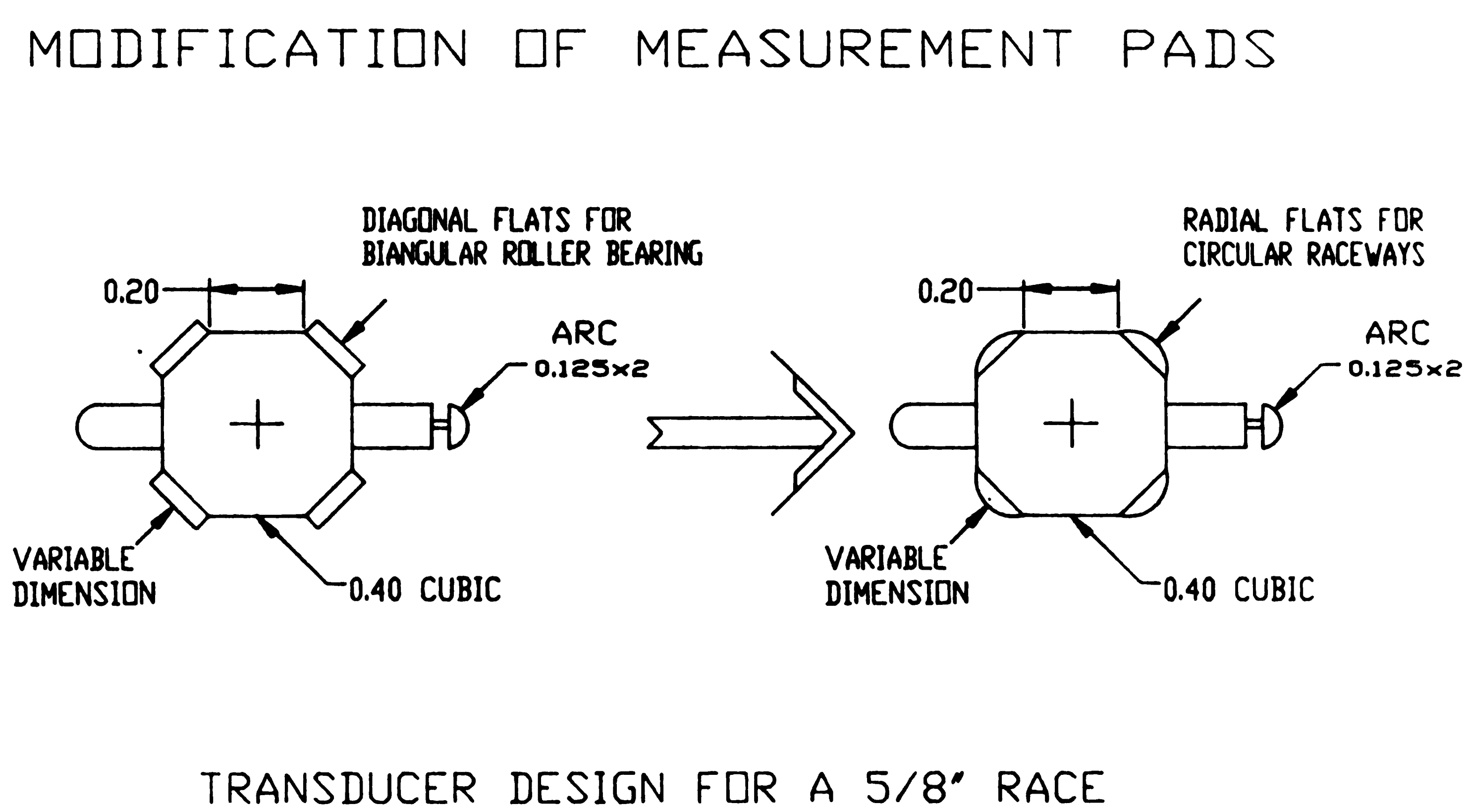


Figure 2.11: Design showing the flexibility and adaptability of the transducer's measuring pads.

The shape or configuration of these pads can be changed to accommodate the different raceway configurations and dimensions; therefore, a common transducer "module" can be created for each "nominal" raceway diameter. For example, if 1" diameter balls are used in a particular raceway, then a transducer can be used with a 1" radial pad configuration.

D. Able to achieve a proper balance between sensitivity and range. Qualitatively, the sensitivity must allow the detection of small dimensional changes within the comparatively large cross-sectional dimension of the bearing race cavity. Preliminary calculations of sensitivity revealed a proper balance of sensitivity and range by achieving a range of 10-20 micro-strain for beam deflections of 1/1000".

A sample test was conducted to verify the experimental procedure, see Table (2.3), and a plot was generated from the data; this is shown in Fig. (2.12). Note the location of the loading plug along each curve. At this location there appears to be a relaxation in both sets of beams which indicates that this location could possibly be used as a reference for initial calibration of the transducer.

DATA FOR SAMPLE TEST

	POINTS	ACTUAL DIAGONAL CHANNEL SIZE	DISTANCE OFF CENTERLINE
CHANNEL #1	1	0.623775	0.311887
	2	0.623803	0.311902
	3	0.623832	0.311916
	4	0.624055	0.312028
	5	0.624202	0.312101
	6	0.624601	0.312301
	7	0.624174	0.312087
	8	0.623946	0.311973
	9	0.623832	0.311916
	10	0.623775	0.311888
CHANNEL #2	1	0.623910	0.311955
	2	0.623128	0.311564
	3	0.622894	0.311447
	4	0.622349	0.311175
	5	0.621881	0.310940
	6	0.623908	0.311954
	7	0.621569	0.310784
	8	0.622426	0.311213
	9	0.622738	0.311369
	10	0.623518	0.311759

Table 2.3: Data points taken from the sample run. These points match with Figure 2.10.

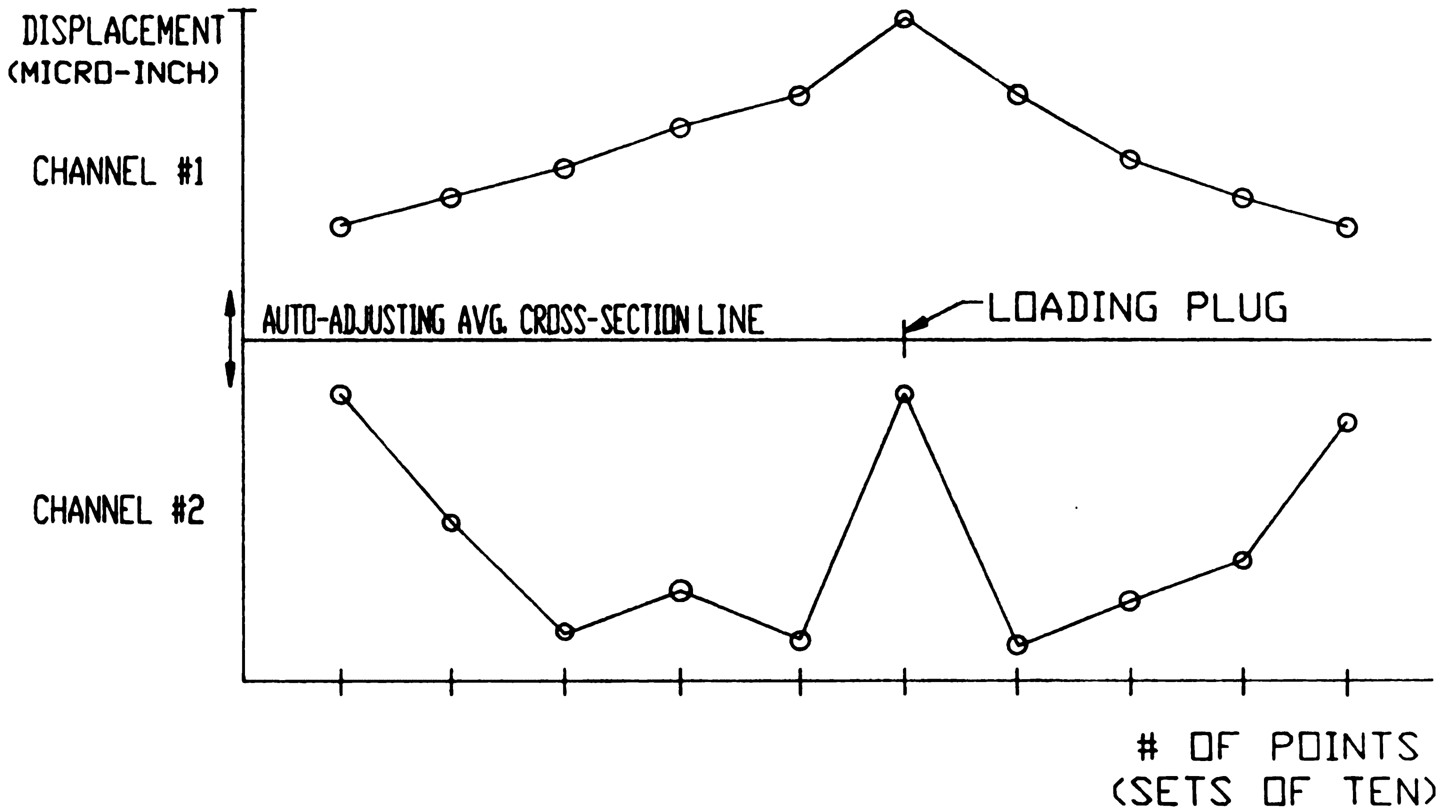


Figure 2.12: Plot showing data from sample test.

IX. SUMMARY

The critical elements of the RSG tranducer design, along with a sample run verifying the transducer's validity, were outlined in the preceding sections. Theoretical calculations revealed that the transducer design could maintain the desired sensitivity (at least 1mv/0.0001" displacement), while the experimental procedure verified that sensitivities as high as 6.1 mv/0.0001" displacement could be achieved by a single set of measuring cantilever beams.

The computer program, though written in Atari Basic, proved very expedient in assimilating the strings of voltage information inputed by the A/D converter. It is worth noting that Atari Basic is similar to other versions of Basic; therefore if desired, it can be easily converted to suit the user's needs.

The following chapter contains concluding remarks, as well as recommendations for further research.

CHAPTER 3

DISCUSSION AND CONCLUSIONS

I. Experimental Results

At the current level of development the means of accurately measuring raceway cavities in large bearings is inadequate. This creates the need to supply industry with a measurement tool which alleviates this problem. The measurement tools described in this study, primarily the electrical resistance strain gage, offer a means of quickly and accurately solving the time-consuming problem of trial and error assembly of large bearings.

In the preliminary stages of the study it became apparent that an RSG transducer could feasibly be designed to maintain accuracy, sensitivity, and range while ultimately collecting tangible data about the cross-sectional area of the bearing raceway. Theoretical calculations were made before and during the calibration process and comparisons with experimental results remained within a "feasible" working range of 10-20 micro-strain per 1/1000" displacement.

In the final stages of the measurement analysis, during the process where the transducer was traversing the bearing cavity and the computer was actively gathering data, a sample test was actuated to trace approximately 300 degrees of the bearing's circumference. Ten data points were taken on each of the two independent channels. The results are listed in Table (2.3) and Fig. (2.12). As stated in the calibration procedure, the actual bearing cavity size was determined and used as a reference to compare differentially with each set of deflections from the cantilever beams. The nominal machined cross-sectional size of the raceway was 0.625 +/- 0.0005 inches while the experimental average cross-section was generated to be 0.624976 inches. The roller size machined for the 5/8" race cavity was 0.594 x 0.625 dia.+/- 0.00020 inches. This roller is therefore compatible with this set of bearing rings, as long as the race cavity diameter does not become less than 0.624976". The testing criteria found in chapter 1, relating breakaway torque and preload requirements, will still have to be checked to verify the roller selection determined by the transducer.

II. FURTHER STUDY/RECOMMENDATIONS

This research began as a feasibility study to determine if a device could be developed to accurately measure the cross-sectional dimensions of raceway cavities in large bearings. This open-ended endeavor led to many creative ideas which led to designing the RSG transducer. This tranducer has been shown to satisfy the established design and testing criteria, but at this time it is still in the prototype stage. Further recommendations therefore are focused on developing this prototype to a final manufacturable design. Ideas should also be focused on developing the software into a more universally compatible form, i.e. convert Atari Basic into BasicA or Quick Basic.

Another area which was not pursued was comparative modes of data collection. The existing physical setup evaluates, both statistically and statically, ten groups of ten data points around the bearing circumference, and the communication between the transducer and computer is keyboard-initiated. It would be more advantageous to record the data continuously while traversing the bearing. This modification can be easily implemented into the existing computer program.

This study remains as an investigation of a unique measurement problem, but the preceeding pages have supported the fact that the RSG transducer is a feasible and creative means to a positive solution of accurately measuring raceway cavities in large bearings.

APPENDICES

A - HISTORICAL BACKGROUND ON RSG'S

B - COMPUTER CODE

APPENDIX A

I. HISTORICAL BACKGROUND ON ELECTRICAL RSG'S

A. Definition of Strain and How it Relates to Displacement

In elementary terms, strain is a change in length of a line segment divided by its original length. The concept of strain is also thought of in terms of deformation and displacement of a certain specimen surface; in this case a cantilever beam.

The general relationship for in-plane strain is given by:

$$\epsilon_{xx} = (l_x - l_o)/l_o = \Delta u/\Delta x \qquad (A.1)$$

where $\Delta u = l_x - l_o$ is the deformation in the x direction over the length of the line segment $l_o = \Delta x$, see Fig. (A.1). Strain measured in this manner is an average because of the limitation incurred by the paramenter l_o (the gage length).

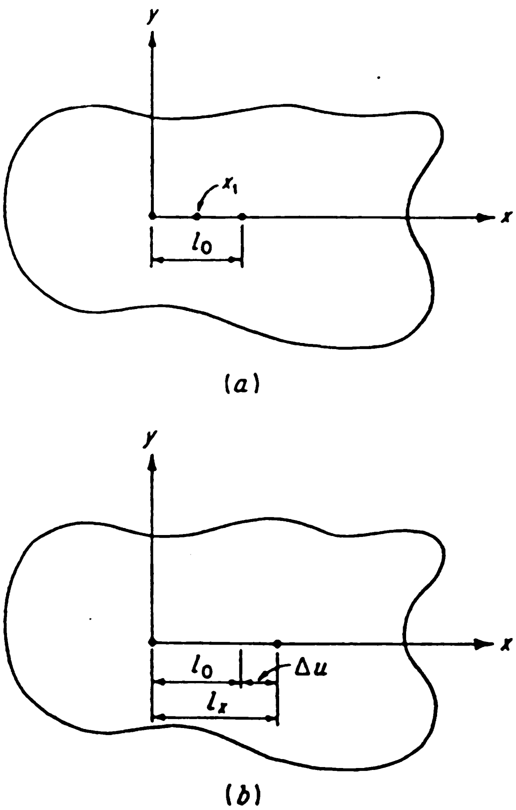


FIGURE A.1: Strain measurement over a short line segment of length l_o: (a) before deformation; (b) after deformation [5].

To curcumvent this error, great effort has been focused on reducing the gage length l_o, but two factors complicate matters. Mechanical difficulties are encountered when l_o is reduced because the gage, inevitably, has a finite size limitation, and the strain being measured is a very small quantity. Suppose, for example, that strain or displacement measurements are to be made with an accuracy of ± 1 μ in/in over a gage length of 0.1 inch. The strain gage must then measure the corresponding displacement to an accuracy of ± 1 x 10E-6 x 0.1 = ± 1 x 10E-7 inches or one ten millionth of an inch. This size and accuracy limitation remains a problem [5].

B. Properties of Resistance Strain Gages

Historically, the development of strain gages is based on mechanical, optical, electrical, acoustical, and pneumatic principles. No single gage system has all the properties required for an optimum gage, but some of the optimum characteristics used to judge the adequacy of a strain gage system are listed below [5].

1. The calibration constant for the gage should be stable and should not vary with time or temperature.

2. The gage should be able to measure strains with an accuracy of ± 1 μ in/in over a strain range of 10%.
3. The gage size i.e., the gage length l_o and width w_o, should be small so that the strain at a point is adaquately approximated.
4. The response of the gage, largely controlled by its inertia, should be sufficient to permit the recording of dynamic strains.
5. The gage system should promote on-location or remote read-out.
6. The output from the gage during the read-out period should be independent of temperature and other environmental parameters.
7. The gage and the associated auxiliary equipment should be economically feasible.
8. The gage system should not involve overcomplex installation and operational techniques.
9. The gage should exhibit a linear response to strain.
10. The gage should be suitable for use as the sensing element in other transducer systems where the unknown quantity, such as displacement, is measured in terms of strain.

Proper consideration was placed on all of the aforementioned criteria before developing the displacement transducer in this study.

In addition to the criteria listed above, it is also worth noting that in selecting a gage for a given application, gage length l_o is one of the most important considerations [5]. The second most important characteristic is gage sensitivity. Sensitivity is the smallest value of strain that can be read on the scale associated with the strain gage. **The term sensitivity should not be mistaken for accuracy or precision**, since very large values of magnification can be built into a gage to increase its sensitivity; but friction, wear, and deflection introduce large errors which limit the accuracy.[5] The choice of a gage is dependent upon the degree of sensitivity required, and a very high sensitivity does not necessarily increase the complexity of the measuring method.

The third basic characteristic of a strain gage is its range. Range represents the maximum strain which can be recorded without resetting or replacing the strain gage.

The range and sensitivity are interelated since very sensitive gages respond to small strains with appreciable indicator deflections and range is usually limited to the full-scale deflection of the indicator. To obtain reasonable performance between sensitivity and range it is often necessary to make a compromise between the two [5].

C. Types of Strain Gages

The major focus of strain gages is to determine the motion between two points a distance l_o apart. The principles employed in strain gage construction classify the gages into the following four groups [5]:

1. Mechanical
2. Optical
3. Electrical
4. Acoustical

The electrical foil strain gage system or transducer was chosen as a measuring device because of its size adaptability and superior sensitivity and range.

The preceding section outlined the background of RSG's and how they can be used to measure displacements. The following section details the performance characteristics that support implementing the electrical resistance strain gage as the measurement tool.

II. PERFORMANCE CHARATERISTICS OF ELECTRICAL RESISTANCE STRAIN GAGES

An electrical resistance strain gage (RSG) is simply a resistor mounted on a flexible carrier that is bonded to a component part, and it exibits the ability to accurately monitor the changes in resistance that correspond to particular deformations in the component part. The gage resistance for the 1000 ohm RSG's used in this study is accurate to approximately ± 0.3%, and the gage factor, which is simply based on a lot number calibration, is certified as 2.11 ± 1.0%.

Though these factors are important, strain accuracy is still directly proportional to how uniformly the gages are applied to each specimen.

When a testing procedure is undertaken using RSG's, and the specimen is subjected to variances in temperature, then attention must be focused on whether or not the changes in resistance are resulting from strain or temperature; see Fig.(A.2). When the ambient temperature changes, four effects that occur are:

1. Changes in the strain sensitivity S_A in the alloys grid
2. Gage grid either elongates or contracts ($\Delta l/l = \alpha\Delta T$)
3. Carrier either elongates or contracts ($\Delta l/l = \beta\Delta T$)
4. Resistance of the gage changes; due to the influence of the temperature coefficient of resistivity in the gage material ($\Delta R/R = \gamma\Delta T$)

Note that the gage reacts to temperature much in the same way as it reacts to mechanical strain due to an applied load, and it is impossible to distinguish between the two. If the gage alloy and the carrier have the same thermal coefficients of expansion, then the term $(\Delta R/R)_{\Delta T}$ vanishes. The gage may still register a change in resistance or strain in the material, but this becomes an apparent strain which actually does not exist in the specimen [6].

Today gages can be purchased that are already temperature compensated, but it is still necessary to compensate the electrical circuit; this can be done with four active gages in a Wheatstone Bridge Circuit, refer to Fig. (2.5).

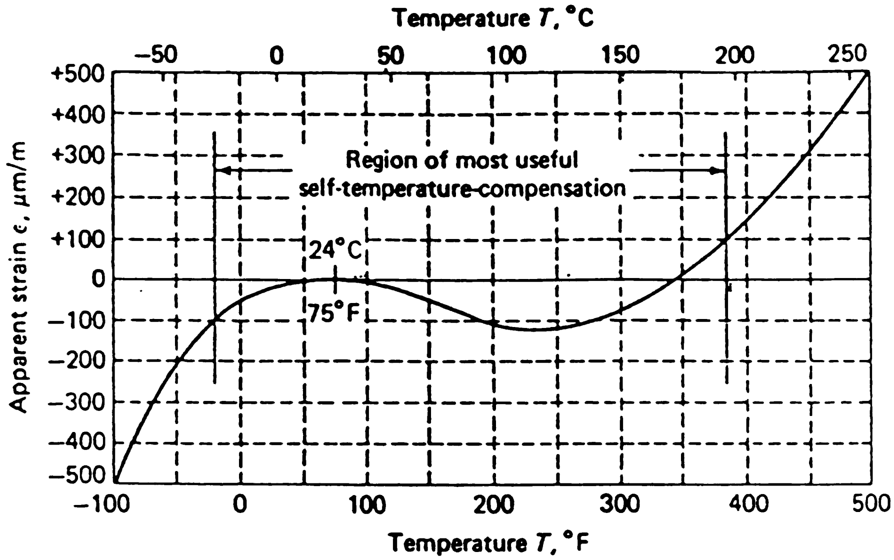


FIGURE A.2: Apparent strain as a function of temperature for an advance alloy temperature compensated strain gage mounted on a specimen having a matching temperature coefficient of expansion [5].

APPENDIX B

COMPUTER CODE

```
1 ? "THIS PROGRAM IS DESIGNED TO GENERATE EXACT DIMENSIONS
OF THE RESPECTIVE BEARING RACEWAY";
2 ? "THE CORRECT ROLLER/BALL SIZE WILL ALSO BE INDICATED"
3 ? " "
4 ? " "
6 DIM
N$(10),NN$(10),B$(100),C$(100),D$(100),E$(10),V1(10,100),V2(
10,100),BRB$(1),FPC$(1),FPR$(1),ACT$(1)
7 GOTO 1448
8 GOTO 1501
9 GOTO 1504
10 GOTO 1523
11 ? "THE FOLLOWING ARE INTERACTIVE QUESTIONS, PLEASE
ANSWER:"
12 GOTO 3000
13 ? "HOW MANY GROUPS OF TEN SAMPLING POINTS ? MAX IS
10":INPUT N$:N=VAL(N$):NN$=STR$(N*10):? N
18 NN=10*N:? NN
21 POKE 82,0
25 CLOSE #1
28 ? " "
29 OPEN #1,13,0,"R1:"
31 ? "31"
32 XIO 36,#1,10,0,"R1:"
35 XIO 38,#1,64,93,"R1:"
37 X10 40,#1,0,0,"R1:"
42 PRINT #1,CHR$(27);"01";CHR$(13);
45 B$=" ":INPUT #1,B$:? "45",B$
48 ? "IMMEDIATE ANALOG INPUT TO BEGIN"
49 ? " "
51 GOTO 108
52 REM
108 ? "THE INDICATED VOLTAGE IS:":? ""
109 ? "CHANNEL #1, "", "CHANNEL #2";
110 DIM KZ$(3)
111 FOR I=1 TO NN
112 INPUT KZ$
114 PRINT #1,"IA1";CHR$(13);
116 INPUT #1,B$:V1(I,1)=I:V1(I,2)=((VAL(B$(4)))/51)
117 PRINT V1 (I,2),"",
118 PRINT #1,"IA2";CHR$(13);
120 INPUT #1,D$:V2(I,1)=I:V2(I,2)=((VAL(D$(4)))/51):PRINT
V2(I,2)
121 NEXT I
122 ?""
123 ? "THE INDICATED DISPLACEMENT IS:"
124 ? ""
125 ? "CHANNEL #1", "", "CHANNEL #2";
```

```
127 DIM KBZ$(3)
129 FOR I=1 TO NN
131 INPUT KBZ$
135 V1(I,2)=(V1(I,2)*392.31):PRINT V1(I,2),"",
141 V2(I,2)=(V2(I,2)*392.31):PRINT V2(I,2)
143 NEXT I
148 ? ""
150 ? "THE AMOUNT OF DEFLECTION IN EACH SET OF BEAMS IS:"
151 ? ""
152 ? "CHANNEL #1", "", "CHANNEL #2";
153 ? ""
154 DIM KZS$(3)
156 FOR I=1 TO NN
158 INPUT KZS$
162 V1(I,2)=(((V1(I,2)-100)/1000)/61000):PRINT V1(I,2), "",
168 V2(I,2)=(((V2(I,2)-100)/1000)/61000):PRINT V2(I,2)
170 NEXT I
171 ? "":? "WHAT IS THE ABSOLUTE DIMENSION OF THE CAVITY?"
172 ? "THE ACTUAL DIAGONAL CHANNEL SIZE IS:"
173 ? ""
174 ? "CHANNEL #1","","CHANNEL #2";
176 DIM KAZ$(3), TOT(10,10), TAV(10), TV(10), AD(10)
177 TOT =0
178 FOR I=1 TO NN
180 INPUT KAZ$
184 V1(I,2)=((V1(I,2)-(AD)*(-1)):PRINT V1(I,2),"",
190 V2(I,2)=((V2(I,2)-(AD)*(-1)):PRINT V2(I,2)
211 ?""
216 ? ""
230 TV=(((V1(I,2))+(V2(I,2)))/2)
231 TOT=TOT + TV
233 NEXT I
234 ? "----------------"
235 TAV=TOT/NN
236 PRINT TAV
237 ? "----------------"
238 ? ""
240 PRINT "THIS IS THE CORRECT ROLLER/BALL SIZE FOR THE
RESPECTIVE BEARING:(DIMENSIONS ARE IN INCHES)"
245 GOTO 300
300 CLOSE #1:?
350 ? ""
354 ? ""
375 ? "RAW DATA IS STORED AS TWO STRINGS A$(I) AND Z$(I) OF
LENGTH 10N; YOU CAN PRINT IT TO DISC OR PAPER"
380 ? ""
381 ? ""
385 ? "YOU CAN THEN PLOT OR PRINT TO DISC OR PRINTER; THE
VARIABLES ARE V1(L,I) AND V2(L,I) WITH DIM N X 10"
```

```
499 INPUT B$
500 ?:? "DO YOU WANT A SCREEN PLOT? (Y,N)":B$=" ":INPUT
B$:IF B$="Y" THEN GOSUB 515
502 ? "DO YOU WANT A PAPER PLOT? (Y,N)":INPUT B$:IF B$="Y"
THEN 1200
503 ? "SAVE VOLTS OR RAW DATA TO DISC? (Y,N)":INPUT B$:IF
B$="Y" THEN 505
504 GOTO 508
505 ? "SAVE VOLTS (V1), (V2) OR DIGITAL DATA STRINGS (A),(Z)
TO DISC--WHICH?(V,A)"
506 INPUT B$:IF B$="V1" THEN GOSUB 1400
507 IF B$="A" THEN GOSUB 1600
508 ? "START PRINT AND PLOT ROUTINES OVER WITH SAME DATA?
(Y,N)":INPUT B$:IF B$="Y" THEN 499
509 ? "START ALL OVER? (Y,N)":INPUT B$:IF B$ = "Y" THEN
GRAPHICS 0:END
510 IF B$<>"Y" THEN GRAPHICS 0:END
515 I=1:J=1:X=9:C=1
520 GRAPHICS 7:COLOR 1
522 GOTO 1100
528 GOTO 698
529 GOTO 502
698 REM "PLOT OF CHANNEL #1"
700 COLOR C
702 INPUT KZ$:X=19
703 PLOT X,TAV + 35
705 FOR I = 1 TO NN
718 Y = ((TAV + 35)-((((AD)-(V1(I,2))))*10000000))
730 X=X + (10)
731 DRAWTO X,Y
740 NEXT I
750 REM "PLOT OF CHANNEL #2"
755 COLOR C
756 INPUT KBZ$:X=19
757 PLOT X,TAV + 35
758 FOR I=1 TO NN
759 Y = ((TAV + 35)-((((AD)-(V2(I,2))))*10000000))
760 X=X + (10)
761 DRAWTO X,Y
762 NEXT I
800 ? "X SCALE (NUMBER OF POINTS)=";NN$:? "Y SCALE
(DISPLACEMENT)=";TAV:?" DONE---";
802 ? "HIT RETURN TO GET CHOICES":INPUT B$
899 RETURN
900 ? "STOP"
1100 ? ""
1110 PLOT 9,70:DRAWTO 9,1
1115 PLOT 8,70:DRAWTO 11,70
1120 PLOT 8,1:DRAWTO 11,1
```

```
1135 PLOT 9,35:DRAWTO 159,35
1140 PLOT 59,31:DRAWTO 59,39
1141 PLOT 7,45:DRAWTO 11,45
1142 PLOT 7,55:DRAWTO 11,55
1143 PLOT 7,65:DRAWTO 11,65
1144 PLOT 7,25:DRAWTO 11,25
1145 PLOT 7,15:DRAWTO 11,15
1146 PLOT 7,5:DRAWTO 11,5
1147 PLOT 19,34:DRAWTO 19,36
1148 PLOT 29,34:DRAWTO 29,36
1149 PLOT 39,34:DRAWTO 39,36
1150 PLOT 49,34:DRAWTO 49,36
1151 PLOT 59,34:DRAWTO 59,36
1152 PLOT 69,34:DRAWTO 69,36
1153 PLOT 79,34:DRAWTO 79,36
1154 PLOT 89,34:DRAWTO 89,36
1155 PLOT 99,34:DRAWTO 99,36
1156 PLOT 109,34:DRAWTO 109,36
1190 GOTO 698
1191 GOTO 503
1200 REM : PLOT ROUTINE FOR 1020 PLOTTER
1201 GOTO 503
1202 TRAP 40000:TRAP 1204
1203 GOTO 1205
1204 ? "PRINTER OFF?":GOTO 502
1205 CLOSE #1:CLOSE #2
1210 OPEN #2,8,0,"P:"
1220 ? #2;""
1225 C=1:? #2;"C"; C-1
1230 ? #2; "M50,    0*X1,80,5"
1240 ? #2; "M50,-950*X0,95,10"
1250 Z=INT (900/(12*N)) +1:IF N>20 THEN Z=4
1252 Q=N:IFQ>C*20 THEN Q=C*20
1255 T=0
1260 ? #2; "C";C-1
1265 Y=80*TOT((C-1)*20 +1,1)
1270 ? #2; "M";50 + Y1; ",";T
1280 FOR L=(C-1)*20 +1 TO Q:FOR I=1 TO 10
1284 Y = 80*TOT (L,I)
1285 ? #2;"D";50 + Y;",";T
1287 T = T + Z:? T,
1290 NEXT I:NEXT L
1295 C = C + 1:IF ((C-1)*20)-N<0 THEN 1252
1399 CLOSE #2:RETURN
1400 GOTO 1599
1448 ? "WHAT TYPE OF BEARING IS BEING ANALYZED?"
1449 ? ""
1450 ? "CHOOSE THE BEARING TYPE"
1451 ? ""
```

```
1452 ? "BRB = BIANGULAR ROLLER BEARING"
1453 ? "FPC = 4 POINT CONTACT BEARING"
1454 ? "FPR = 4 POINT RADIAL CONTACT BEARING"
1455 ? "ACT = ANGULAR CONTACT THRUST BEARING"
1456 ? ""
1457 ? ""
1497 INPUT C$
1499 IF C$ = "BRB" THEN ? "THE ANALYSIS OF A BIANGULAR
ROLLER BEARING FOLLOWS"
1500 GOTO 8
1501 ? ""
1502 IF C$ = "FPC" THEN ? "THE ANALYSIS OF A 4 POINT CONTACT
BEARING FOLLOWS"
1503 GOTO 9
1504 ? ""
1520 IF C$ = "FPR" THEN ? "THE ANALYSIS OF A 4 POINT RADIAL
CONTACT BEARING FOLLOWS"
1522 GOTO 10
1523 ? ""
1530 IF C$ = "ACT" THEN ? "THE ANALYSIS OF AN ANGULAR
CONTACT THRUST BEARING FOLLOWS"
1532 GOTO 12
1599 RETURN
1600  ? "NOT AVAILABLE"; GOTO 1799
1799 RETURN
1800 ? "NOT AVALABLE"; GOTO 2099
2099 RETURN
2200 ? "*******************************************"
2300 ? "*******************************************"
2400 ? "     CALIBRATION SUBROUTINE"
2450 ? "*******************************************"
2455 ? "*******************************************"
2500 ? ""
2600 ? ""
3000 DIMCV1(10),CV2(10),CD1(10),CD2(10),DK1(10),DK2(10),
SLP(10),AV(10),INC(10),AV2(10),SLP$(1),AD$(1),AV$(1)
3005 ? ""
3006 ? ""
3007 ? "THE CALIBRATION CONSTANTS FOR ABSOLUTE DIMENSIONS OF
THE BEARING RACEWAY CAVITY ARE AS FOLLOWS:"
3008 ? ""
3009 ? ""
3010 ? "WHAT ARE THE DIMESIONS OF THE TWO CALIBRATON
CAVITIES?":INPUT DK1:? DK1:? "DISK #1 = 0.6248"
3011 ? ""
3012 ? ""
3015 INPUT DK2: ? DK2: ? "DISK #2 = 0.6252"
3016 ? ""
3017 ? ""
```

```
3020 ? "WHAT IS THE VOLTAGE AND DISPLACEMENT ASSOCIATED WITH
BOTH OF THE CALIBRATION CAVITIES?"
3021 REM
3022 ? ""
3023 ? "VOLTAGE FROM DISK #1=":INPUT CV1:? CV1
3024 REM
3025 ? "VOLTAGE FROM DISK #2=":INPUT CV2: ? CV2
3026 REM
3027  ? ""
3030 ? "DISPLACEMENT FROM DISK #1=":INPUT CD1:? CD1
3031 ? ""
3032 ? "DISPLACEMENT FROM DISK #2=":INPUT CD2: ? CD2
3033 ? ""
3037 REM
3038 ? ""
3040 ? "COMPUTE THE SLOPE OF THE CALIBRATION CURVE TO
DETERMINE THE ZERO REFERENCE CALIBRATON CONSTANT"
3041 ? ""
3042 ? ""
3045 ? " SLOPE = SENSITIVITY, WHICH EQUALS ..."
3047 INPUT SLP$:SLP = (((CV1-CV2)/(CD1-CD2)/10)):? SLP$:?
"(MV/0.0001 INCH DISPLACEMENT)"
3048 ? ""
3049 ? ""
3050 ? "INTERPOLATE BETWEEN THE TWO VOLTAGE VALUES TO FIND
THE VOLTAGE VALUE FOR ABSOLUTE 0.625 +/- 0.0002 INCHES"
3051 ? ""
3053 ? "INPUT THE ABSOLUTE VOLTAGE READING FROM THE
VOLTMETER:"INPUT AV: ? AV
3054 ? ""
3055 ? "ABSOLUTE VOLTAGE = AV = (CV1 + (INC*(CV2-CV1)))"
3056 ? ""
3057 ? "COMPUTE THE INCREMENT (INC) FOR THE EQUATION (AV):"
3058 ? ""
3059 INC = CV1-AV:? INC
3060 ? ""
3075 ? "THE ABSOLUTE DISPLACEMENT = (AD) AND IS COMPUTED
USING THE FOLLOWING EQUATION:"
3076 ? ""
3078 ? "AD=(DK1+(INC*(DK2-DK1)))"
3079 ? ""
3080 AD = (DK2-(INC*(DK2-DK1))):? AD
3081 ? ""
3082 ? ""
3090 ? "PLUG THE CALCULATED VALUE FOR THE ZERO REFERENCE
DISPLACEMENT (AD) INTO THE EQUATION FOR ACTUAL DIMANSION"
3091 ? ""
3100 GOTO 13
```

BIBLIOGRAPHY

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