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Evaluation of Electrolytic Tilt Sensors for Measuring Model Angle of Attack in Wind Tunnel Tests

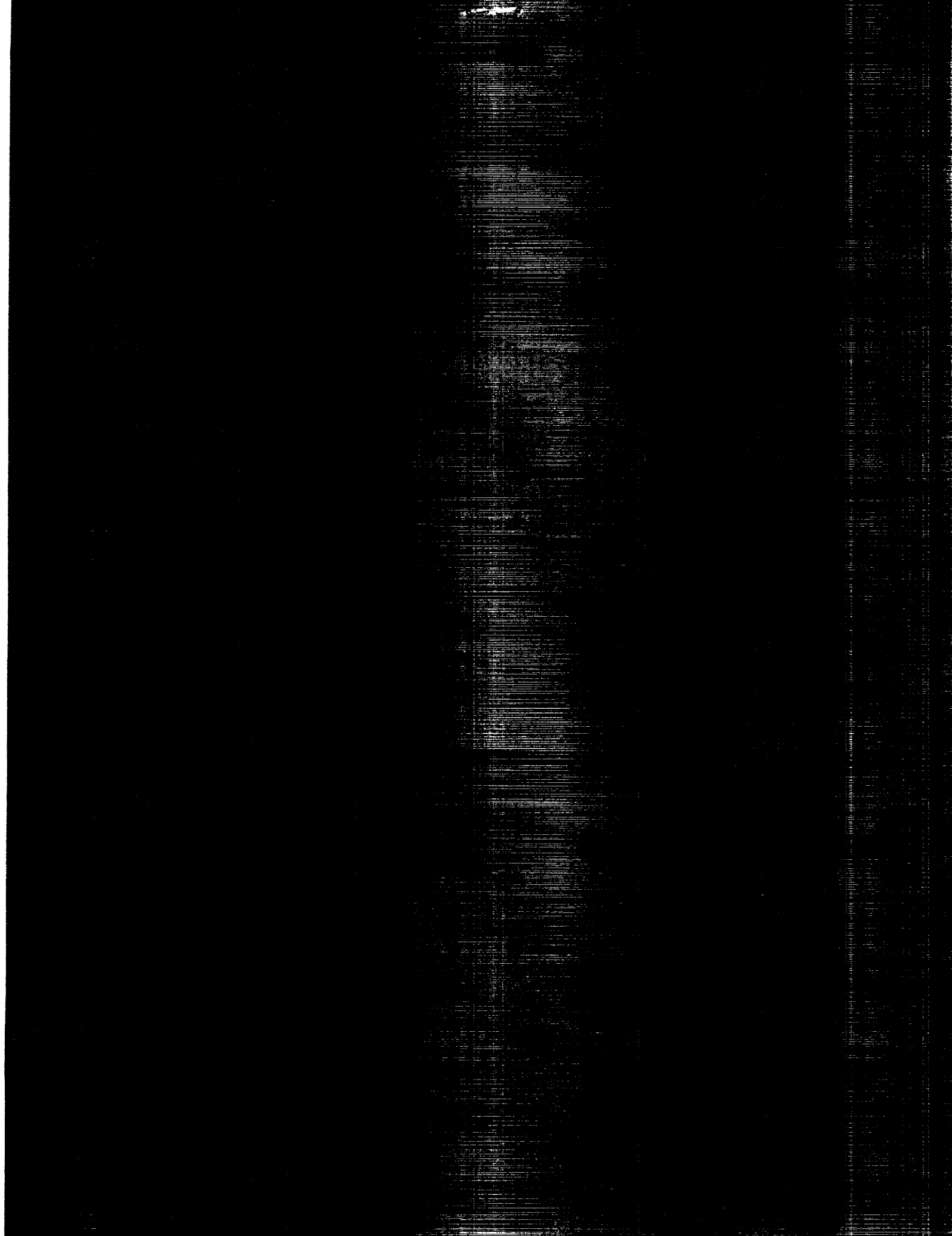Douglas

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Evaluation of Electrolytic Tilt Sensors for Measuring Model Angle of Attack in Wind Tunnel Tests

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Summary

Eight electrolytic tilt sensors were evaluated as potential replacements for servo accelerometers used in angle-of-attack measurements. The areas evaluated included linearity, hysteresis, repeatability, temperature characteristics, roll-on-pitch interaction, sensitivity to lead-wire resistance, step response time, and rectification. The evaluation results indicated that the Spectron model RG-37 sensors have the highest accuracy in terms of linearity, hysteresis, repeatability, temperature sensitivity, and roll sensitivity. A comparison of the sensors with the servo accelerometers revealed that the accuracy of the RG-37 sensors was on the average about one order of magnitude inferior. Even though a comparison indicated that each tilt sensor cost about one-third that of each servo accelerometer, the sensors are considered unsuitable for angle-of-attack measurements. However, the potential exists for other applications such as wind tunnel wall-attitude measurements where the errors resulting from roll interaction, vibration, and response time are less and the sensor temperature can be controlled.

Introduction

The servo accelerometer is the conventional instrument for measuring model attitude or angle of attack in wind tunnel tests at the Langley Research Center (ref. 1). A typical servo accelerometer is shown in sketch A. In spite of its accuracy, repeatability, and relatively fast response, it suffers from three shortcomings which are listed as follows:

1. Fragility: Experience indicates that improper handling can easily damage the accelerometer because of its delicate design.

2. Cost: Each servo accelerometer can cost up to several thousand dollars.

3. Bulkiness: The size of the servo accelerometer usually dictates the minimum size of the wind tunnel model. The servo accelerometer package routinely used at Langley is 1.625 in. in length and 1.188 in. in diameter. Photographs of the unit are shown in figure 1.

In view of these drawbacks, it is necessary to consider other types of sensors as potential replacements for the servo accelerometers. The replacement should be smaller, more rugged, and less expensive.

Electrolytic tilt sensors described in reference 2 meet these criteria. The objective of this evaluation was to determine if the tilt sensors are adequate replacements for the servo accelerometers in terms of accuracy, repeatability, and dynamic response.
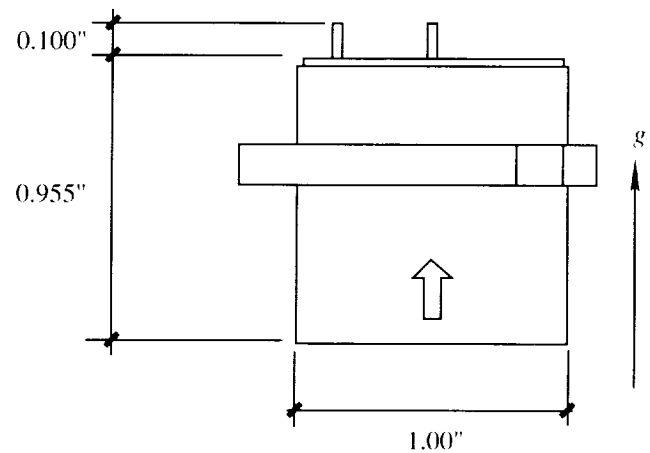
Sketch A

The evaluation involved an extensive series of tests on the tilt sensors. The series of tests measured the sensor sensitivity, linearity, repeatability, hysteresis, temperature characteristics, roll-on-pitch interaction, sensitivity to lead-wire resistance, step response, and rectification (variations in the direct-current (dc) level resulting from vibrations).

Physical Description of Electrolytic Tilt Sensor

The electrolytic tilt sensors selected for this study were manufactured by Spectron Glass and Electronics, Incorporated. (See ref. 2.) The mechanical and electrical schematics of the tilt sensors are shown in figure 2. The exterior of the sensor resembles the glass vial of a carpenter's level. The hermetically sealed glass vial has three electrodes and is partially filled with an electrically conductive fluid.

The tilt sensor functions like a liquid potentiometer. The electrically conductive fluid creates a variable resistance between the electrodes. When the sensor is in the null or balanced position, the resistances between the center electrode to each outside electrode are equal. Tilting the sensor from its balanced position changes the two resistances producing an electrical output proportional to the tilted angle. A complete list of the Spectron electrolytic tilt sensors tested is shown in table 1; included are their model numbers, serial numbers (SN), and manufacturer's specified measuring ranges.

Test Equipment

The test equipment used is briefly described in the following paragraphs.

Test Block

A 6- by 5- by 5/8-in. aluminum block was used for mounting the tilt sensors. Eight sensors were installed on the test block for simultaneous testing.

Signal Conditioner

The electrolytic tilt sensor requires external alternating-current (ac) excitation. A signal conditioner, shown in figure 3, contains the modulation, demodulation, and interface circuitry required to operate the tilt sensor (ref. 3). Eight signal conditioners were installed in an aluminum chassis used for this test.

Precision Angle Indexers

Two precision angle indexers were used to provide angular inputs to the tilt sensors. The fully automated indexer is a dual-axis dividing head (an 18-in. table for roll indexing and an 8-in. table for pitch indexing). This unit, mounted on a concrete block, can be seen on the left in figure 4. It provides integer angles in roll and pitch simultaneously with an accuracy of 1 arc second. The indexer, which is shown in figure 5, is a single-axis dividing head. It is driven by a stepper motor and a single-axis stepper-motor controller. This unit, with a precision rotary encoder attached to its main shaft to monitor the angle setting, provides fractional angular input with an accuracy of 1 arc second.

Data Acquisition System

The data acquisition system (DAS) consists of a scanner multimeter with an IEEE-488 parallel interface as the front end and an IBM-compatible personal computer (PC) as the master controller. A serial interface is used to communicate between the master controller and the stepper motor controller. The DAS subsystems are mounted in the instrumentation rack in figure 3. Data acquisition and instrument control software for the PC were written in BASIC language. A flowchart of this program is shown in figure 6.

Temperature Chamber

A temperature chamber, which is shown in figure 7, was used to house the sensors on the test block for temperature sensitivity testing. Automated temperature control of this test chamber was provided by a temperature controller. A digital thermometer was used to independently monitor the temperature of the test block.

Mechanical Shaker

A mechanical shaker with its associated electronics was used to perform the rectification test. Figure 8 is a photograph of the mechanical shaker.

Test Setup

The three test setups devised are briefly discussed as follows:

1. The linearity, repeatability, and step response time tests were conducted on the single-axis dividing head. The aluminum test block with eight tilt sensors was attached to the dividing head. Angle indexing was provided by the dividing head.

2. The dual-axis system provided angle indexing for both the temperature and the interaction effect of roll on pitch (referred to subsequently as the "roll-on-pitch interaction tests"). For the temperature test, the aluminum block was fastened to the end of an 18- by 5- by 1-in. steel extension plate and inserted inside the temperature chamber. The other end of the extension plate was fastened to the 8-in. dual-axis table. The 8-in. table provided angle indexing, and the temperature controller provided temperature regulation. For the roll-on-pitch interaction test, both the 8-in. and the the 18-in. tables were used.

3. The rectification test was performed on the mechanical shaker with its associated signal conditioning and recording devices.

Test Procedures

The evaluation procedures involved seven tests designed to investigate pertinent characteristics of the tilt sensors. The procedures and objectives are summarized as follows:

Linearity Test

A preliminary investigation indicated that the sensors are more linear within the measuring range of $-5°$ to $5°$. The linearity test was thus carried out on this range only. This test was conducted on the single-axis dividing head at room temperature. The head was commanded to index from the $-5°$ position to the $5°$ position and then back to the $-5°$ position in $0.1°$ increments. At each increment, the sensors were allowed to settle for 1 minute before the output voltages were recorded. This test determined both the linearity and the hysteresis of the sensors.

Repeatability Test

The repeatability test was accomplished by repeating a linearity test six times over 72 hours at $110°F$. This test is important in determining the stabilities of the sensors in terms of their sensitivities and biases.

Temperature Sensitivity Test

This test was performed on the 8-in. table of the dual-axis system with the test block inserted in

the temperature chamber. Chamber temperature set points used were 73°F, 90°F, 100°F, 110°F, 140°F, and 160°F. At each temperature set point, a linearity test was conducted at angle increments of 1° to obtain the sensitivities at that temperature. The sensors were then repositioned on the extension bracket by turning them 180° in the yaw plane. Another linearity test was then conducted at the same temperature. This procedure was needed to cancel out the misalignment resulting from the extension bracket to obtain the true biases of the sensors. The objective of this test was to correlate temperature to both the sensitivities and biases of the sensors.

Roll-on-Pitch Interaction Test

Since the tilt sensor contains moving fluid, a slight roll motion will affect its performance. In this test, the test block with the eight sensors was placed on the 8-in. table. Roll input was introduced by setting the 18-in. table at 5°, -3°, 1°, 1°, 3°, and 5° positions. At each of these settings, the 8-in. table was commanded to provide -4°, 0°, and 4° in pitch. To obtain the true biases of the sensors at those roll angles at every 0° pitch angle set point, the sensors were again repositioned on the 8-in. table by turning them 180° in the yaw plane. With this procedure, the outputs of the sensors then indicated the roll-on-pitch interactions.

Lead-Wire Sensitivity Test

As mentioned in the "Introduction," the tilt sensors are liquid potentiometers. Therefore, their sensitivities and biases are also functions of the resistance of the lead wires. For wind tunnel applications, the resistance of the lead wires is more significant because the wires can be up to 300 ft in length. In addition, portions of the lead wires may be exposed to different temperatures that would cause their resistances to vary. The objective of this test was to find out how much the sensitivities of the sensors would be affected. In this test, a 10-ohm resistor (which corresponds to 600 ft of No. 22 lead wire) in parallel with a switch is inserted between the sensor and the signal conditioner. A schematic drawing of this wiring is shown in sketch B. Using the on/off switch settings on the resistors at each angle position (-4°, 0°, or 4°), the changes in the sensitivities and biases of the sensors were investigated.

Step Response Test

For this test, the dividing head was used. The table was stepped from the 0° position to the 1° position in 42 msec. The time response, or the output voltage versus time, of each sensor was recorded for 5 minutes. This procedure established the sensor response time to a sudden change in the tilt level.

Sketch B
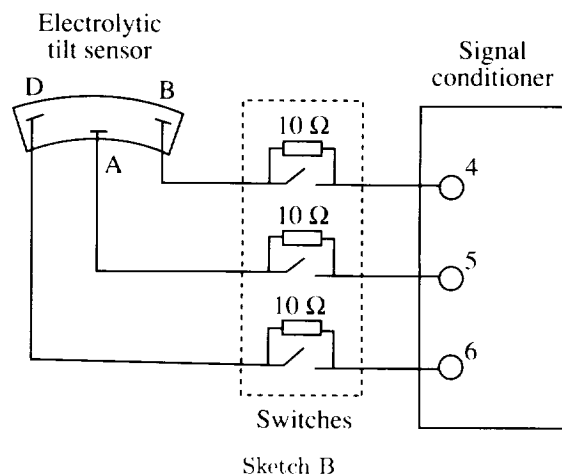
Rectification Test

Since vibration is always present in the wind tunnel test environment, it is necessary to conduct a rectification test to investigate the projected performance of the sensors in a wind tunnel. A rectification test measures the dc response of a sensor when it is subjected to vibrations. In this series of tests, each sensor was mounted on the mechanical shaker at fixed tilt levels of 5°, 0°, and 5°. Random frequencies from 20 to 5000 Hz for all three orthogonal axes (longitudinal, lateral, and vertical) were then applied at a root-mean-square (rms) magnitude of $1g$, $2g$, or $3g$ (where $1g \approx 32.174$ ft/sec^2) for a duration of 40 sec each. Conducting this testing at different g levels and tilt levels is necessary to identify any observable pattern from the results. The dc biases of each sensor were recorded before, during, and after each test.

Results and Discussion

The results of this evaluation are summarized in table 1 and are presented in figures 9 to 45. Some observations from the results are discussed in the following paragraphs.

Linearity Test

The linearity test results summarized in table 1 are expressed in terms of maximum error, 1σ standard deviation of the error, and maximum hysteresis. Sensor errors presented in figures 9 to 16 are the differences between the input angles and the predicted angles computed from a third-order regression on the sensor output data. These errors will be referred to as the "3rd-order errors" for the rest of this report.

Sensor serial number (SN) 563 had the largest maximum 3rd-order error of 0.088° and the largest 1σ error of 0.030°. Sensor SN 266 had the smallest

maximum 3rd-order error of 0.007° and the smallest 1σ error of 0.003°. For hysteresis error, sensor SN 546 had the highest error of 0.021° and sensor SN 266 had the smallest error of 0.003°.

This set of tests will be referred to as the "baseline test" for the rest of this report.

Repeatability Test

In the repeatability test, linearity tests were conducted six times over 72 hours. The temperature was set at 110°F during the test to ensure that the results were not affected by temperature changes. The repeatability errors, which are expressed in terms of sensitivity (sens.) shifts and bias shifts, are found in figures 16 to 21. The maximum sensitivity shifts and bias shifts are also summarized in table 1. Sensor SN 546 had the highest maximum sensitivity shift of 0.09 percent, and SN 268 had the lowest maximum sensitivity shift of 0.01 percent. In terms of bias shift, SN 3007 was the highest with a value of 0.004°, and SN 268 was the lowest with a value of 0.002°.

Temperature Sensitivity Test

The results of the temperature sensitivity test are also shown in table 1 and figures 23 to 28. Table 1 lists both the temperature coefficients of the sensitivities and the biases of the sensors.

It is clear from these figures that both the sensor sensitivities and biases vary with temperature. The sensitivities were found to vary linearly with temperature. For the sensors under evaluation, SN 3007 had the highest maximum sensitivity shift of 0.15 percent/°F, and SN 264 had the lowest maximum sensitivity shift of 0.03 percent/°F. For bias shift, SN 3009 was the highest with a value of 0.004 deg/°F, and SN 268 was the lowest with a value of less than 0.001 deg/°F.

Roll-on-Pitch Interaction Test

The sensitivities and the biases of the sensors at various roll angles are shown in figures 29 to 34 and are summarized in table 1.

The results indicate that both the sensitivities and the biases varied with the roll angle. Sensor SN 563 was the most sensitive to roll with a maximum sensitivity shift of 0.19 percent/deg roll. The least sensitive was SN 268, which had a maximum sensitivity shift of 0.03 percent/deg roll. The biases listed in the table, which represent the maximum values measured for the entire interaction test for each of the sensors, are less than 0.002°.

Lead-Wire Sensitivity Test

The results of the lead-wire resistance sensitivity test are summarized in table 1. The results indicate

that sensor SN 563 had the highest sensitivity shift of 0.49 percent, and SN 3007 was the least sensitive with a sensitivity shift of 0.09 percent. The change in sensitivity was caused by the increase in impedance on the overall bridge circuit resulting from the increased wire resistance. Bias shifts in this test were found to be negligible.

Step Response Test

Table 1 also lists the length of the response times that the sensors took to reach 99 and 99.9 percent of their final values from the step response test. A typical 1° step response of SN 264 is shown in figure 35 at room temperature and in figure 36 at 160°F. It can be seen that increasing the sensor temperature can reduce the response time. The 99-percent response time corresponds to the time required for the sensor to reach within 0.01° of the 1° input angle. SN 3007 had the fastest response time of 10 sec, and SN 540 had the slowest response time of 120 sec. The 99.9-percent response time is included as an indication of the settling time of the sensor. The slow settling time is caused by the slow movement of the electrolytic fluid dripping away from the inner wall of the vial as the sensor is tilted.

Rectification Test

Rectification test results are also summarized in table 1 and are shown in figures 37 to 45. The dc biases are the differences between the dc bias shifts during and after the tests. In general, there are no predictable patterns and the dc bias shifts at level position are less than 0.01°.

Performance Comparisons of Tilt Sensors and Servo Accelerometers

Comparisons are made that relate the performance of each model of electrolytic tilt sensor to that of a typical angle-of-attack servo accelerometer. Table 2 lists the average errors of each model in the categories of comparison. For each model, the rms sum of these average errors is compared with that of the servo accelerometer. The data of the servo accelerometer are obtained by averaging the acceptance test data of the servo accelerometers used in angle-of-attack measurements at Langley. In addition, the costs of both the tilt sensors and the servo accelerometer are compared. The cost of the tilt sensors listed in table 2 includes the signal conditioning unit which converts the sensor to a dc unit similar to that of the servo accelerometer.

For ease in comparisons, the errors in temperature sensitivity, roll sensitivity, wire-resistance sensitivity, step response time, and rectification are represented in degrees. Since the sensors are expected

to be used in wind tunnels, these comparisons are based on the possible errors that the sensors may experience in most wind tunnel environments. The temperature error is the error resulting from a 40°F change in temperature when the sensor is tilted 5° about its sensitive axis. The roll error represents the error occurring when the sensor measures a 5° pitch and simultaneously undergoes a 1° roll. The wire-resistance error is the maximum error when the wire resistance increases by 5 ohms, which is approximately 300 ft of No. 22 cable. The response time error is the difference between the steady-state reading and the reading at 5 sec when a step input is applied to the sensor. Five sec is the typical delay time for most wind tunnel data acquisitions. The rectification error represents the maximum rms bias shift of the three axes combined during the random rectification test at $3g$ rms at level position.

Table 2 shows that the performance of the electrolytic sensors is more than one order of magnitude worse than that of the servo accelerometers. However, their costs are less than one-third the cost of the servo accelerometers.

Concluding Remarks

The results of this evaluation indicate that the performance of the electrolytic tilt sensors is inferior to that of a typical servo accelerometer used at the Langley Research Center. One undesirable aspect of the tilt sensors is their slow response time. Also, unlike the servo accelerometers, measurements are provided by the moving electrolytic fluid within the sensors that makes upside-down measurements

impossible. Measurements provided by moving electrolytic fluid also limit the sensor measuring ranges, and they become sensitive to roll interaction. These disadvantages rule out the possibility for the tilt sensors to be used as a viable alternative for making precision angle-of-attack measurements in wind tunnel testing.

The sensors do, however, have the potential for other applications where stringent performance requirements are not needed. One example is in making wind tunnel wall-attitude measurements. In this application, the response time is not as critical as in angle-of-attack measurements because of the slow movement of the wind tunnel walls. Thermal control can be used to minimize the temperature effects on sensitivity and bias. The error due to roll interaction is negligible if the level of roll is within 1°. The problem that may be encountered in this application is the vibration generated by the wind tunnel. The random rectification test results indicate that the sensors are sensitive to vibration and lack a predictable pattern.

References

1. *Q-Flex^R Accelerometers Instruction Manual.* Sundstrand Data Control, Inc.

2. *Electrolytic Level Sensors.* Spectron Glass and Electronics, Inc.

3. *Universal Signal Conditioner MUPI-2.* Spectron Glass and Electronics, Inc.

Table 1. Evaluation Results of Tilt Sensors

Error source	Variable	Sensor model CG-50 for ±7° range for SN—			Sensor model CG-57 for ±12° range for SN—		Sensor model RG-37 for ±10° range for SN—		
		540	546	563	3007	3009	268	264	266
Linearity	Sensitivity, V/deg[a]	0.599	0.623	0.612	0.365	0.335	0.328	0.319	0.320
	Max. error, deg[b]	0.048	0.050	0.088	0.032	0.032	0.009	0.011	0.007
	1σ std. deviation, deg	0.015	0.015	0.030	0.011	0.012	0.004	0.003	0.003
Hysteresis, deg		0.015	0.021	0.008	0.012	0.014	0.013	0.006	0.003
Repeatability	Max. sens. shift over 3 days, percent	0.05	0.09	0.07	0.07	0.07	0.03	0.04	0.06
	Max. bias shift over 3 days, deg	0.003	0.003	0.003	0.004	0.001	0.002	0.002	0.002
Temperature coefficients	Max. sens. shift, °F[c]	0.08	0.08	0.09	0.15	0.12	0.03	0.03	0.03
	Max. bias shift, deg/°F	0.000	0.000	0.000	0.001	0.004	0.000	0.000	0.000
Roll-on-pitch interaction	Max. sens. shift, percent/deg roll	0.16	0.07	0.19	0.13	0.05	0.03	0.07	(d)
	Max. bias shift, deg/deg roll	0.002	0.001	0.001	0.002	0.002	0.001	0.001	(d)
Wire-resistance sensitivity shift, percent		0.78	0.59	0.76	0.25	0.34	1.06	1.19	1.23
Response time	At 99 percent, sec	120	80	80	10	20	60	50	55
	At 99.9 percent, sec	230	250	170	125	125	180	230	150

Table 1. Concluded

Error source		Variable		Sensor model CG-50 for ±7° range for SN			Sensor model CG-57 for ±12° range for SN−		Sensor model RG-37 for ±10° range for SN		
				540	546	563	3007	3009	268	264	266
Random rectification result	0° offset	3g rms	X-axis	0.008	0.010	0.005	0.003	0.001	0.001	0.002	0.001
			Y-axis	0.005	0.010	0.008	0.003	0.003	0.013	0.010	0.010
			Z-axis	0.000	0.000	0.010	0.003	0.008	0.008	0.007	0.003
		2g rms	X-axis	0.000	0.005	0.003	0.001	0.000	0.000	0.000	0.000
			Y-axis	0.003	0.002	0.005	0.000	0.001	0.005	0.005	0.003
			Z-axis	0.001	0.000	0.005	0.001	0.000	0.005	0.005	0.003
		1g rms	X-axis	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.001
			Y-axis	0.001	0.000	0.000	0.001	0.001	0.001	0.000	0.001
			Z-axis	0.000	0.000	0.003	0.000	0.000	0.001	0.001	0.000
	5° offset	3g rms	X-axis	0.020	0.042	0.043	0.003	0.008	0.001	0.022	0.000
			Y-axis	0.008	0.000	0.000	0.015	0.008	0.029	0.046	0.001
			Z-axis	0.005	0.005	0.005	0.003	0.001	0.005	0.007	0.001
		2g rms	X-axis	0.008	0.012	0.003	0.001	0.001	0.001	0.001	0.001
			Y-axis	0.000	0.001	0.008	0.005	0.010	0.026	0.029	0.005
			Z-axis	0.000	0.001	0.003	0.003	0.001	0.003	0.015	0.000
		1g rms	X-axis	0.000	0.000	0.001	0.000	0.002	0.000	0.000	0.000
			Y-axis	0.000	0.001	0.003	0.008	0.015	0.011	0.005	0.005
			Z-axis	0.001	0.000	0.000	0.000	0.003	0.005	0.000	0.005
	5° offset	3g rms	X-axis	0.025	0.012	0.003	0.003	0.005	0.001	0.007	0.003
			Y-axis	0.000	0.002	0.001	0.018	0.001	0.013	0.017	0.015
			Z-axis	0.001	0.007	0.008	0.010	0.001	0.005	0.007	0.005
		2g rms	X-axis	0.003	0.001	0.003	0.001	0.003	0.001	0.000	0.005
			Y-axis	0.005	0.010	0.005	0.005	0.005	0.029	0.002	0.003
			Z-axis	0.003	0.002	0.003	0.000	0.005	0.005	0.000	0.005
		1g rms	X-axis	0.003	0.001	0.001	0.002	0.000	0.001	0.000	0.003
			Y-axis	0.001	0.001	0.001	0.003	0.003	0.011	0.000	0.003
			Z-axis	0.003	0.002	0.002	0.001	0.001	0.003	0.001	0.003

[a] Gains of the signal conditioning units are standardized.

[b] Linearity error is the deviation from a 3rd-order fit of a calibration from 5° to 5°.

[c] Computed with respect to the baseline sensitivity.

[d] Not applicable.

Table 2. Comparison of Average Error of Tilt Sensors
With That of Typical Servo Accelerometer

[All values are given in degrees]

Error source	Typical servo accelerometer	Electrolytic tilt sensors being evaluated		
		CG-50	CG-57	RG-37
Linearity	0.001	0.062	0.032	0.009
Hysteresis	0.001	0.015	0.013	0.007
Repeatability	0.003	0.007	0.006	0.004
Temperature sensitivity	0.004	0.167	0.370	0.060
Roll sensitivity	Negligible	0.008	0.007	0.004
Wire-resistance sensitivity	Negligible	0.011	0.003	0.010
Step response time	0.001	0.187	0.016	0.047
Rectification	0.005	0.012	0.006	0.013
rms of averages	0.007	0.259	0.372	0.079
Cost[a]	$2000.00	$600.00	$600.00	$600.00

[a]The costs of the tilt sensors involve converting the units to dc devices comparable to those of the servo accelerometer.
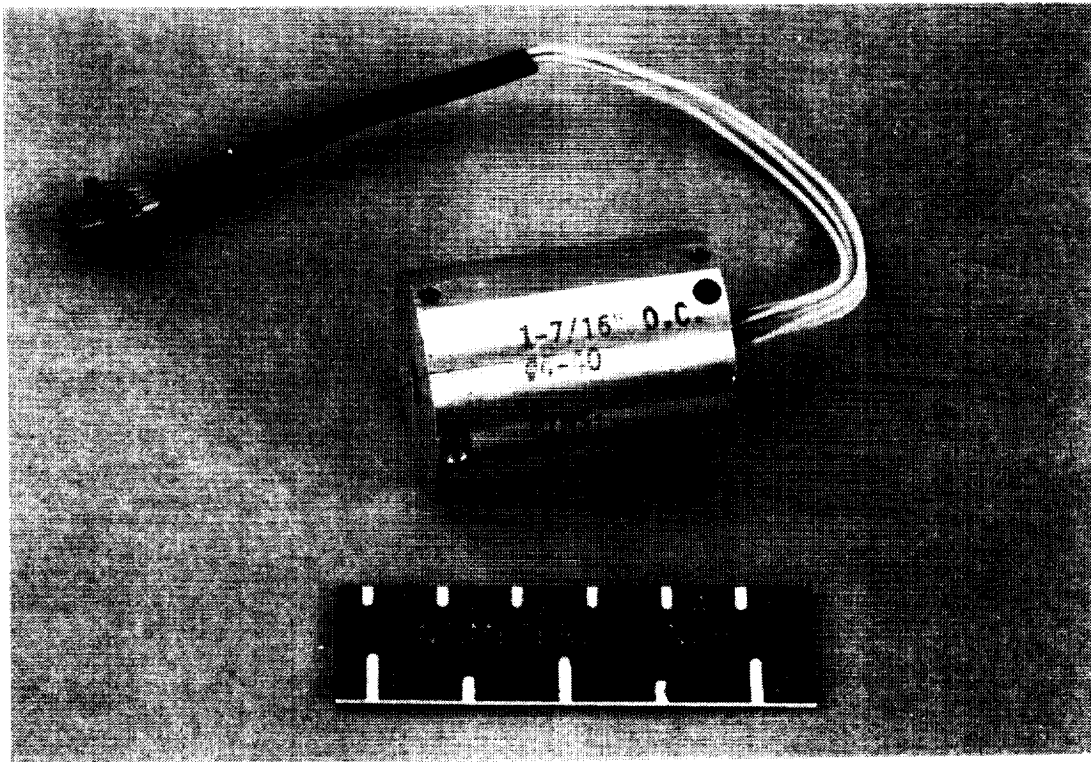
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(a) Entire servo accelerometer package.
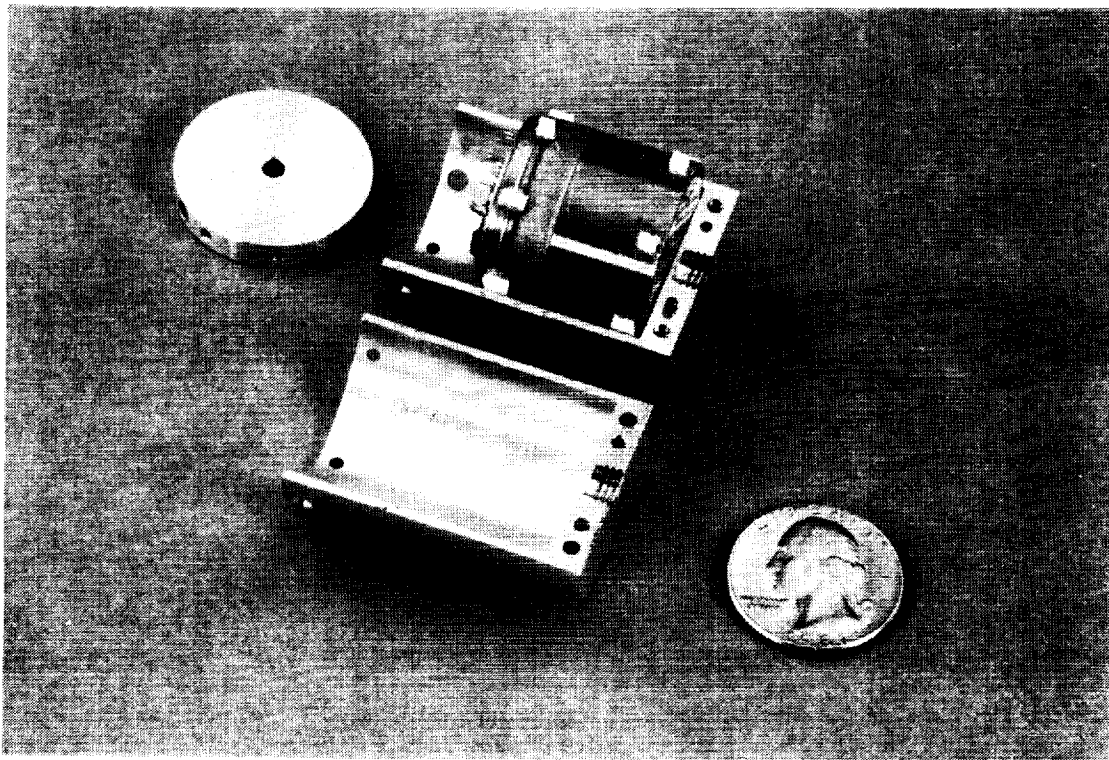
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(b) Disassembled servo accelerometer package.

Figure 1. Servo accelerometer package used at Langley.
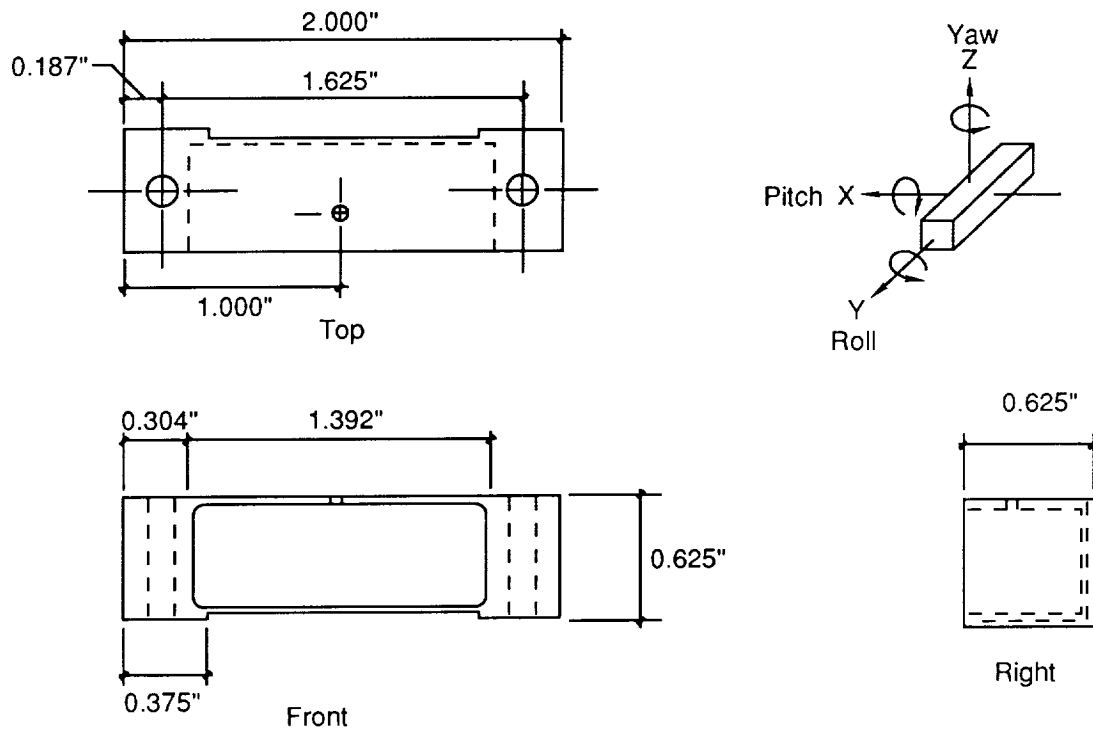
(a) Housing of electrolytic tilt sensor.
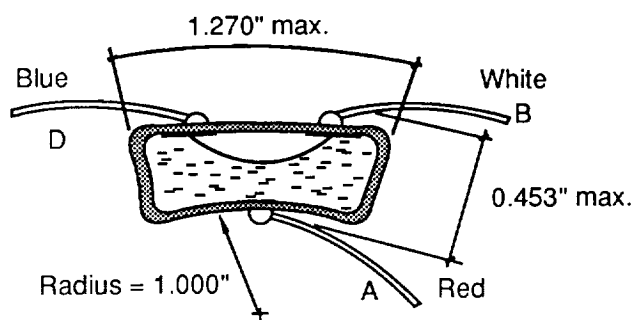
(b) RG-37 electrolytic tilt sensor.
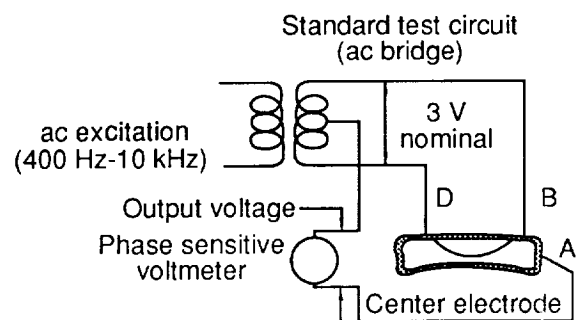
(c) Electrical schematic drawing.

Figure 2. Spectron electrolytic tilt sensor.
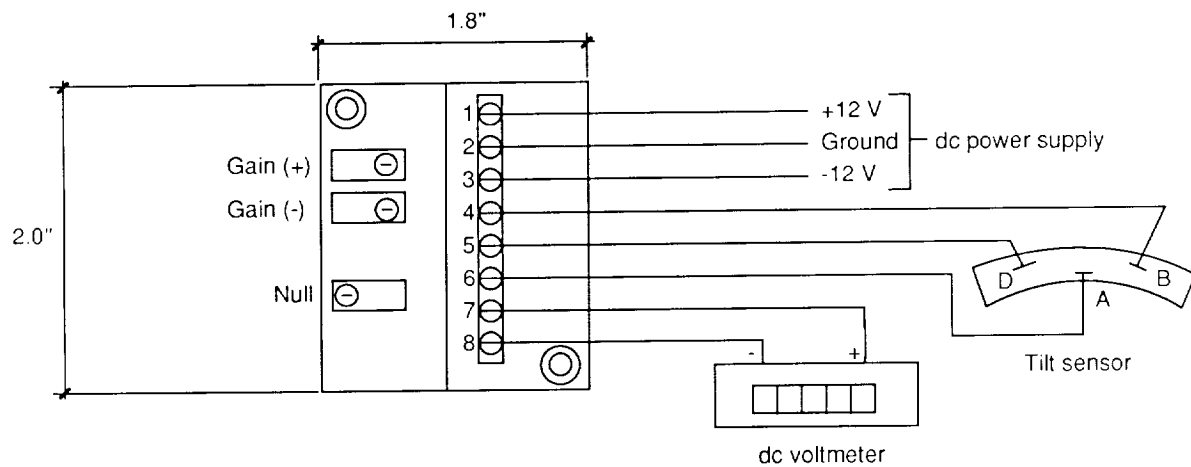
Figure 3. Signal conditioning module.
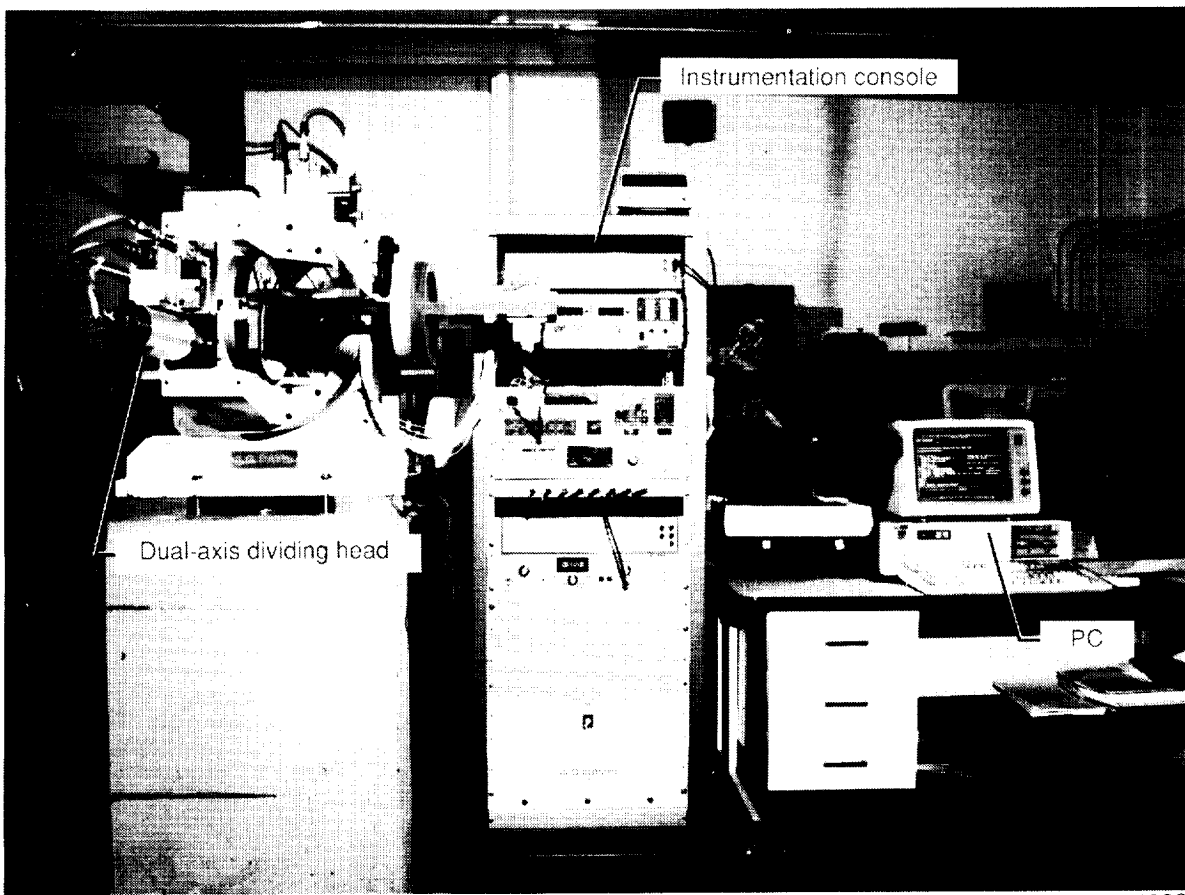
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Figure 4. Test equipment.

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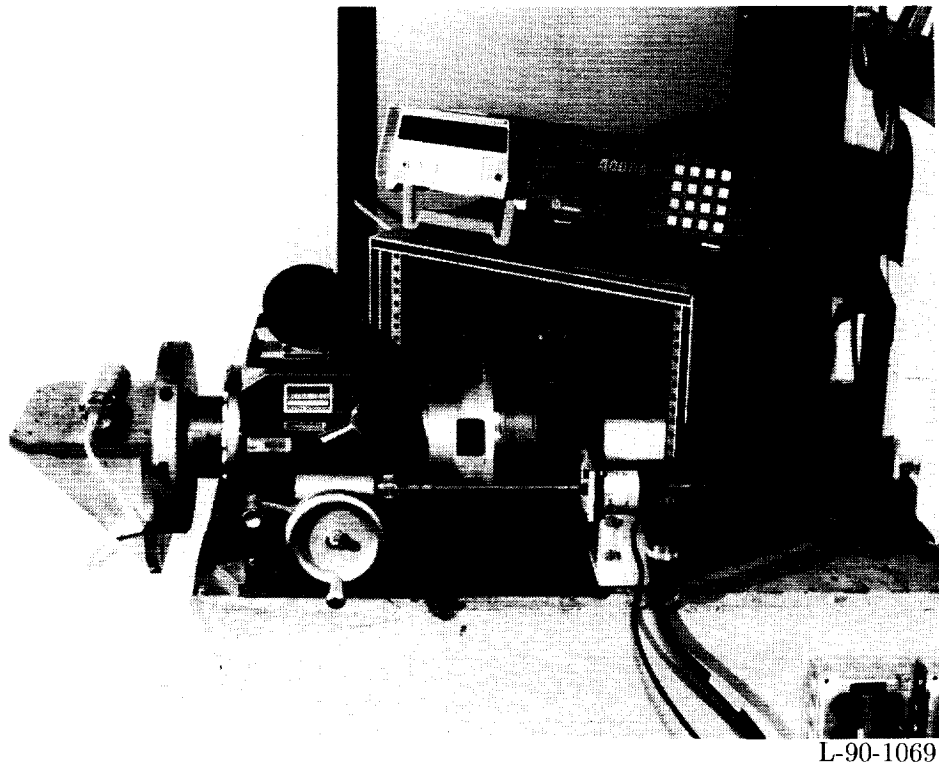
Figure 5. Single-axis dividing head.
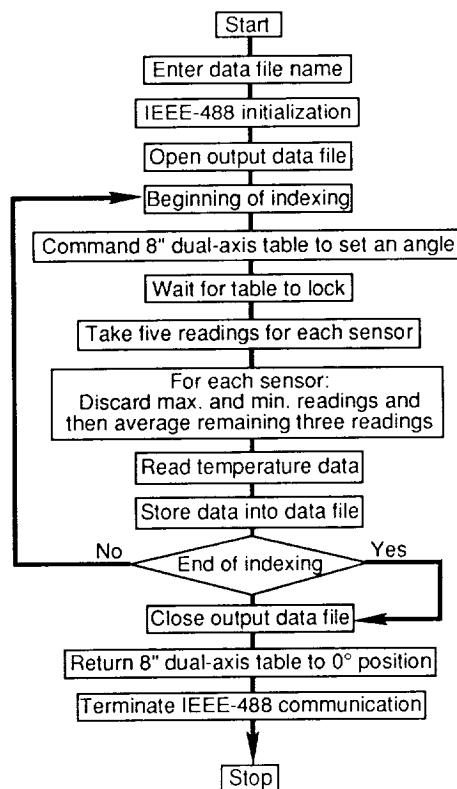
Figure 6. Flowchart of software data acquisition and control.
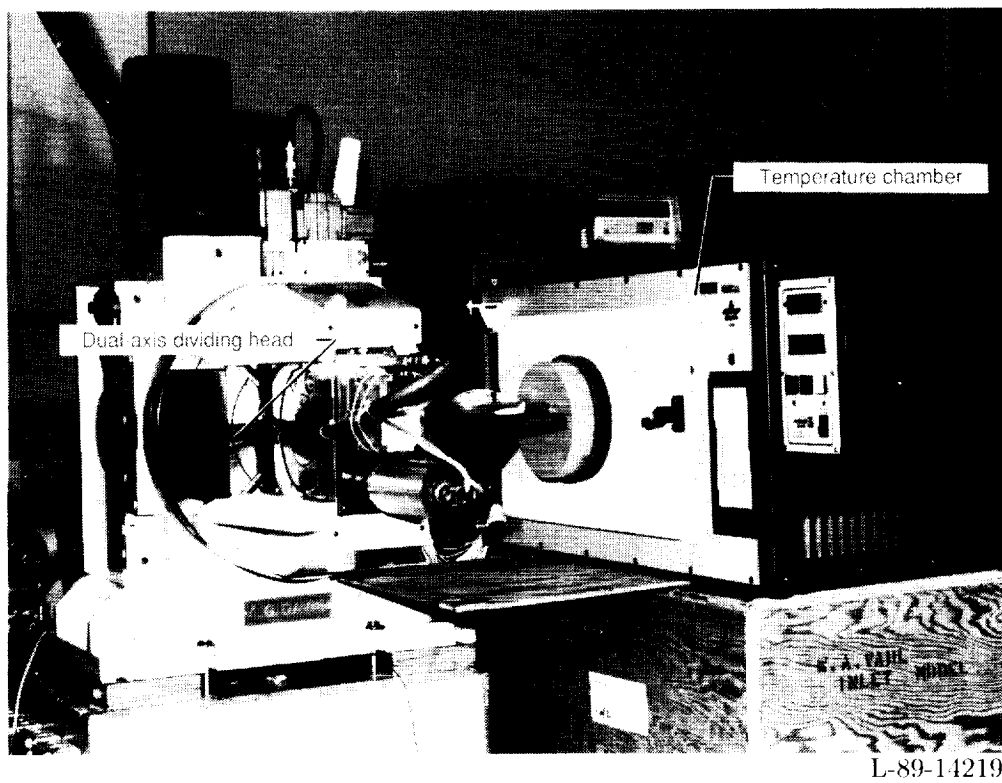
Figure 7. Temperature sensitivity test equipment.
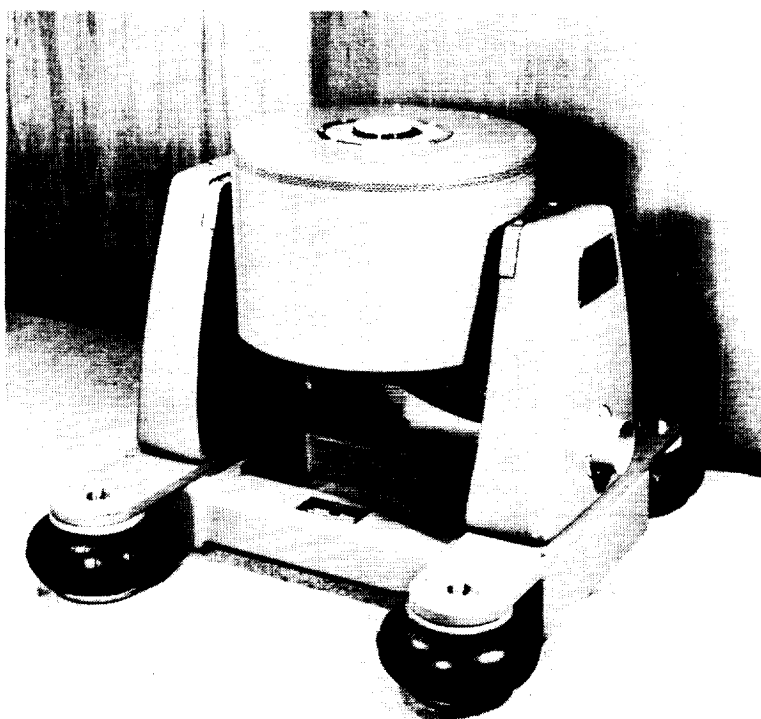
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Figure 8. Mechanical shaker.
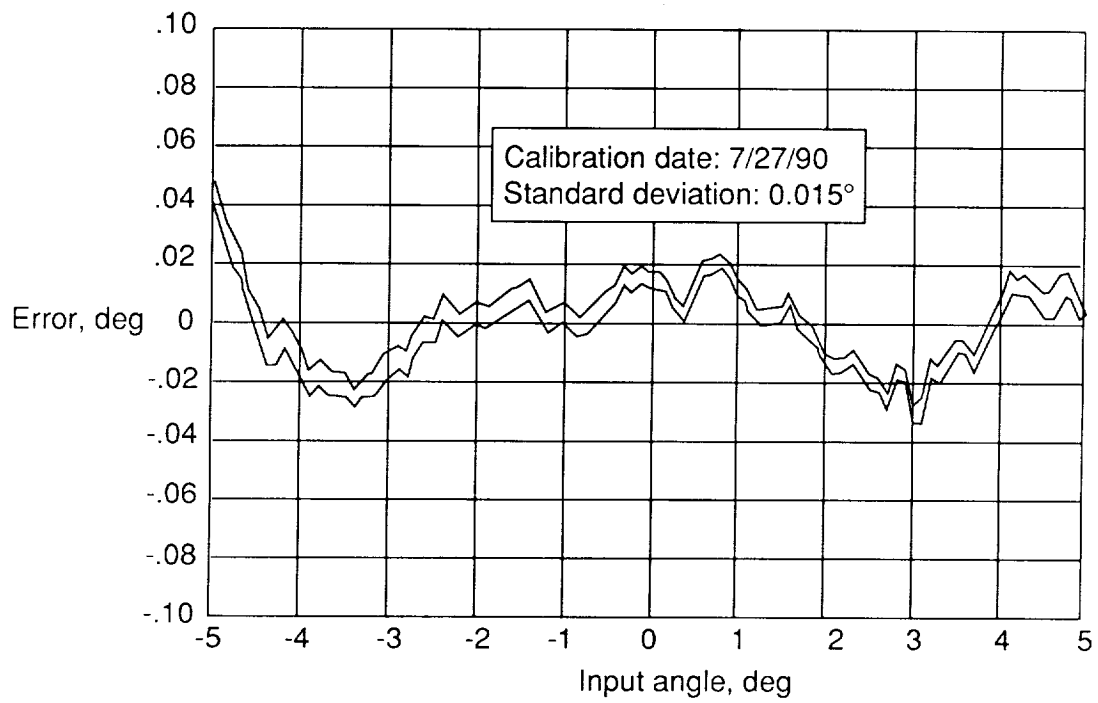
Figure 9. Deviation of tilt sensor SN 540 from 3rd-order fit at 73°F.
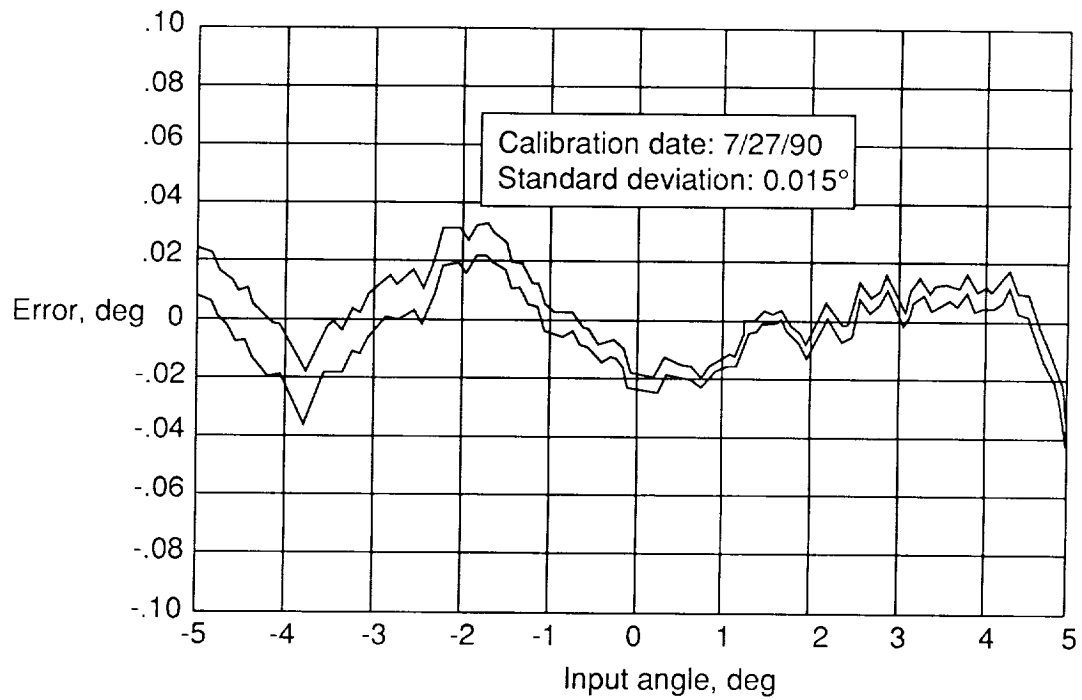
Figure 10. Deviation of tilt sensor SN 546 from 3rd-order fit at 73°F.

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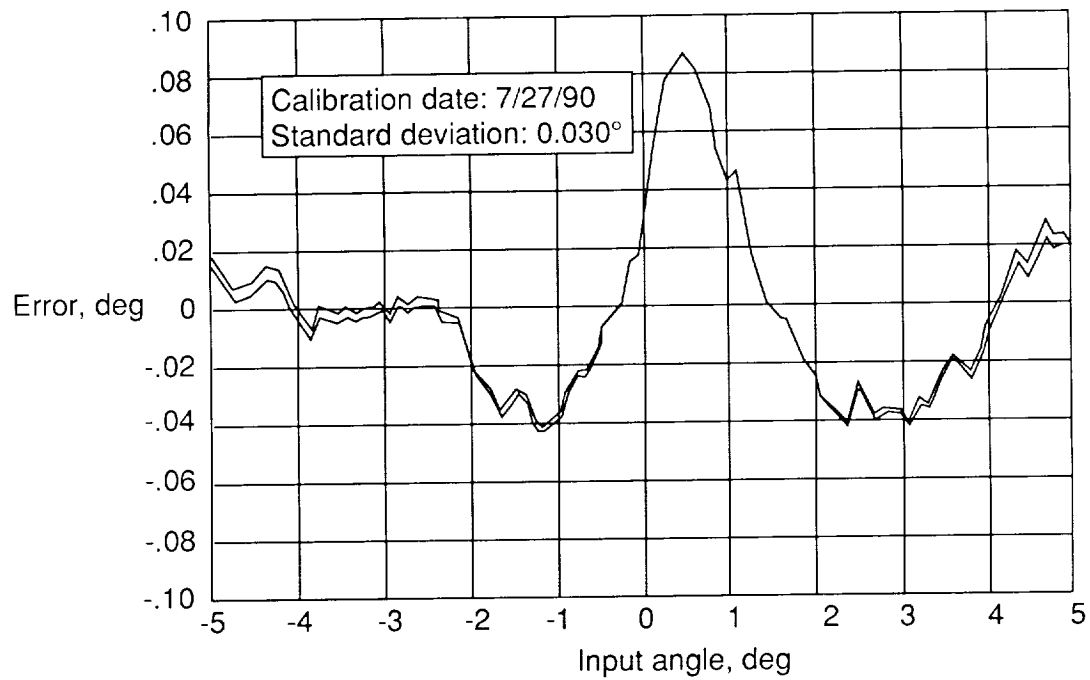
Figure 11. Deviation of tilt sensor SN 563 from 3rd-order fit at 73°F.
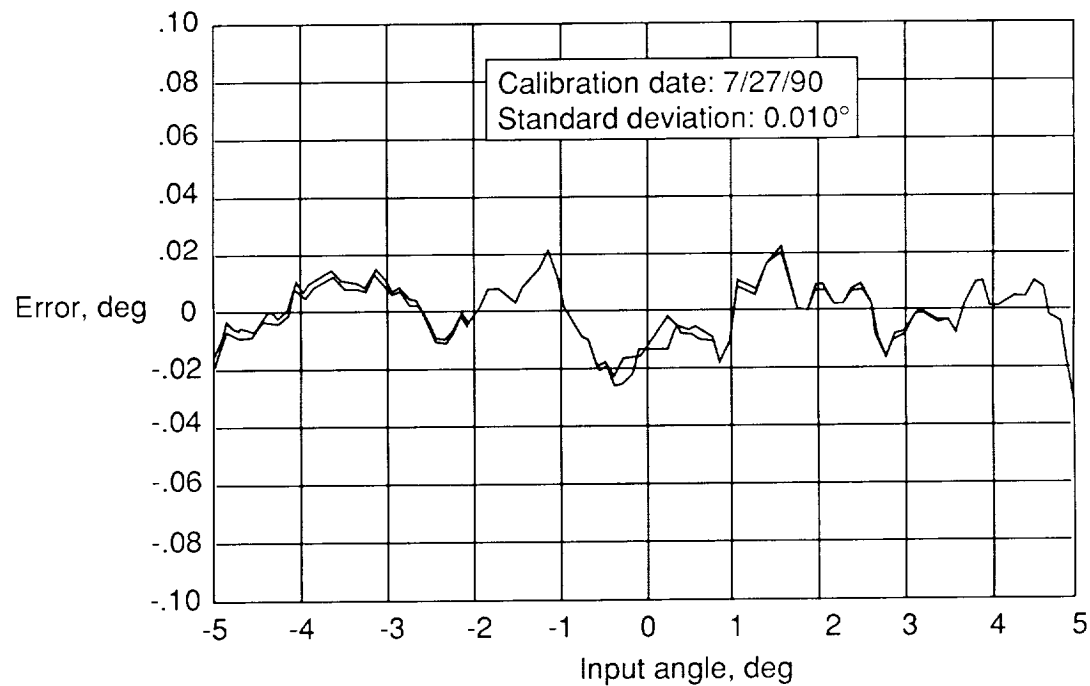
Figure 12. Deviation of tilt sensor SN 3007 from 3rd-order fit at 73°F.
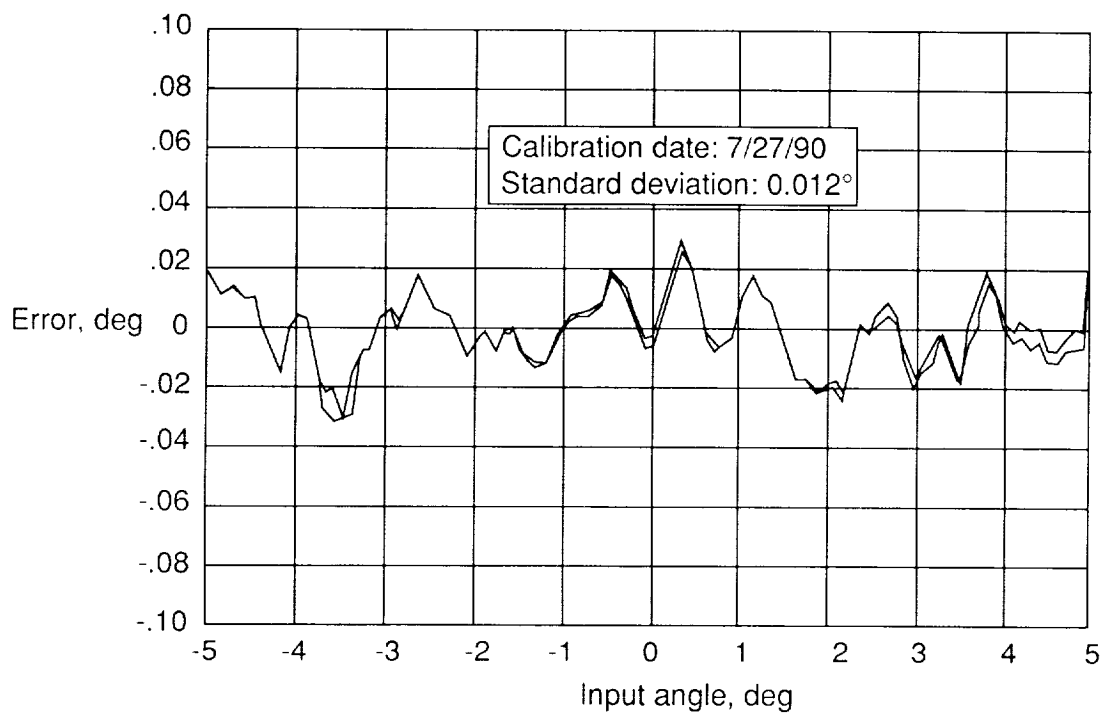
Figure 13. Deviation of tilt sensor SN 3009 from 3rd-order fit at 73°F.
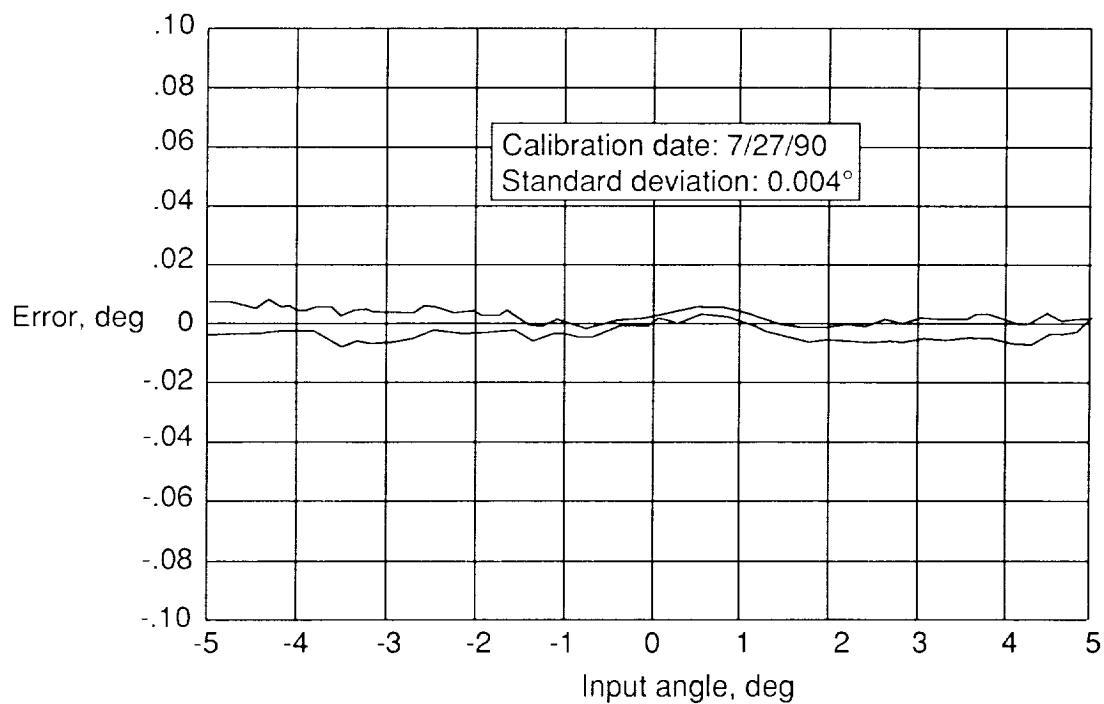
Figure 14. Deviation of tilt sensor SN 268 from 3rd-order fit at 73°F.
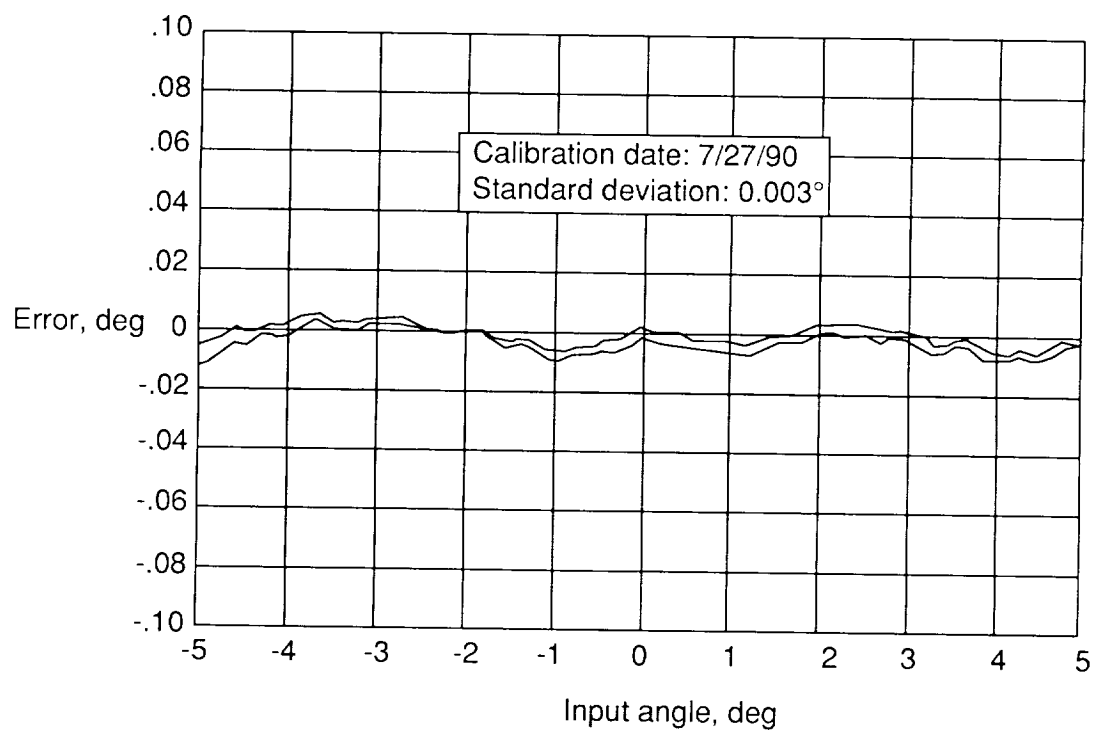
Figure 15. Deviation of tilt sensor SN 264 from 3rd-order fit at 73°F.
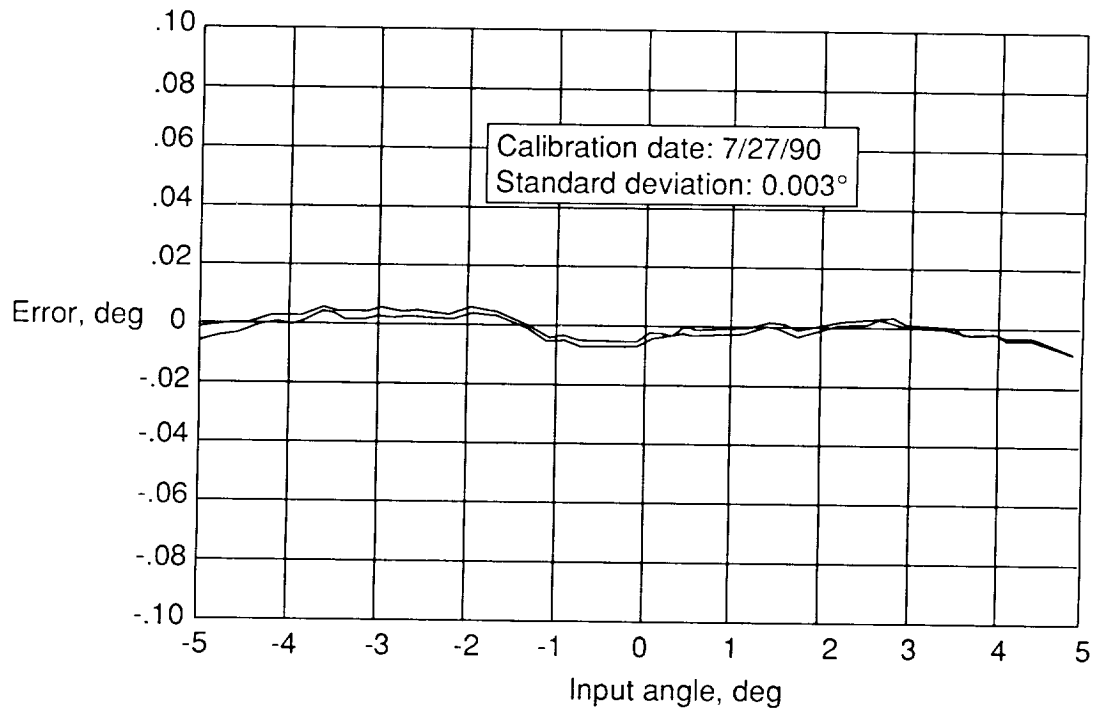
Figure 16. Deviation of tilt sensor SN 266 from 3rd-order fit at 73°F.
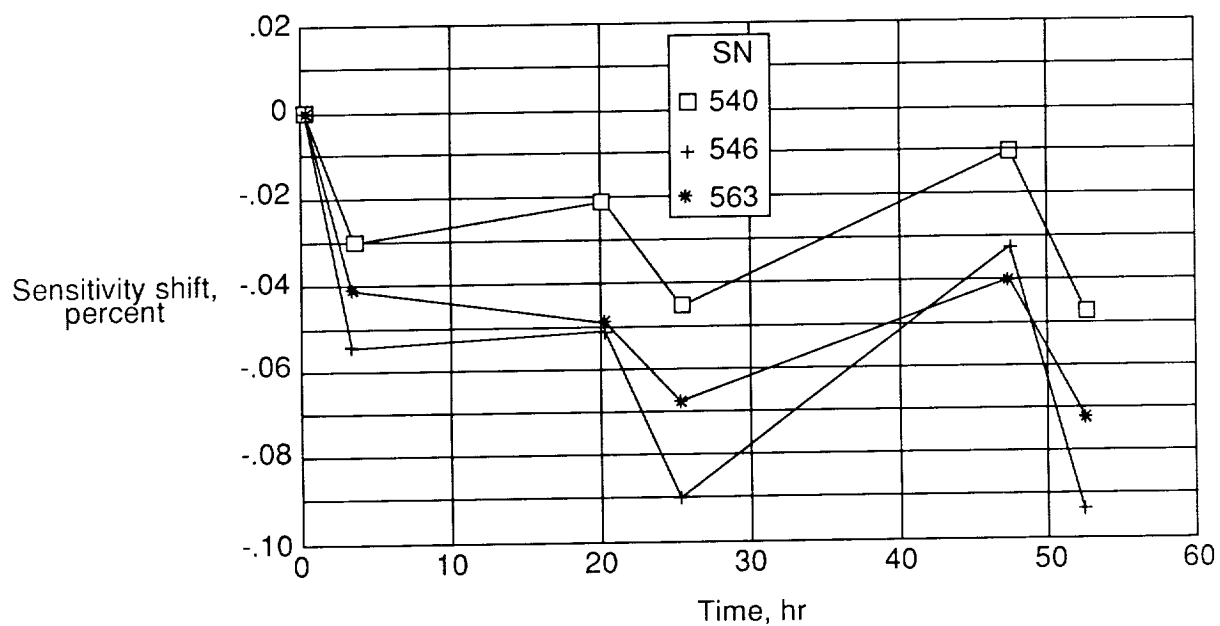
Figure 17. Sensitivity repeatabilities of tilt sensor model CG-50 at 110°F.
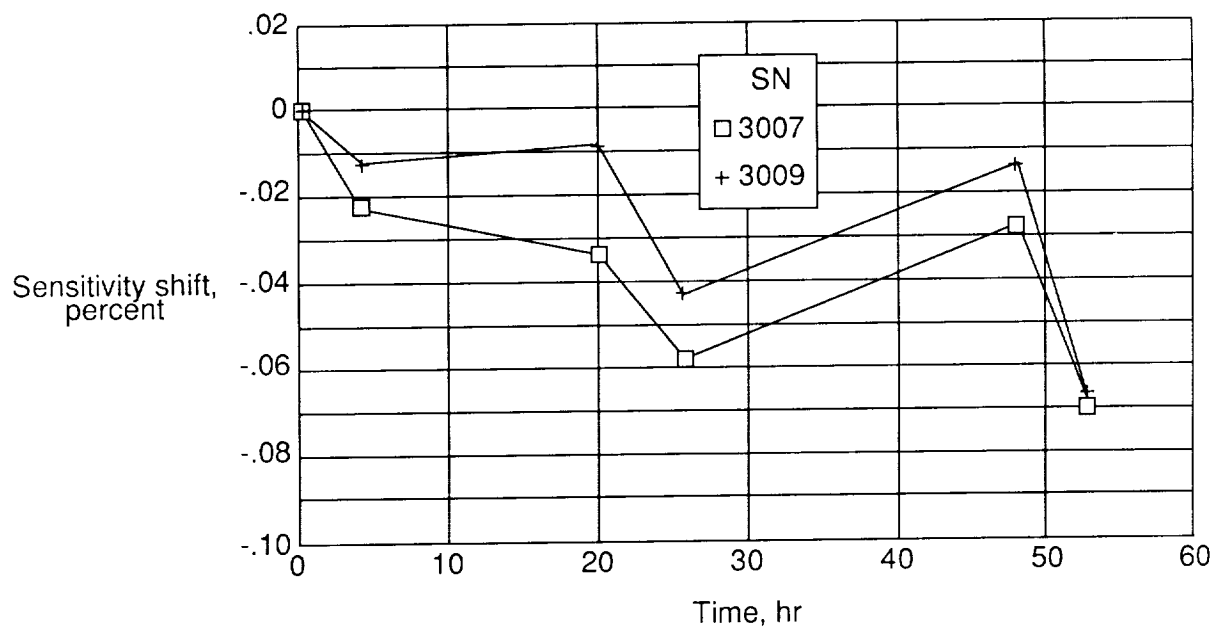
Figure 18. Sensitivity repeatabilities of tilt sensor model CG-57 at 110°F.
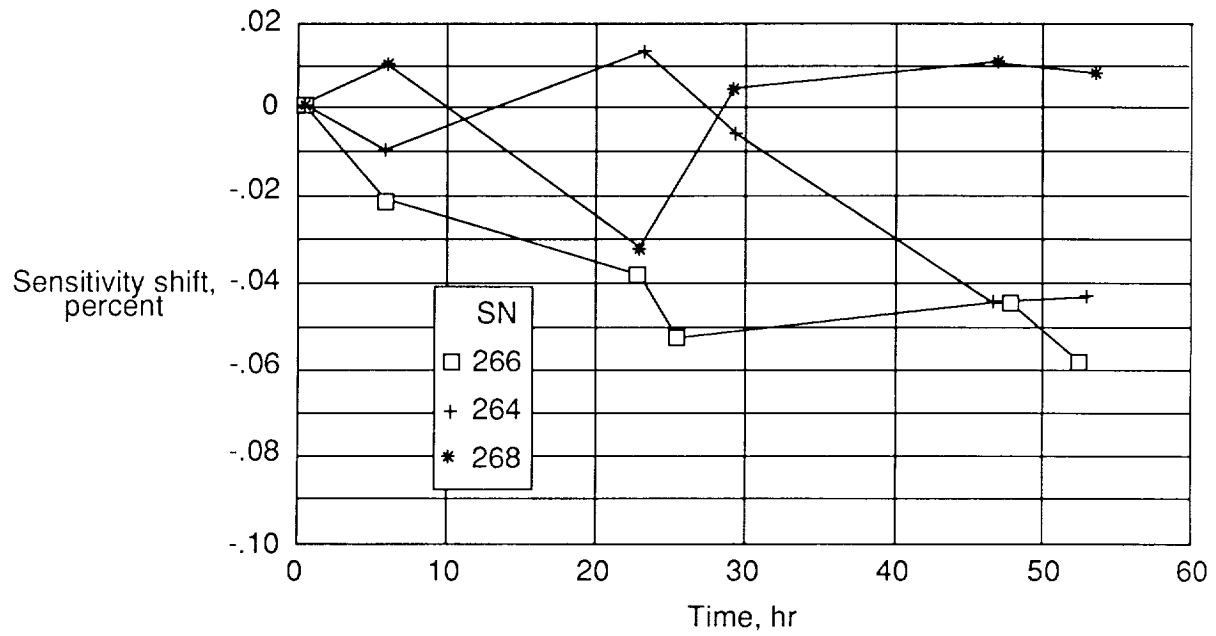
Figure 19. Sensitivity repeatabilities of tilt sensor model RG-37 at 110°F.
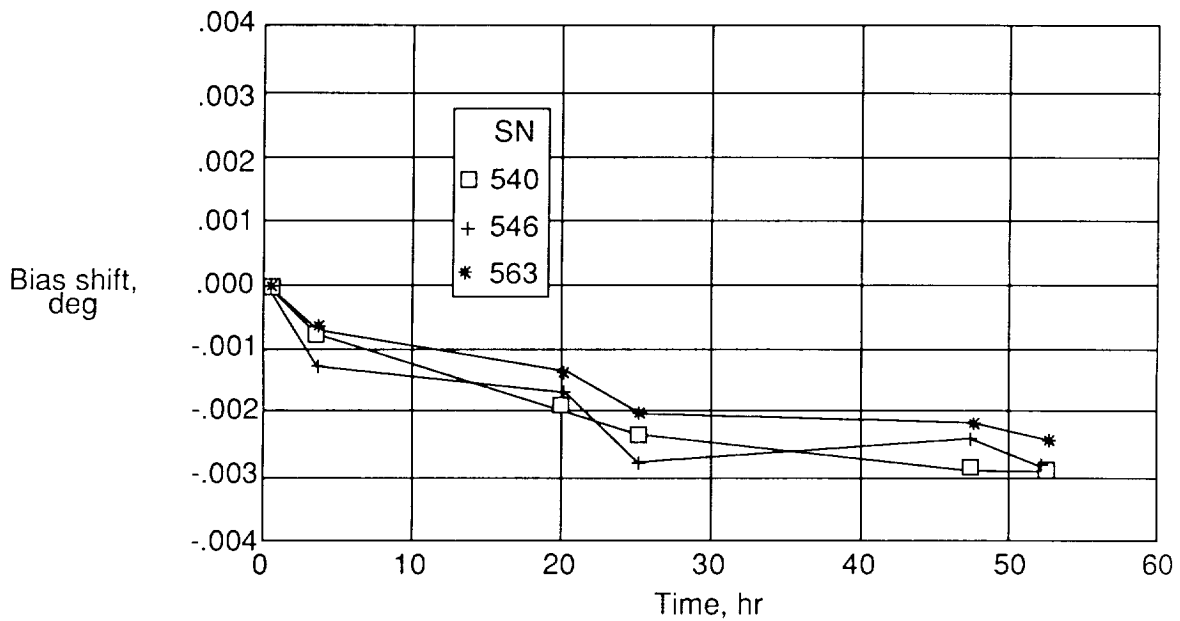
Figure 20. Bias repeatabilities of tilt sensor model CG-50 at 110°F.
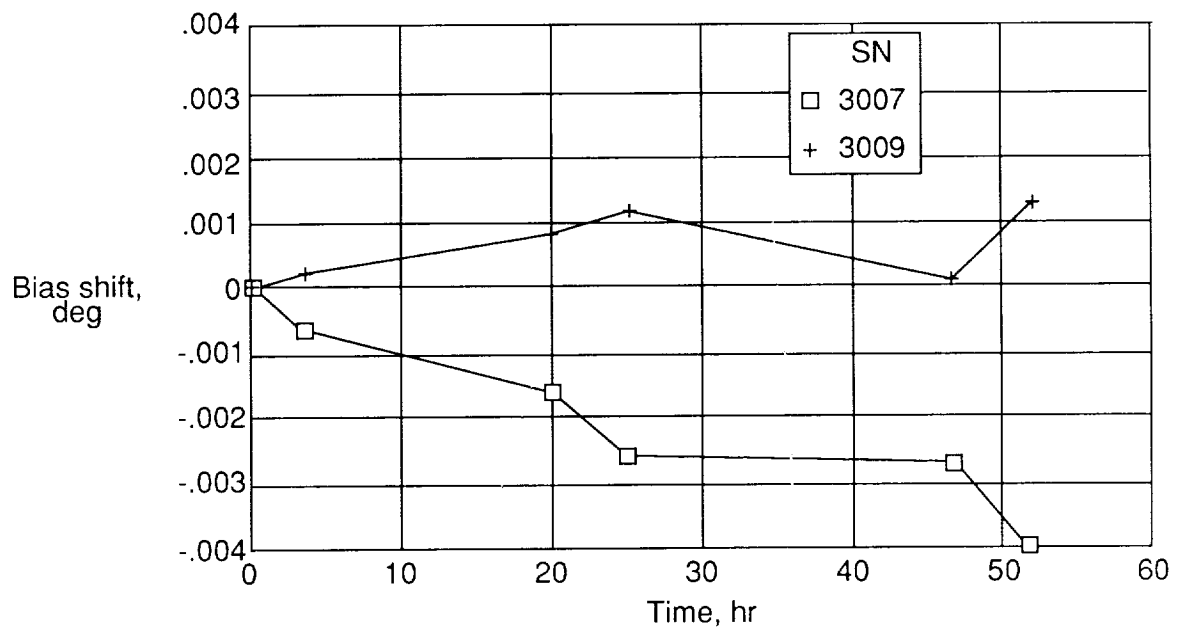
Figure 21. Bias repeatabilities of tilt sensor model CG-57 at 110°F.
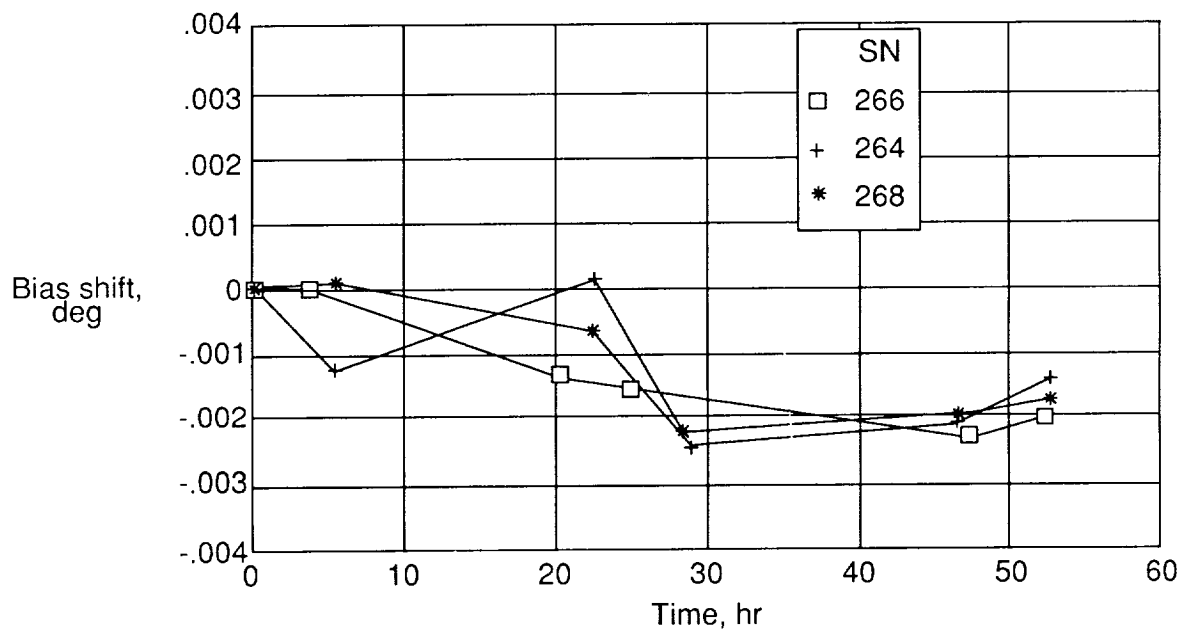
Figure 22. Bias repeatabilities of tilt sensor model RG-37 at 110°F.
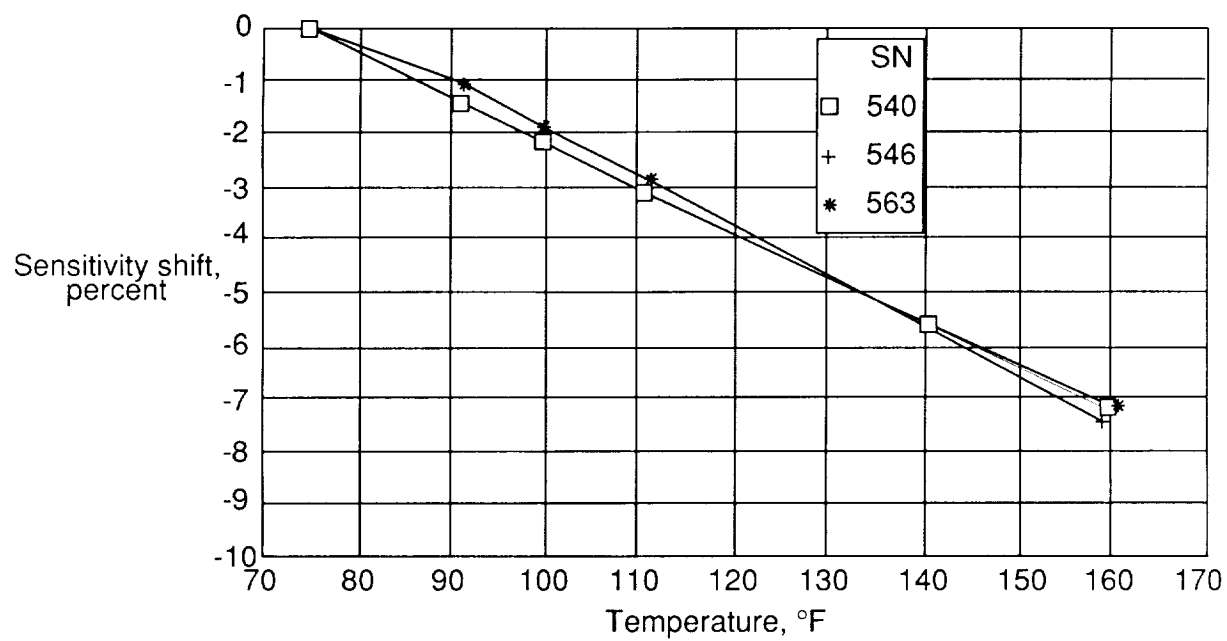
Figure 23. Variation of sensitivity with temperature for tilt sensor model CG-50.
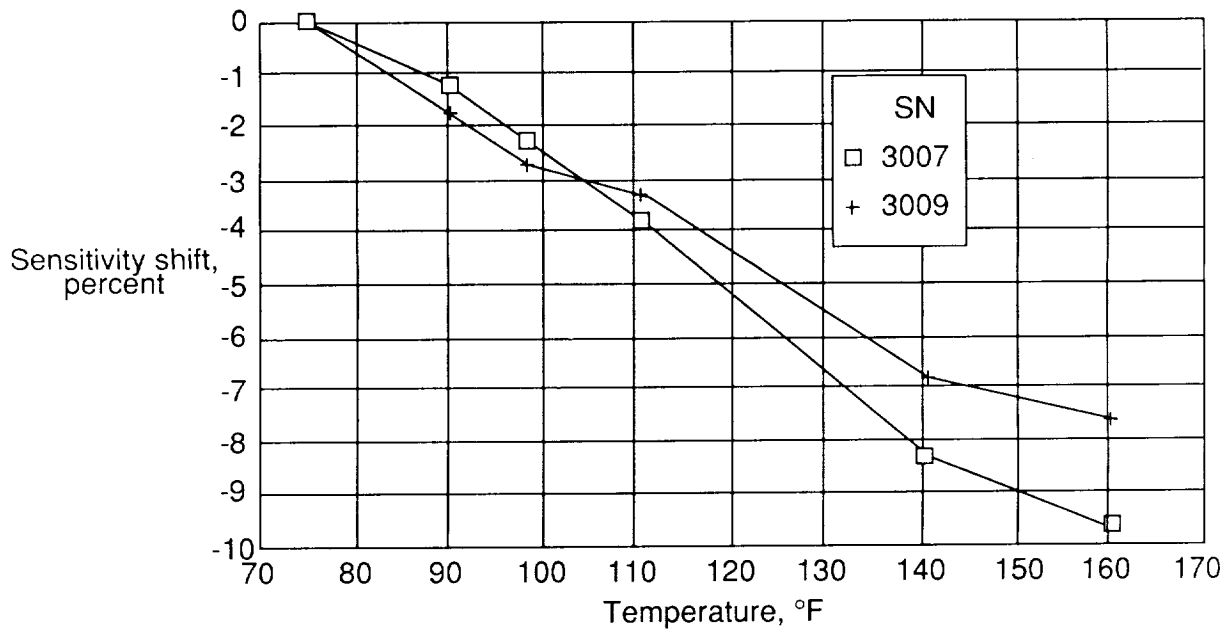
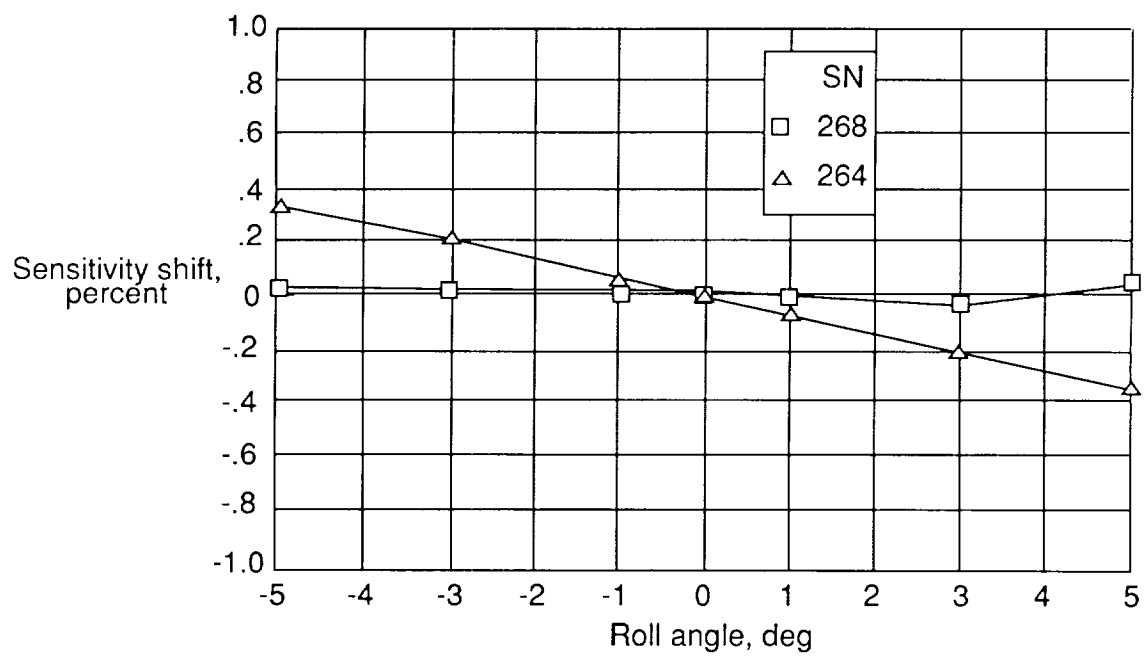Figure 24. Variation of sensitivity with temperature for tilt sensor model CG-57.
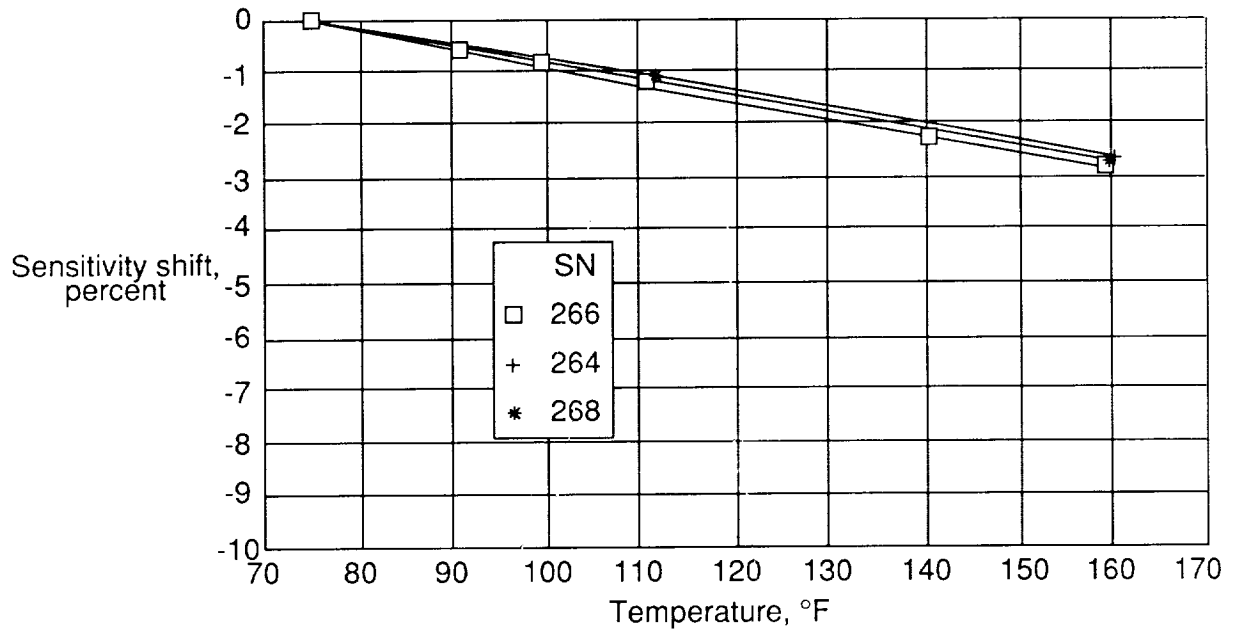
Figure 25. Variation of sensitivity with temperature for tilt sensor model RG-37.
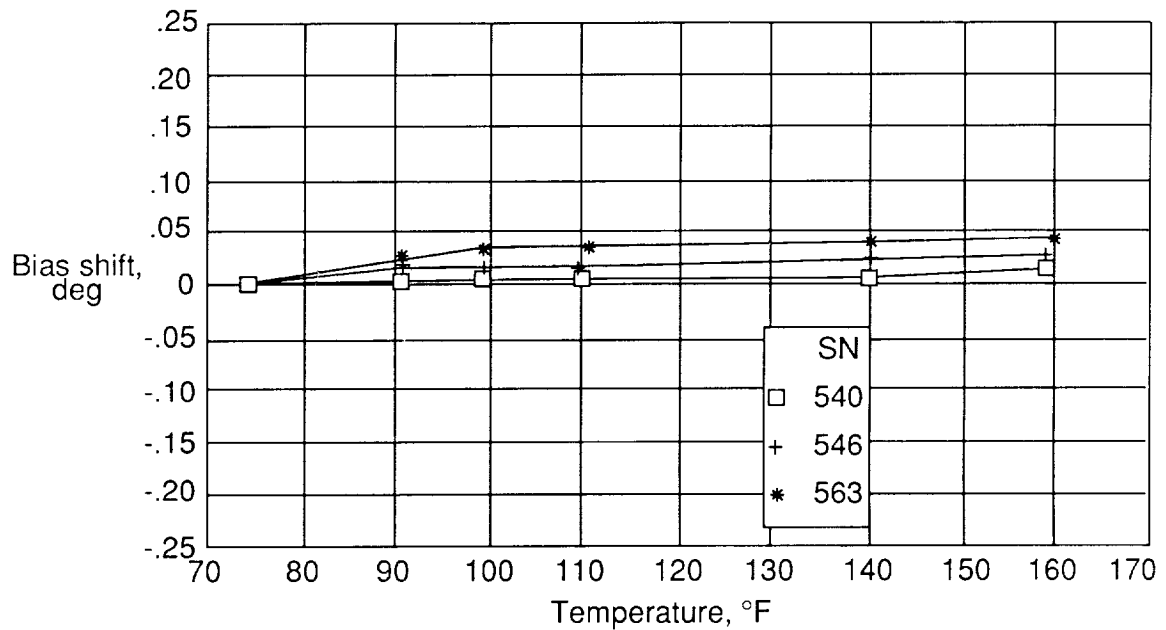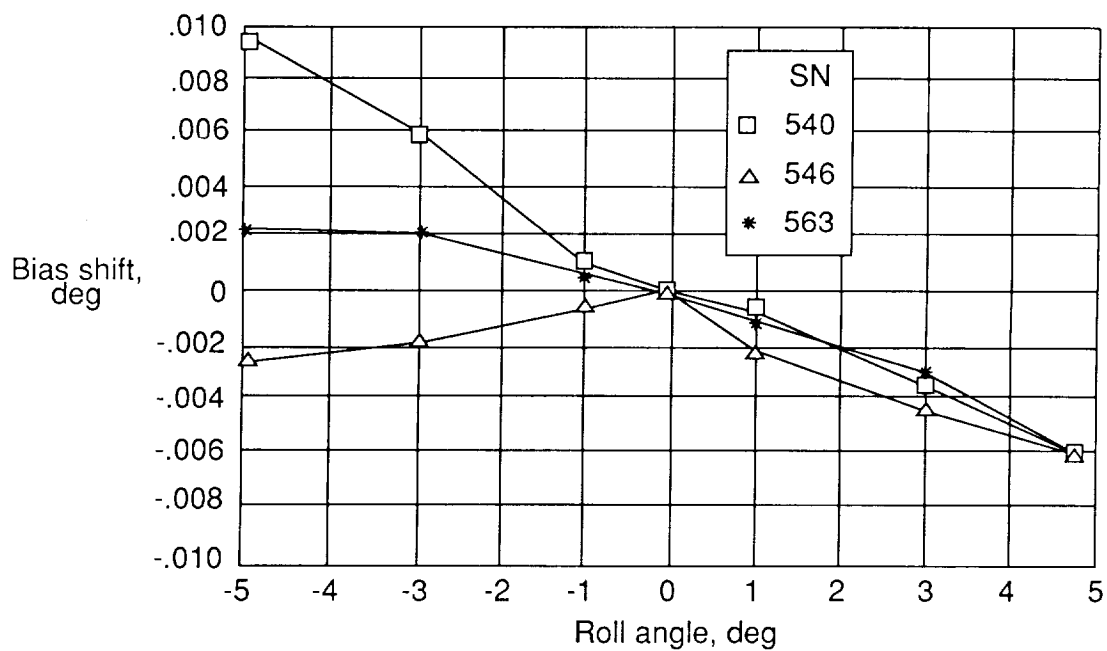
Figure 26. Variation of bias with temperature for tilt sensor model CG-50.
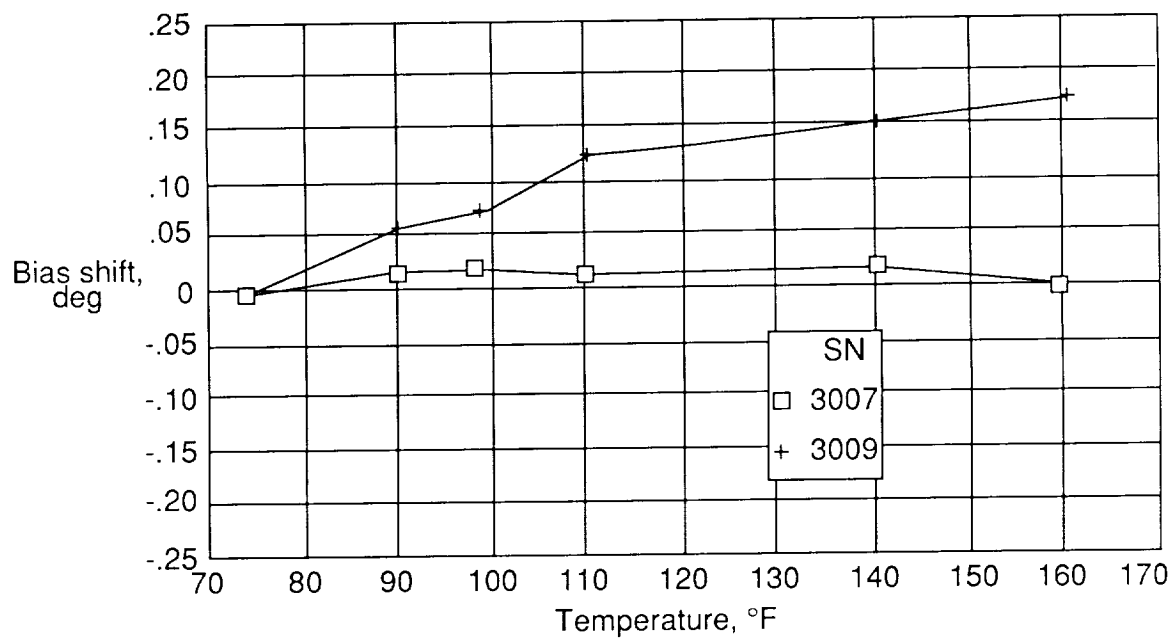
Figure 27. Variation of bias with temperature for tilt sensor model CG-57.
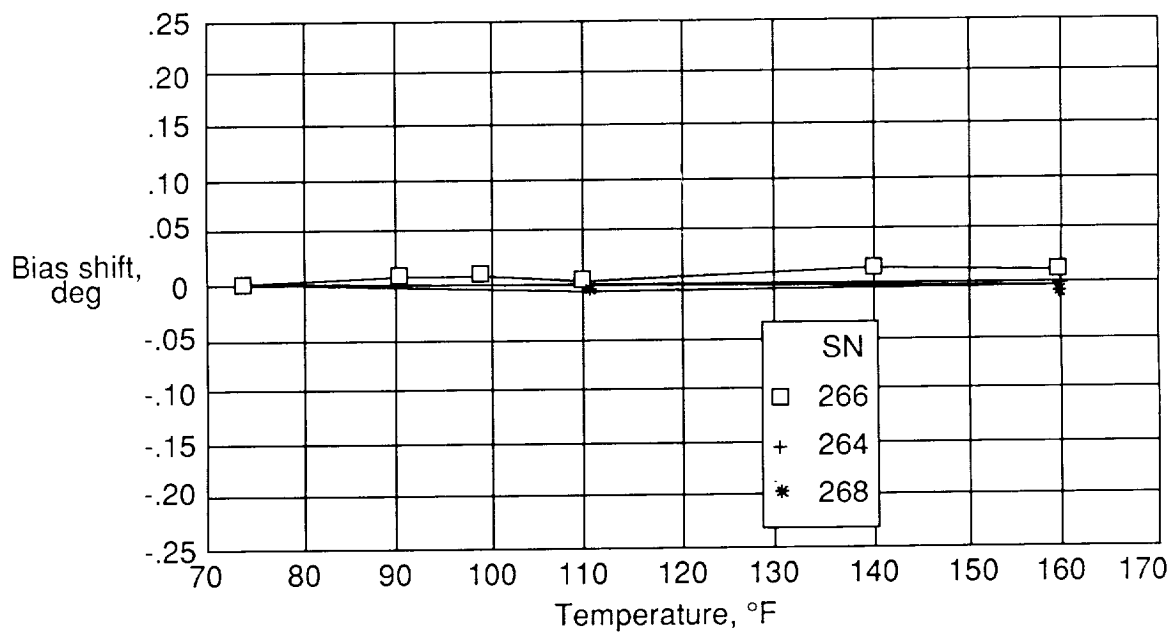

Figure 28. Variation of bias with temperature for tilt sensor model RG-37.
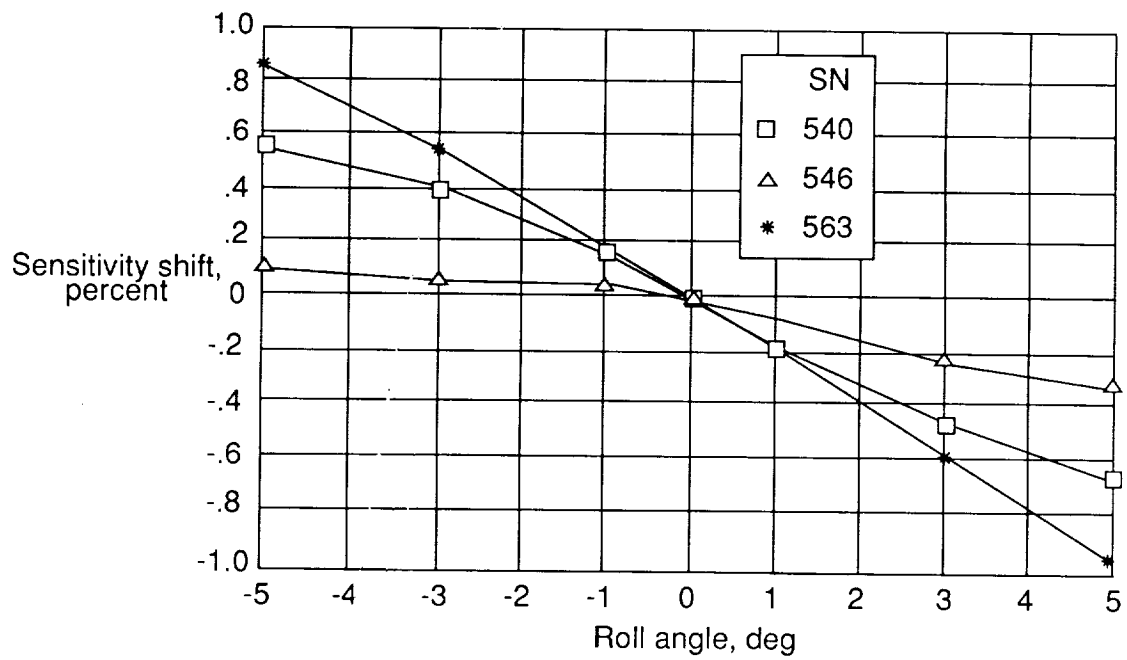
Figure 29. Variation of sensitivity with roll angle for tilt sensor model CG-50.
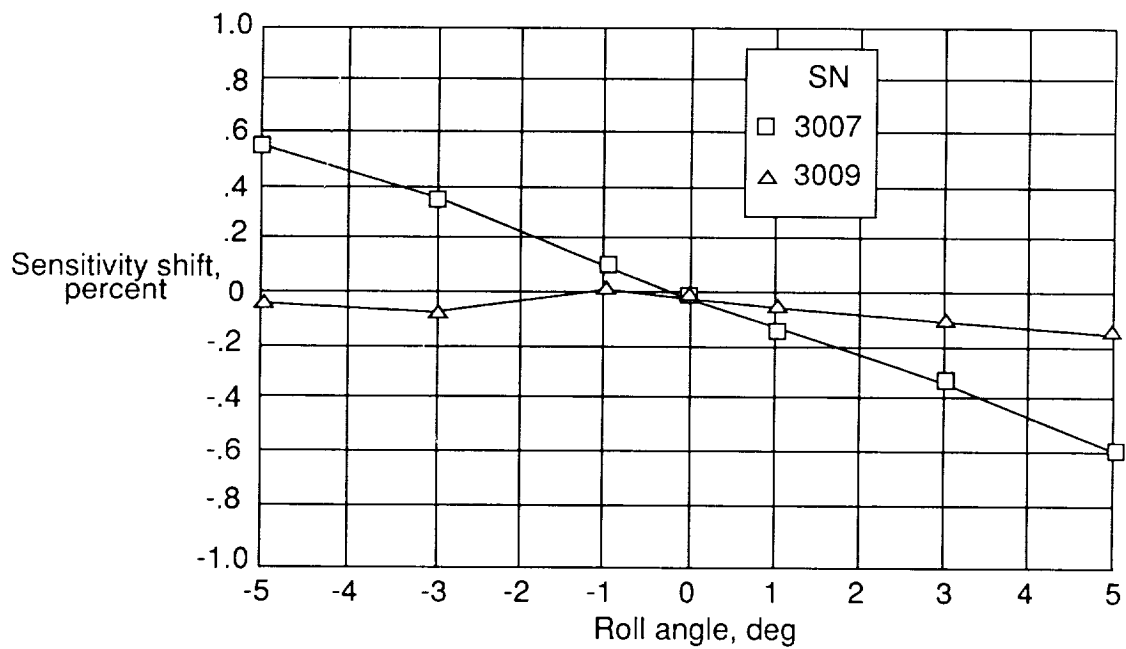
Figure 30. Variation of sensitivity with roll angle for tilt sensor model CG-57.

Figure 31. Variation of sensitivity with roll angle for tilt sensor model RG-37.

Figure 32. Variation of bias with roll angle for tilt sensor model CG-50.
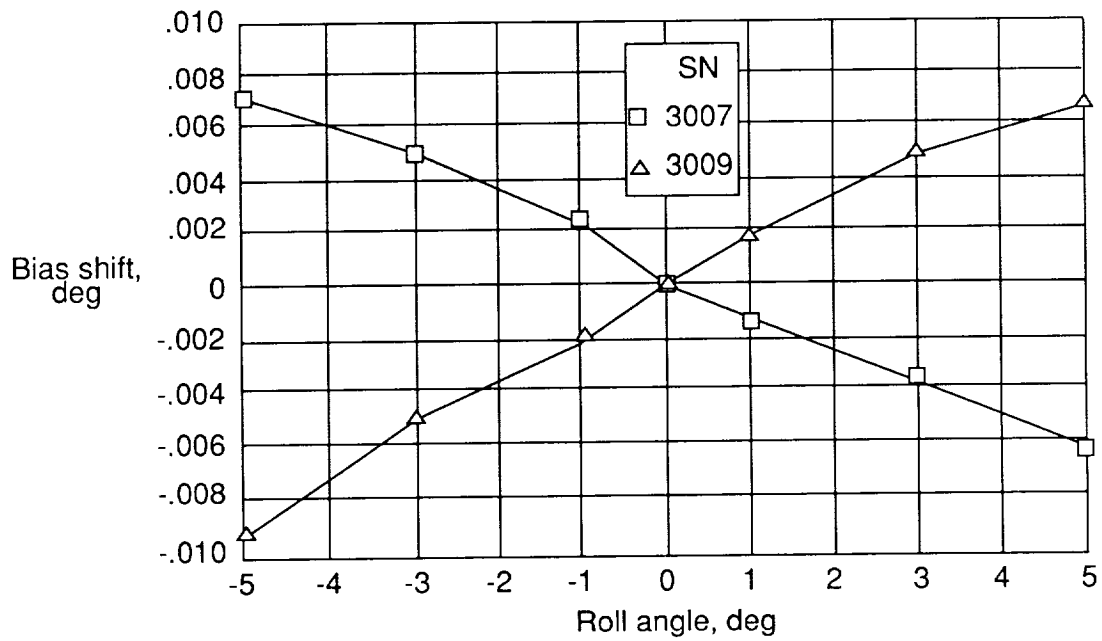
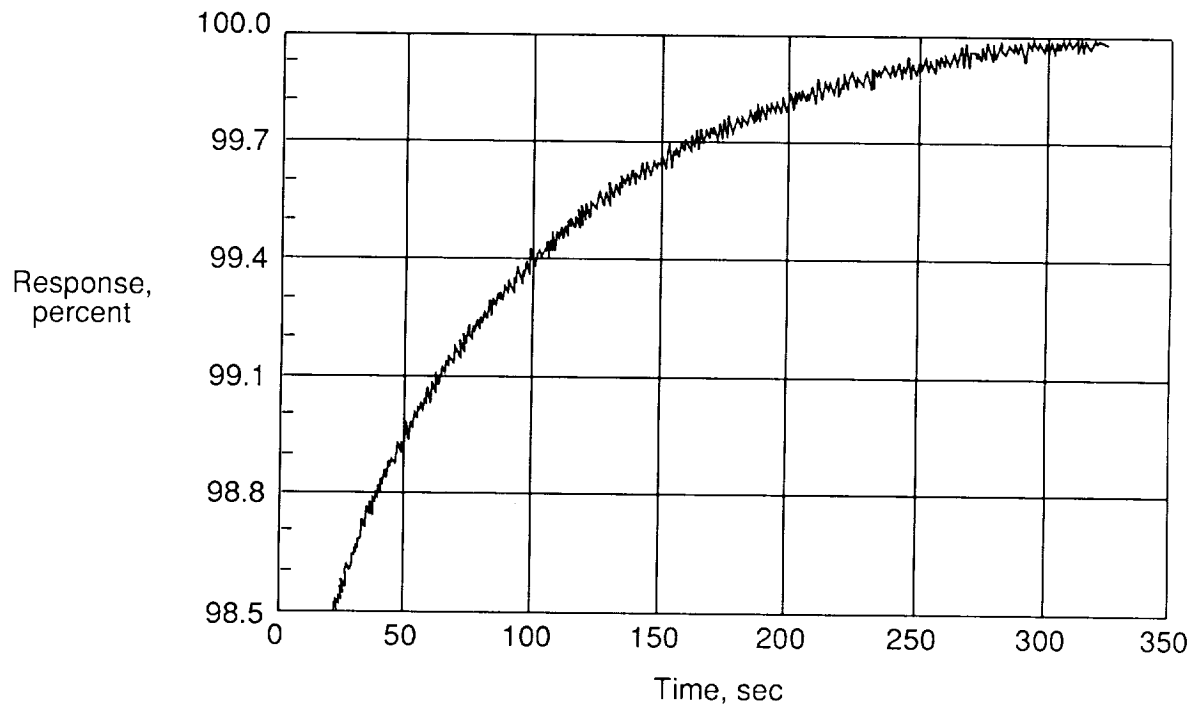Figure 33. Variation of bias with roll angle for tilt sensor model CG-57.
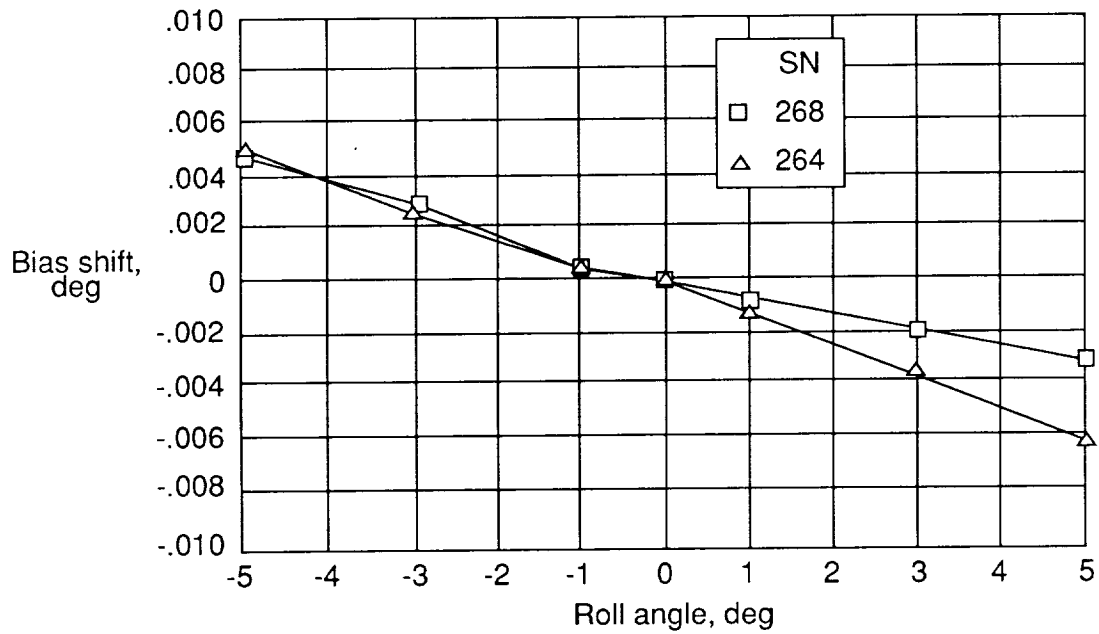
Figure 34. Variation of bias with roll angle for tilt sensor model RG-37.

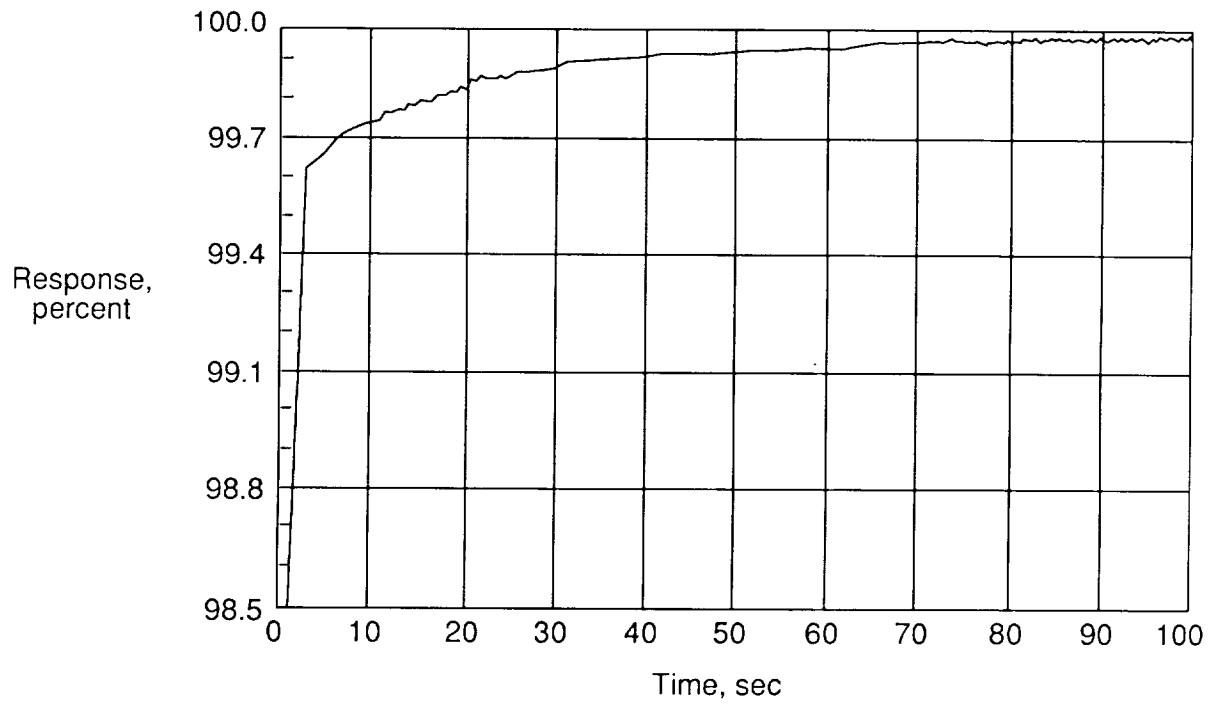Figure 35. Time history of 1° step response of tilt sensor SN 264 at 73°F.

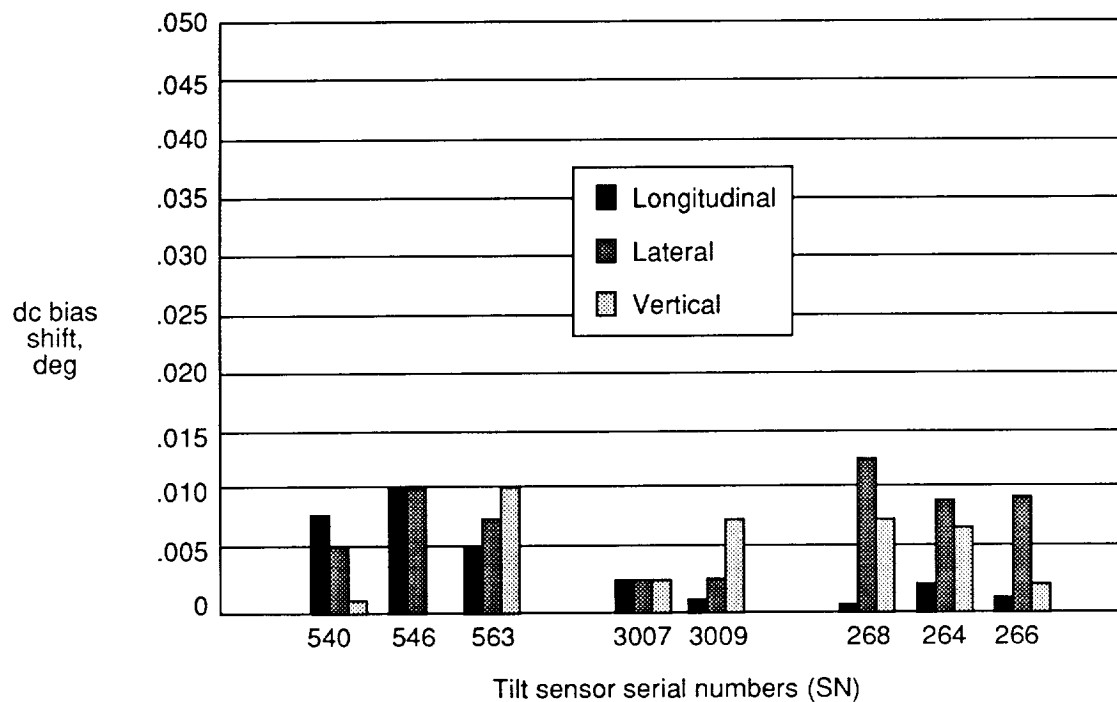Figure 36. Time history of 1° step response of tilt sensor SN 264 at 160°F.

Figure 37. Random rectification test showing dc bias shift of tilt sensors at $3g$ rms at level position.
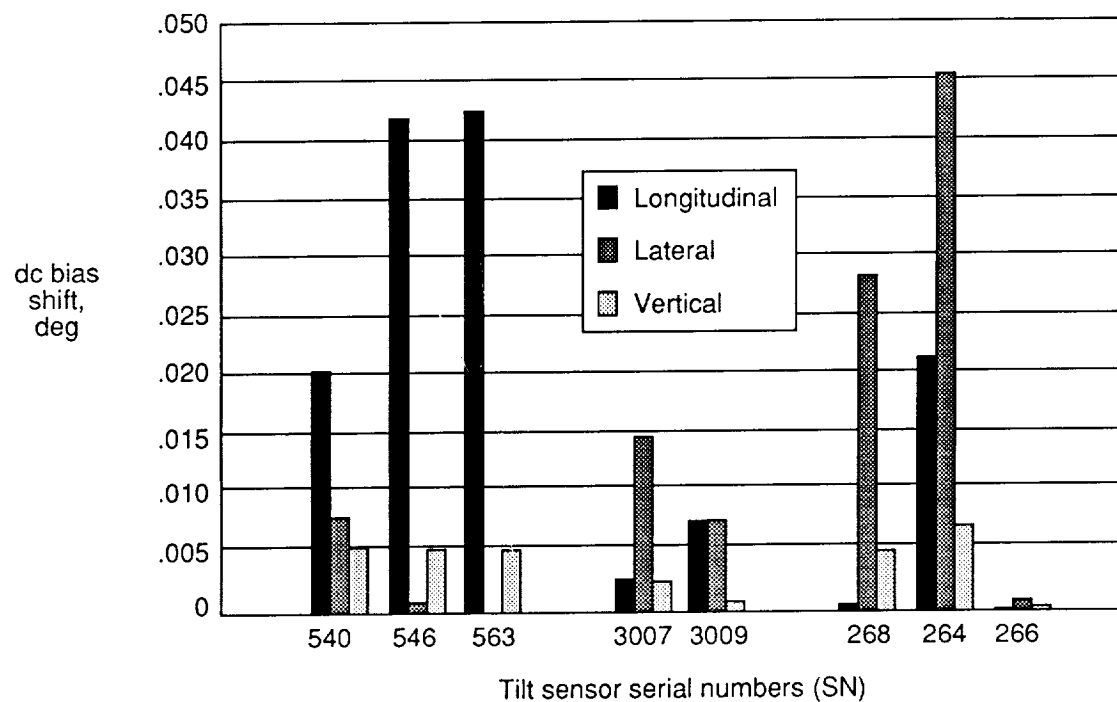

Figure 38. Random rectification test showing dc bias shift of tilt sensors at $3g$ rms at 5° tilt level.
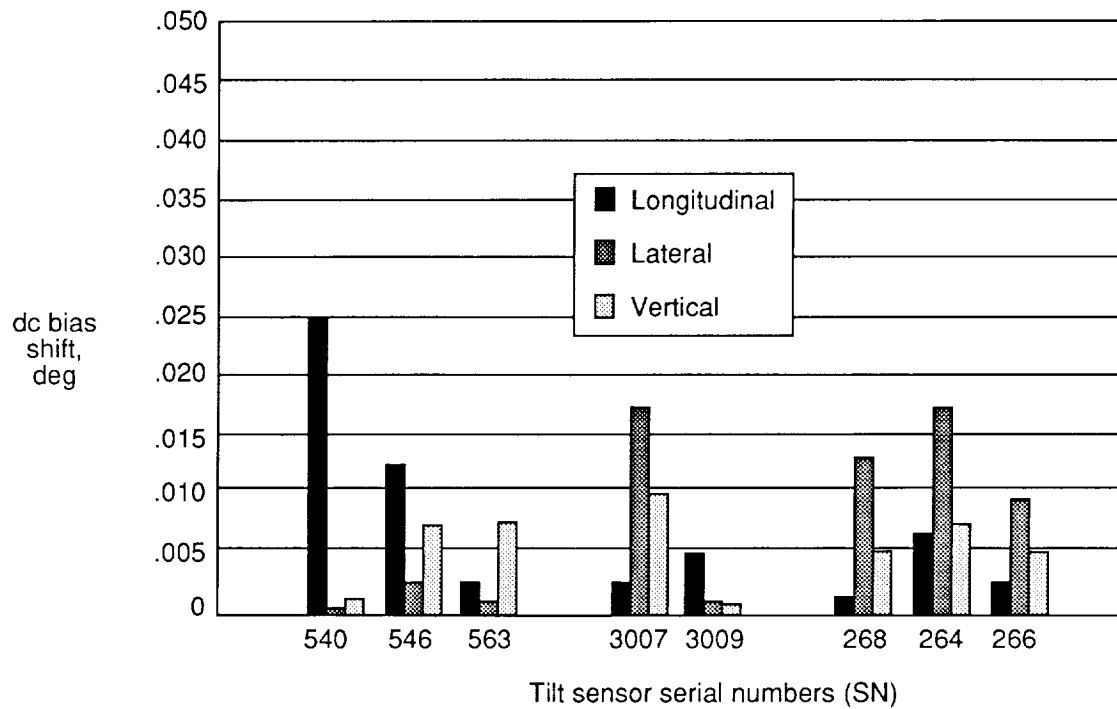
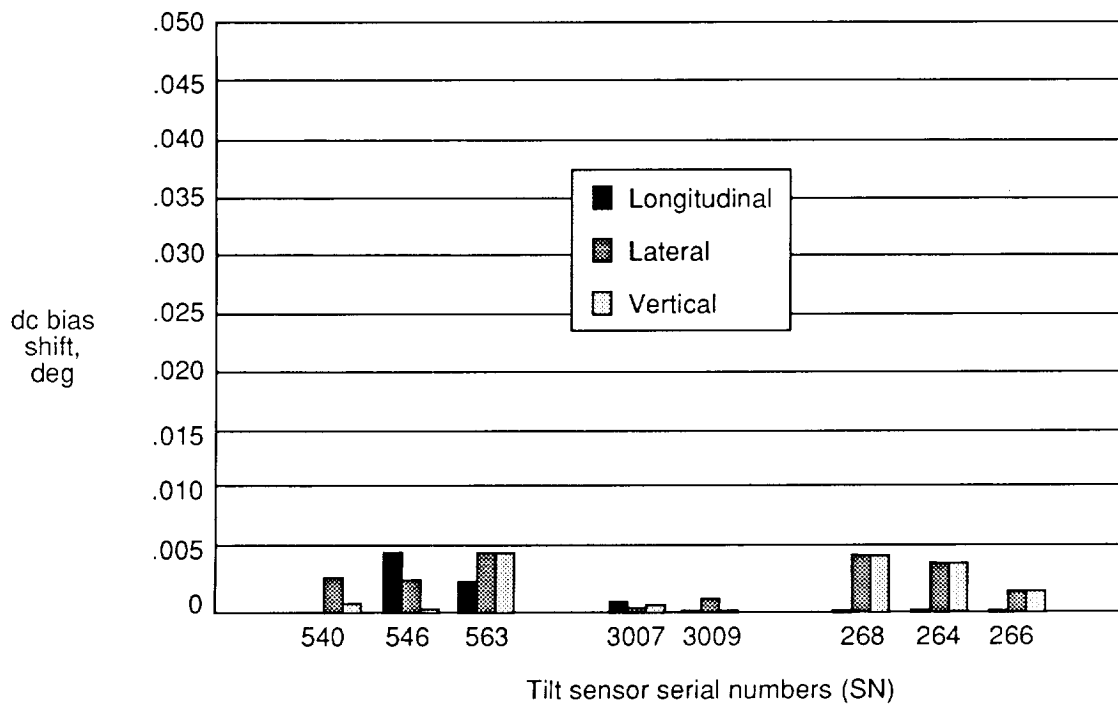Figure 39. Random rectification test showing dc bias shift of tilt sensors at $3g$ rms at 5° tilt level.

Figure 40. Random rectification test showing dc bias shift of tilt sensors at $2g$ rms at level position.
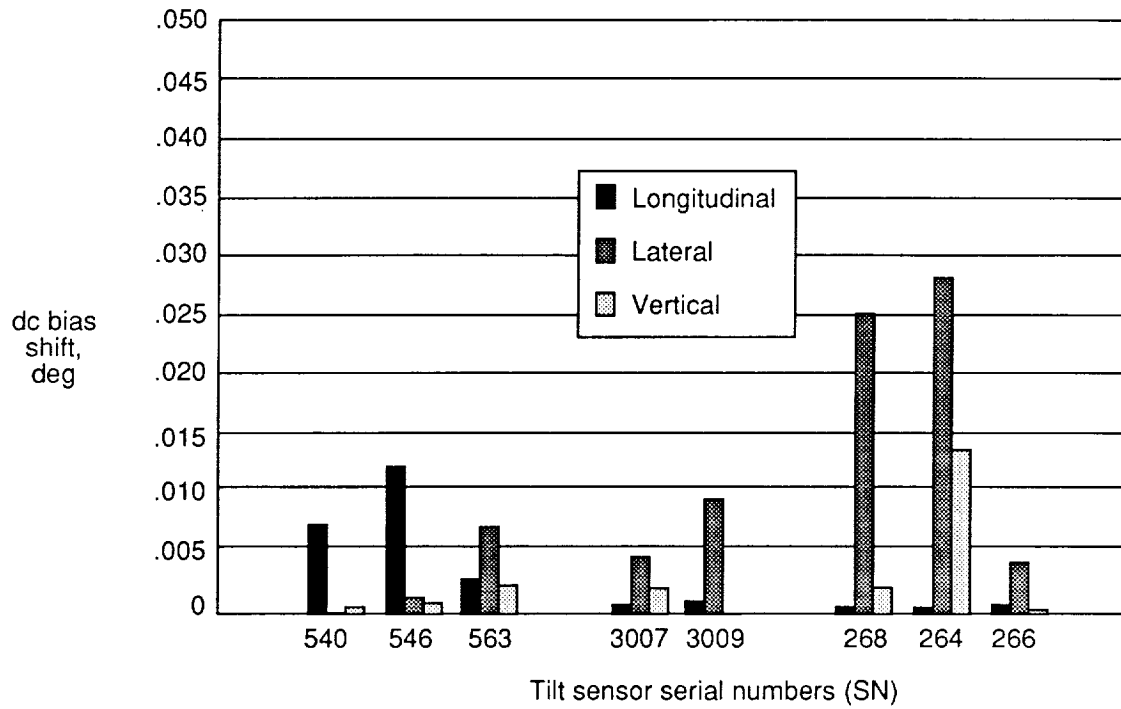
Figure 41. Random rectification test showing dc bias shift of tilt sensors at $2g$ rms at $5°$ tilt level.

Figure 42. Random rectification test showing dc bias shift of tilt sensors at $2g$ rms at $-5°$ tilt level.

Figure 43. Random rectification test showing dc bias shift of tilt sensors at $1g$ rms at level position.
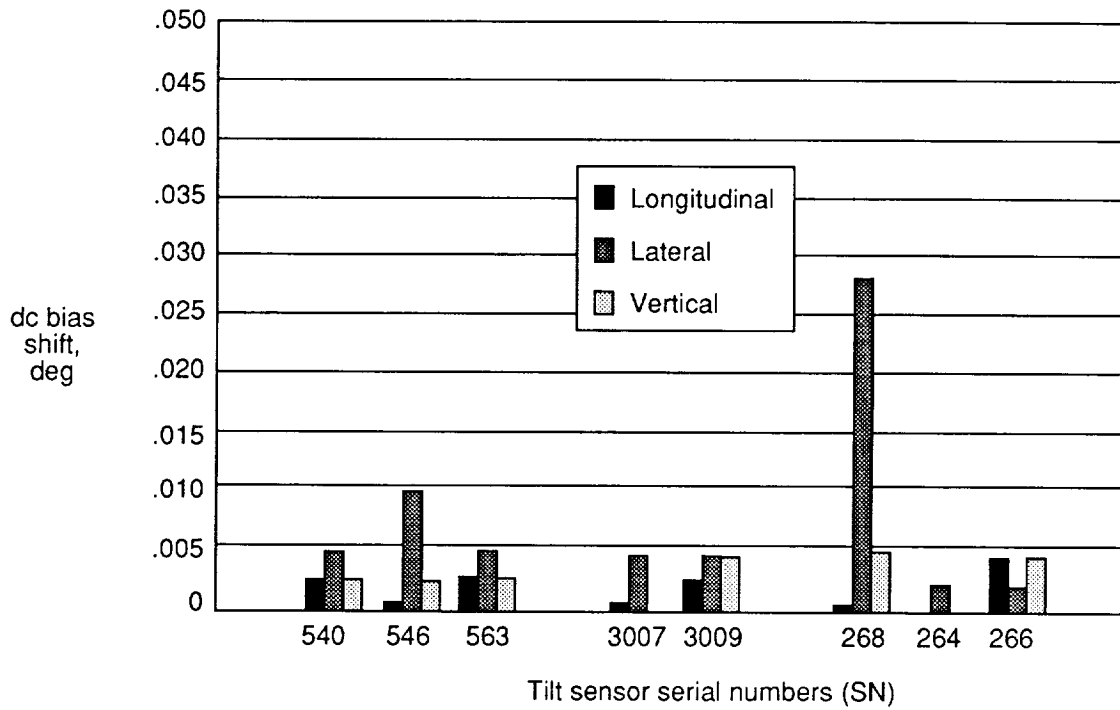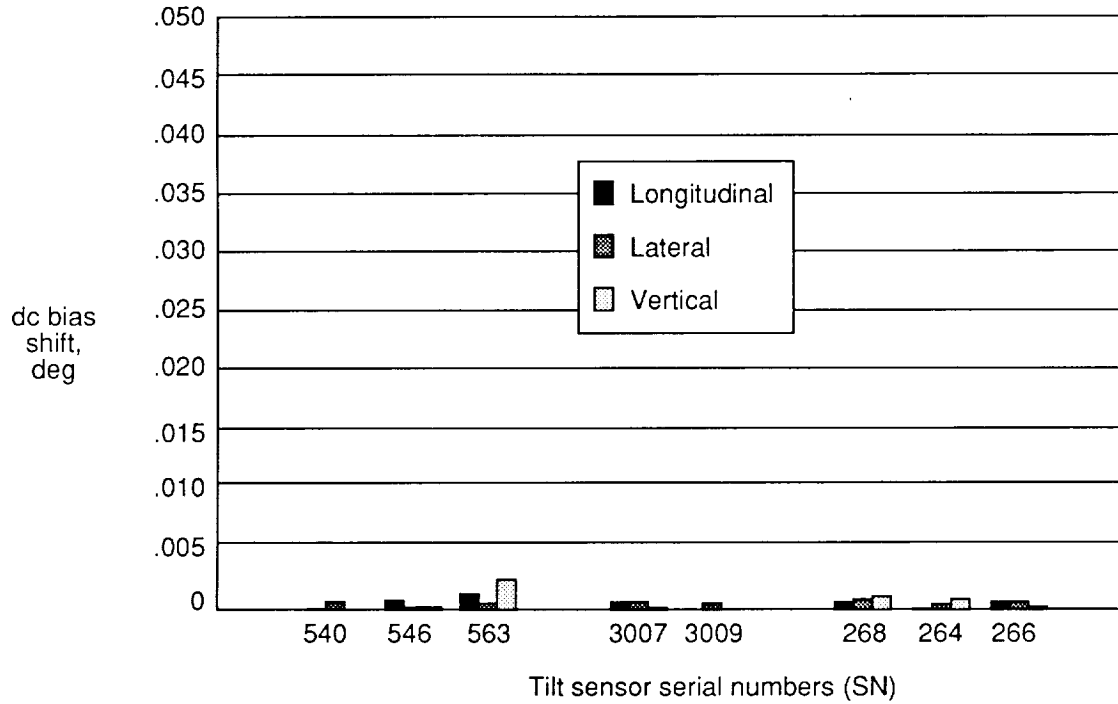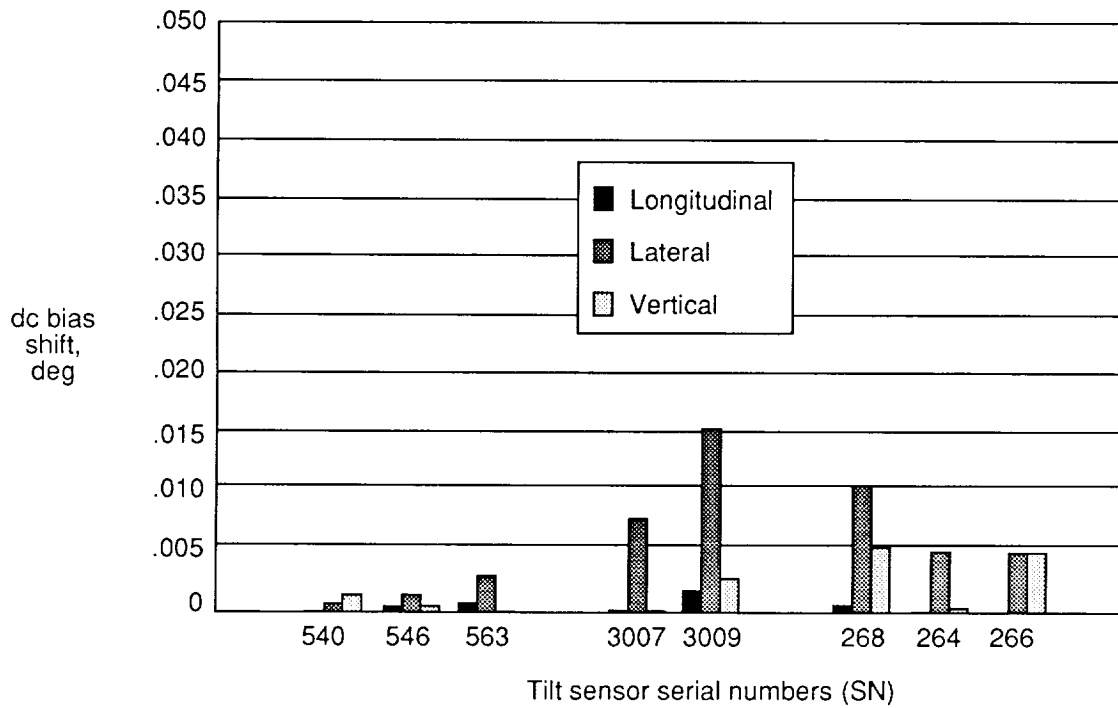

Figure 44. Random rectification test showing dc bias shift of tilt sensors at $1g$ rms at 5° tilt level.
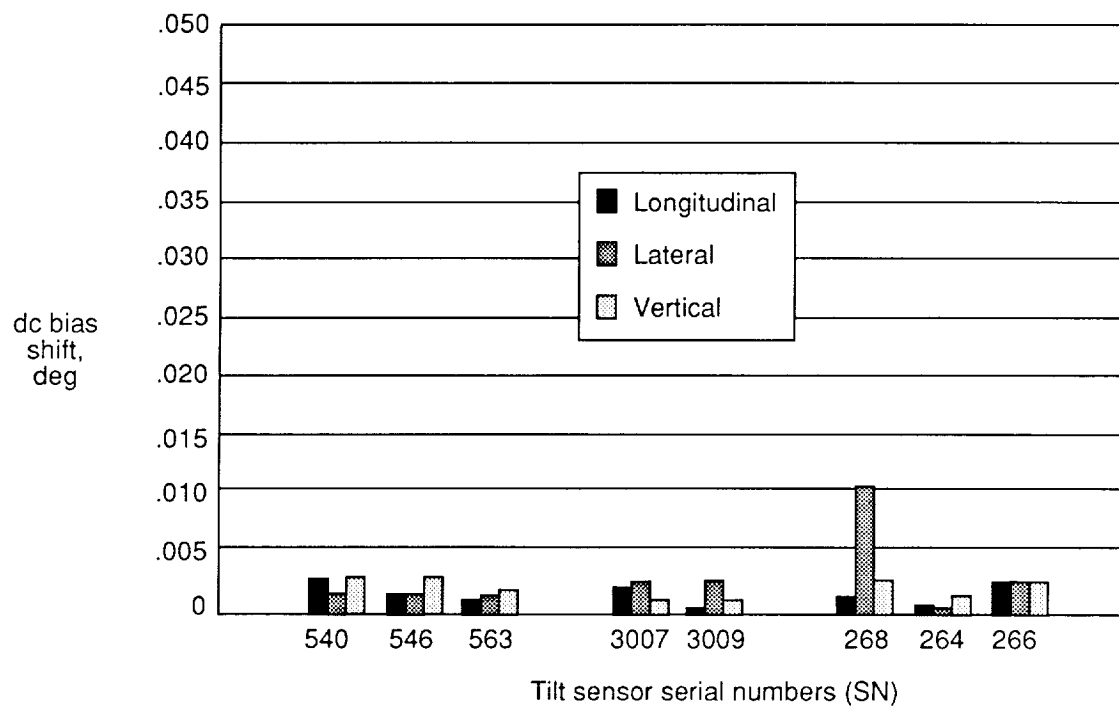
Figure 45. Random rectification test showing dc bias shift of tilt sensors at $1g$ rms at $-5°$ tilt level.

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13. ABSTRACT *(Maximum 200 words)*
The results are presented of a laboratory evaluation of electrolytic tilt sensors as potential candidates for measuring model attitude or angle of attack in wind tunnel tests. The performance of eight electrolytic tilt sensors was compared with that of typical servo accelerometers used for angle-of-attack measurements. The areas evaluated included linearity, hysteresis, repeatability, temperature characteristics, roll-on-pitch interaction, sensitivity to lead-wire resistance, step response time, and rectification. Among the sensors being evaluated, Spectron model RG-37 electrolytic tilt sensors have the highest overall accuracy in terms of linearity, hysteresis, repeatability, temperature sensitivity, and roll sensitivity. A comparison of the sensors with the servo accelerometers revealed that the accuracy of the RG-37 sensors was on the average about one order of magnitude worse. Even though a comparison indicates that the cost of each tilt sensor is about one-third the cost of each servo accelerometer, the sensors are considered unsuitable for angle-of-attack measurements. However, the potential exists for other applications such as wind tunnel wall-attitude measurements where the errors resulting from roll interaction, vibration, and response time are less and sensor temperature can be controlled.

14. SUBJECT TERMS
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