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Douglas T. Wong
Langley Research Center, Hampton, Virginia

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National Aeronautics and
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Langley Research Center
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EVALUATION OF THE PROTOTYPE DUAL-AXIS WALL ATTITUDE MEASUREMENT SENSOR

by

Douglas T. Wong
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia

ABSTRACT

A prototype dual-axis electrolytic tilt sensor package for angular position measurements has been built and evaluated in a laboratory environment. The objective of this project was to investigate the use of this package for making wind tunnel wall attitude measurements for the National Transonic Facility (NTF) at NASA Langley Research Center (LaRC). The instrumentation may replace a more costly and less rugged servo accelerometer package, called angle-of-attack (AOA) package, currently in use for wall attitude measurements. The dual-axis electrolytic tilt sensor package contains two commercial electrolytic tilt sensors thermally insulated with NTF foam, all housed within a stainless steel package. The package is actively heated and maintained at 160°F using foil heating elements.

The laboratory evaluation consisted of a series of tests to characterize the linearity, repeatability, cross-axis interaction, lead wire effect, step response, thermal time constant, and rectification errors. Tests revealed that the total root-mean-square (RMS) errors are 0.084 degree for the x-axis sensor, and 0.182 degree for the y-axis sensor. The RMS errors are greater than the 0.01-degree specification required for NTF wall attitude measurements. It is, therefore, not a viable replacement for the AOA package in the NTF application. However, with some physical modifications, it can be used as an inexpensive 5-degree range dual-axis inclinometer with overall accuracy of 0.1 degree under less harsh environments. Also, the data obtained from the tests can be valuable for wind tunnel applications of most types of electrolytic tilt sensors.

INTRODUCTION

Test section wall attitude measurements are required for certain aerodynamic tests conducted at the NTF. Several instrumentation systems have been developed to make these measurements. One instrument utilized a resistive potentiometer mounted parallel to actuators that moved the tunnel wall. This instrument measures the relative linear displacement between the wall and a fixed reference ground. It has limited accuracy and suffers from output bias shifts due to the movement of the reference ground and contraction of the potentiometer during cryogenic operation.

A second instrument uses a simple pendulum to make wall attitude measurements. The pendulum, which was attached to an angular displacement transducer, was housed within a large thermally controlled enclosure. Measurements were obtained by the relative angular displacements between the wall and the pendulum. The disadvantages of this device include long-time constant, fragility, and large size.

A third instrument, currently in use, is the servo accelerometer package normally used for aerodynamic model angle-of-attack measurements at Langley Research Center. This package provides fast response with an overall accuracy of 0.01 degree. However, it is fragile and costly.

Commercially available electrolytic tilt sensors have become more attractive for the NTF application. The intent of this study is to determine if the tilt sensor is a viable replacement for the existing servo accelerometer (AOA package) currently in use.

This report documents a newly designed, thermally controlled, dual-axis, electrolytic tilt sensor package as a potential candidate for wall attitude measurements. An extensive series of tests were performed to evaluate its performance. The results of these tests are presented and discussed in this report.

For a wind tunnel wall attitude sensor to provide satisfactory measurements in the NTF, it should meet the following requirements:

1. Overall error of less than ±0.01 degree (reference 1)
2. Operate under cryogenic temperatures
3. Insensitive to tunnel wall vibration loads
4. Small physical size

The overall accuracy is defined as the total RMS error due to linearity, hysteresis, repeatability, temperature, cross-axis interaction, lead wire sensitivity, and rectification.

PHYSICAL DESCRIPTION OF THE DUAL-AXIS WALL ATTITUDE MEASUREMENT SENSOR PACKAGE

Figures 1 and 2 are photographs of the assembled and disassembled package. The package contains two 2.625 x 0.625 inch electrolytic tilt sensors mounted perpendicular to each other. These are the sensors with serial numbers 264 and 268 evaluated in reference 2. Tilt sensor number 264 is designated as the x-axis sensor, while tilt sensor number 268 is designated as the y-axis sensor. Figure 3 contains the mechanical and electrical schematics, and the rotational degree-of-freedom designations of the tilt sensors.

The dual-axis measurement package consists of a stainless steel case enclosing the tilt sensors, heating elements, a temperature sensor, thermal insulation, and mechanical mounting surfaces. The electrolytic tilt sensors are mounted on an aluminum base enclosed by an inner $2.13 \times 2.13 \times 2.13$ inch aluminum case. The aluminum case is effectively a miniature oven. Heat is provided by six 2×2 inch, 5.3 ohm foil heater strips cemented to the outer surfaces of the aluminum case. A temperature sensor is attached to one of the spacers of the aluminum base to monitor internal case temperature. A thermal insulation layer of 0.5-inch-thick NTF foam surrounds the aluminum inner case. A steel leaf spring is compressed into the gap between the insulation layer and the stainless steel case to prevent relative motions. The outermost layer is the $3.570 \times 4.220 \times 2.788$ inch 347 stainless steel case with flanges to provide top, bottom, and rear external mounting surfaces.

During normal operation, the sensors are maintained at a constant temperature of 160°F to minimize the thermal errors described in reference 2. The electrical schematic for the sensor package illustrating detailed wiring is shown in figure 4.

EVALUATION TEST EQUIPMENT

A series of tests were designed to evaluate the performance of the dual-axis wall attitude measurement package. The equipment used for this testing is described below.

Two dividing heads were used as calibration standards. Both units provide angle indexing accuracy of 1 arc second. A single-axis dividing head was used in the linearity, repeatability, lead wire sensitivity, step response, and thermal time constant tests. A dual-axis dividing head was used in the cross-axis interaction test. All temperature tests were conducted in a temperature chamber. Both sine and random rectification tests were carried out on a electro-mechanical shaker. Data were acquired using a scanning digital multimeter controlled by a personal computer through an IEEE-488 interface. Except when mentioned otherwise, all tests were conducted with a 7-ft. cable.

TEST PROCEDURE AND RESULTS

The evaluation consisted of a series of nine tests. Details of each test are discussed below.

LINEARITY TEST

For each axis of the sensor package, a linearity test was conducted using the single-axis dividing head. The sensor package was initially mounted on the single-axis dividing head. With one measurement axis properly aligned with the rotational axis of the dividing head, dividing head rotation should only generate an input angle for that sensor. Any output from the other sensor is considered as cross-axis interaction.

In each linearity test, the output voltages of both sensors and the input angles were recorded. The dividing head was indexed from -5 degrees to +5 degrees and then back to -5 degrees in 0.25-degree increments. This test determined the sensitivity, bias, and cross-axis interaction of both sensors. The bias was the average of the outputs from 0-degree pitch input before and after the package was rotated through 180 degrees in the x-y plane.

The results of the linearity tests are illustrated in figures 5 to 8. The errors shown in these figures are the deviations between the sensor output and the result of a third order regression fit. Figure 5 shows that the x-axis sensor had a maximum nonlinearity error of 0.008 degree and maximum hysteresis error of 0.008 degree. The sensitivity and bias of the x-axis sensor were found to be 0.3048 volt/degree and 0.036 degree (0.010973 volt), respectively. Figure 6 indicates that the y-axis sensor had a maximum nonlinearity error of 0.016 degree and a maximum hysteresis error of 0.016 degree. The sensitivity and bias of the y-axis sensor were found to be 0.3153 volt/degree and 0.186 degree (0.058646 volt), respectively. Figure 7 illustrates the cross-axis interaction of the x-axis sensor. The changes in voltage output of the off-axis (non-measurement axis) sensor from 0-degree off-axis input were converted into degrees using its sensitivity established from the linearity test. Figure 8 illustrates the cross-axis interaction of the y-axis sensor. The figure indicates that the sensor was not mounted orthogonally to the sensor case. This explains the larger nonlinearity error of the y-axis sensor shown in figure 6.

REPEATABILITY TEST

The linearity test was repeated over several days to determine the repeatability characteristics of the sensor package. The shifts in sensitivity and bias for each sensor are presented in figures 9 and 10. The maximum sensitivity shifts of the x-axis and y-axis sensors are respectively 0.06 percent and 0.02 percent over 6 days. The maximum bias shifts of the x-axis and y-axis sensors are respectively 0.004 degree and 0.002 degree over 6 days.

TEMPERATURE TEST

This test was performed to determine the characteristics of the package under cryogenic temperatures. A cantilevered arm made of SS-347 steel was used to extend the sensor package into a temperature chamber with settings at 73°F (ambient), 0°F, -100°F, -200°F, and -293°F. A linearity test was repeated at each of the temperature settings to obtain the temperature sensitivity. The bias of each axis at each temperature was obtained from averaging the zero output voltages before and after the sensor was rotated through 180 degrees in the horizontal plane.

Figure 11 is a plot of the shifts in sensor sensitivity as a function of temperature. The sensitivity shift is expressed as a percentage of sensor sensitivity at ambient temperature. Both sensors varied in sensitivity within $\pm$0.07 percent indicating that the package interior temperature was controlled within $\pm$1°F over the entire temperature range (ref. 2).

Bias shifts are plotted in figure 12. The x-axis sensor bias shift was found to be more pronounced when the package was exposed to cryogenic temperatures. The x-axis sensor varied by 0.033 degree, and the y-axis sensor varied by 0.006 degree when the chamber temperature was varied over the test range. Other than temperature, factors such as warping of the cantilevered mounting arm under cryogenic temperatures may have also caused the bias shifts. The heater power requirement was found to increase from 5.6 watts to 20.8 watts as the chamber temperature was decreased from ambient to -293°F.

CROSS-AXIS INTERACTION TEST

In this test, the package was mounted onto the dual-axis dividing head. The off-axis was rotated from -5 to 5 degrees in 2-degree increments by one table of the dual-axis dividing head. At each 2-degree increment, the on-axis (active measurement axis) was rotated in the usual fashion for a linearity test by the other dividing table. The bias and sensitivity at each 2-degree increment were computed. The effect of cross-axis interactions was then determined from the sensitivity and bias shifts with respect to zero-degree off-axis input.

Figure 13 is a plot of the shift in sensor sensitivity as a function of off-axis input angle. The sensitivity shift is expressed as a percentage of sensor sensitivity at zero degree off-axis angle. The maximum sensitivity shift of the x-axis and y-axis sensors are 0.37 percent at -5 degree roll (refer to figure 3 for rotational degree-of-freedom designation) and 0.52 percent at 5-degree roll, respectively. The curve of the x-axis sensor reveals that its maximum sensitivity does not occur at zero-degree roll, but at a roll angle larger than -5 degrees. This indicates that the sensor is internally offset in roll within the sensor holder.

Figure 14 is a plot of the bias shifts due to cross-axis input. The x-axis sensor had a negligible bias shift, while the y-axis sensor bias shift was 0.113 degree. The larger linear output of the y-axis sensor indicates that it was not mounted orthogonally to the sensor case. This corresponds to a horizontal misalignment angle of approximately 1.125 degrees (see Appendix).

LEAD WIRE SENSITIVITY TEST

Tests were conducted at room temperature to determine the effect of lead wire length on sensor output. The original 7-ft. cable was replaced with a 280-ft. (22 AWG) cable. These tests involved linearity comparisons between the 7-ft. and the 280-ft. cables. The linearity tests with the 280-ft. cable were repeated over 6 consecutive days to study the effect of long lead length on the repeatability of each sensor.

In addition, the linearity tests were repeated with the sensor package and 50 feet of the 280-ft. cable inside the temperature chamber at -290°F. This is to simulate the NTF environment in which only about 50 feet of the cable will be exposed to the cryogenic temperatures. The sensitivity and the bias shifts under these conditions were computed.

A comparison of the results due to different cable lengths revealed a sensitivity shift of -2.25 percent on the x-axis sensor and -2.13 percent on the y-axis sensor. The bias shift was found to be 0.082 degree for the x-axis sensor and 0.076 degree for the y-axis sensor. The amount of sensitivity shifts for both axes appears to be high compared with the results obtained in reference 2.

Figures 15 and 16 illustrate the results of the repeatability test with the 280-ft cable. The sensitivity shift was found to be 0.36 percent for the x-axis sensor and 0.08 percent for the y-axis sensor. The bias shifted by 0.018 degree for the x-axis sensor and by 0.008 degree for the y-axis sensor.

Compared with the result of the repeatability test for the 7-ft. cable, the results are much less repeatable with the long cable. It is possible that the load impedance added by the longer cable may have caused the observed variation in the test results.

When the package and first 50 feet of the longer cable were exposed to -290°F, the sensitivity of both the x-axis and the y-axis sensors increased 0.19 percent and 0.17 percent, respectively. The bias shift was found to be less than 0.001 degree for both axes. These results suggest that the changes are mostly resistive.

STEP RESPONSE TEST

This test determined the response time constant of each sensor to a step change in angular attitude. The sensor package was initially mounted on the single axis table with one sensor properly aligned with the rotational axis of the dividing head. The table was then stepped from the zero-degree to the one-degree position in 42 milliseconds. The time response, or the output voltage versus time, was recorded for 5 minutes. This procedure was repeated for the other sensor.

Figures 17 and 18 show the results of this test. The x-axis sensor achieved 99 percent (0.01 degree) of its final value within 1 second and 99.9 percent (0.001 degree) of its final value within 65 seconds. The y-axis sensor also achieved 99 percent of its final value within 1 second but 99.9 percent of its final value within 32 seconds. Clearly, the sensors have fast initial responses, but slow settling times. The slow settling time is caused by wetting of the sensor internal wall by the electrolytic fluid when the sensor is tilted.

SINE RECTIFICATION TEST

This test provides information on the DC error response or rectification error when the sensor package is subjected to vibrations at various frequencies. This information can be used to identify the band of frequencies which cause unacceptable DC error. The sensor package was mounted on a mechanical shaker table and was subjected to a swept sinewave input from 10 Hz to 5000 Hz at 1 G rms level. This test was performed three times with the sensor package mounted in the three orthogonal orientations to determine both on-axis and off-axis rectification errors. The DC biases of both sensors were recorded and plotted.

The results of these tests are presented in figures 19 through 24. Figures 19 and 22 are plots of the on-axis rectification errors while the rest are plots of the off-axis errors. The overall trend shown in these figures reveals that the sensors are more sensitive to low frequency vibrations from 10 Hz (the lowest frequency available from the shaker at 1 G rms acceleration level) to 100 Hz. In addition, for vibrations beyond 100 Hz, the rectification errors are generally less than ± 0.01 degree. Notice that the rectification errors due to either of the off-axis excitations are greater than the error due to on-axis excitation for both sensors. For the x-axis sensor, the maximum rectification error was 0.78 degree at 15 Hz, and 0.45 degree at 14 Hz for the y-axis sensor. These off-axis rectification errors are substantially higher than the 0.01 degree requirement.

RANDOM RECTIFICATION TEST

The sine rectification test setup was repeated using a random vibration input from 20 to 5000 Hz at 3 G rms level. Random rectification errors for the two sensors were recorded over a 3-minute period. During this period, the shaker table was off for the first 60 seconds. Random vibration was then applied during the next 30 seconds, followed by a 90-second interval without shaker input. Errors data are presented in figures 25 through 30. The overall random rectification errors are found to be less than 0.01 degree for both sensors of the package.

THERMAL TIME CONSTANT TEST

This test was used to determine the thermal time constant of the sensor package. It was conducted at both ambient and cryogenic temperatures.

In the ambient test, the sensor package was first exposed to 73°F until a thermal equilibrium was achieved. Thermal time constant testing began with the application of power to the sensor heaters. The output of the temperature controller and the outputs of both sensors were periodically recorded for 3 hours.

In the cryogenic test, the sensor package attained a thermal equilibrium at 73°F before it was placed inside the temperature chamber. The chamber temperature, initially at 73°F, was then lowered to -293°F. The heater controller voltage output and the null outputs of both sensors were recorded for the next 3 hours. Note that the sensor package was actually subjected to a ramp instead of a step change in temperature since the chamber temperature could not be instantaneously lowered to -293 °F. Although no actual testing was conducted, it is known by experience that the temperature chamber takes about 15 minutes to achieve this low temperature.

Figures 31 and 32 illustrate the results of these two tests. Both figures show that the temperature controller voltage remained unchanged for 30 minutes into the test. This provides a good indication that the package had reached thermal equilibrium. The output of either sensor at that time did not vary more than 0.01 degree. The estimated thermal time constant of the sensor package when suddenly exposed to -293°F after warming up is approximately 15 minutes. This is equal to the difference between the total settling time in the cryogenic test (30 minutes) and the approximate chamber temperature settling time (15 minutes).

CONCLUDING REMARKS

Table 1 provides an approximate estimation of the performance of the package if it is used for wall attitude measurements in the NTF facility. Note that most of the tests were conducted using the 7-ft. cable. The 280-ft. AWG 22 cable was only introduced at a later time in the lead wire sensitivity test to simulate an actual setup in the wind tunnel. The errors given under the linearity, hysteresis, temperature, roll-on-pitch interaction, and random rectification in the table are from the test results with the 7-ft. cable. They should give an estimation of the performance of an actual package for wind tunnel use. It was found from the lead wire sensitivity test that the linearity and hysteresis errors did not change much when the AWG 22 cable was used. For the other error sources (temperature, roll-on-pitch interaction, and repeatability), it is assumed that they are solely caused by external environments and should be similar no matter which cable is used.

The temperature error given in the table is the error resulting from 250°F change in temperature when the sensor is tilted 5 degrees about its sensitive axis. The wire resistance error is the error when the length of the AWG 22 cable is 280 feet and with its 50 feet exposed under -250°F.

The roll-on-pitch interaction error represents the residual error of the roll-on-pitch interaction at 5 degrees. The errors listed are the sum of the errors due to internal misalignments, which are 0.024 degree and 0.140 degree for the x and y axis, respectively, and the yaw misalignment resulting from the mounting flange clearance holes. As seen from Part B of the Appendix, the clearance holes cause an additional error of 0.04 degree on both axes.

The random rectification error represents the maximum rms bias shift of the three axes combined during the random rectification test at 3 G rms at level position. Because random rectification represents the error due to a broader frequency spectrum, it is presented in favor of the sine rectification error. If the frequency response of the wind tunnel is known, the average sine rectification error over the frequency bandwidth should be used.

The error due to step response is not considered because the response for wall attitude measurement is usually sufficiently long that the step response error becomes negligible. The resulting total rms error for the x-axis sensor is 0.084 degree and for the y-axis sensors is 0.182 degree. They are thus, far beyond the requirement of 0.01 degree.

The roll-on-pitch interaction error in the table actually can be reduced. There are two ways to achieve this. One is to provide a curve fit to correct the error mathematically. The drawback is that introduction of mathematical correction could make the entire system more complicated. Since the roll-on-pitch interaction is caused by improper sensor alignments, the other method is to align the sensors properly. However, it is difficult to physically align the sensor properly since too many individual parts are involved and each can cause misalignment when assembled. Also, several iterations may be required. Regardless of which method is used, it is important to minimize misalignments due to mounting of the package. Therefore, dowel holes should be added on the mounting flange to reduce yaw misalignment due to clearance holes.

The temperature error can also be reduced mathematically. However, this is only possible when the warping of the extension bracket during the temperature test was repeatable. It allows the offset errors due to bracket to be largely eliminated.

It is important to note that the package is assumed to be exposed to a randomly vibrating environment. If the wind tunnel vibration frequencies are predominantly low frequencies (below 50 Hz), the rectification error would be substantially higher. This would make the sensor package unsuitable for wall attitude measurements. The lead wire resistance test indicated that there is a stability problem both in biases and sensitivities when the 280-ft. AWG 22 cable is used. In addition, the mounting flanges of the housing need to be redesigned to three-point mounts instead of four-point mounts. This is because the extra mounting point could cause warping of the housing due to the additional stresses created. As indicated by the warm-up test result, the package required approximately 45 minutes to warm up (30 minutes from power on to the controlled temperature, and 15 additional minutes after exposure to cryogenic temperature). It is, therefore, highly recommended that the unit be warmed up for at least that long before it is used for cryogenic measurements.

Although the package was found to have some drawbacks for extreme environment measurements, one should not overlook its potential considering its small linearity error, good repeatability, and small random rectification error (when a short cable is used). With some physical improvements, it can be used as an accurate and inexpensive 5-degree range dual-axis inclinometer with overall accuracy of 0.1 degree under less harsh environments.

REFERENCES

1. Finley, T.; and Tcheng, P.: Model Attitude Measurements at NASA Langley Research Center. AIAA Paper No. 92-0763, Reno, Nevada, 1992.

2. Wong, Douglas T.: Evaluation of Electrolytic Tilt Sensors for Measuring Model Angle of Attack in Wind Tunnel Tests. NASA TM 4315, 1992.

APPENDIX

A. CALCULATION OF INTERNAL YAW MISALIGNMENT ANGLE

The yaw misalignment angle ψ, is defined to be the offset angle of the roll axis with the measurement axis in the pitch-roll plane. Therefore, when ψ is 0 degree, the sensor achieves its minimum sensitivity of 0 V/deg. When ψ is 90 degrees, the sensor should achieve its maximum sensitivity. The relationship between the sensitivity and the yaw misalignment angle is defined by the following equation:

$$S_i = S\cos(90 - \psi) \tag{A-1}$$

where S is the sensor maximum sensitivity, and S_i is the sensitivity at ψ. According to the result of the linearity test, S of the y-axis sensor is 0.3153 V/deg. S_i at ψ is the slope of y-axis sensor curve in figure 9, which is 0.0069 V/deg. Therefore, the internal yaw misalignment of the y-axis sensor should be about 1.125 degrees.

B. CALCULATION OF YAW MISALIGNMENT ERROR DUE TO MOUNTING FLANGE CLEARANCE HOLES

Figure A-1 depicts the maximum possible misalignment due to the clearances between the screws and the clearance holes on one flange of the package. According to the figure and the definition of ψ given in section A above, when measurement is made with the y-axis sensor, yaw misalignment caused by clearance holes alone is 90-0.443, or 89.557 degrees. The change in sensitivities are calculated from equation (A-1) to be -0.003 percent in both axes, which corresponds to less than 0.001 degree error at 5 degrees.

The bias change at 5 degrees can be calculated from the equation below:

$$\Delta b = 5^\circ(\cos 89.557 - \cos 0) \tag{A-2}$$

which turned out to be 0.04 degree.

Table 1. Estimation of the Overall Error for
NTF Wall Attitude Measurements

Error Sources	Errors in Degree	
	X Axis (SN 264)	Y Axis (SN 268)
Linearity Error (±5 Degrees)	0.008	0.016
Hysteresis	0.008	0.016
Repeatability	0.036	0.012
Temperature at -250 °F	0.037	0.008
Wire Resistance Error	0.010	0.009
Roll-on-Pitch Interaction	0.064	0.180
Random Rectification	0.005	0.003
Total RMS Error	0.084	0.182

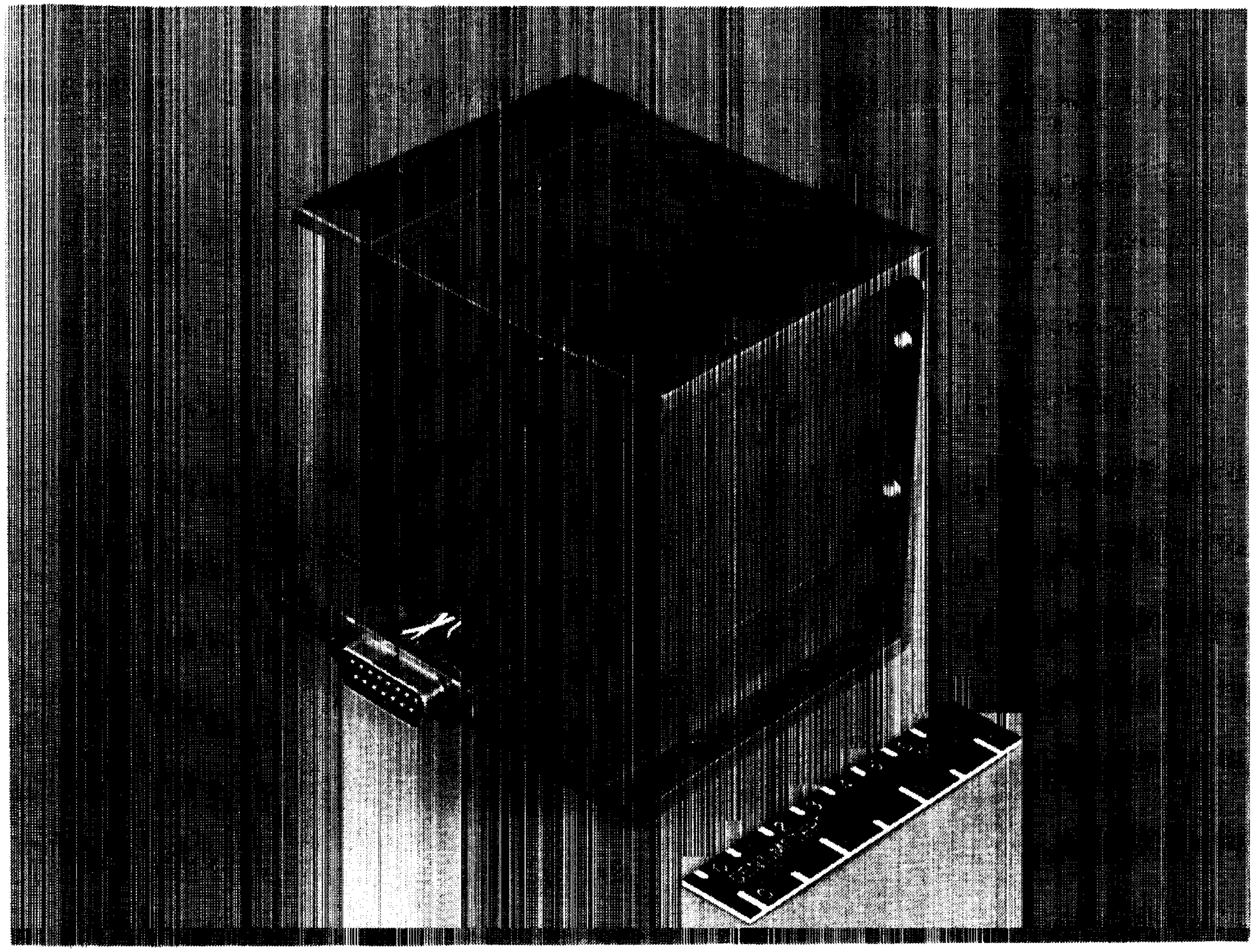


Figure 1. Dual-Axis Wall Attitude Measurement Sensor

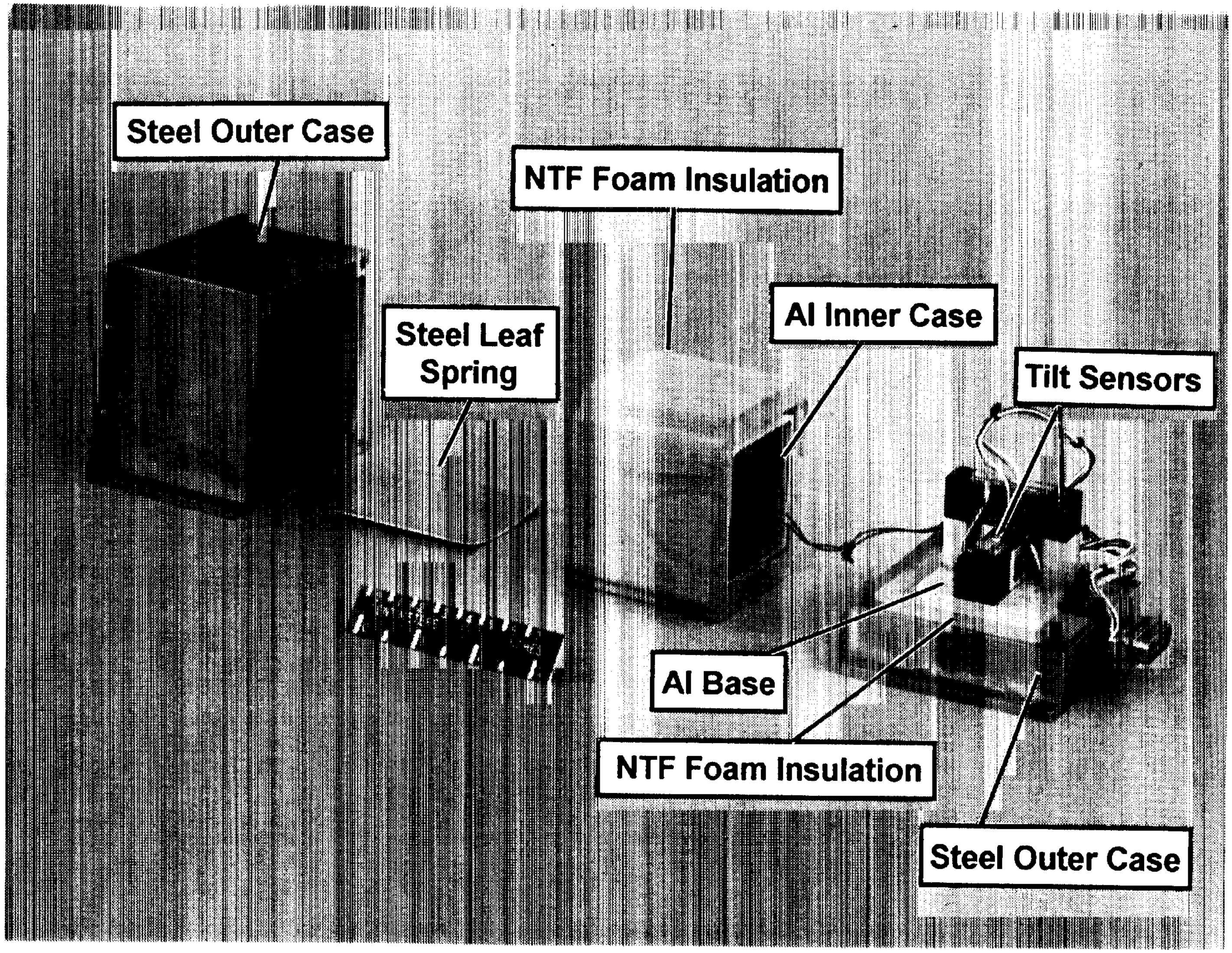
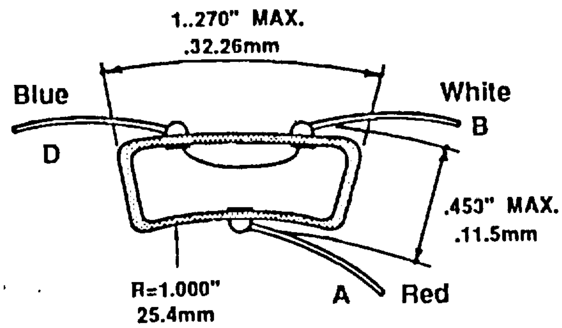
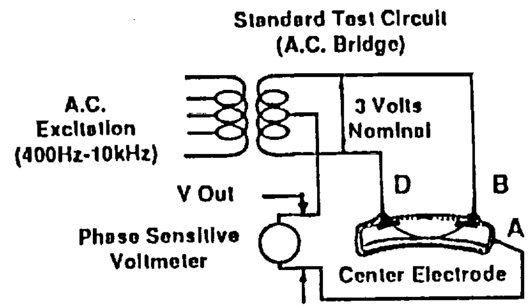


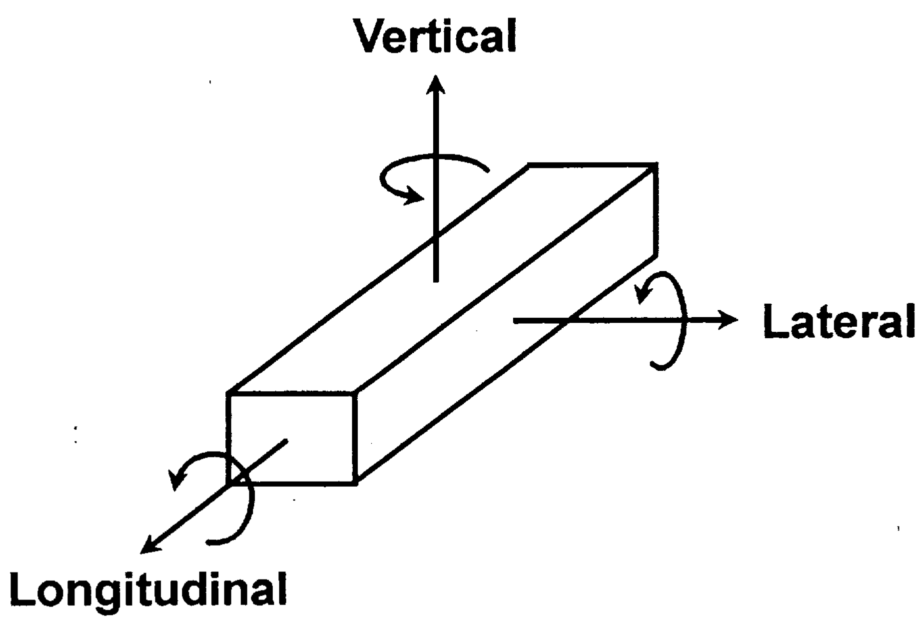
Figure 2. Disassembled Dual-Axis Attitude Measurement Sensor



Mechanical Schematic



Electrical Schematic



Sensor Mounting Block

Figure 3. Electrolytic Tilt Sensor

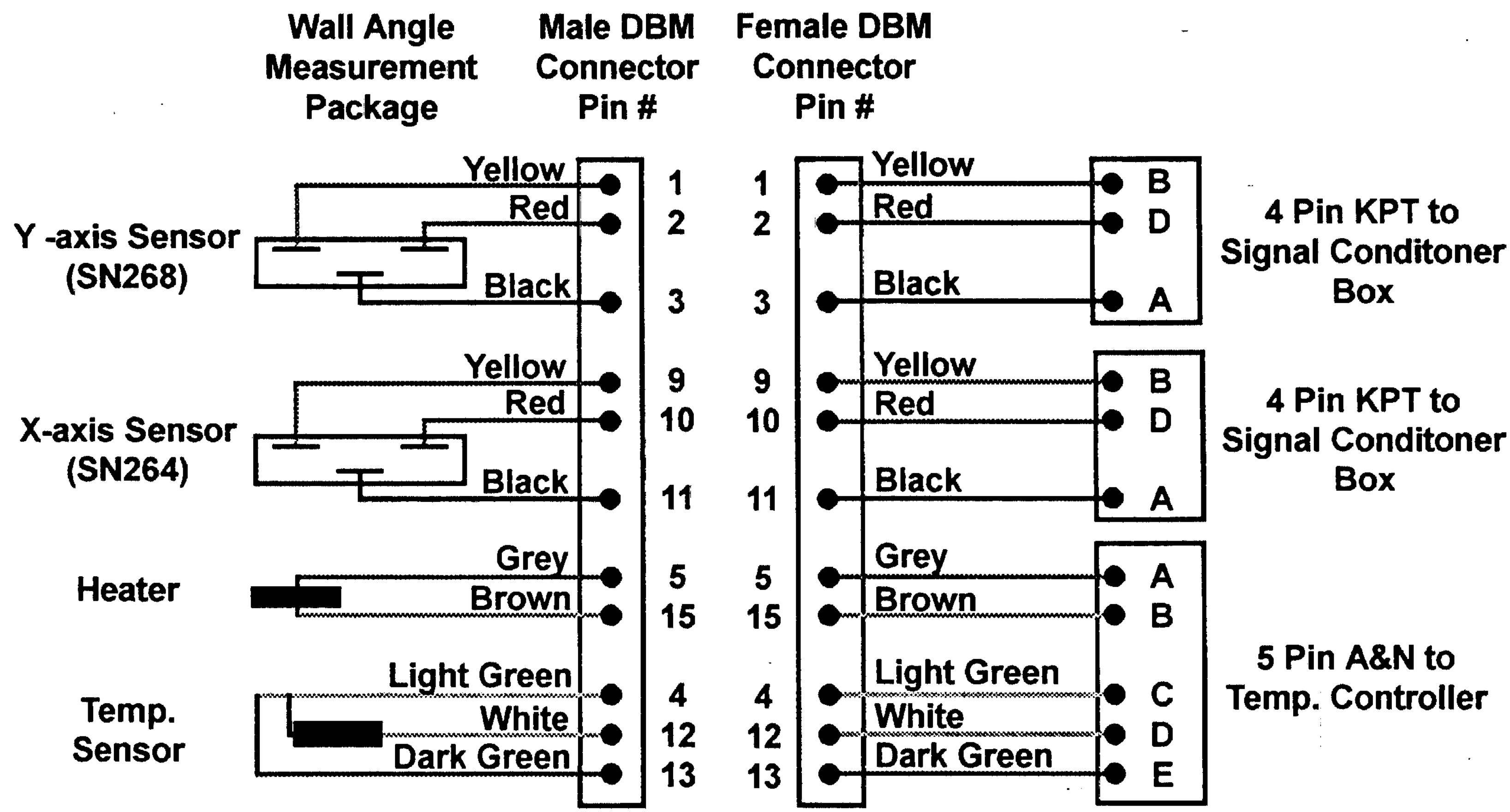


Figure 4. Wiring Schematic of the Sensor Package

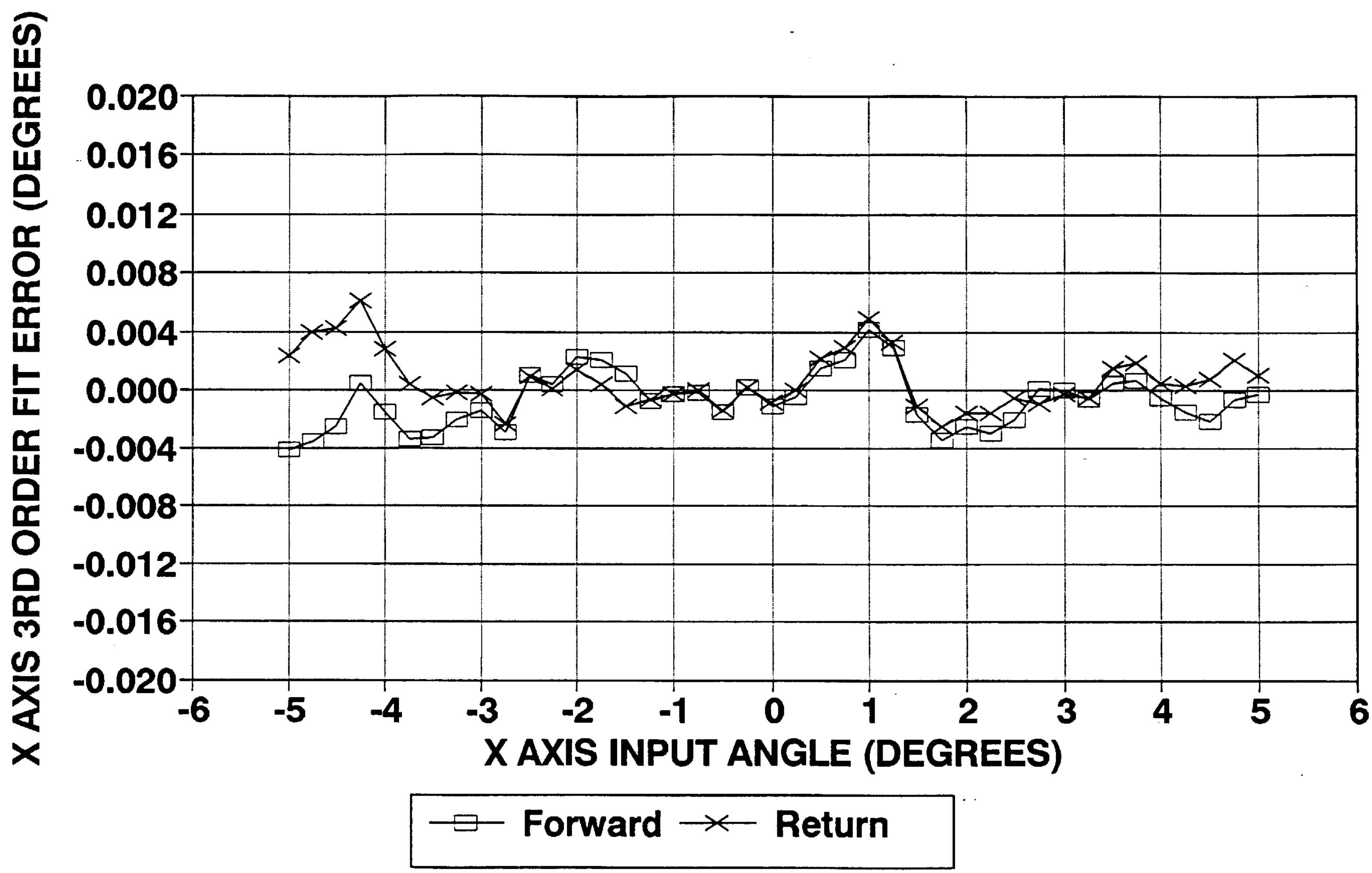


Figure 5. Wall Attitude Measurement Sensor Package
X Axis 3rd Order Error

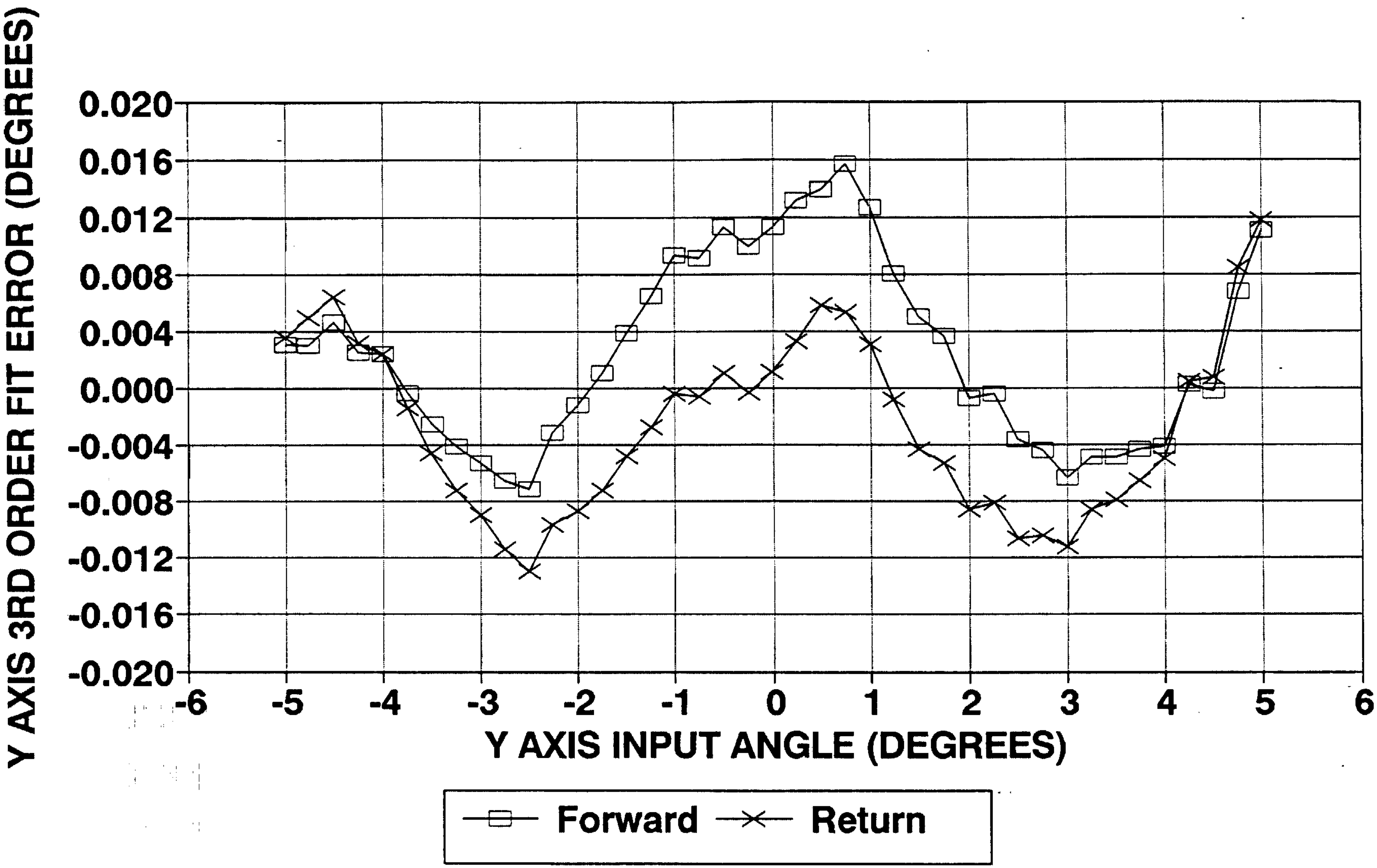


Figure 6. Wall Attitude Measurement Sensor Package
Y Axis 3rd Order Fit Error

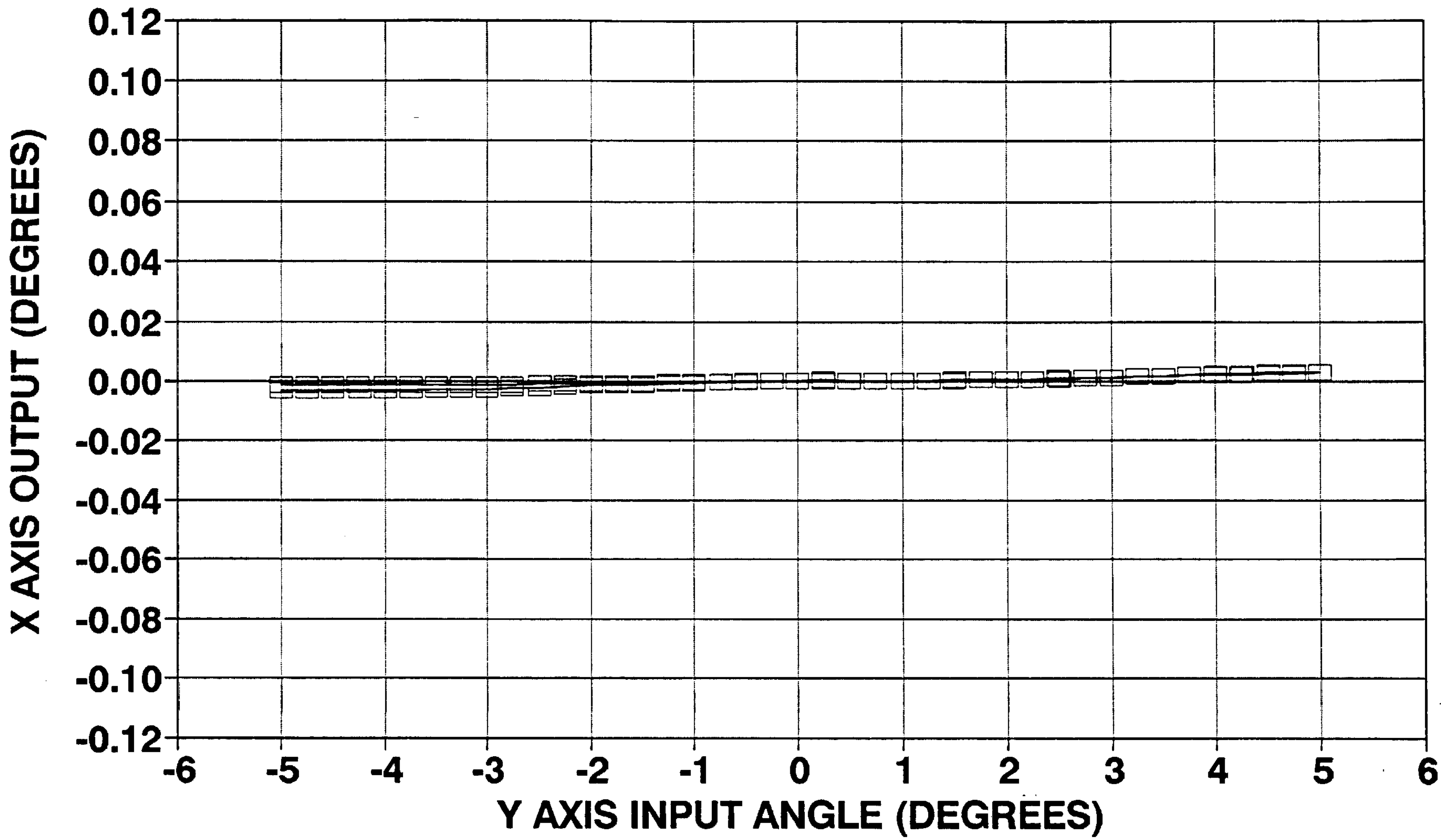


Figure 7. Wall Attitude Measurement Sensor Package Nonsensitive X Axis Output

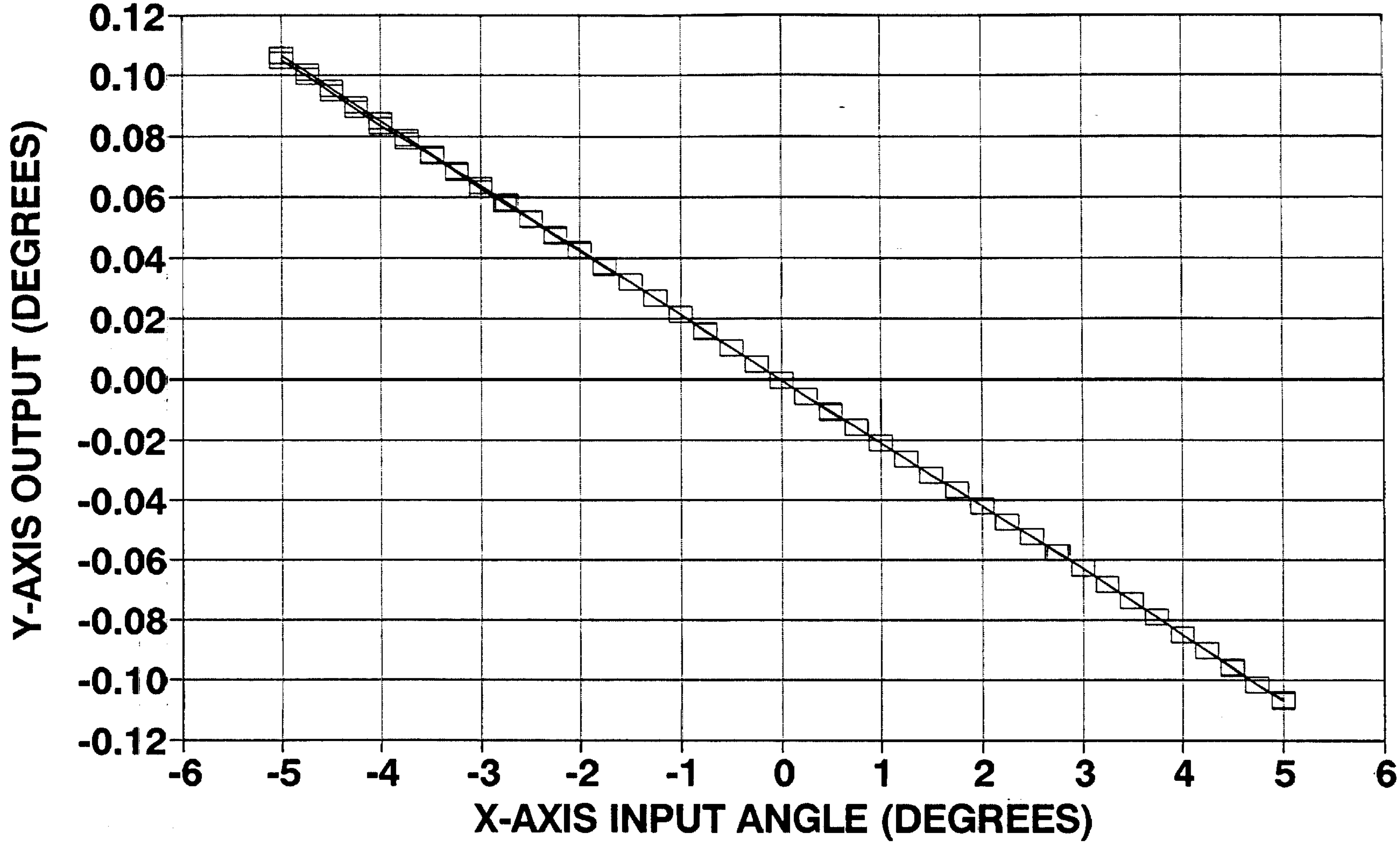


Figure 8. Wall Attitude Measurement Sensor Package Nonsensitive Y Axis Output

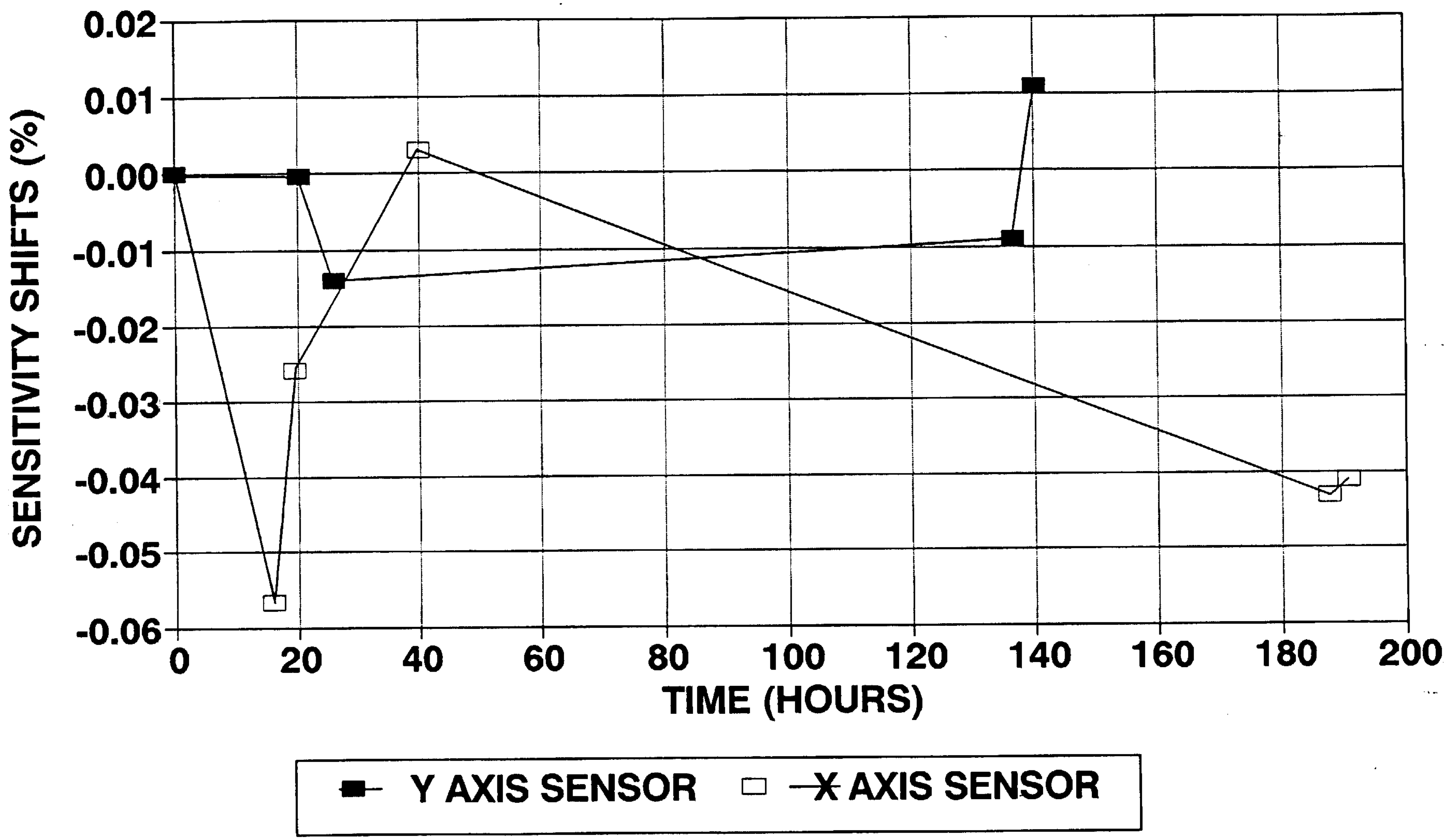


Figure 9. Wall Attitude Measurement Sensor Package Sensitivity Repeatabilities

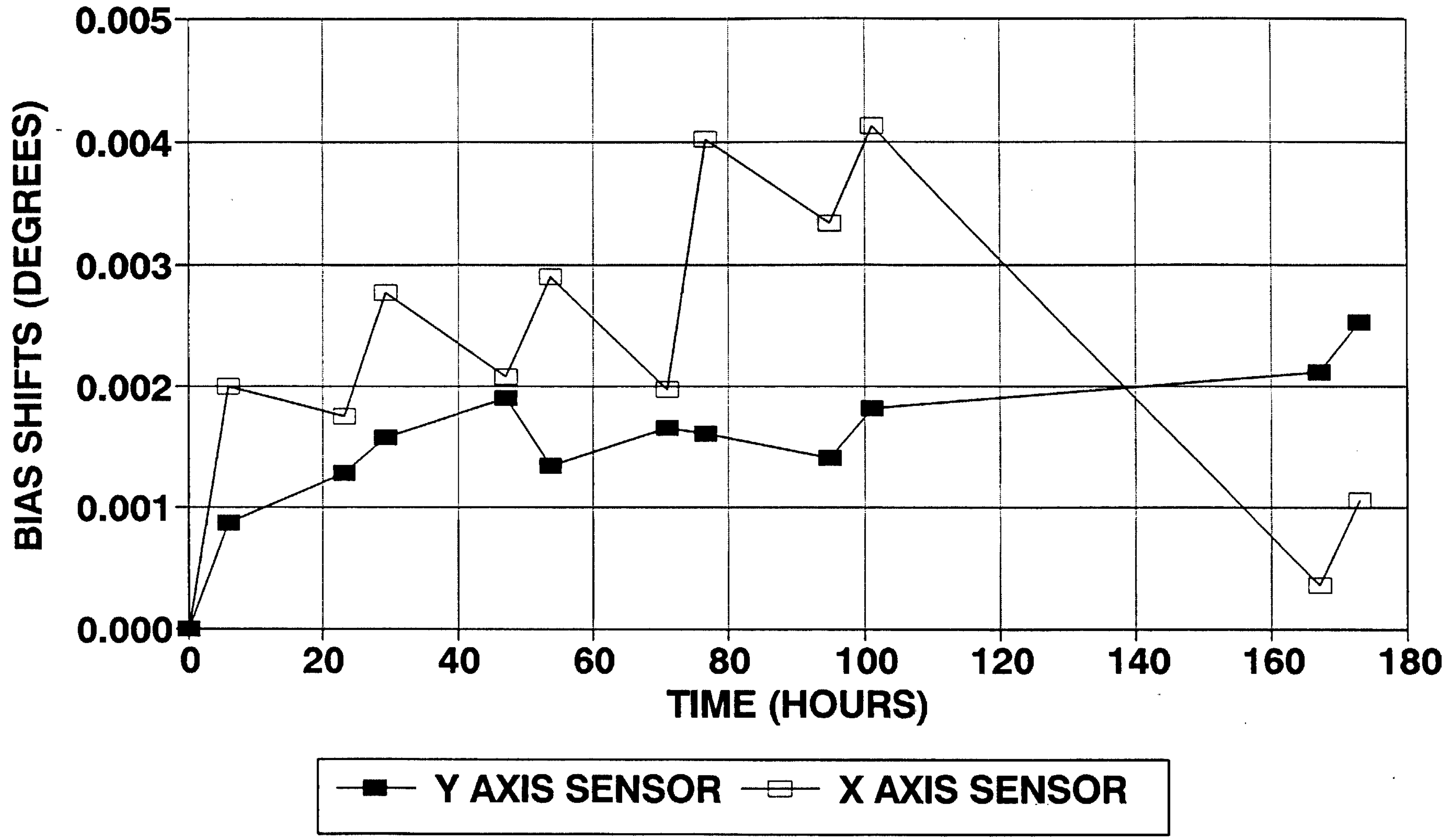


Figure 10. Wall Attitude Measurement Sensor Package Bias Repeatabilities

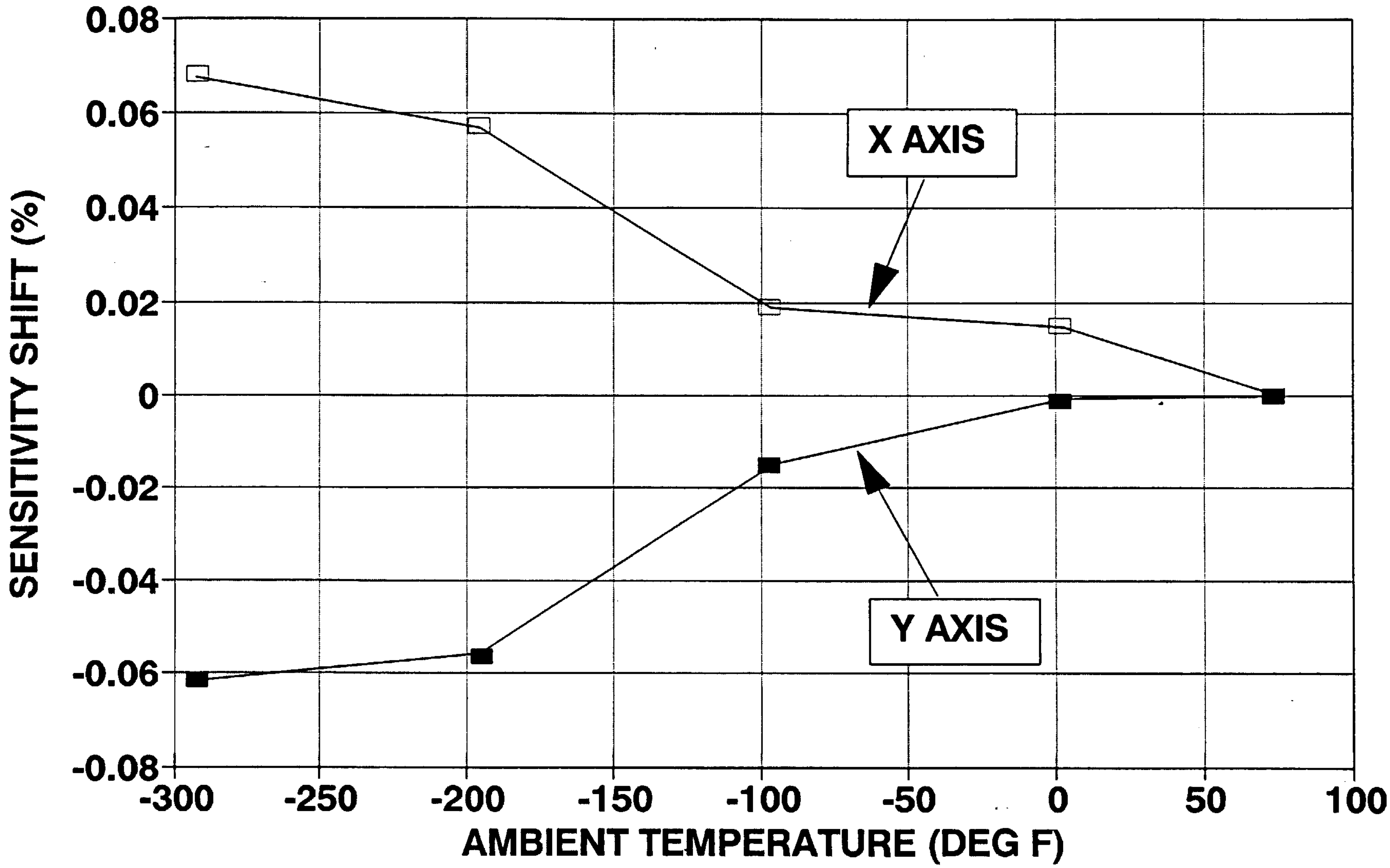


Figure 11. Wall Attitude Measurement Sensor Package Sensitivity Shifts Versus Temperature

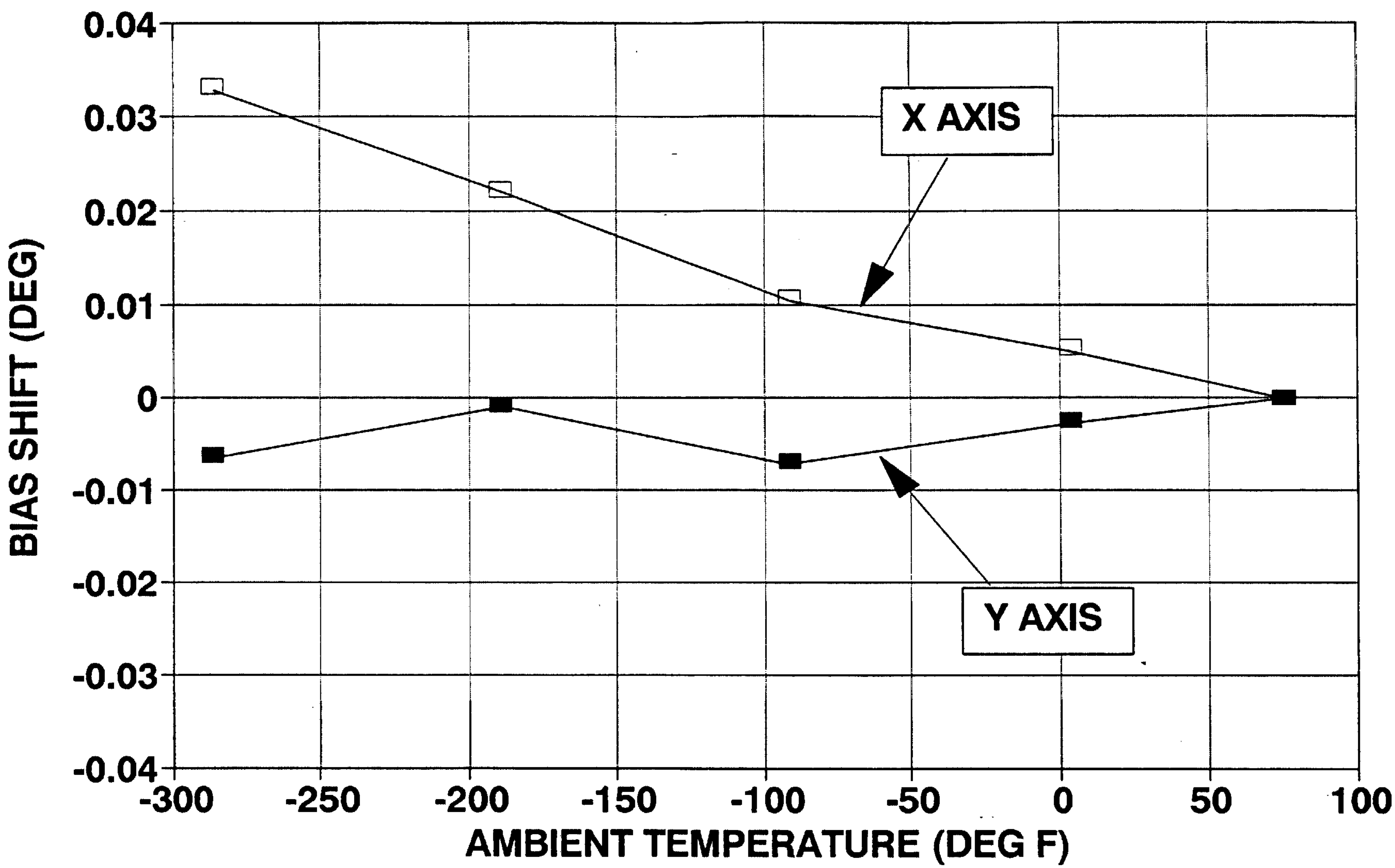


Figure 12. Wall Attitude Measurement Sensor Package Bias Shifts Versus Temperature

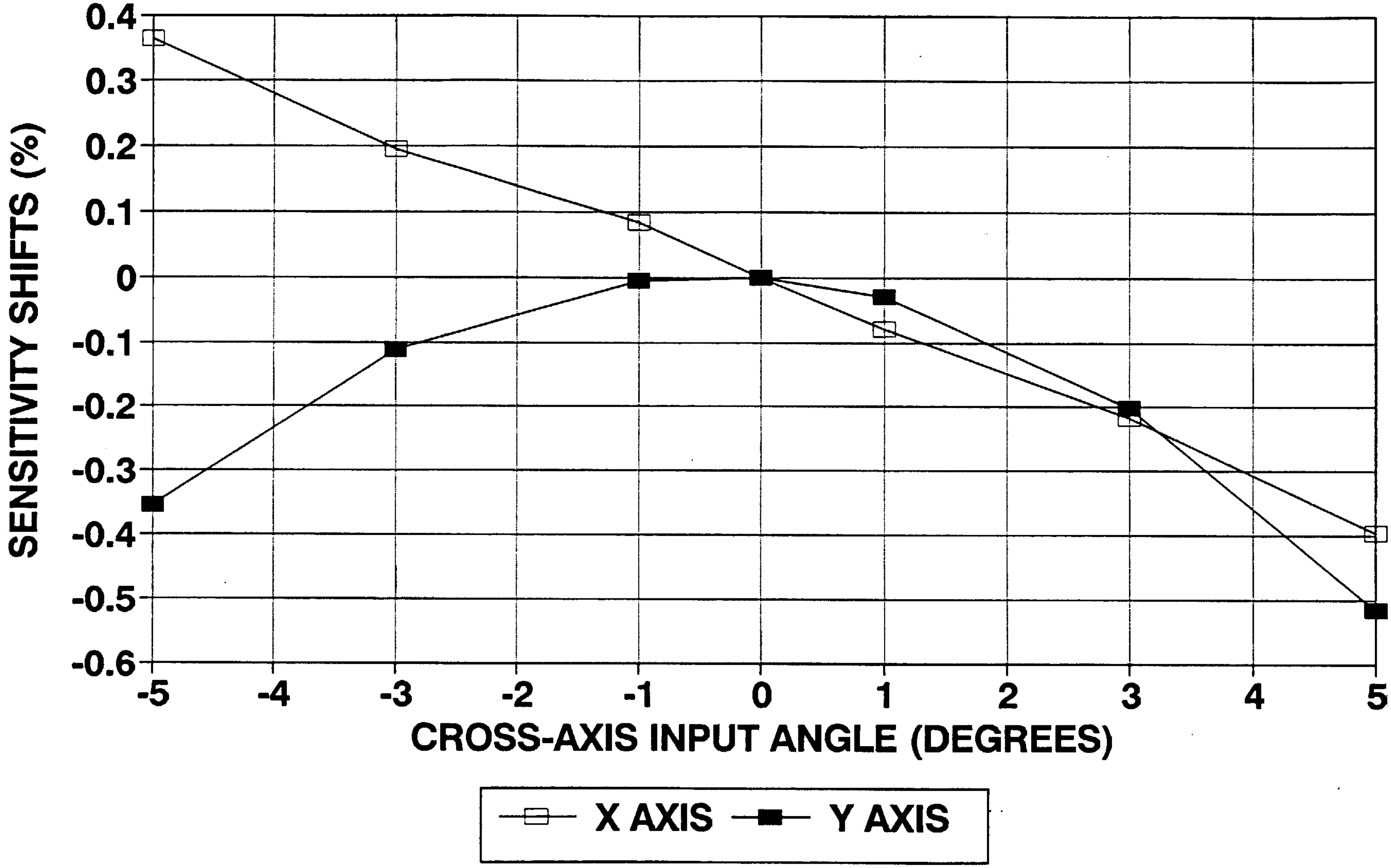


Figure 13. Wall Attitude Measurement Sensor Package Sensitivity Shifts vs. Off-Axis Input Angle

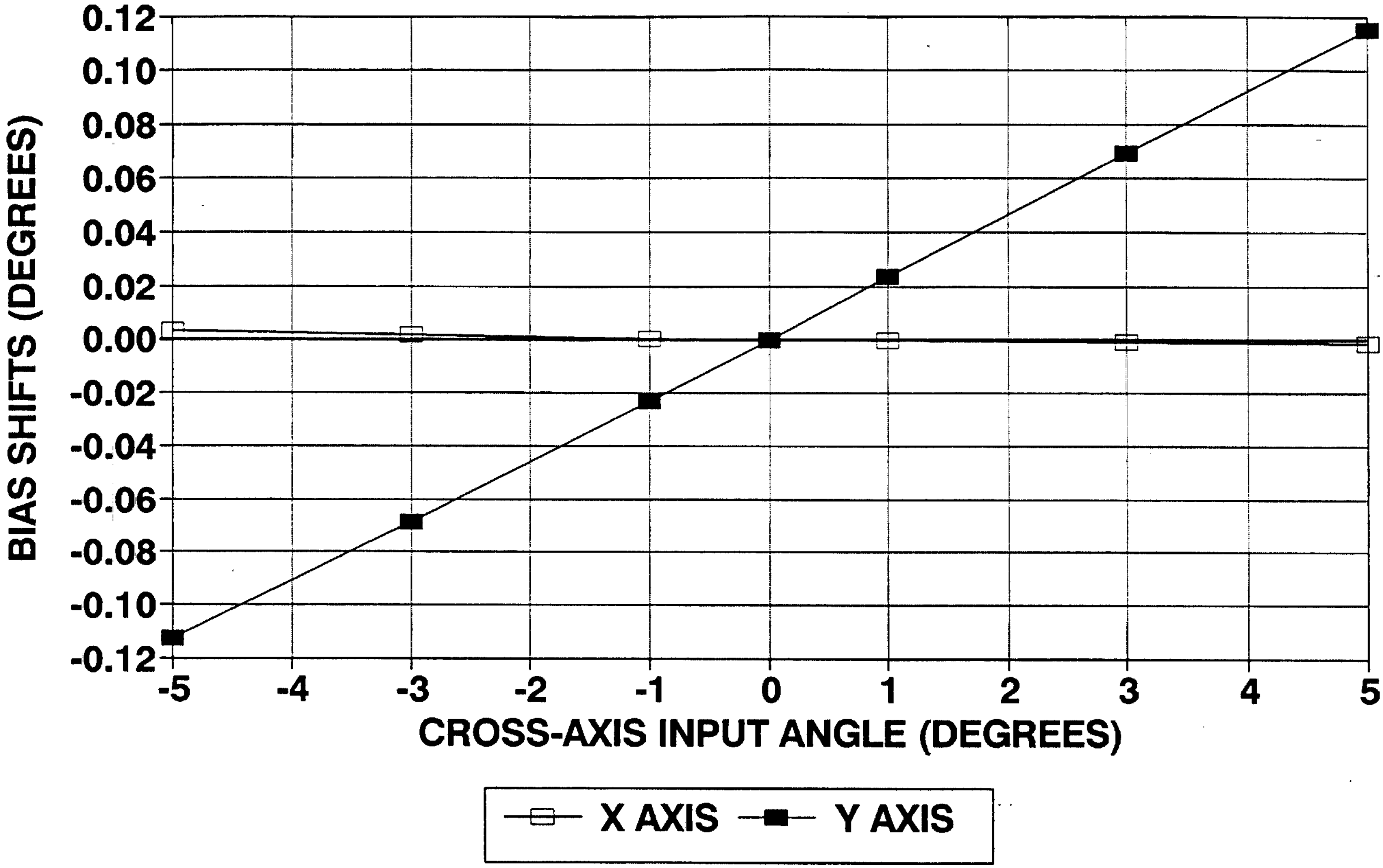


Figure 14. Wall Attitude Measurement Sensor Package Bias Shift vs. Off-Axis Input Angle

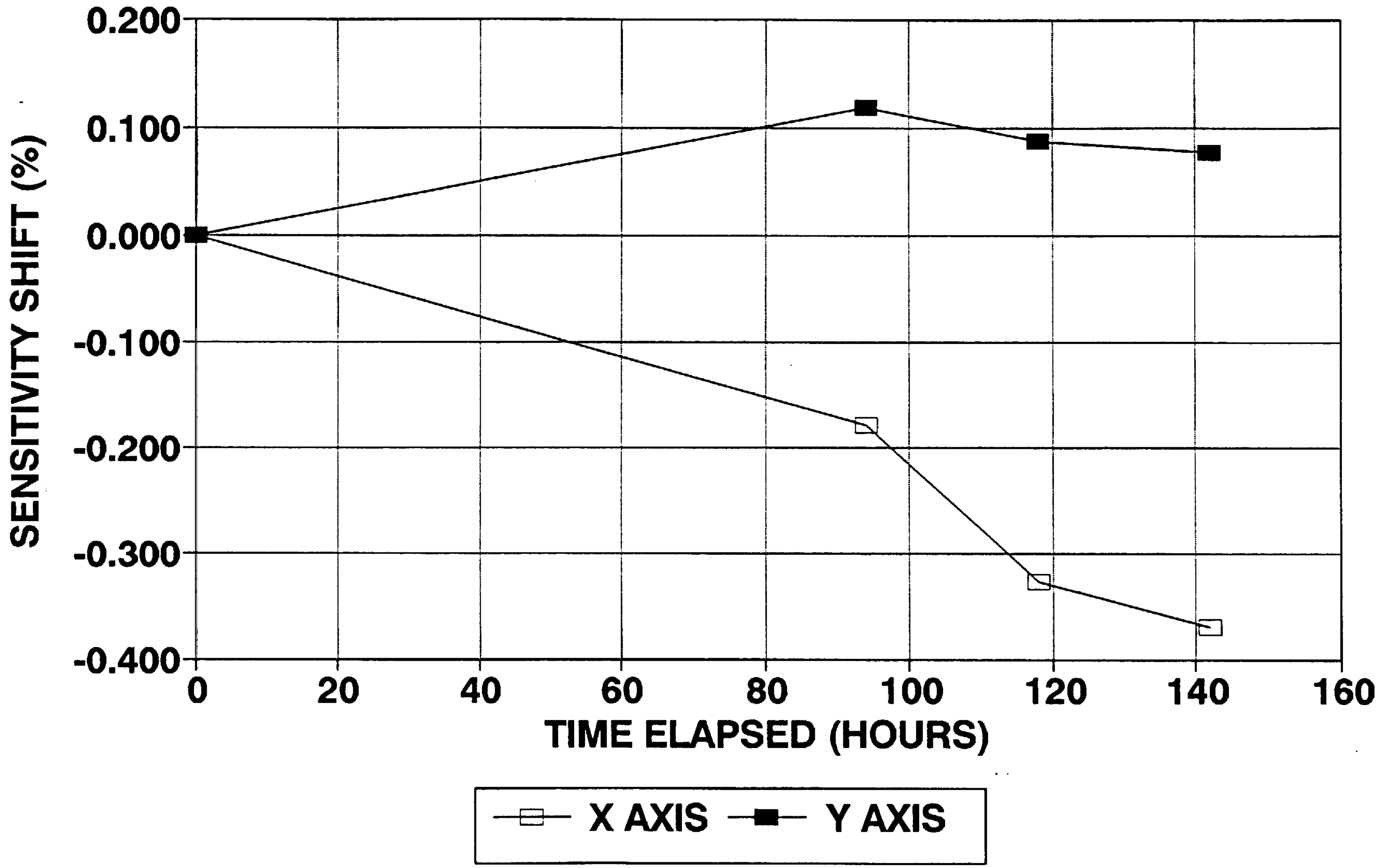


Figure 15. Wall Package Long Cable Sensitivity Repeatability Result

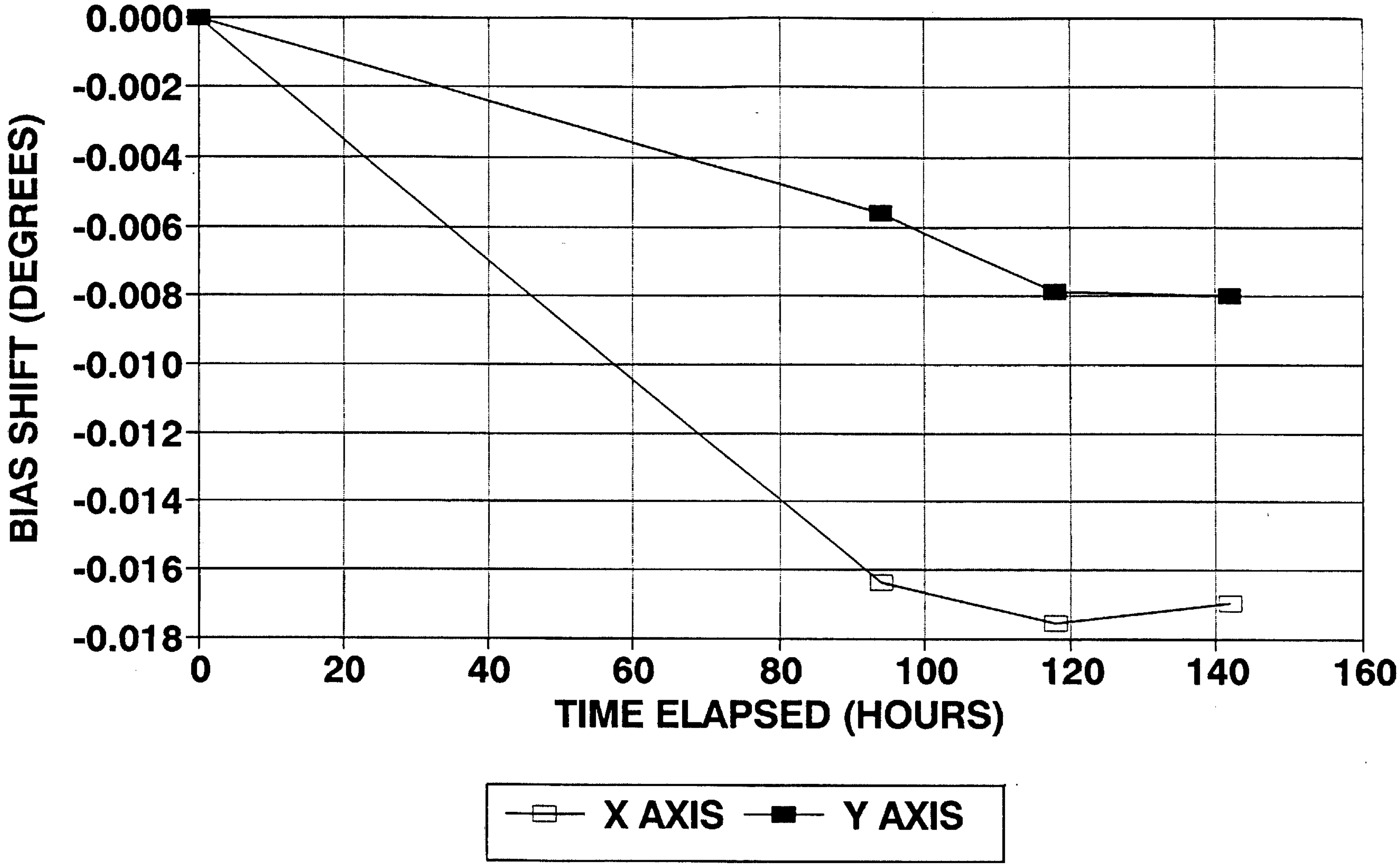


Figure 16. Wall Package Long Cable Bias Repeatability Result

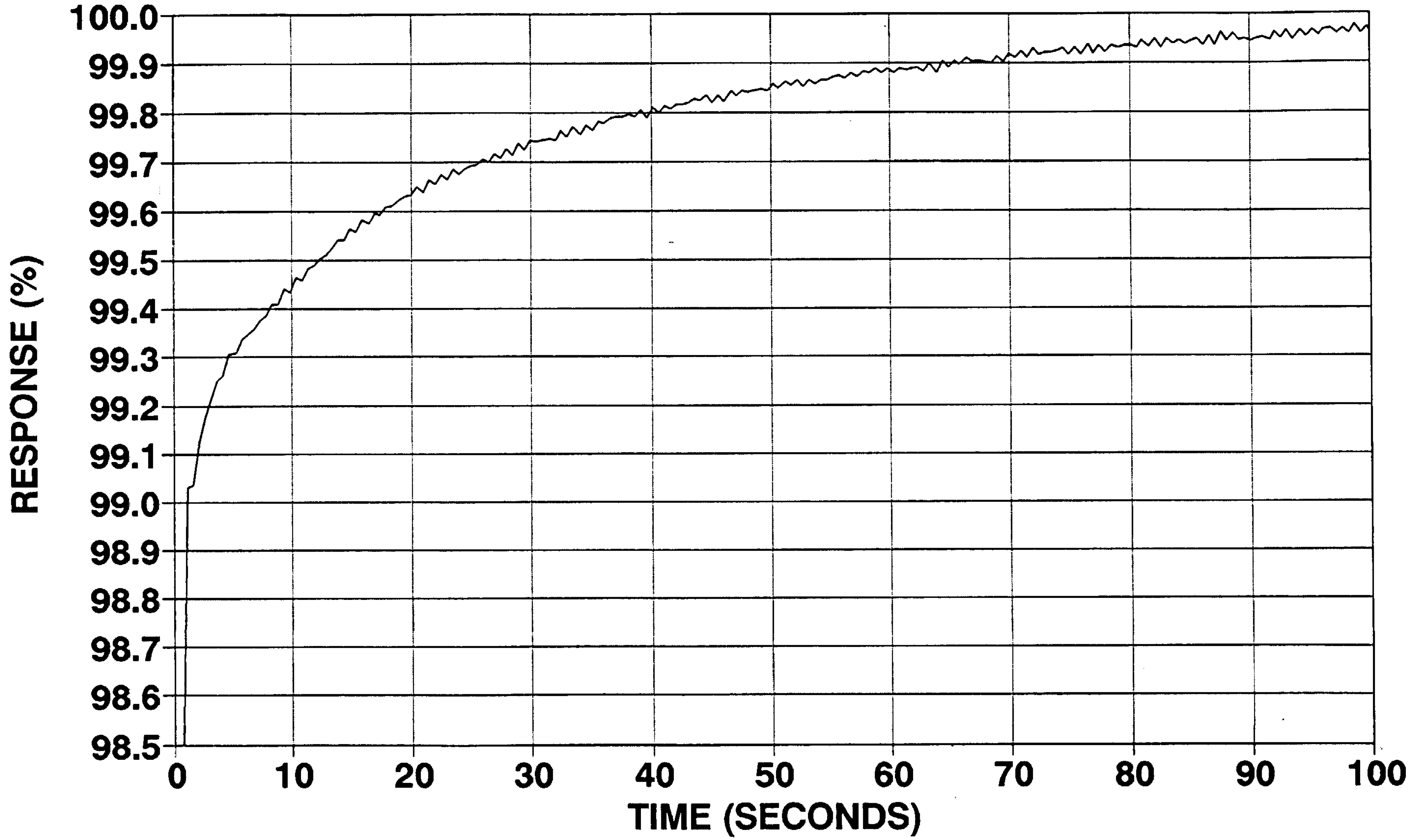


Figure 17. X Axis Tilt Sensor 1-Degree Step Response Time History

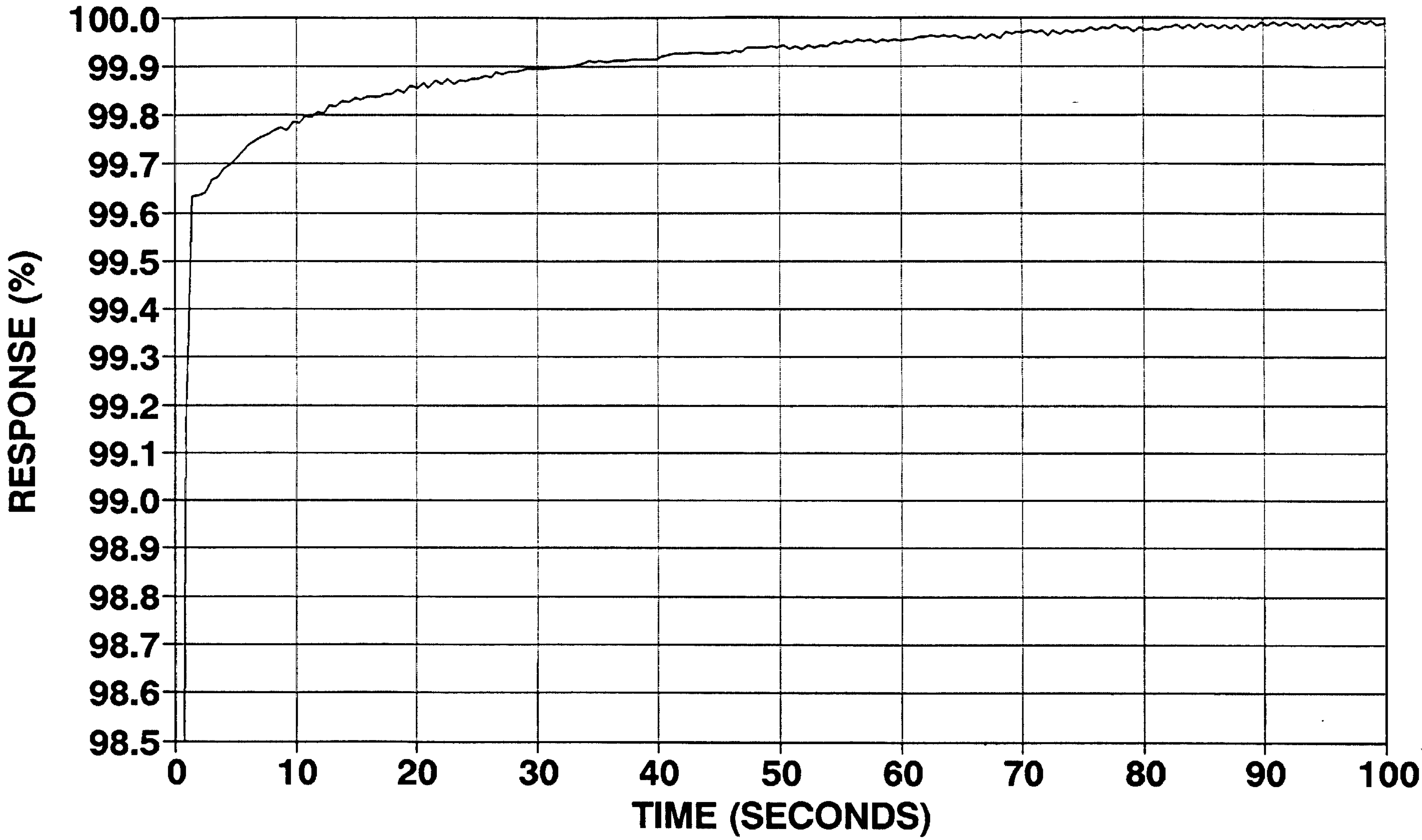


Figure 18. Y Axis Tilt Sensor 1-Degree Step Response Time History

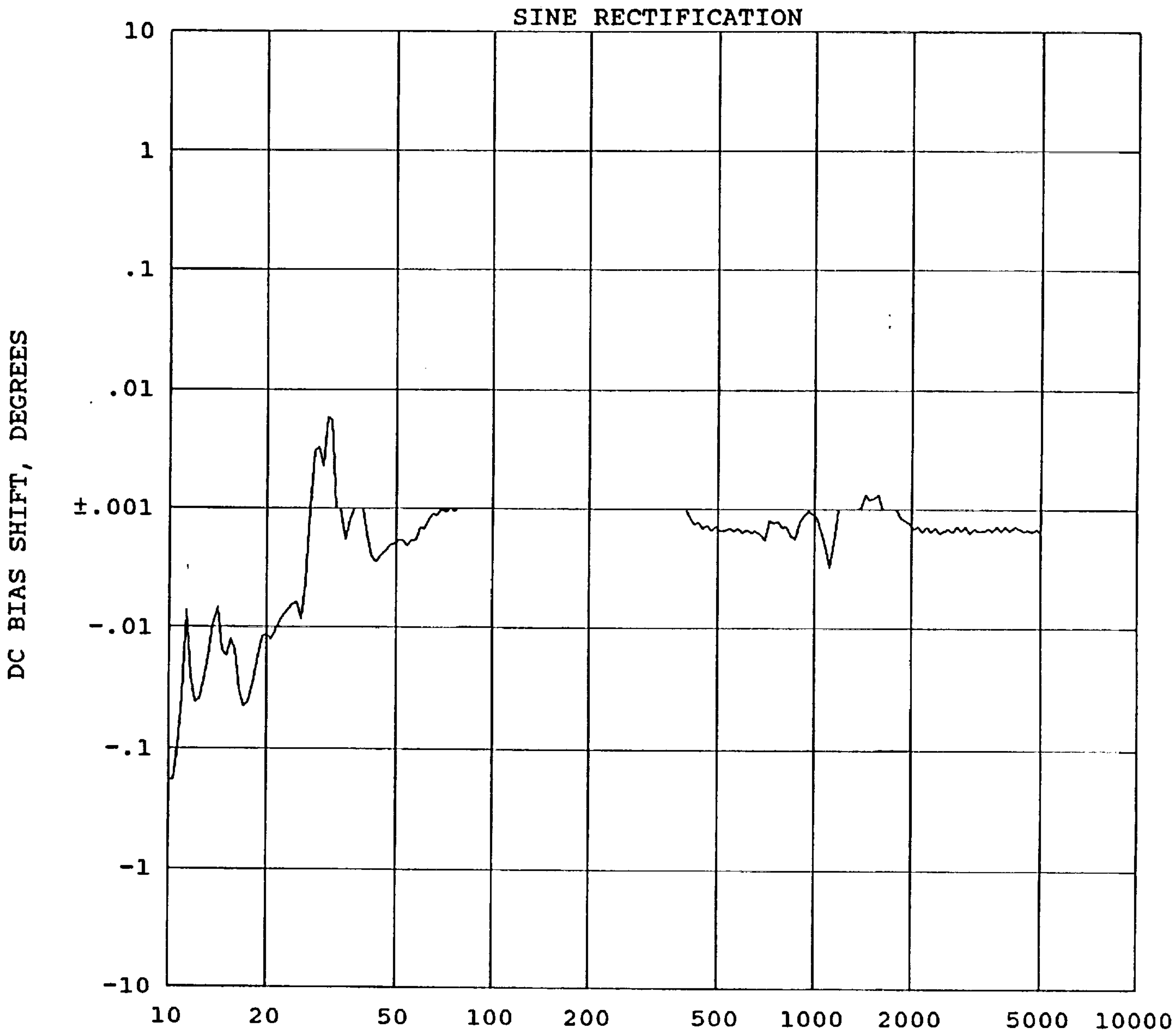


Figure 19. X Axis Tilt Sensor Rectification at 1G rms from 10 to 5000 Hz (Longitudingal Direction)

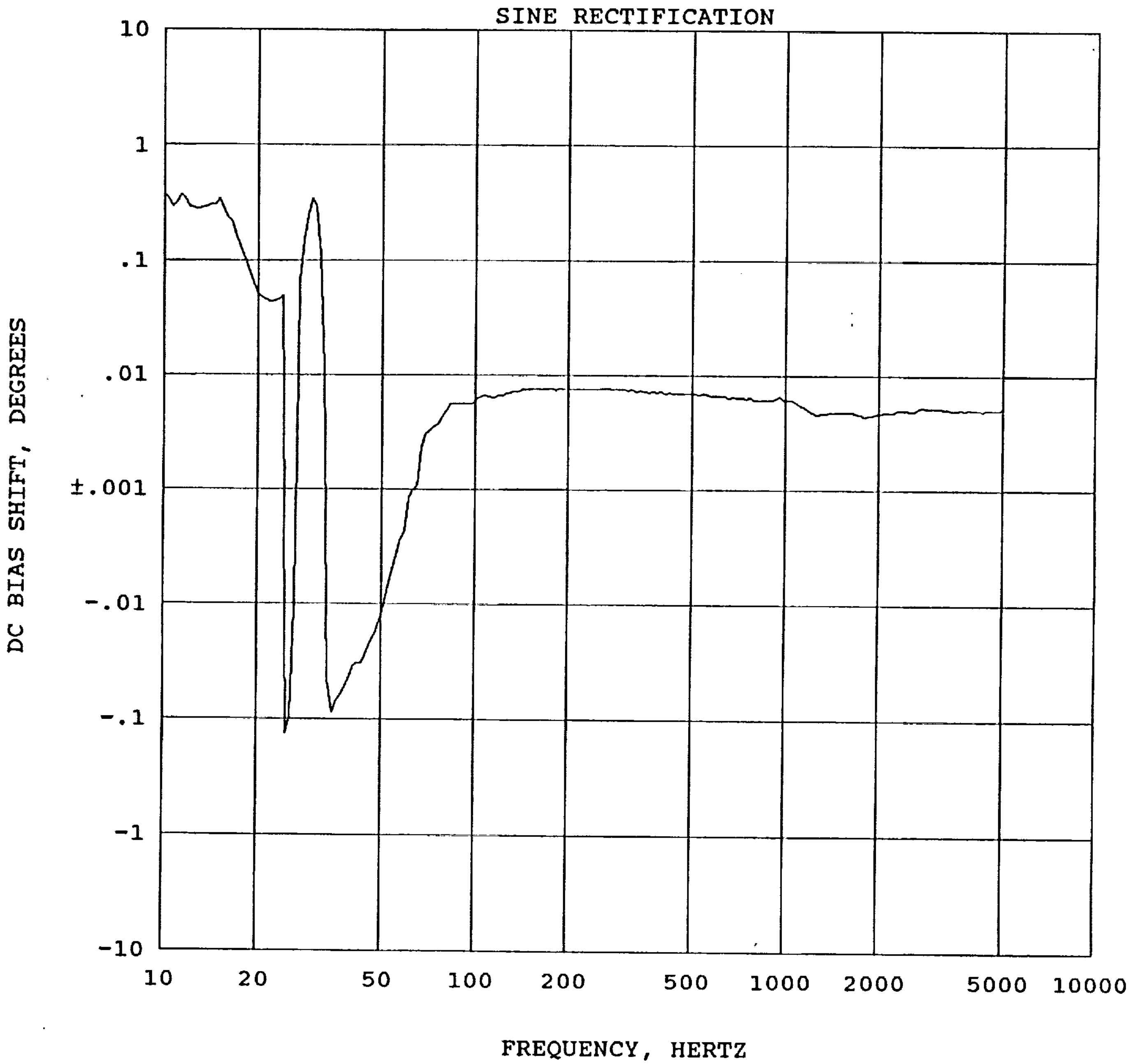


Figure 20. X Axis Tilt Sensor Rectification at 1G rms from 10 to 5000 Hz (Lateral Direction)

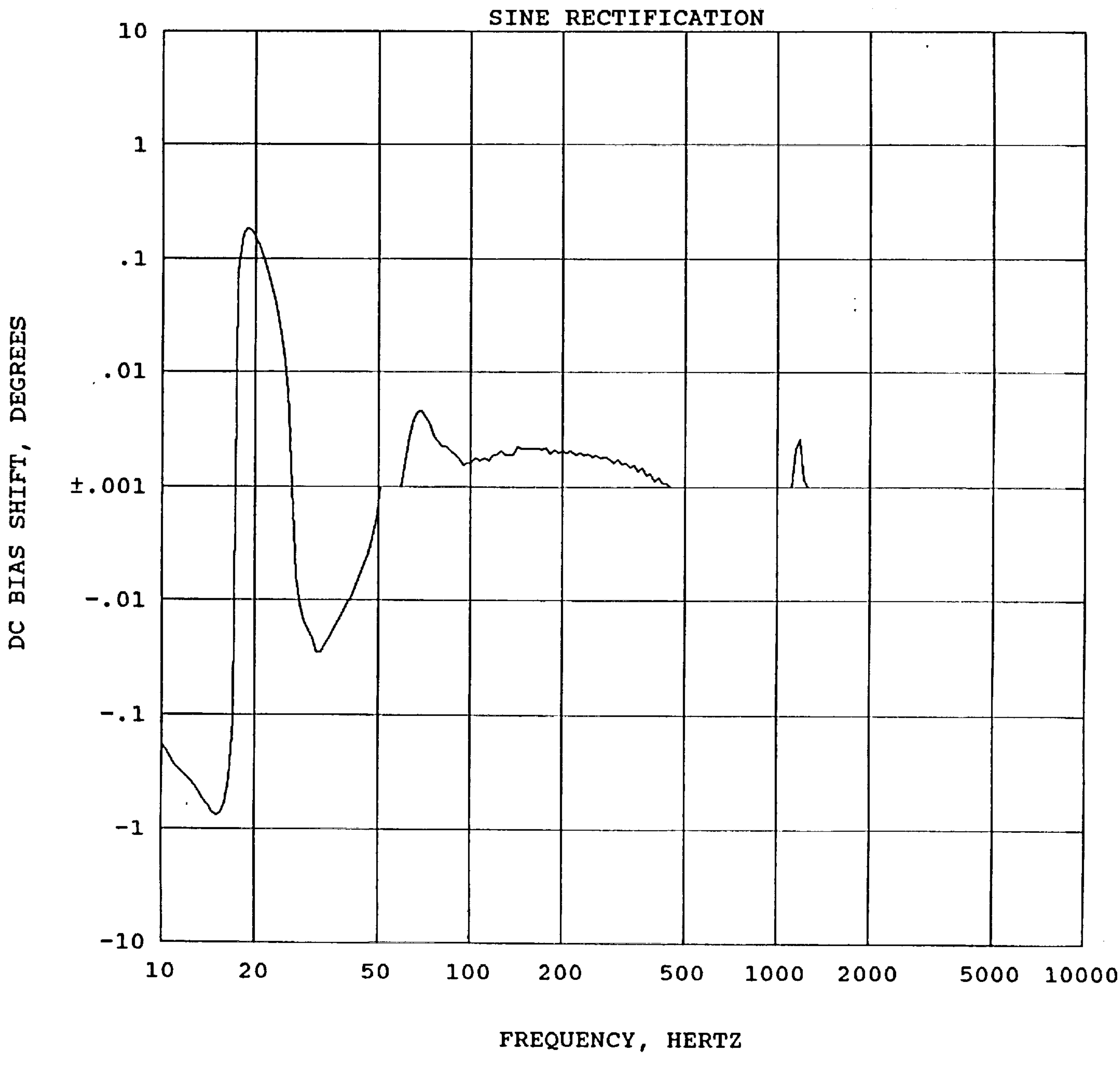


Figure 21. X Axis Tilt Sensor Rectification at 1G rms from 10 to 5000 Hz (Vertical Direction)

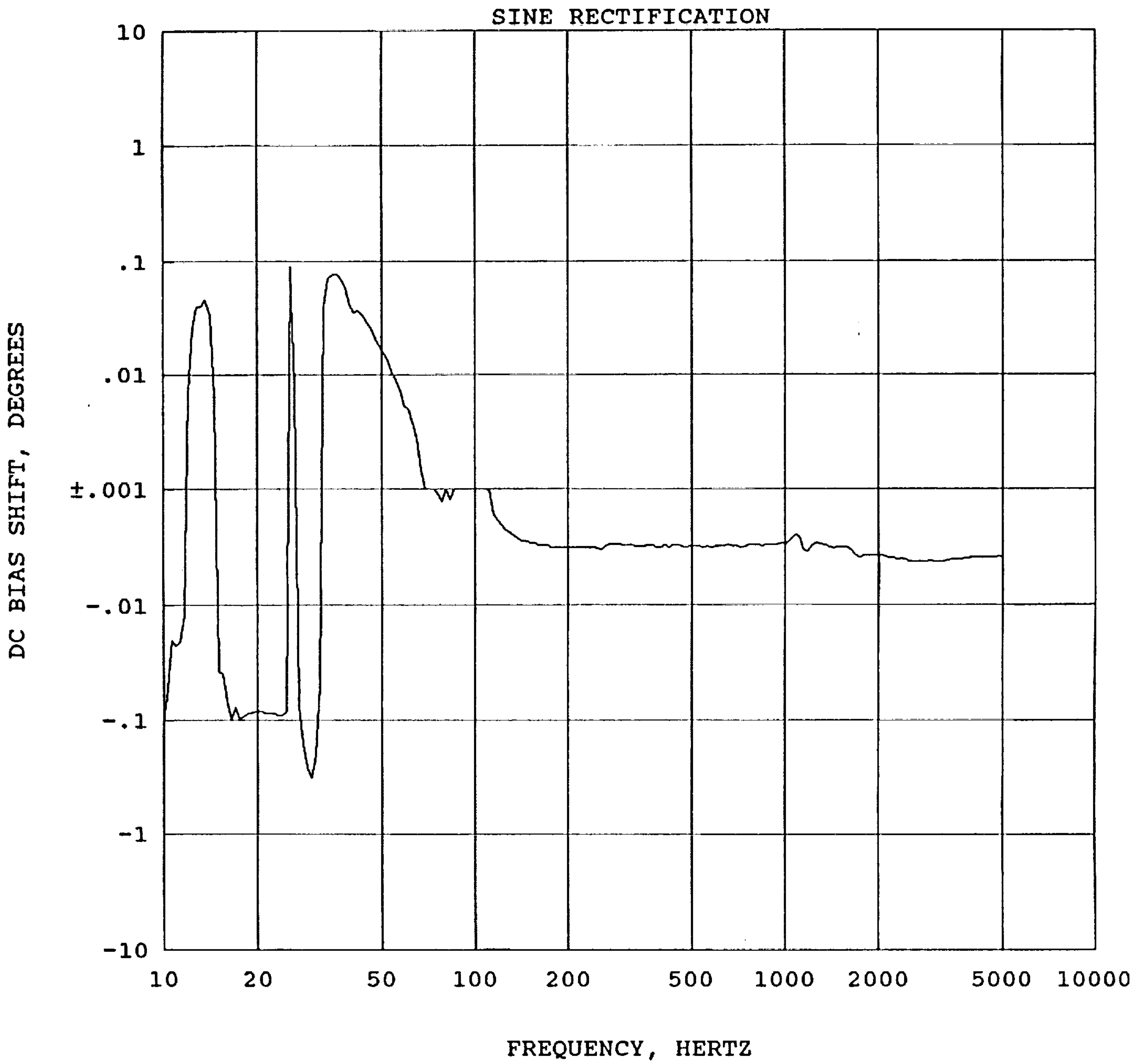


Figure 22. Y Axis Tilt Sensor Rectification at 1G rms from 10 to 5000 Hz (Longitudinal Direction)

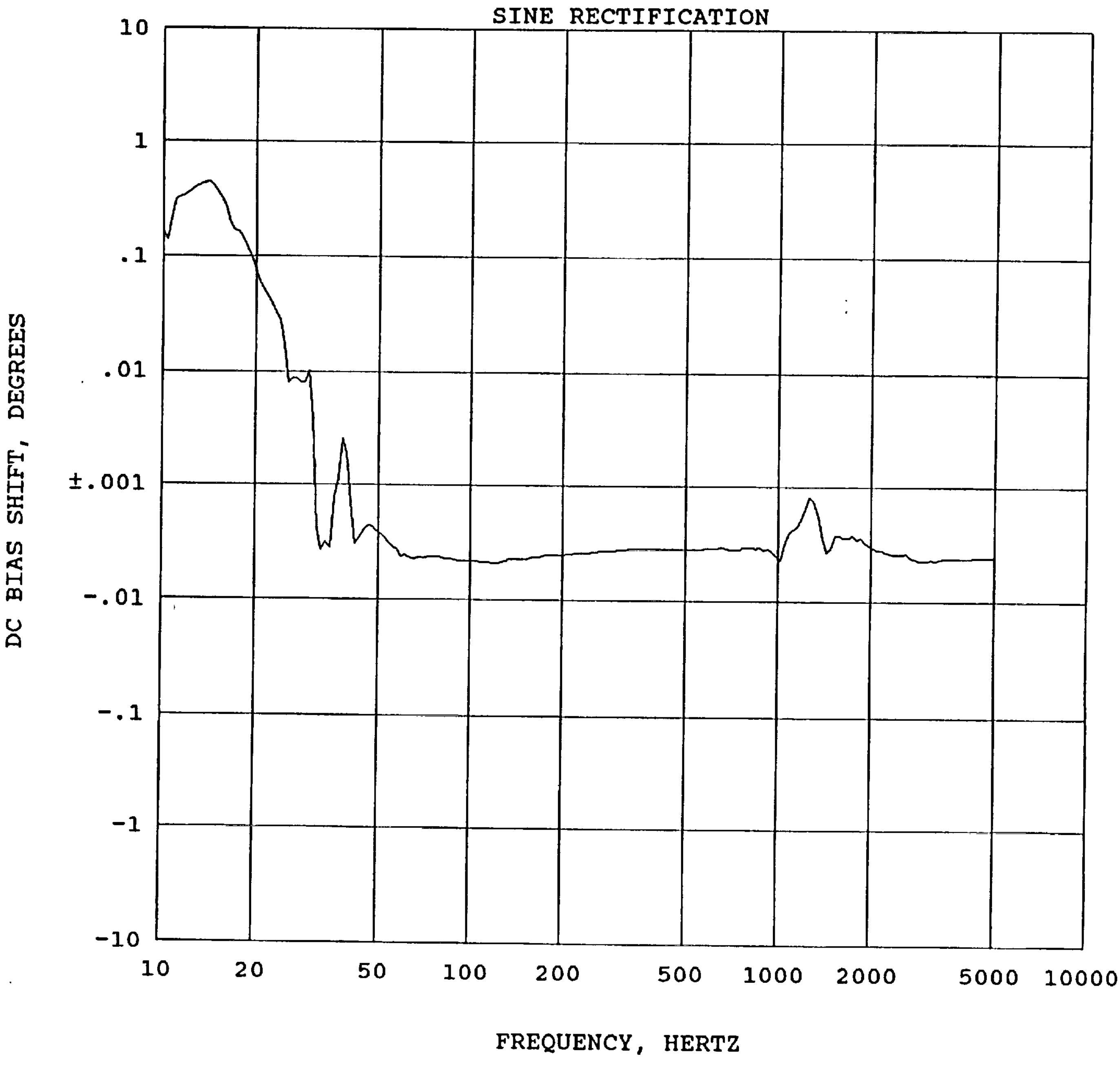


Figure 23. Y Axis Tilt Sensor Rectification at 1G rms from 10 to 5000 Hz (Lateral Direction)

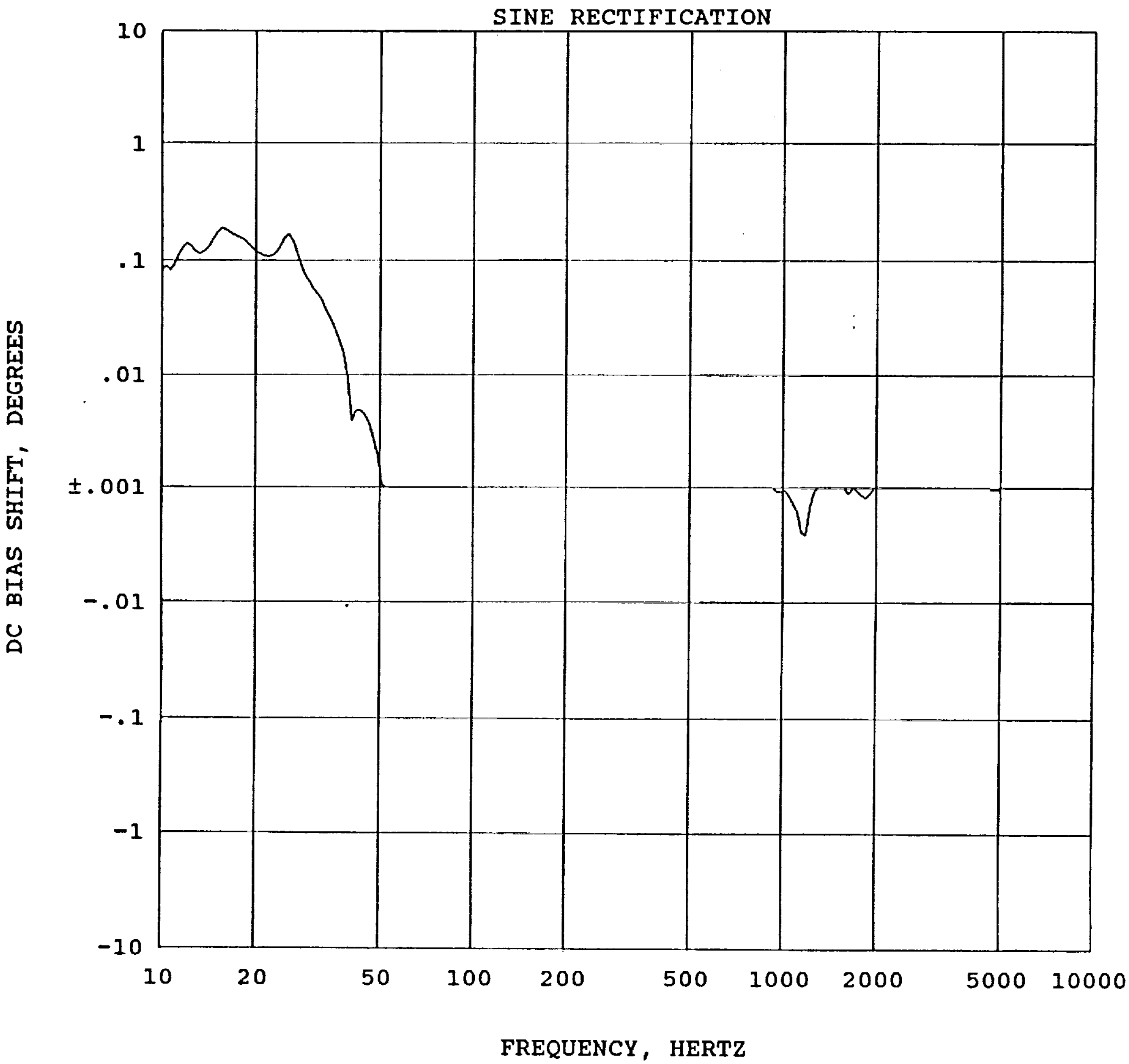


Figure 24. Y Axis Tilt Sensor Rectification at 1G rms from 10 to 5000 Hz (Vertical Direction)

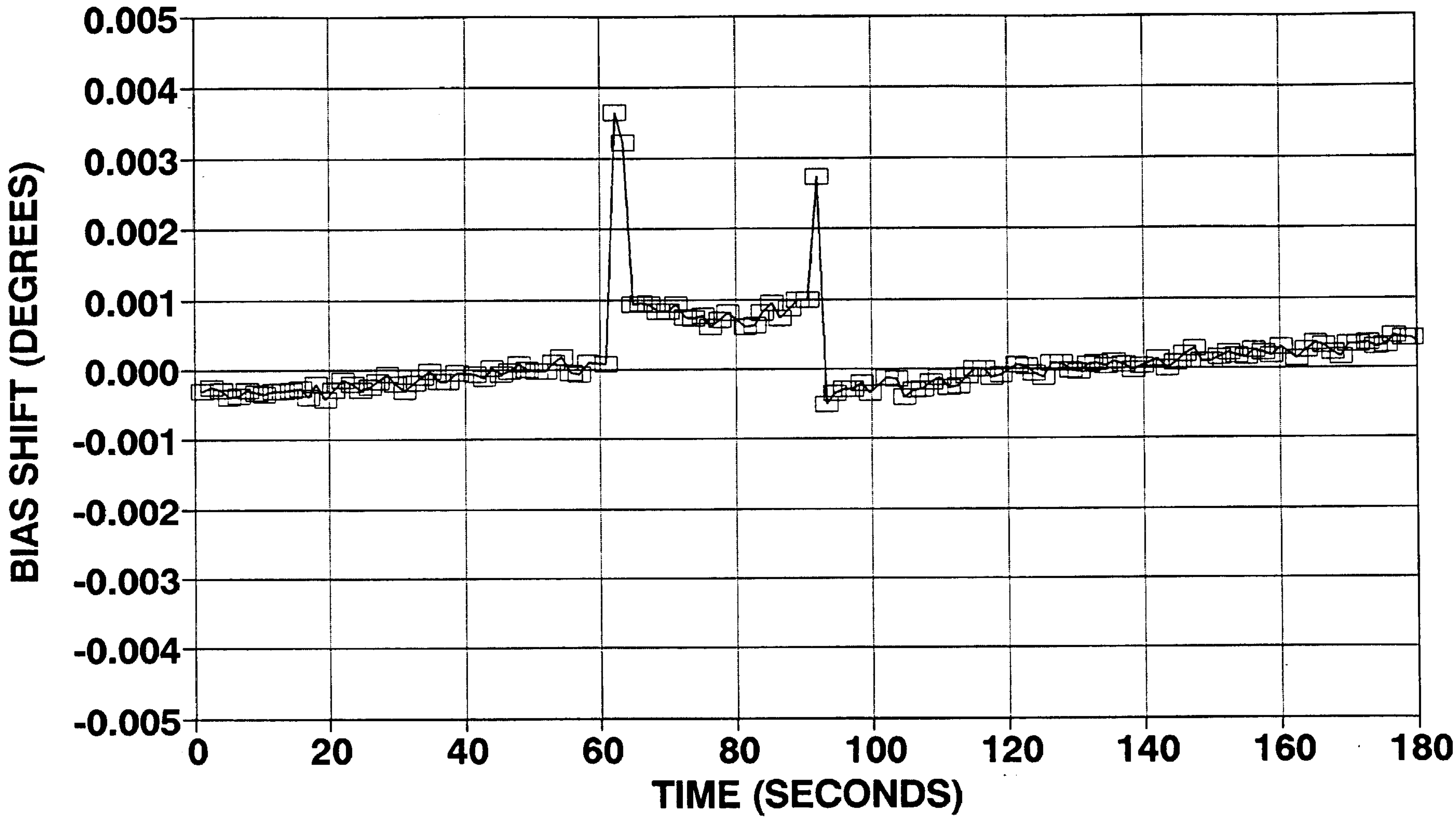


Figure 25. X Axis Tilt Sensor Random Rectification Result at 3G RMS 20 to 5000 Hz, Longitudinal Direction

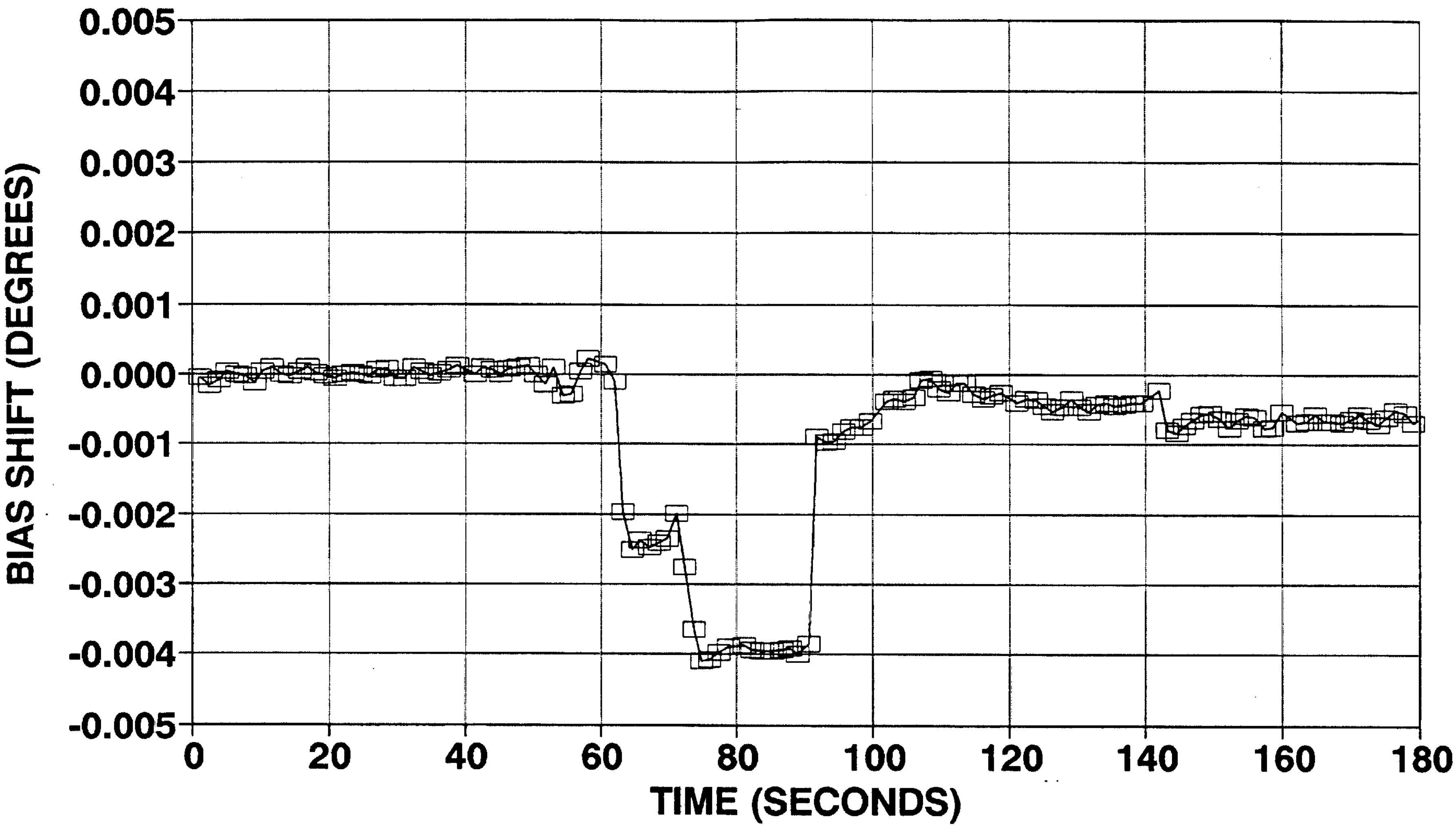


Figure 26. X Axis Tilt Sensor Random Rectification Results at 3G RMS 20 to 5000 Hz, Lateral Direction

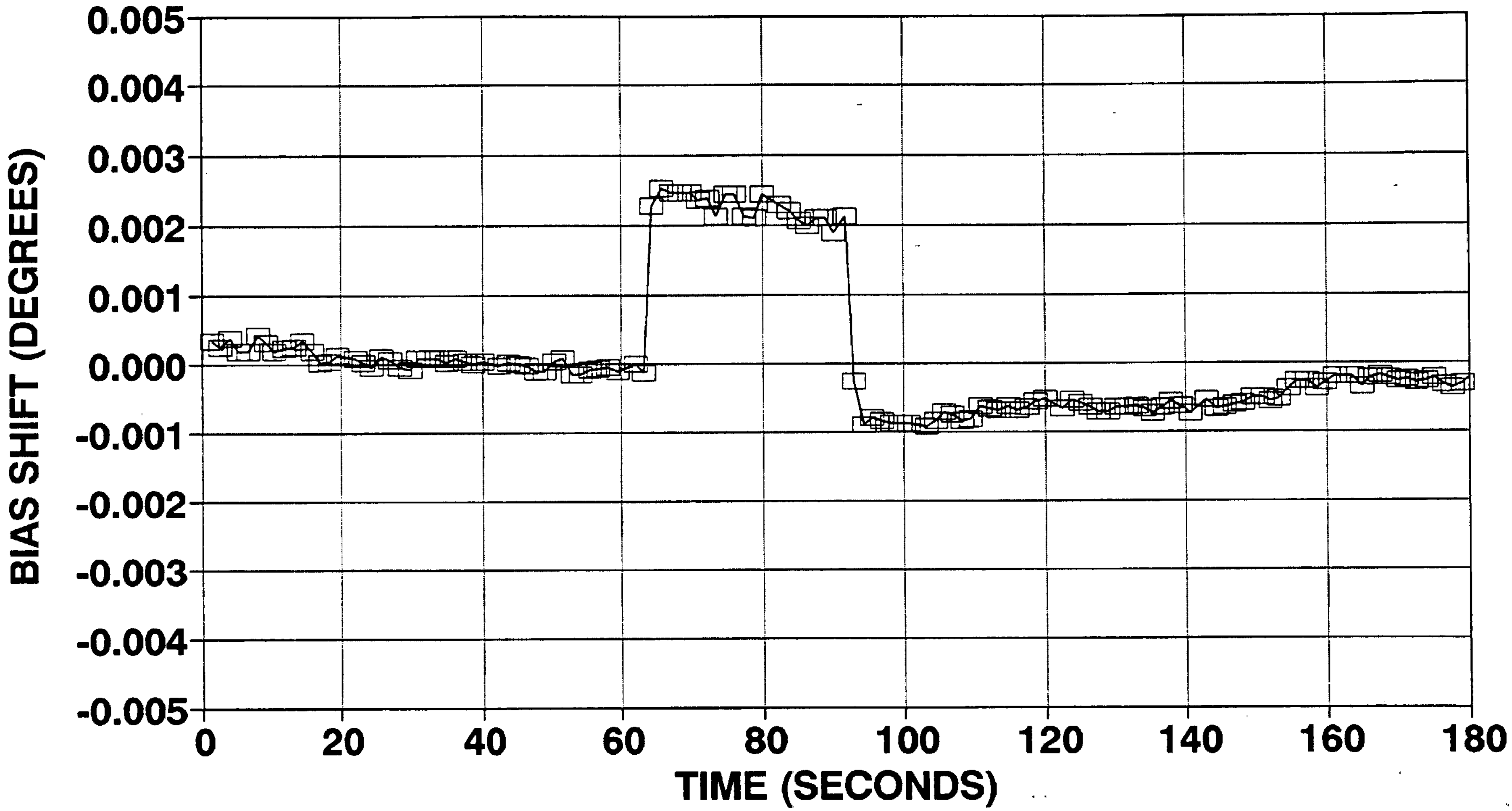


Figure 27. X Axis Tilt Sensor Random Rectification Result at 3G RMS 20 to 5000 Hz, Vertical Direction

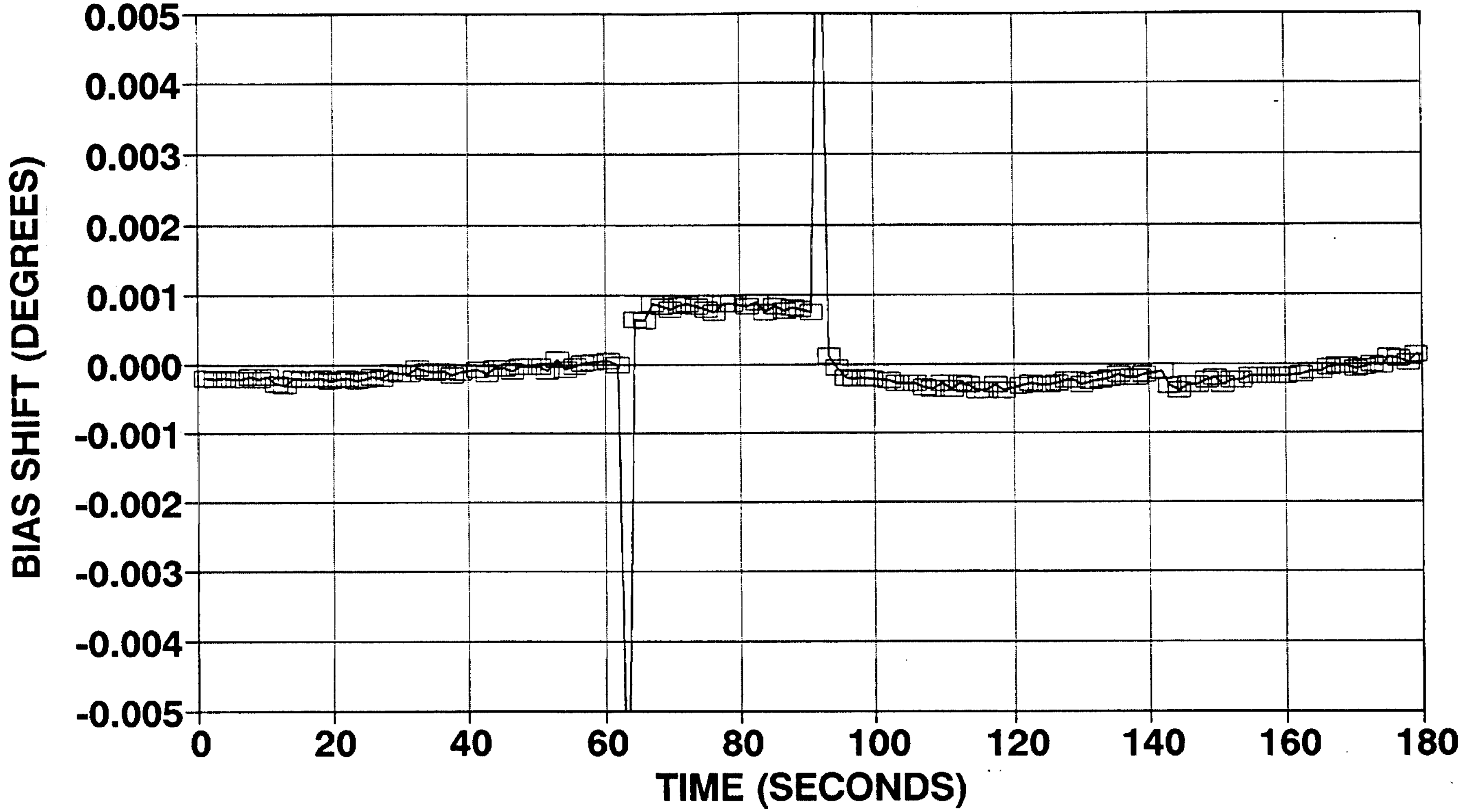


Figure 28. Y Axis Tilt Sensor Random Rectification Result at 3G RMS 20 to 5000 Hz, Longitudinal Direction

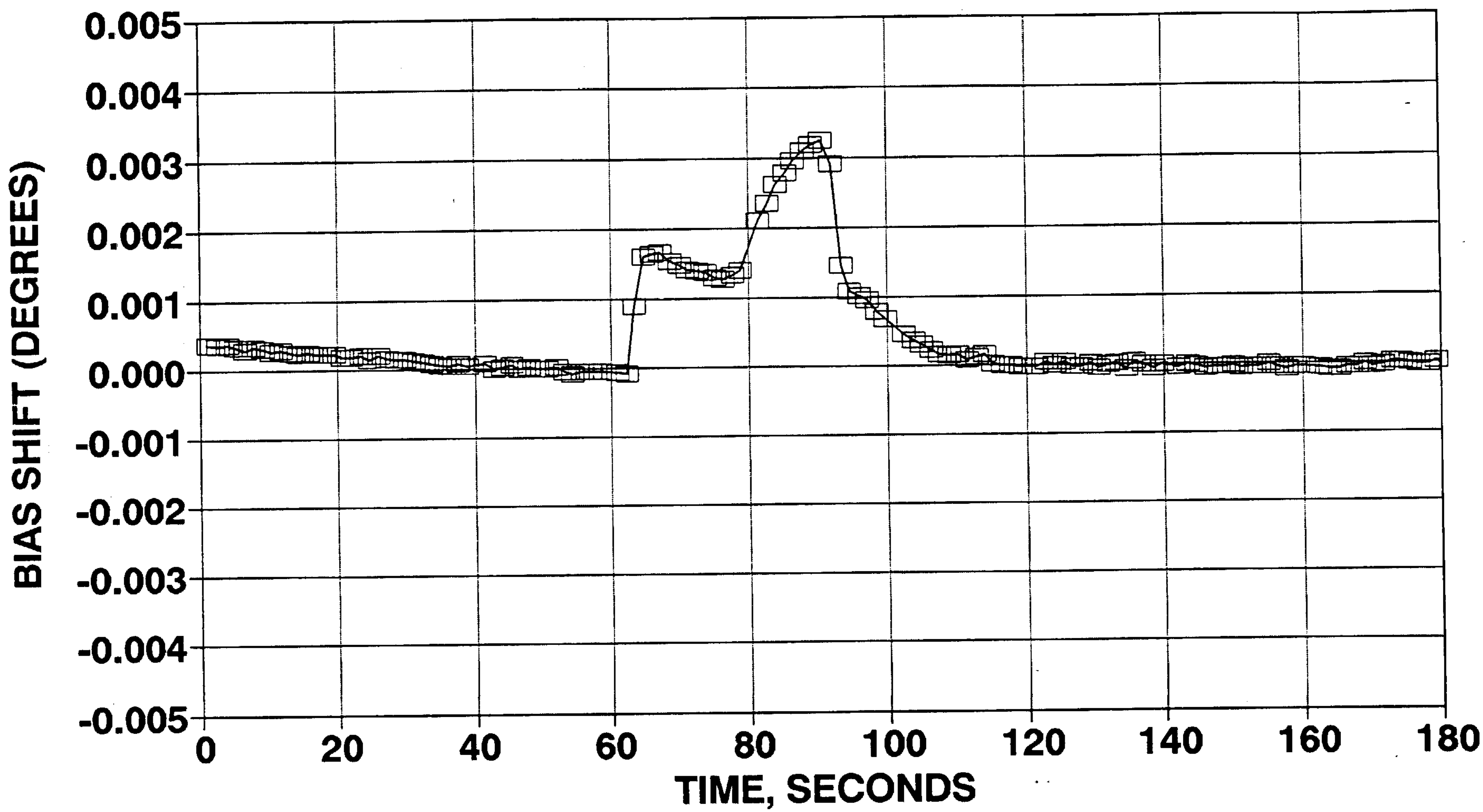


Figure 29. Y Axis Tilt Sensor Random Rectification Result at 3G RMS 20 to 5000 Hz, Lateral Direction

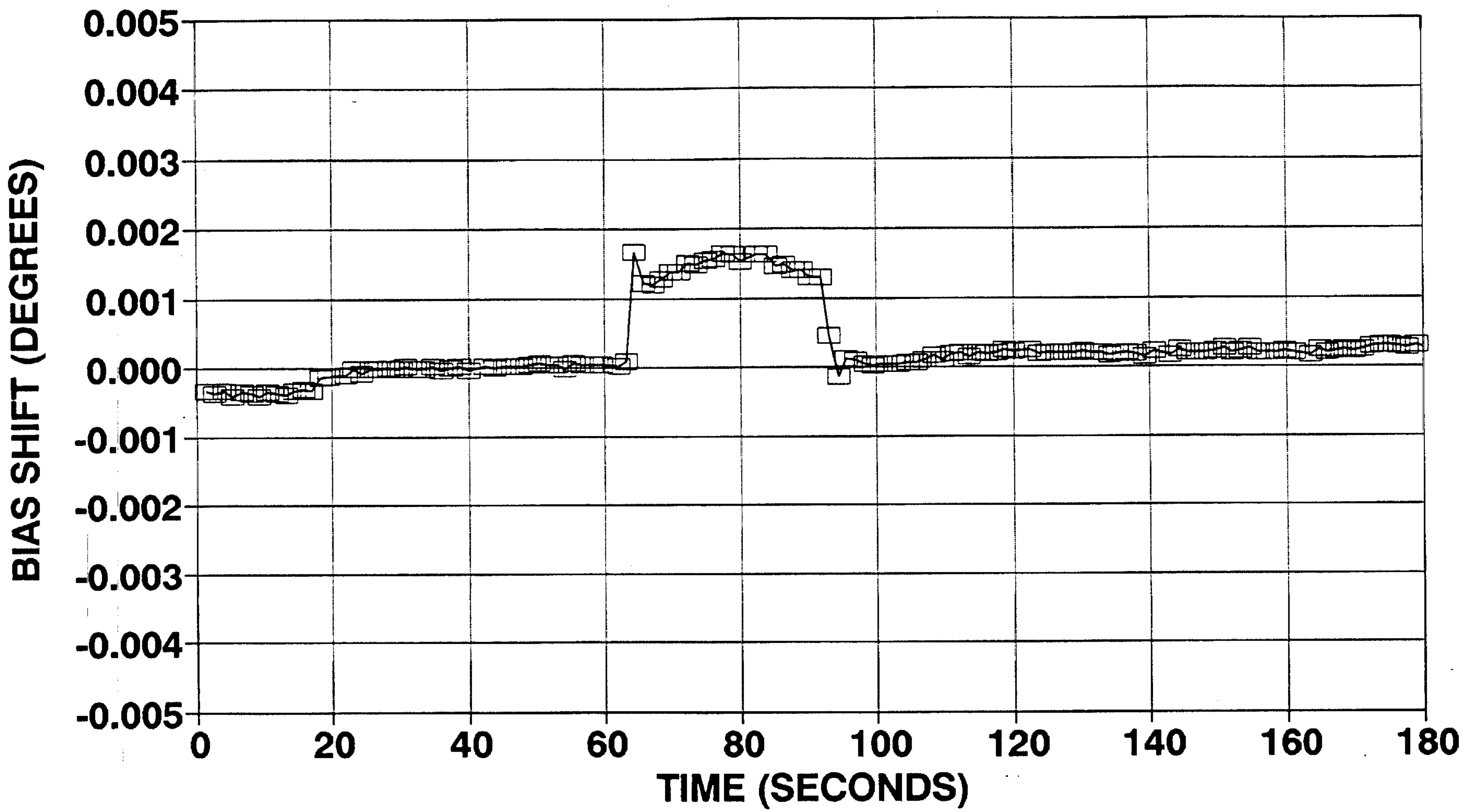


Figure 30. Y Axis Tilt Sensor Random Rectification Result at 3G RMS 20 to 5000 Hz, Vertical Direction

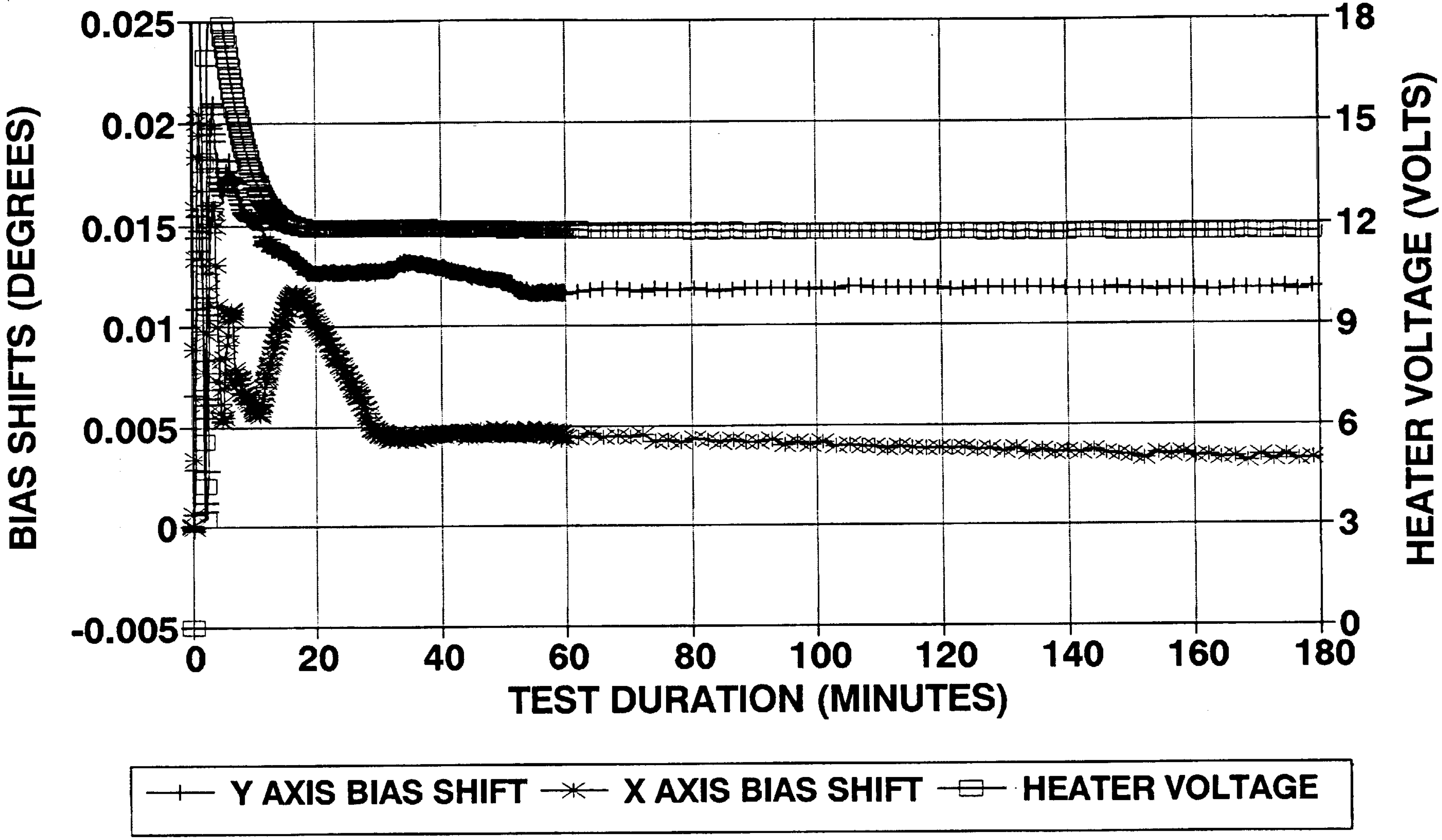


Figure 31. Wall Attitude Measurement Sensor Package Warmup Data at 73 deg F

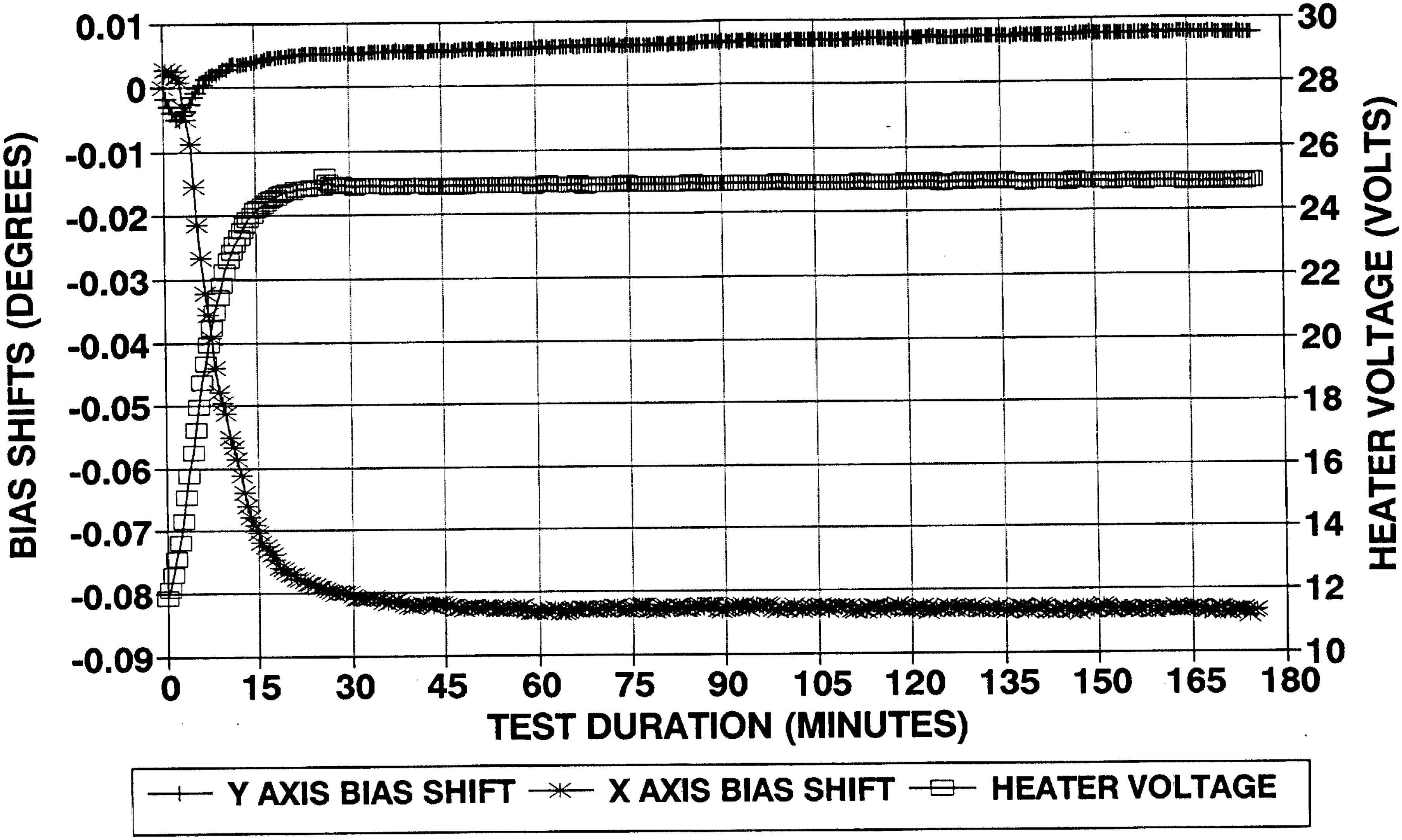


Figure 32. Wall Attitude Measurement Sensor Package Warmup Data at -293 deg F

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Douglas T. Wong

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13. ABSTRACT *(Maximum 200 words)*

A prototype dual-axis electrolytic tilt sensor package for angular position measurements was built and evaluated in a laboratory environment. The objective of this project was to investigate the use of this package for making wind tunnel wall attitude measurements for the National Transonic Facility (NTF) at NASA Langley Research Center (LaRC). The instrumentation may replace an existing, more costly, and less rugged servo accelerometer package (angle-of-attack package) currently in use. The dual-axis electrolytic tilt sensor package contains two commercial electrolytic tilt sensors thermally insulated with NTF foam, all housed within a stainless steel package. The package is actively heated and maintained at 160°F using foil heating elements. The laboratory evaluation consisted of a series of tests to characterize the linearity, repeatability, cross-axis interaction, lead wire effect, step response, thermal time constant, and rectification errors. Tests revealed that the total RMS errors for the x-axis sensor is 0.084 degree, and 0.182 degree for the y-axis sensor. The RMS errors are greater than the 0.01 degree specification required for NTF wall attitude measurements. It is therefore not a viable replacement for the angle-of-attack package in the NTF application. However, with some physical modifications, it can be used as an inexpensive 5-degree range dual-axis inclinometer with overall accuracy approaching 0.01 degree under less harsh environments. Also, the data obtained from the tests can be valuable for wind tunnel applications of most types of electrolytic tilt sensors.

14. SUBJECT TERMS
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