C6-3203/401

OPTICAL BEAM STEERING DEVICE
FINAL REPORT

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ABSTRACT

This report describes an optical beam steering device (OBS) built by the Electro-Optical Laboratory (EOL) of Autonetics, North American Aviation, Inc. (NAA), under NASA Contract NAS5-9688. The device is intended to be used in conjunction with lasers as a means of changing the direction of the laser beam in a controlled manner by an electrical command signal.

The concept employed for the OBS is based upon the use of piezoelectric bender bimorphs as the active deflection elements. Essentially all of the critical design requirements are met by the device.

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I. INTRODUCTION

Laser tracking and radar systems, as well as laser recording and display devices, have one thing in common — they require a technique for pointing the beam so that its position can be controlled and accurately known. The objectives of the work performed under NASA contract NA5-9688 by the Electro-Optical Laboratory (EOL) of Autonetics, North American Aviation, Inc.(NAA), were to design and fabricate an optical beam steerer (OBS) that would meet the performance specifications given in Table 1.

The concept employed for the OBS built under this contract is based upon the use of piezoelectric bender bimorphs as the active deflection elements. These bender bimorphs are discussed in more detail in a subsequent section of this report. The use of strain gages on the bender bimorph as a means of obtaining accurate position information for use in a feedback loop is a new and unique concept.

Table 1. Critical Design Specifications

Specification	Notes	Value
Size	Optical head only	Not to exceed 6 x 6 x 12 in.
Transmission	0.5 to 4 microns	50% minimum
	Variation in transmission as a function of deflection is not to exceed 10%.	
Clear aperture	Ratio of input to output beam diameters is to be constant within 10% over entire range of deflection.	1/2-in. diameter
Optical quality	Maximum total wave-front distortion	$\lambda/4$ at 0.5μ
Steady-state deflection		
Maximum		±2 deg
Repeatibility		±60 $\widehat{\text{sec}}$
Linearity		The ratio of the beam deflection to the input signal shall not vary more than 5% over entire deflection range.

Table 1. (Cont)

Specification	Notes	Value
Rise Time	Time is measured from when an electrical input reaches 90% of its peak value to when the beam reaches 95% of its intended steady-state deflection.	0.5 msec
Environmental resistance (operating)		
Temperature		0 to 100 F
Relative humidity		5 to 95%
Periodically varying deflection rate		0 to 250 Hz
Input signal		Approximately 5 mvolt for full scale deflection

II. SYSTEM DESCRIPTION

A. OVERALL SYSTEM

The optical beam steering (OBS) system is packaged into two components, an optical head and an electronic package (both shown in Figure 1), and includes the requisite inter-unit cabling. The optical head consists of two fixed mirrors arranged in a periscope configuration, and two movable mirrors attached to bender bimorphs, which, in turn, are clamped in special adjustable mounting fixtures. Since all major power dissipative components are in the electronics package, the power dissipation in the optical head is essentially negligible, approximately 200 milliwatts or less. As a result, the temperature rise within the head is very small. This is an important consideration in a precision optical system because any hot elements would disturb the optical path.

The electronics package consists of the necessary high-voltage driver amplifiers for the piezoelectric transducers, input amplifiers for signal scaling, feedback position signal circuitry, strain gage bridge circuits, a regulated excitation voltage source for the bridge circuit, and the bridge circuit output amplifier. Figure 2 illustrates the signal flow and shows the interrelation of the various components.

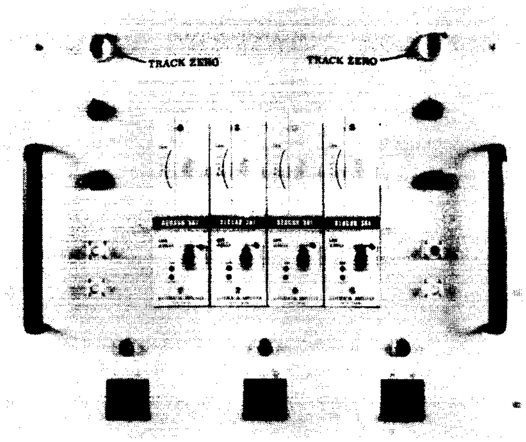
B. TRANSDUCERS

Each beam deflection transducer used in the device consists of a piezoelectric bender bimorph strip upon which a lightweight, high optical quality mirror is mounted. Two strain gages are mounted on each side of the bimorph strip near the base. There are two transducers in the OBS, one each for vertical and horizontal deflection.

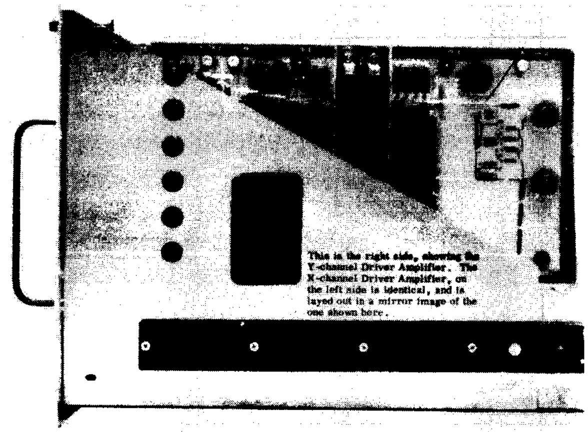
1. Piezoelectric Bender Bimorph

The piezoelectric bender bimorph consists of two thin strips of piezoelectric material bonded with a very thin conductive medium and coated on the outer surfaces with a conductive material. By means of the three conductive surfaces formed by the coatings and the bond, an electrical field can be applied independently across the two pieces of the piezoelectric material. The piezoelectric material is polarized such that when the electric field is applied across the thickness dimension, one piece will lengthen while the other will shorten. As a result, the bimorph unit bends in much the same manner as a bimetal thermometer bends due to differential thermal expansion. As the bimorph bends, the mirror fastened to the end of the bimorph tilts, causing a beam reflected from it to be deflected through an angle that is proportional to the applied voltage.

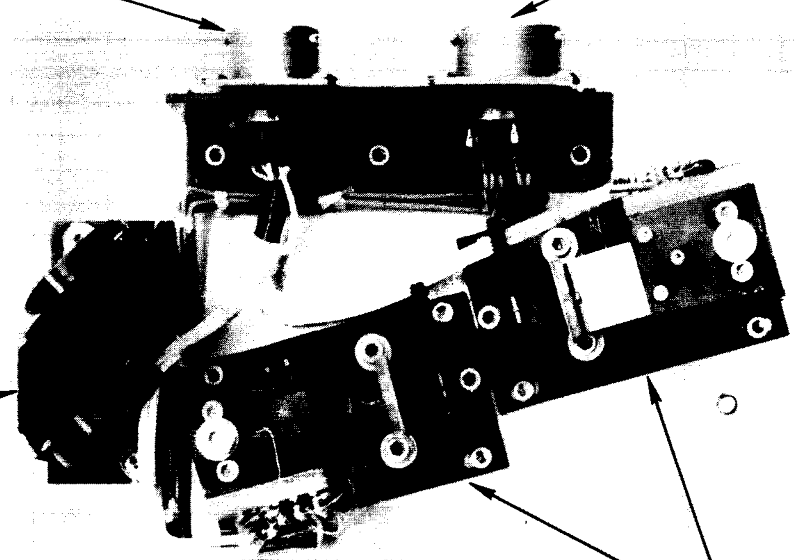
The bender bimorphs used in the OBS are made from Electramite 1512 piezoelectric ceramic, which is purchased in uncut sheets with electrodes coated onto each side by the silver-frit technique. The piezoelectric material is cut to size and cemented together with a thin wire mesh at the interface



Electronics Rack, Front View



Electronics Rack, Side View



Optical Head, Top View

Figure 1. System Components

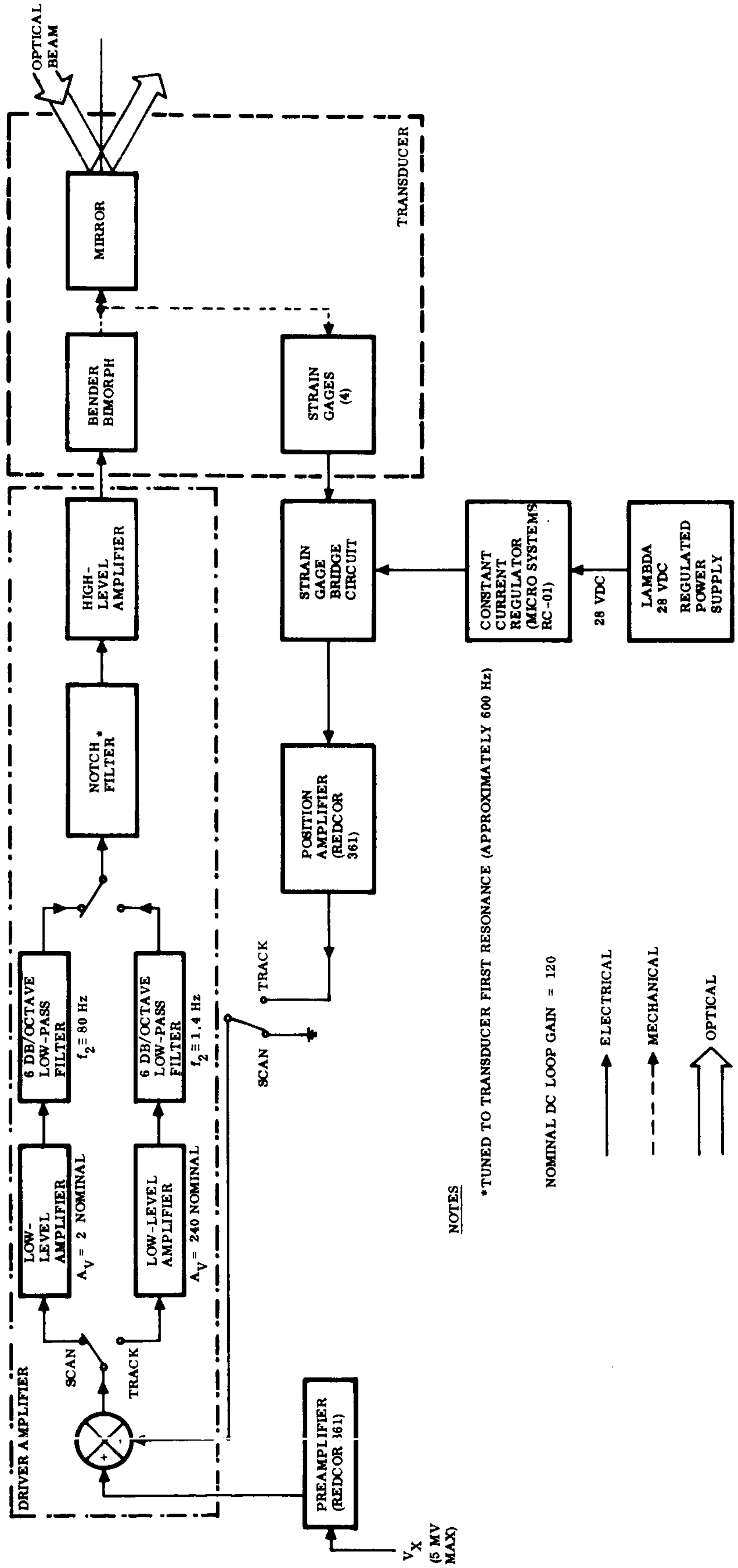


Figure 2. Signal Flow Diagram

between the two slabs. This mesh provides electrical connection and mechanical bonding between the two pieces. Small diameter, annealed gold wires attached with a conductive epoxy to the bimorph's three electrodes provide electrical leads. The final electrode surface area is established by masking and sand-blasting to remove the unwanted electrode material in the clamping area where the bender bimorph is clamped into the support, and in the region at the coupling section where the bimorph is coupled to the mirror.

2. Mirrors

The transducer mirrors are approximately 0.63 inches in diameter. The mirror blanks are ultrasonically milled to produce a ribbed pattern in the back of the blank for the purpose of weight reduction. Using this technique, the mass of the mirrors can be reduced by approximately 50 percent of that of the solid blank. The ribbed mirrors weigh about one-half gram each. After ultrasonic milling, the mirrors are ground and polished to approximately a one-eighth wave (at 0.5μ) optical surface quality, and then aluminized and overcoated with silicon-monoxide to provide a hard surface that can withstand careful cleaning.

A special coupling section to connect the mirror to the bender bimorph is required to effect a rigid coupling capable of withstanding the dynamic loads produced as the transducer scans, and at the same time to prohibit the transfer of stresses into the mirror, which would cause warping of the optical surface. The coupling section is fabricated out of the same material as the mirror itself to minimize thermally induced warpage stresses. It is bonded between the mirror and bender bimorph by means of epoxy.

3. Strain Gages

Since the strain in the bimorph strip is essentially proportional to the mirror angle, each bender bimorph is instrumented with four strain gages to generate a position feedback signal. The four strain gages are connected into a four-arm strain gage bridge circuit. This results in a temperature compensation that is superior to that which would be obtained with a two-arm bridge, and in addition yields twice the output scale factor per unit deflection.

The strain gages used on the transducer are of the miniature silicon semiconductor type. These afford a gage factor of 50 to 100 times that of conventional strain gages, and thus produce a much better signal-to-noise ratio for the position signal, and require less amplification in the position signal path.

The strain gages must be carefully mounted by using precision techniques to ensure a uniform and thin glue line, which is required to minimize any error in the position signal due to hysteresis in the bonding between the strain gage and the bender bimorph. This mounting technique requires the use of a stereo microscope to achieve the required alignment accuracy of the strain gages with respect to the bender bimorph, and with respect to each other. When properly mounted, the strain gages are capable of a readout accuracy of more than one-half percent.

C. FOLDING MIRRORS

In addition to the two transducers in the optical head, there are two fixed folding mirrors of high optical quality (approximately one-twentieth wave) which are arranged in a fixed, periscope-type mounting. The purpose of the two folding mirrors is to bring the output beam into collinearity with the input beam.

D. ADJUSTABLE TRANSDUCER MOUNTS

Special transducer mounts were designed to allow 3 degrees of freedom in position, as well as rotational adjustments. The most important feature of the design is that the transducer mirror is positioned at the rotation axis of the mount so rotational adjustments can be made without introducing any translation of mirror position. This feature eliminates any necessity for the mirrors to be made larger than the size required by optical considerations.

E. SPECIAL ELECTRONIC COMPONENTS

1. Amplifiers

Each channel is provided with three amplifiers: an input preamplifier, the strain gage bridge amplifier, and the main driver amplifier. The system input preamplifiers, which are not in the position feedback loop, provide a scale factor adjustment at the interface between the OBS and the system that provides the input signals. The strain gage position amplifiers and the input preamplifiers are Redcor 361 instrumentation type amplifiers, which have high common-mode rejection and very long term stability (in the order of days). The driver amplifiers are specially designed by Autonetics. These amplifiers are necessary at the last stage to provide the high voltage at low current levels required by the piezoelectric transducers.

2. Signal Filters

Two types of signal filters are used, both in the open-loop (scan mode) and the closed-loop (track mode), to protect the transducers and to optimize the response. In the open-loop mode, a simple 6 db per octave filter is used to roll off the system response below the first resonant frequency of the transducer, which is nominally at 640 Hz. This 6 db per octave filter, in combination with a second notch filter tuned to the transducer's first resonant frequency, reduces the amount of energy coupled into the transducer at resonance to limit the deflection to the rated maximum.

In the closed-loop mode, both filters are required for loop stability and optimum transient response. The corner frequency of the 6 db per octave, low-pass filter is set at a value that produces loop stability for the required loop gain. The low-frequency loop gain of the system is approximately 120 to provide the required one part in 120, or one arc minute positioning accuracy. Stability and transient response considerations then fix the corner frequency of the low-pass filter at 3 or 4 Hz.

3. Power Supplies

Four separate solid-state power supplies are used in this system, and each supplies power to both channels. Both +15 volt and -15 volt power supplies are used to provide low-level operating voltages for the driver amplifiers, the signal preamplifiers, and the mode-switching relays in the electronics package. A 28-volt power supply is used solely to provide power to the strain gage bridge circuit on each transducer. An 850-volt power supply is used to provide the high voltage to the transducer driver amplifiers.

4. Strain Gage Bridge

The strain gage bridge circuit for each transducer includes all four strain gages on the transducer. The excitation for the bridge circuit is provided by a regulated 28-volt power supply through a constant current module, which is used to improve the temperature error characteristic of the strain gages. The bridge voltage is amplified by the position amplifier. In the track mode of operation, the position amplifier output is compared to the amplified input voltage which commands the desired angle. The difference is then amplified and used to drive or position the transducer.

III. RESULTS OF PERFORMANCE TESTS

A. OPTICAL TRANSMISSION

The reflectivity of each of the four mirrors in the optical head was tested individually over the spectral range of 0.4 to 1.0 micron by the vendor who performed the aluminizing and overcoating of the mirror. The spectral reflectivity of the folding and transducer mirrors is plotted in Figure 3.

The total transmission of the system was measured at EOL at a single wavelength of 0.6328 microns. This measurement was made using a collimator with an aperture stop to allow a beam of exactly one-half inch diameter to pass. As there are no significant changes in transmission as a function of angle for the small angular variations experienced in operation of the device, the transmission measurement was made on axis only. A photomultiplier tube was used to detect and measure the light transmitted through the OBS optical system; this measurement was then compared with the measurement taken without the OBS in the optical path. By this method, an average transmission of 48 percent was measured.

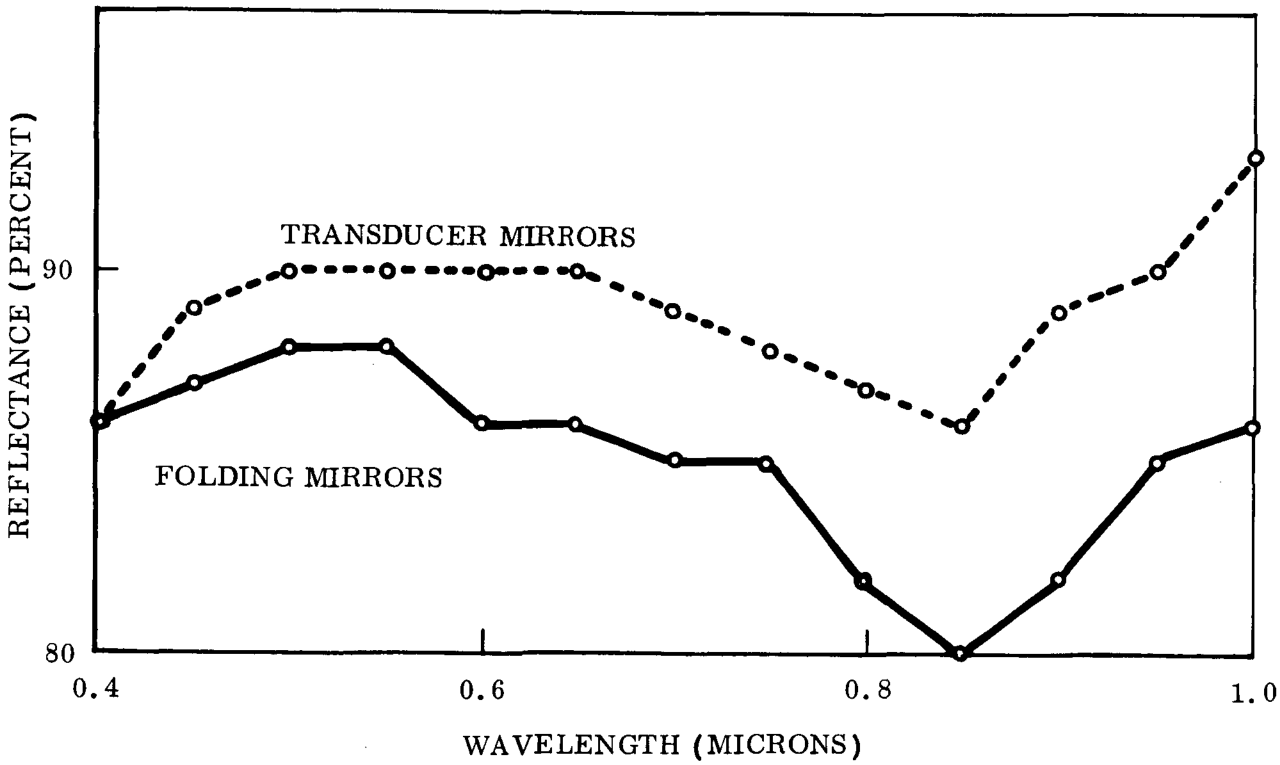


Figure 3. Spectral Reflectivity

B. OPTICAL QUALITY

The overall optical quality of the OBS was measured by placing the optical head in one leg of a Twyman-Green interferometer, and measuring the wave-front distortion across the aperture in two orthogonal directions. The average distortion measured was one-third wavelength at 0.5 microns.

C. STEADY-STATE DEFLECTION MODE

Measurement of the optical beam deflection in the following tests was made by projecting the output beam over a 500-inch optical path to a screen. The angular deflection was then calculated in terms of lineal deflection at the screen.

1. Maximum Deflection

The maximum deflection angle was measured in the steady-state deflection mode by inserting a d-c input voltage corresponding to the desired deflection angle and measuring the deflection of a beam transmitted through the device. A deflection capability of ±2 degrees on each axis, and on both axes simultaneously, was measured by this technique.

2. Deflection Rate

For this measurement, one deflection axis of the OBS was used to produce a sinusoidal scan of the transmitted optical beam. The other axis, the one being tested, was then programmed with a repetitive train of pulses synchronized to the sinusoidal scan on the other axis. An optical pulse response display, very similar to that produced on an oscilloscope used to measure the pulse response of an electrical circuit, was produced on the screen at the end of the test range. In contrast to the oscilloscope analogy, however, the sweep was sinusoidal rather than linear. To minimize the error in making measurements on this nonlinear time base, measurements were made in the central 10-percent region of the scan where the linearity was sufficient for the required measurement accuracy.

The specific aspects of the measured pulse response were the pulse delay (i.e., the time interval between the insertion of the electrical command pulse and the 10-percent response point of the optical deflection); the rise time, defined as the time interval between 10 percent and 95 percent of full-scale response; the settling time for the optical deflection to arrive within a 10-percent error band centered about the final value; and the percent of overshoot of the optical deflection above the desired full-scale response value.

For the X-axis transducer, the delay was 0.62 msec for a positive pulse and 1.19 msec for a negative pulse. The pulse delay time was not measured for the Y-axis transducer. The rise times measured on both transducers with both positive and negative pulses ranged from 1.12 msec to 3.13 msec. The settling times, measured in the same manner, ranged from zero (i.e., never leaving the error band) to 19.1 msec. The measured overshoot ranged from 1 to 6 percent, depending on the transducer and the polarity of the test pulse.

3. Deflection Repeatability and Linearity

The deflection repeatability and linearity data were taken by applying a d-c input signal to the system and then increasing it by steps of 10 percent of full scale. By progressing from zero to full scale in one direction on one axis, and from that point back through zero to full scale in a negative direction and then back to zero, the hysteresis loop of the optical beam deflection system was traced. This was repeated in the opposite direction, that is, starting from zero and going to the negative full scale. The entire procedure was repeated with the other transducer. Figure 4 shows a typical plot of these data. A linearity of better than one percent (zero based) was measured, and a repeatability of one percent was established for both axes.

4. Frequency Response

The frequency response was measured in the steady-state deflection mode by applying a constant amplitude sine-wave electrical signal to the input of the system and measuring the peak-to-peak optical deflection produced by this input signal. While the input amplitude was maintained constant, the frequency was varied from dc up to and beyond the roll-off of the system response. Figures 5 and 6 show the normalized frequency response for the X- and Y-transducer, respectively, in the closed-loop, steady-state deflection mode.

D. PERIODICALLY VARYING DEFLECTION MODE

The maximum deflection rate in the periodically varying deflection mode (open-loop mode) was measured by a technique similar to that used for the frequency response measurement previously described. An electrical signal generator, used to produce a sinusoidal input signal of constant amplitude, was adjusted for maximum deflection at a low frequency. The input signal was then maintained constant, and the frequency was varied from near dc up to and above the limiting response of the system. Peak-to-peak optical deflection amplitudes were measured at discrete frequencies.

Normalized frequency response of the system was measured from 5 to 1,000 Hz. Figure 7 shows the detailed frequency response curve where the 3 db bandwidth is approximately 230 Hz.

E. BEAM DIAMETER

Beam diameter and vignetting measurements were made as a function of the beam deflection angles produced on each axis. The test was implemented using a collimator and an aperture stop to produce a nearly diffraction-limited one-half inch diameter beam. The beam was transmitted through the beam steerer and imaged on a ground-glass screen, on which an opaque disc slightly smaller than one-half inch in diameter was located. When the disc was aligned on-axis, a bright ring, somewhat similar to a corona, appeared around the edge. This bright ring was used to determine whether any vignetting was produced by the beam. If the beam was vignetted, the bright ring was obliterated over part of the diameter of the circle in the output plane. The measurement was made on-axis, and then the beam steerer was caused to produce a steady positive or negative maximum deflection. In addition, all combinations of

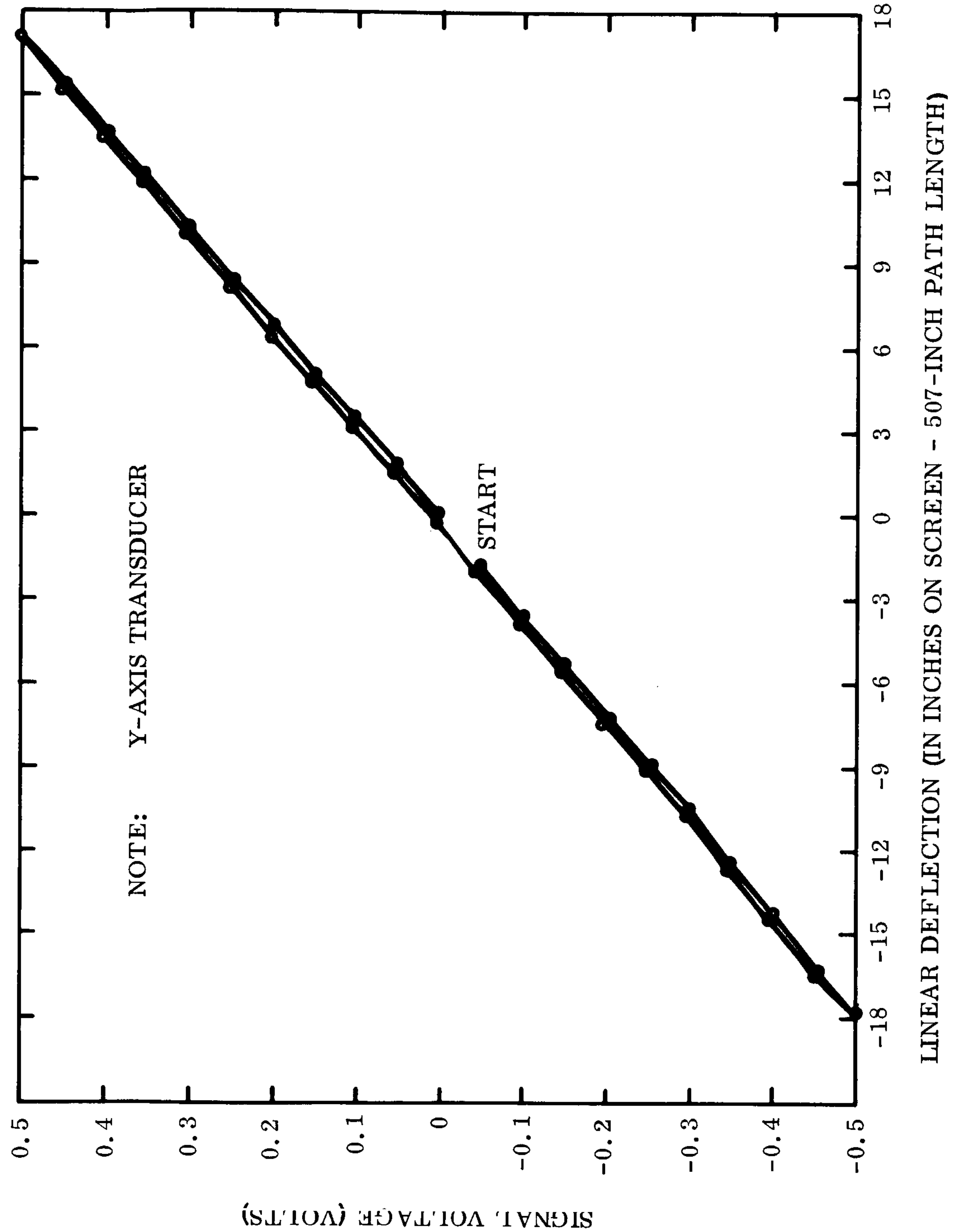


Figure 4. Deflection Versus Voltage, Typical Hysteresis Loop

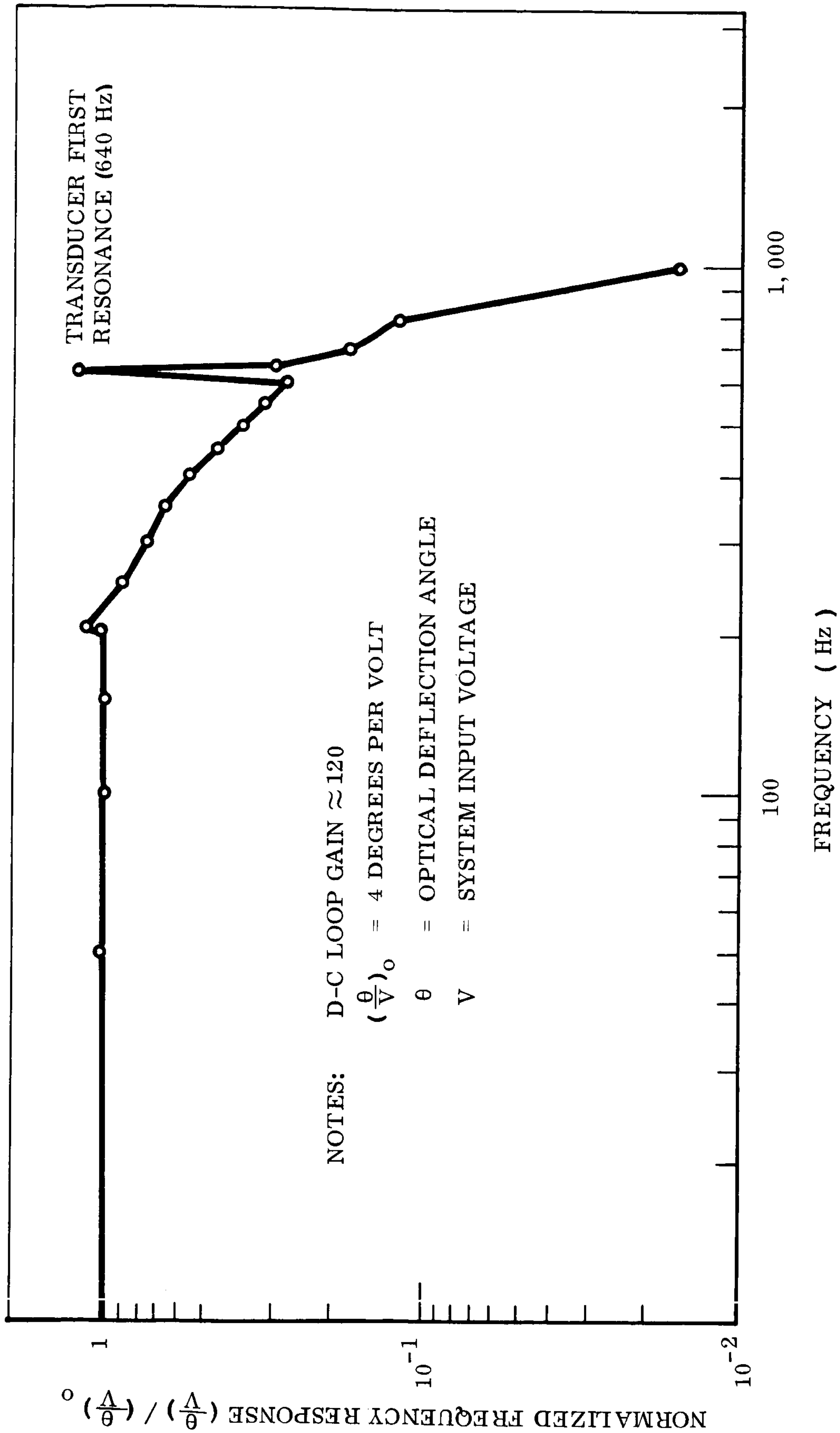


Figure 5. Small-Signal, Closed-Loop (Track Mode) Frequency Response — X-Channel

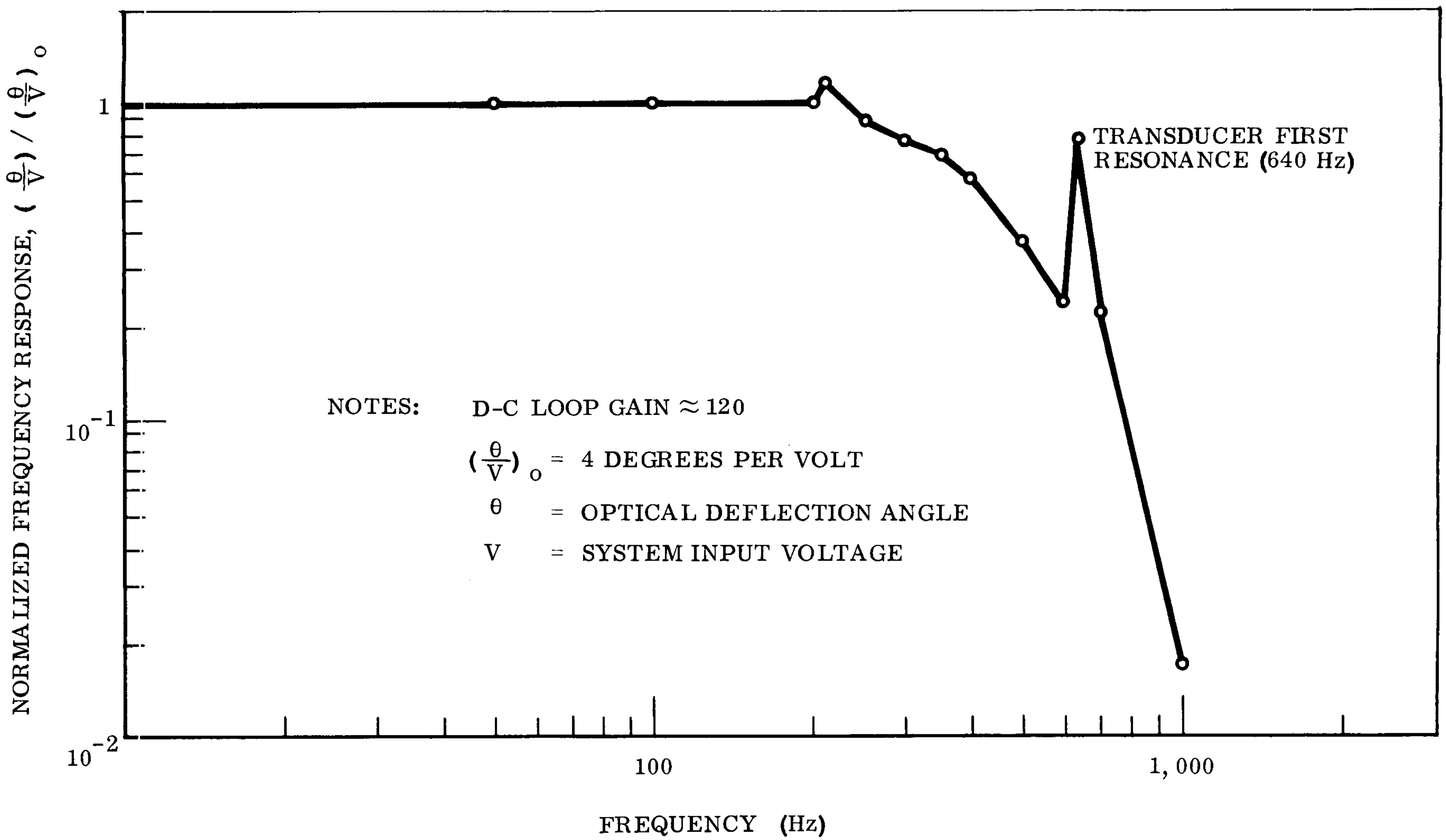


Figure 6. Small-Signal, Closed-Loop (Track Mode) Frequency Response — Y-Channel

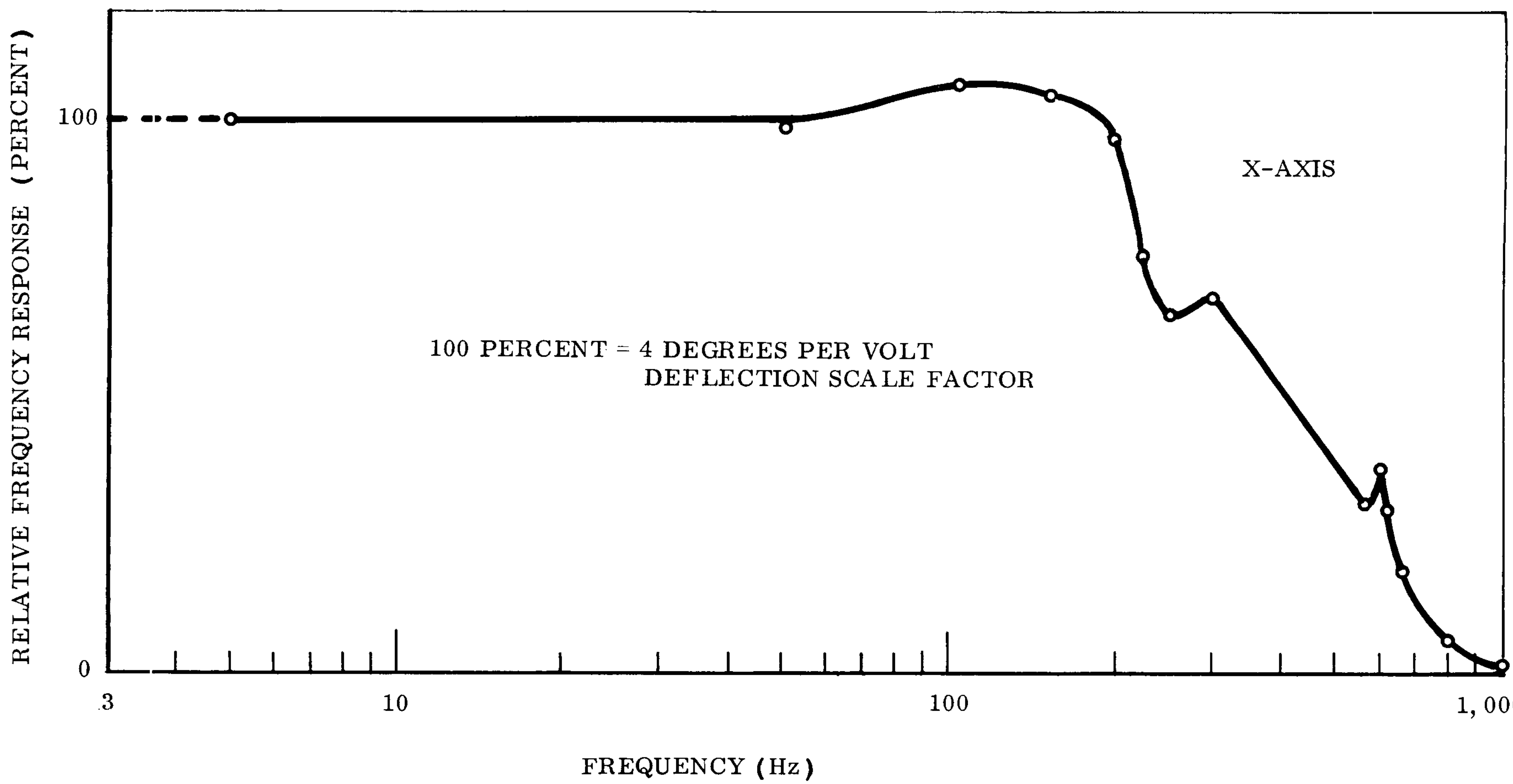


Figure 7. Open-Loop Frequency Response — X-Channel Only

maximum positions of the beam were produced by deflection on both axes simultaneously. The ground glass screen was realigned at each of these points on axis of the output beam, and the vignetting was determined by observation of the edge of the opaque disc.

Only very slight vignetting (a few thousandths of an inch) was observed in a few of the beam positions. For all other extreme positions, no vignetting was observed.

F. ENVIRONMENTAL RESISTANCE

Operation of the device was tested under various conditions of temperature and humidity by Wiley Labs, a subcontractor testing laboratory. Tests were made at two discrete end-limit points, one a 100 F temperature and 80-percent relative humidity; and the other at 0 F and 50-percent humidity, the minimum relative humidity that the test chamber was capable of establishing at that temperature. The device was maintained in open-loop operation at full amplitude beam deflection during all the measurements. Performance was verified by projecting an optical beam through a window in the test chamber, through the OBS, out a second window in the chamber, and onto a projection screen. The Y-axis transducer only was driven sinusiodally at full amplitude at a frequency of 200 Hz. During the testing of this unit, the dew point conditions were inadvertently achieved by Wiley Labs, causing condensation to be deposited out on the optical surfaces and on the transducers themselves. While this is not a recommended mode of operation, it was noted that no failures resulted. The device continued to be operable thereafter with no measurable deterioration of performance.

The OBS operated normally under the extreme environmental conditions to which it was subjected, and careful examination revealed no deterioration of the device.

G. MECHANICAL RESONANT FREQUENCY

The only significant mechanical resonant frequencies in the OBS are those of the beam deflection transducers. The resonant frequency of each transducer was measured by first applying a one-Hz sinusoidal drive voltage of sufficient amplitude to produce a deflection amplitude of 10 percent of maximum. The frequency was then slowly increased by increments, while the drive voltage was adjusted to maintain the 10-percent deflection amplitude. The frequency requiring the lowest drive voltage is the resonant frequency. For both transducers tested, the lowest resonant frequency is about 640 Hz.

H. CALIBRATION ERROR AS A FUNCTION OF TEMPERATURE

Since it was not feasible to make an optical measurement of the calibration error as a function of temperature, this test was made by measuring the strain gage bridge output signal directly as a function of temperature. This approach is based upon the assumption that the only significant error as a function of temperature for the system when operated in a closed-loop mode is that of the strain gage bridge. This assumption is valid because the only elements of concern are those in the position feedback path, i.e., the strain gage bridge and the Redcor amplifier. The amplifier's error as a function of temperature is negligible over the range of interest, so the strain gage bridge is the only component of concern. Any errors in scale factor or output level in the forward path between the input command signal and the transducer position is reduced by a factor of 120 by virtue of the closed-loop gain of the system. This is one of the reasons for operating the transducer in a closed loop.

The calibration error test was performed by placing the optical head in an environmental temperature chamber that could be programed for temperatures either above or below ambient. There was no drive signal applied to the transducer; therefore, the position of the transducer was established as zero deflection. The bridge circuit was first balanced or nulled at ambient temperature; the temperature was then reduced to 20 F, increased to ambient, raised to 100 F, and brought back to ambient. The equipment was allowed to reach thermal equilibrium at each temperature before any data were taken. At each temperature the output voltage of the strain gage bridge was recorded; if there were no errors, these voltages would have been zero. The scale factor of the system, that is, the voltage output of the strain gage bridge as a function of a given angle, was then measured at the ambient temperature and used to compute the actual angular error as determined from measuring the strain gage bridge voltage as a function of temperature.

Figure 8 shows the calibration error as a function of temperature for both transducers. Note the hysteresis effect. In normal system use this error can be made zero at any temperature within the rated operating range by adjustment of the "track zero" control.

I. PERFORMANCE SUMMARY

Table 2 is a summary of the OBS's measured performance.

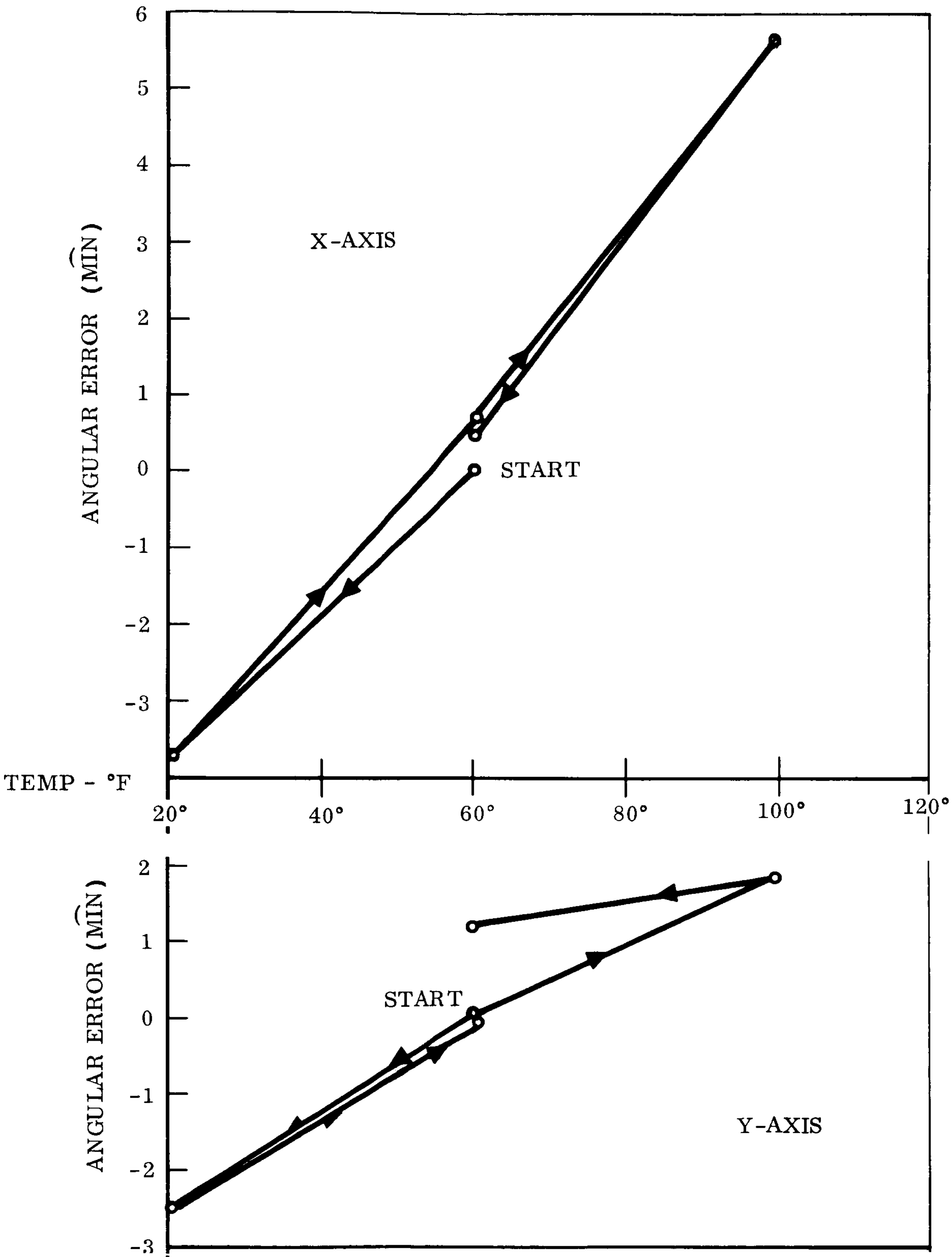


Figure 8. Calibration Error Versus Temperature

Table 2. Measured Performance Summary

Characteristics	Measured Performance
Total optical transmission	48% at 0.6328 μ
Overall optical quality	1/3 wavelength at 0.5 μ
Steady-state deflection	
Maximum (each axis)	±2 degrees
Pulse delay (between command and 10% response)	
Positive pulse	0.62 msec
Negative pulse	1.19 msec
Rise time (10 to 95%)	1.12 to 3.13 msec
Settling time (10% error band)	0 to 19.1 msec
Overshoot (percent of final value)	1 to 6%
Repeatability	1%
Linearity (zero-based)	1%
Frequency response (3 db bandwidth)	Approximately 340 Hz (see Figures 5 and 6)
Periodically varying deflection frequency response (3 db bandwidth)	Approximately 230 Hz (see Figure 7)
Beam diameter	Essentially one-half inch diameter for all deflection positions
Environmental resistance (operating)	
Temperature	0 to 100 F
Relative humidity	50 to 80%
First mechanical resonance frequency	Approximately 640 Hz

IV. NEW TECHNOLOGY – STRAIN GAGE BRIDGE ON A BENDER BIMORPH

Use of strain gages to measure the optical angle of a mirror mounted on the end of a cantilever beam (piezoelectric bimorph) is a new technology employed in the development of the OBS. Beam deflections are measured directly by the strain gage. The geometrical relationship between the bimorph deflection and the optical deflection angle allows determination of the latter. The accuracy of this technique is better than one percent of the optical beam's full-scale deflection. This is a unique innovation in that this is a first time that strain gages have been used to measure the bending of a piezoelectric bender bimorph beam.