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DEVELOPMENT OF A PRECISION, WIDE-DYNAMIC-RANGE ACTUATOR FOR USE IN ACTIVE OPTICAL SYSTEMS

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ABSTRACT

This paper describes the design, operation, and performance of a wide-dynamic-range optical-quality actuator developed at the Lockheed Palo Alto Research Laboratory. The actuator uses a closed-loop control system to maintain accurate positioning and has an rms noise performance of 20 nm. A unique force offloading mechanism allows the actuator coil to dissipate less than 3 mW under quiescent conditions. The total available mechanical range is 2 mm. In addition to describing the actuator and its performance, this paper describes the operation of an experimental segmented optical system that uses 18 of these actuators to show how the actuator is integrated into an actual system.

INTRODUCTION

As requirements for ground- and space-based directed-energy, communication, and astronomical optical systems become more demanding, the size of the primary reflectors for these systems is steadily increasing. Large reflectors provide more efficient energy concentration at distant targets, or, in the case of astronomical instruments, their increased collecting area substantially improves the fundamental sensitivity and resolution of the instrument. For nearly 40 years, the largest available astronomical-quality reflector was the 5-m mirror of the Hale telescope. It is now commonplace to consider building optical systems with apertures in the 10- to 30-m range. The W. M. Keck Telescope, presently under construction in Hawaii, will have a 10-m-diameter primary mirror [1]. When completed, it will be the largest astronomical telescope ever built. NASA's currently planned Large Deployable Reflector (LDR), an orbiting infrared telescope, will have a 17- to 20-m primary mirror [2].

Three approaches are being developed for producing large optics. The simplest is to fabricate lightweight monolithic optical blanks as large as 8 m using a unique spin-casting technique [3]. The second approach is to make a thin monolithic meniscus mirror with up to several hundred actuators attached to the back surface [4]. These actuators can bend the glass to control the mirror figure and achieve a high-quality optical surface [5]. The third approach uses segmented mirrors, a physical necessity for larger systems and

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the only realistic solution for space applications for which size, weight, and in-orbit deployment are critical.

In the latter two approaches, unacceptable deformations result from the inherent flexibility and thermal sensitivity of either the mirror itself or the structure supporting the mirror; thus, active-control systems must be used to maintain the geometric integrity of the reflecting surface. Actuators that can deform a monolithic mirror, or align mirror segments with respect to each other, are essential to this new technology. In the Keck telescope, for example, the primary mirror is composed of 36 actively-controlled hexagonal segments that require a total of 108 actuators [6].

The design of segment-positioning actuators is a major technological challenge in the development of segmented optical systems. These actuators are required to have extremely low noise levels, be able to generate substantial forces over a wide mechanical range, and be able to support the segment (depending upon the application) in a 1-g field. They must also have a bandwidth sufficient to accommodate the spectra of the disturbances. In addition, because of thermal and power considerations, given that a typical large system may have several hundred actuators, energy dissipation must be minimized.

This paper describes the design, operation, and performance of a wide-dynamic-range optical-quality actuator developed at the Lockheed Palo Alto Research Laboratory. The actuator uses a closed-loop control system to maintain accurate positioning and has an rms noise performance of 20 nm. A unique force offloading mechanism allows the actuator coil to dissipate less than 3 mW under quiescent conditions. The total available mechanical range is 2 mm. The operation of an experimental segmented optical system that uses 18 of these actuators is also described, to show how the actuator is integrated into an actual system.

ACTUATOR DESIGN REQUIREMENTS

This section describes the main requirements and design considerations for segment alignment-control actuators. These requirements are also generally applicable to figure control actuators.

Dynamic Range and Sensitivity

In order to install and align a set of several hundred actuators in a segmented system that uses standard mechanical fabrication tolerances, each actuator must have a total range of motion on the order of millimeters. Irregularities and dimensional changes in the backup structure can then be compensated for without exceeding the displacement capability of the actuation system. Since each segment must be positioned to an accuracy on the order of 100 nm or better, the resultant dynamic range of the actuators must be on the order of 100,000:1.

In closed-loop operation, in which the control system drives the actuator in such a way as to zero out error signals derived from external sensors (e.g., edge sensors), the primary limiting factors are the actuator noise and its resolution. The larger of these two defines the actuator sensitivity and thus the low end of the dynamic range. As long as open-loop operations or feed-forward techniques are not required, the absolute accuracy of the actuator is not critical and does not impact the definition of its dynamic range.

Actuator Roughness

Unlike rigidly-mounted optical systems, large space systems, with their inherent flexibility, are very sensitive to uneven motions occurring in any part of the structure. Stepper motors for example, when used to move relatively massive segments, can induce unwanted modal excitations. Bearings, gears, roller screws, and other sliding mechanisms typically operate with friction and stiction characteristics that may seriously affect the performance of the system. These nonlinear effects often result in limit-cycle behavior that is unacceptable for an optical-quality actuator.

Power Dissipation

One of the major difficulties associated with more conventional actuator designs is the inability to maintain position in the face of a constant load without continuous power input. This power requirement has three disadvantages. First, it places an unnecessary burden on the system power supply; especially considering a large system which may have a hundred or more actuators. Second, the heat generated can deform the mirror or the support structure, thus requiring even more power from the actuators to compensate, which eventually leads to thermal runaway. Third, excessive heat from the actuators causes thermal pollution of sensitive infrared detection systems.

Power dissipation can be very severe for direct-drive actuators when they must, for any significant period of time, support a segment in a 1-g field or deform the surface of a mirror to correct for aberrations or wavefront errors. Thus, power efficiency becomes an important driver of the actuator design.

Bandwidth

Truly "static" alignment is an abstract notion. In a real system, the question always arises as to how often this alignment must be performed. Thus, because time is involved, the process is no longer "static" and the notion of bandwidth must be introduced, whether it be 0.1 Hz or 100 Hz. The problem is that the control system, and thus the actuators, must be able to respond at least as quickly as the disturbances that they are trying to correct. Structural deformations may take as long as several seconds (e.g., thermal effects, gravity vector changes), to just fractions of a second (e.g., distortion during slews, structural vibrations). For space applications in which a rapid response is often critical, a wide bandwidth is essential to optimize the operating duty cycle of the system.

Reliability

The reliability of the actuators is a critical issue for space applications, since failure of even a single actuator may degrade the performance of the entire system. Many systems remain dormant, either on the ground prior to launch or in space for some indeterminate length of time, and then must be ready to operate instantaneously on command. Thus, the reliability of the actuators is an important design consideration.

ACTUATOR DESIGN

Review of Existing Technology

The problem of accurate position control has been approached in different ways depending upon the application. The oldest and most commonly used approach is through a combination of motor (stepper or dc) and gear or screw mechanisms. The stroke can be very large, but accuracy and resolution are limited by several factors such as friction, stiction, backlash, bearing and gear train compliance, etc. Increasing the gear ratio may increase resolution, but will decrease the bandwidth proportionally; thus the combination of gear ratio and rotor inertia usually results in relatively low bandwidths.

The Keck telescope uses a hybrid actuator in which part of the gear ratio is provided hydraulically, thereby improving accuracy and resolution. However, the total equivalent gear ratio results in a bandwidth of less than 2 Hz. The original design for these actuators was purely mechanical, with a high-precision roller screw. The design could only achieve the desired 50-nm resolution by modeling friction effects in a dedicated control microprocessor that was required for each actuator.

Piezoelectric devices have been developed to specifically address active-optics problems. These direct-drive, analog actuators have essentially infinite resolution but a very small stroke; typically a few tenths of micrometers. They can also be very high bandwidth. However, because of creep, hysteresis and thermal sensitivity, they are not very accurate. More advanced designs improve the accuracy using feedback techniques. Finally, the high voltage required to drive piezoelectric actuators is usually undesirable for space applications.

Piezoelectric materials are used in quite a different way in the inchworm actuator. Here they move a rod by a calibrated quantity. When the process is repeated, the rod advances by another step, and so on. In between moves, the rod is held firmly in place, thus no power is needed and the whole process is much less sensitive to the characteristics of the piezoelectric material. However, the resolution is now limited to that of the gripping procedure, and the actuator is very slow and still requires high voltages.

Another very commonly used actuator is the voice-coil type. In the classical design, the force-generating coil moves inside a field created by a permanent magnet. In more recent designs, a permanent magnet moves inside a coil, or electromagnets interact with each other. All these designs are capable of large stroke and infinite resolution when driven by analog electronics. These actuators are basically force actuators, thus the position of the moving element is not related to the commanded current in a direct and precise manner. Another more severe drawback is that they require a constant supply of power in order to maintain a given force level. However, they can have high bandwidth and are very simple and reliable.

New Actuator Concept

The previous discussion indicates that conventional actuator designs are limited in at least one of five major characteristics and are thus unsuitable for active segment alignment or figure control. These five characteristics are dynamic range, bandwidth, friction/stiction, static force handling, and power consumption.

The approach taken for the Lockheed actuator addresses these five problems in a systematic manner, as summarized in Table 1.

First, dynamic range and bandwidth considerations mandate the use of a voice-coil-type actuator as the basic drive motor. To overcome the lack of accuracy and repeatability of the device, a local analog servo loop controls the coil current using a highly accurate position sensor.

The friction/stiction problem is solved by eliminating all bearings and bushings and relying solely on flexural elements. In this way, the need for lubrication is eliminated and the mechanism is extremely smooth. Also the device may stay inoperative for an indefinite amount of time without incurring the risk of locking its moving parts because of lubricant dry-up, vacuum welding, etc.

To obtain the correct output force level, constrain the degrees of freedom of the output shaft, and minimize power consumption, a four-bar linkage that acts as a lever is used.

One of the major difficulties associated with more conventional actuator designs, the inability to maintain position in the face of a constant load without continuous power input, is solved through the use of a force offloading system. This separately controlled automatic system uses a special control loop with a very long time constant that uses a small, separate actuator to move a spring attached to the main linkage mechanism of the actuator. When steady state is reached, the spring supplies a force to the output shaft which almost exactly balances the constant load seen by the main actuator.

Table 2 summarizes the characteristics of conventional actuators and compares them to the Lockheed design. The highlighted ratings indicate characteristics unacceptable in a segment alignment-control actuator.

SYSTEM DESCRIPTION

Figure 1 is a schematic diagram of the actuator and the electronic control system that drives it. The main force-producing actuator is shown attached to the output shaft by a special four-bar linkage. The linkage is arranged so that it provides a five-to-one reduction in linear travel and a corresponding five-to-one increase in force output. The moving components in the four-bar linkage are connected with flexures so that there are no backlash or friction-producing components in the drive train. The four-bar linkage with reduction ratio is shown in detail in Figure 2.

The actuator operates under closed-loop control by measuring the location of the output shaft with an inductive position sensor and comparing the commanded position with the measured position. The position error is then processed by the analog control electronics and a power amplifier provides the drive current to the moving-magnet actuator.

A separately-controlled automatic system to provide force offloading is shown in Figure 1. This system uses a special control loop with a very long time constant to measure the current in the main force-producing actuator. When the absolute value of this current exceeds approximately 60 mA, a small servomotor, the force compensation actuator in Figure 1, is commanded to move a leaf spring attached to the linkage mechanism of the main actuator. The leaf spring applies a force to the actuator which the primary control system senses and causes the main actuator to counteract. Because the primary control loop has a much faster response time (by four orders of magnitude) than the offload controller, the net disturbance to the position of the output shaft is essentially zero. As the leaf spring continues to slowly apply more force, the current required by the main actuator is constantly reduced. When the current in the main actuator drops below 20 mA, the offloading system shuts off and holds its last commanded position until the current again exceeds 60 mA. Of course, if the load on the actuator is truly constant, the current will remain between 20 and 60 mA indefinitely and the offload system will not be enabled again. The offload sequence is illustrated in detail in Figure 3.

The mechanical operating range of the Lockheed actuator is 2 mm. Because the actuator control system is entirely analog, it has essentially infinite resolution. However, practical limitations such as noise from the sensor and electronics mean that the limit of resolution is approximately 20 nm. Thus, the dynamic range of mechanical motion is 100,000:1. The key to this extremely wide dynamic range is the closed-loop control system which constantly monitors and corrects the position of the output shaft of the actuator. In order to obtain this performance, the control system relies on the precise measurement of the position of the output shaft. This is accomplished through the use of an inductive position sensor attached to the bottom of the actuator case.

One of the primary benefits of the use of closed-loop control is that the actuator position is no longer affected by disturbances or the magnitude of the external load. In particular, because the flexures which allow the four-bar linkage to operate do have a finite transverse stiffness, they will deflect slightly under load. Thus, the use of closed-loop control to compensate for these minute transverse deflections is essential if the actuator is to have optical-quality performance.

The exploded view of the Lockheed actuator in Figure 4 shows the location of the various components. An operational prototype of the actuator is shown in Figure 5, with a portion of its case removed so that the internal components can be seen more easily. A schematic block diagram of the electronic control system is shown in Figure 6 and the actual electronic hardware required to drive the actuator is shown in Figure 7.

ACTUATOR PERFORMANCE

The performance of the Lockheed actuator has been characterized by measurements of time and frequency responses, the noise-equivalent position, and the effectiveness of the force offloading system.

The Bode plot of Figure 8 shows the actuator bandwidth set at 43 Hz. The resonance associated with the transverse compliance of the flexures in the four-bar linkage can be seen in the response dip at 115 Hz. The actuator has been tested to a bandwidth of 140 Hz driving a 1-kg load. However, because of the particular application (described in a later section), the bandwidth has been intentionally reduced.

One of the most important performance parameters for a closed-loop positioning system is the noise-equivalent position, i.e., the limit on the resolution of the actuator based on the noise in the sensor and electronics. Two measures of position noise with a 100-Hz cutoff frequency are shown in Figure 9; one for the actuator operating open loop and one for closed-loop. The two traces have rms values of 17 and 20 nm, respectively. The implication of nearly identical values of open- and closed-loop rms noise-equivalent position is that the actuator control system is operating at essentially the limit of sensor noise and environmentally-induced disturbances.

The ability of the actuator and the force-offloading system to respond to very rapid changes in applied load is illustrated in Figures 10 and 12. In Figure 10, the time scale has been expanded to show the well-damped nature of the response and the insensitivity of the actuator position to the applied load. Figure 11 shows the response of the high-bandwidth-position control loop and the low-bandwidth force-offload control loop. The current in the coil of the force-generating actuator is shown decreasing with a very long time constant (on the order of 20 sec, or a bandwidth of 0.008 Hz) to a steady-state value of 30 mA.

The angle of the control arm which moves the force-bias leaf spring is shown in Figure 12 along with the coil current. The change in angle of the control arm as it bends the leaf spring is exactly in opposition to the coil current. It is interesting to note how small an angular motion is required to compensate for the 5-N load. The right hand abscissa indicates that the arm has rotated a total of only 6.5 deg.

The performance characteristics of the Lockheed actuator are summarized in Table 3.

APPLICATION

The primary motivation for developing the Lockheed actuator was to provide control capability for an experimental segmented optical system called the Advanced Structures/Controls Integrated Experiment (ASCIE). The ASCIE consists of a 2-m, seven-segment, actively controlled primary mirror supported by a lightweight truss structure. The actuator described in this paper is used to control the six peripheral segments of the primary mirror which surround the central fixed segment. Each segment can be positioned in three degrees of freedom: piston and two axes of tilt. An array processor connected to a digital computer is used to compute the commands to the 18-segment actuators. Measurements of how well each of the segments is aligned are provided by edge sensors which determine the relative position of a segment with respect to its neighbors.

The ASCIE laboratory hardware is shown in the photographs of Figures 13 and 14. The back structure of the ASCIE reflector and the actuators can be seen clearly in Figure 14. The performance of the ASCIE system when the segment actuators are being driven by the segment alignment control system is shown in Figures 15 and 16. Figure 15 shows the positions of the three actuators controlling the position of one of the segments. Note that the actuators move several hundred nanometers over a period of 5-sec in response to commands from the control system. Figure 16 shows the motion of the segment itself. Even though each of the three control actuators is moving in different directions, the segment maintains extremely accurate alignment in all three degrees of freedom.

CONCLUSIONS

This paper has described the design, development, and performance characteristics of a special actuator whose wide dynamic range, precise positioning capability, high bandwidth, and low static power consumption make it directly applicable for use in actively controlled optical systems. One of the main applications for this type of actuator is for segment position control in large segmented reflectors. A specific example is discussed in which 18 of these actuators are used to control the segment positions of a 7-segment segmented-optics testbed called ASCIE. Laboratory tests of actuator performance as part of the ASCIE system indicate that segment position can be held to piston rms values of less than 100 nm and tilt rms values of less than 200 nrad. This performance meets the requirements for an astronomical-quality optical surface and indicates that the actuator design described in this paper has successfully met its original design objectives.

REFERENCES

1. Nelson, J. E., Mast, T. S., and Faber, S. M.: The Design of the Keck Observatory Telescope (Ten Meter Telescope). Keck Observatory Report Number 90, Berkeley, CA, January 1985.

2. Swanson, P. N., Gulkis, S., Kuiper, T. B., and Kiya, M.: Large Deployable Reflector (LDR): A Concept for an Orbiting Submillimeter-Infrared Telescope for the 1990's. Optical Engineering, Vol. 22, March 1983, pp. 725-731.

3. Angel, J. R. P., and Hill, J. M.: Steps Toward 8-m Honeycomb Mirror Blanks-III: 1.8-m Honeycomb Sandwich Blanks Cast from Borosilicate Glass. Proceedings of the SPIE Conference on Advanced Technology Optical Telescopes II, Vol. 444, 1983, p. 194.

4. Woltjer, L., et al.: Proposal for the Construction of the 16-m Very Large Telescope. European Southern Observatory, Garching, FRG, March 1987.

5. Bushnell, D.: Aiming an Electromagnetic Beam by Bending Segments of a Large Reflecting Surface. AIAA Journal, Vol. 17, No. 4, April 1979.

6. Mast, T. S., and Nelson, J. E.: Figure Control for a Fully Segmented Telescope Mirror. Applied Optics, Vol. 21, 1982, pp. 2631-2641.

TABLE 1. LOCKHEED SOLUTION TO LIMITATIONS OF CONVENTIONAL DESIGNS

Problem	Solution
Dynamic Range	Use of electromagnetic actuator in an analog closed loop using special low-noise sensor electronics
Bandwidth	Use of electromagnetic actuator and moderate equivalent gear ratio
Stiction/friction	No bearings or lubricants Exclusively flex pivots
High power consumption	Four-bar linkage (lever) and force unload system
Inability to cancel static forces	Force unload system

TABLE 2. COMPARISON OF ACTUATOR CHARACTERISTICS

Actuator Type	Dynamic Range	Accuracy	Resolution	Smoothness	Bandwidth	Idle Power	Reliability
Stepper- or DC-motor-driven gear/screw	Large	Medium	Medium	**Poor**	**Low**	Low	Poor to Medium
Hydromechanical (Keck Telescope)	Medium	Good	Good	Good	**Low**	Low	Medium
Piezoelectric (open-loop)	**Small**	**Poor**	Good	Good	High	Low	Medium
Piezoelectric (with feedback)	**Small**	Good	Good	Good	High	Low	Medium
Inch-worm	Large	Good	Medium	Medium	**Low**	Low	Medium
Voice-coil (open-loop)	Medium	**Poor**	Good	Good	Medium	High	Good
Lockheed Design	Large	Good	Good	Good	Medium	Low	Good
Ideal Actuator	Large	Good	Good	Good	High	Low	Good

TABLE 3. PERFORMANCE CHARACTERISTICS OF THE LOCKHEED ACTUATOR

Dynamic Range	100,000:1
Total Mechanical Range	± 1 mm
Noise-Equivalent Position	20 nm (rms, measured using a 100-Hz filter)
Friction/Stiction	None
Typical Static Power Required	10 mW
Maximum Available Bandwidth	140 Hz
Maximum Available Force	± 45 N
Weight	700 g
Operational Features	• soft startup and shutdown • automatic force unloading • all-analog electronics

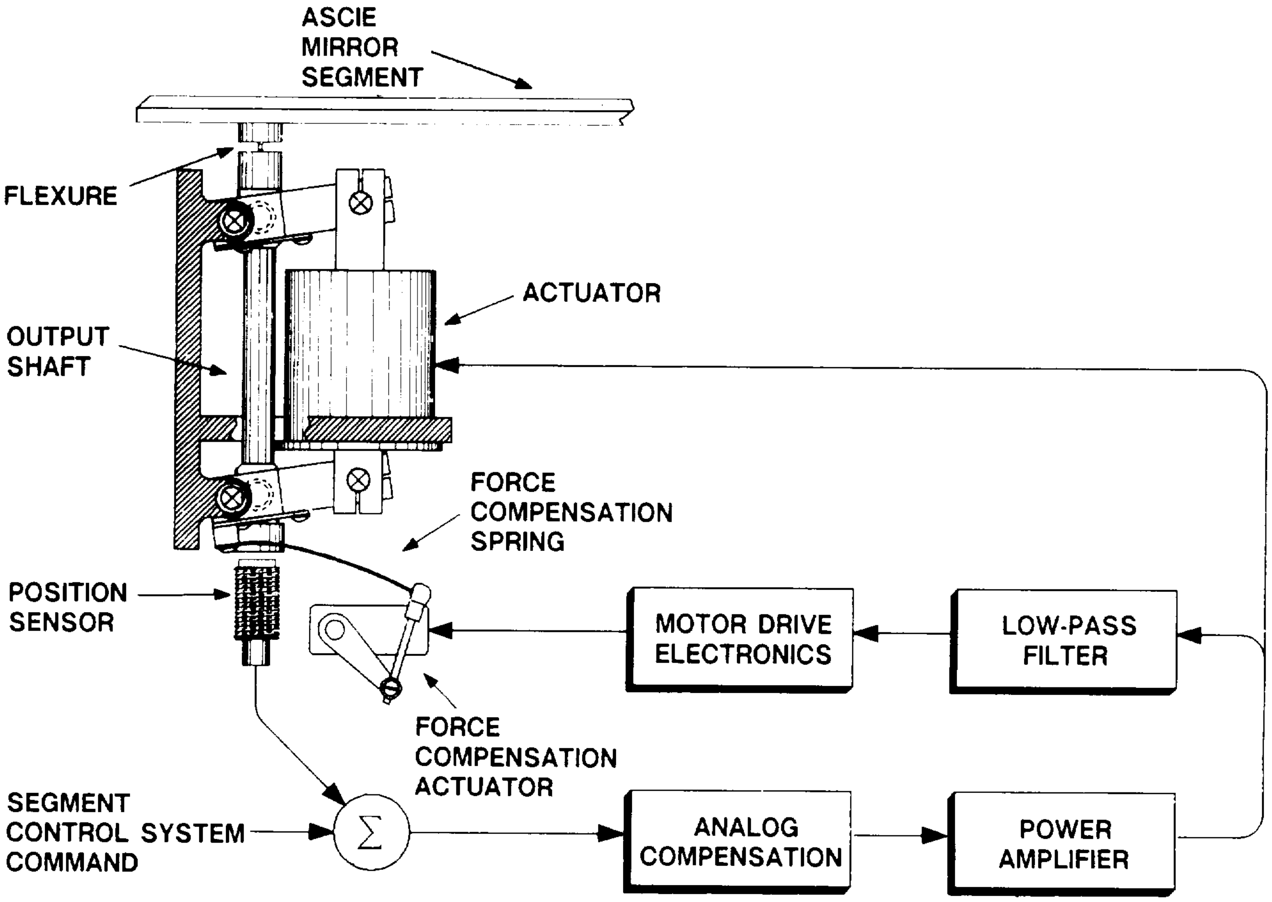

Figure 1. Schematic diagram of Lockheed actuator and closed-loop control system.

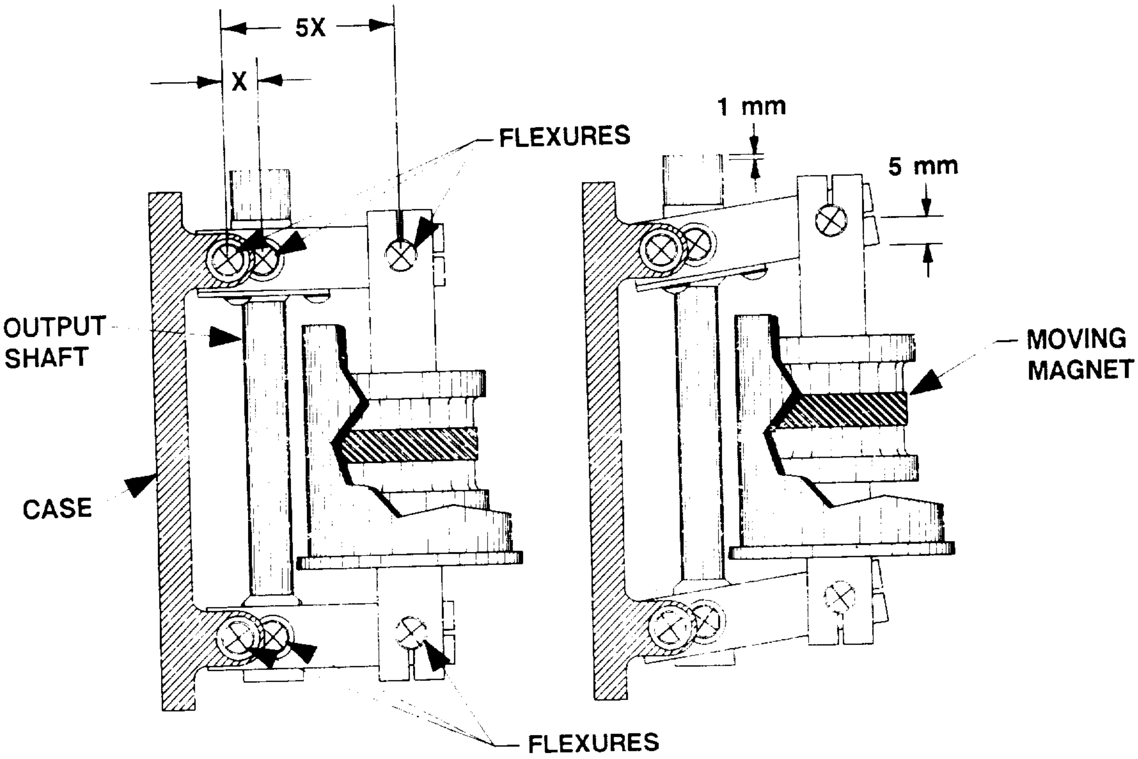

Figure 2. Four-bar linkage with 5:1 reduction ratio.

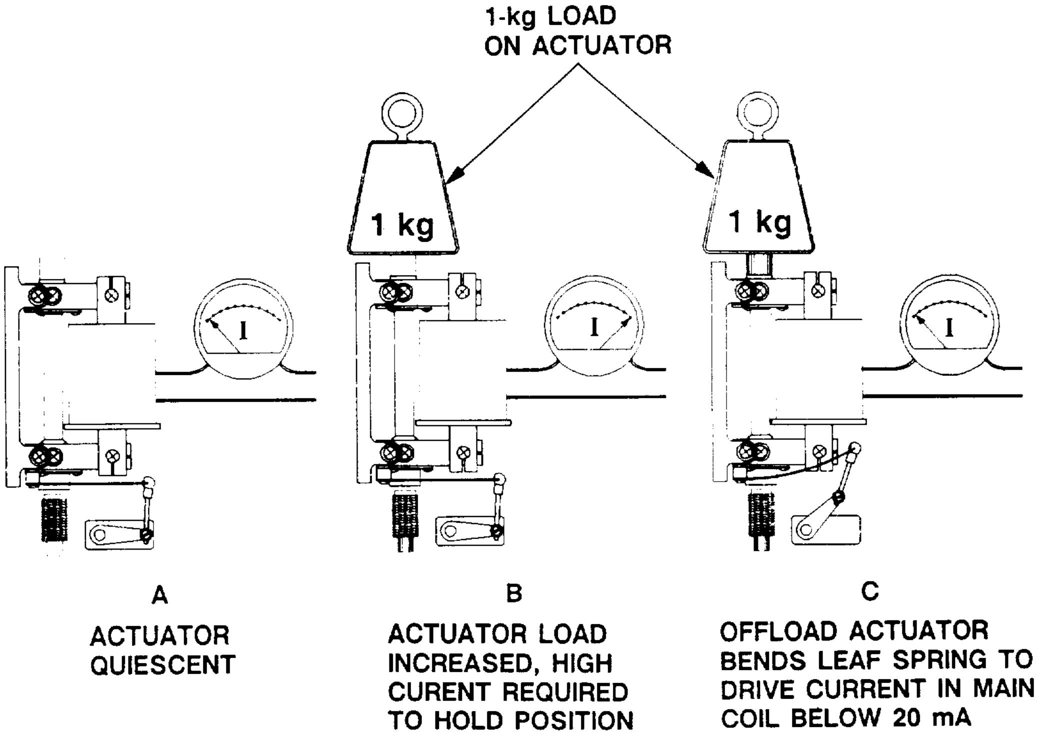

Figure 3. Operation of force-offloading system.

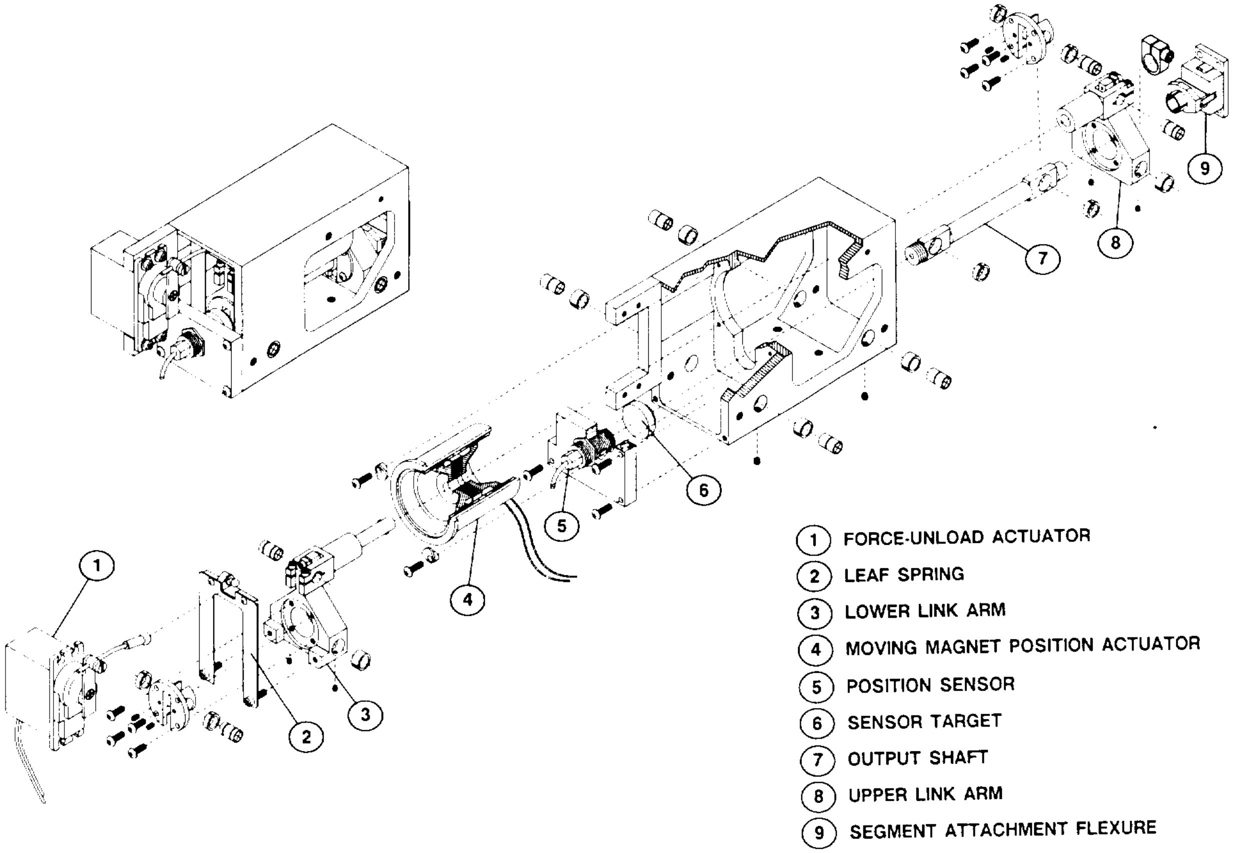

Figure 4. Exploded view of actuator mechanical components.

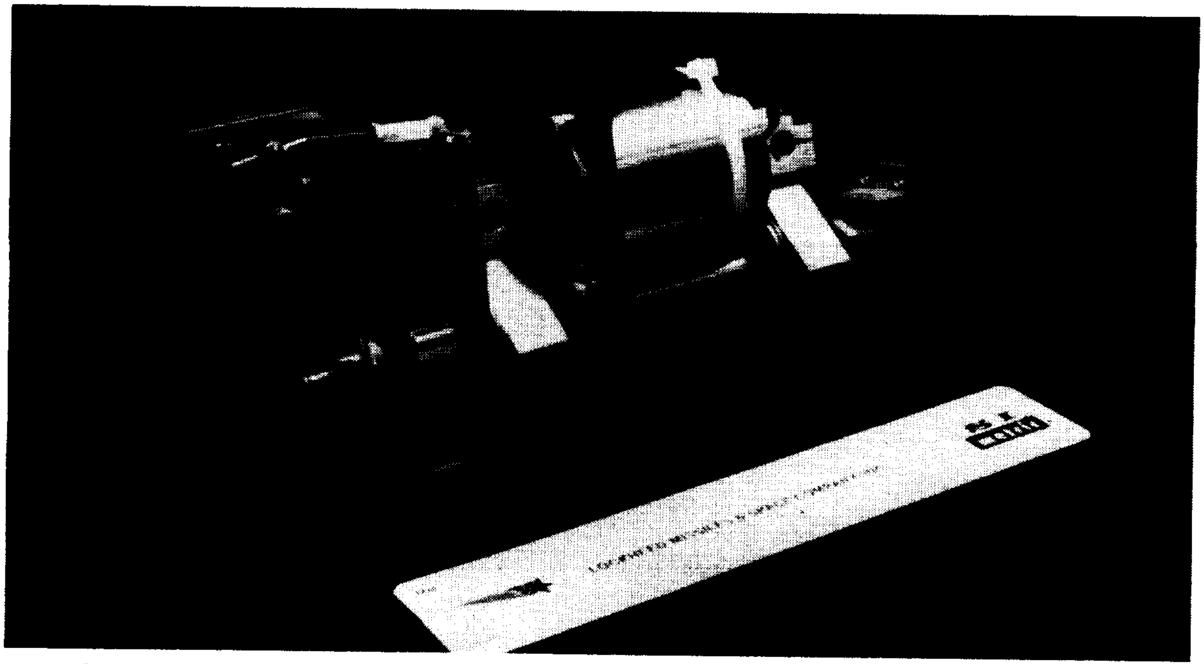

Figure 5. Cutaway version of actuator showing internal assembly.

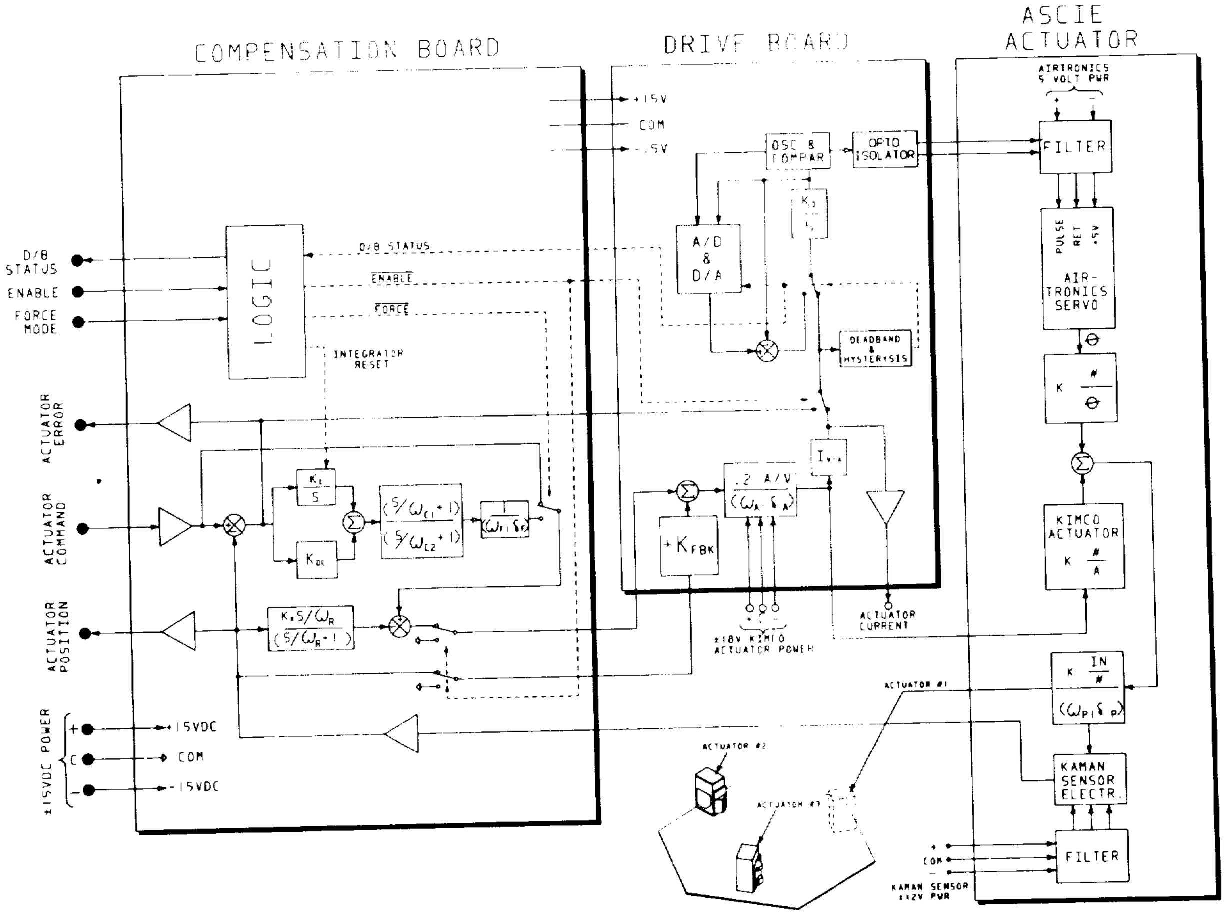

Figure 6. Schematic block diagram of actuator electronic control system.

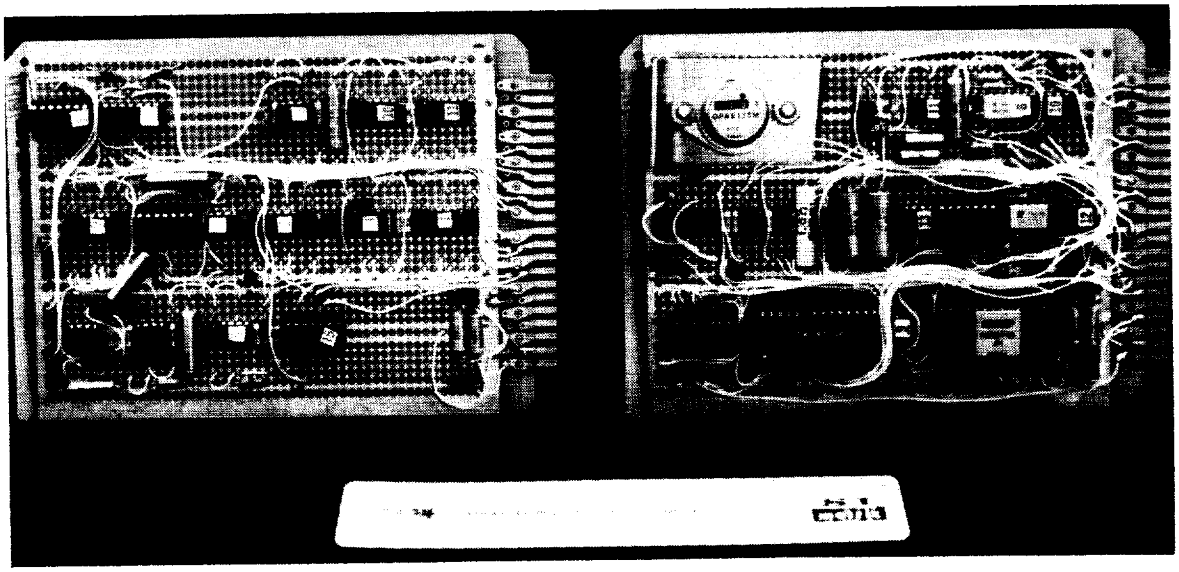

Figure 7. Electronics required for actuator drive and control.

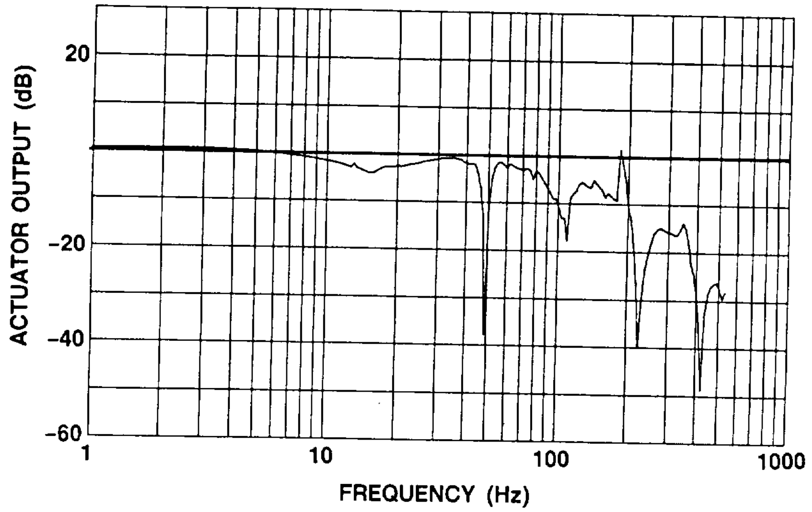

Figure 8. Bode plot of actuator response.

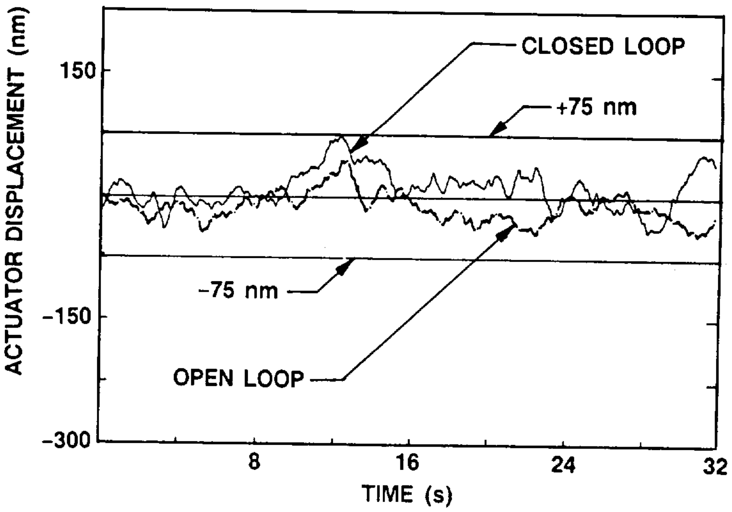

Figure 9. Actuator position noise under open- and closed-loop conditions.

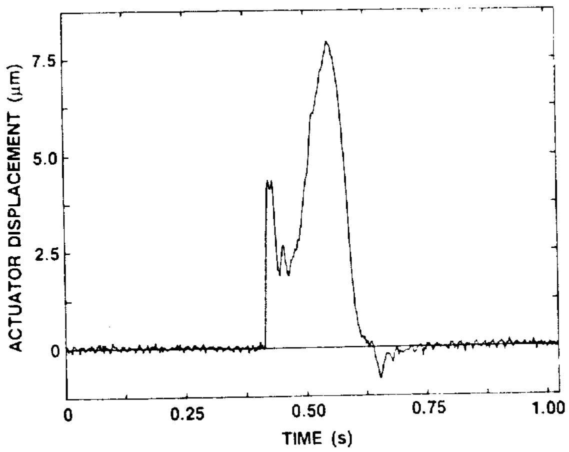

Figure 10. Actuator position response to a step increase in applied load.

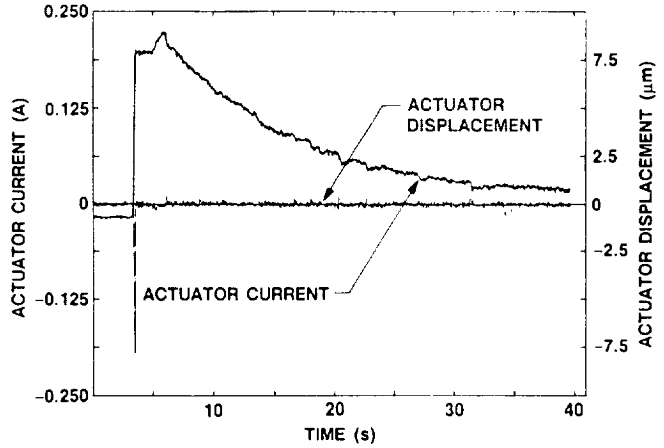

Figure 11. Actuator position response and current required after a step increase in applied load.

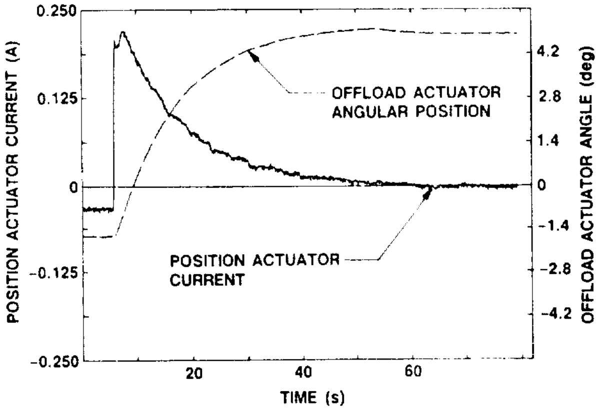

Figure 12. Actuator position response and motion of offloading actuator control arm after a step increase in applied load.

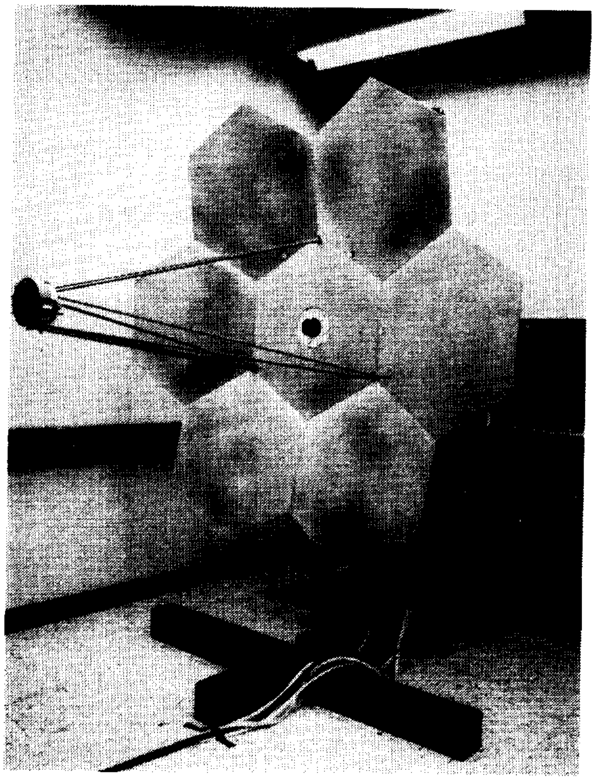

Figure 13. Front view of the Advanced Structures/Control Integrated Experiment (ASCIE).

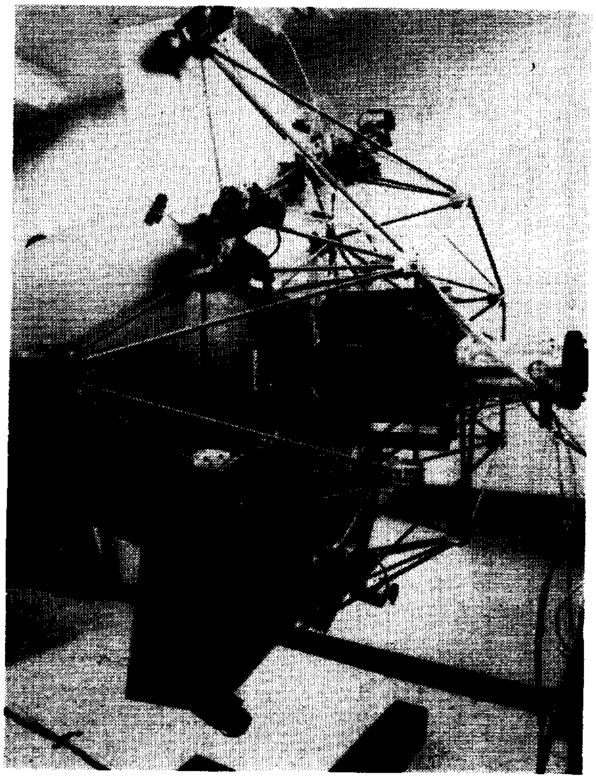

Figure 14. Rear view of ASCIE showing locations of segment-control actuators.

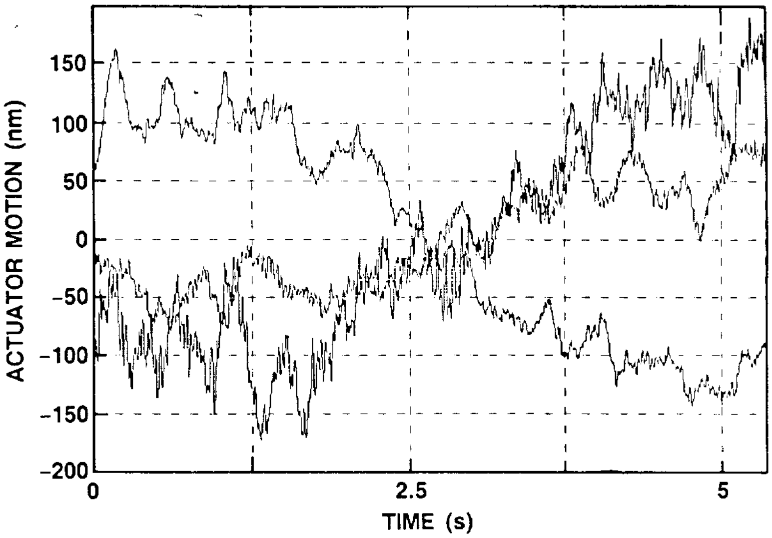

Figure 15. Actuator motion during 5-sec period while controlling the tilt and piston of an ASCI segment.

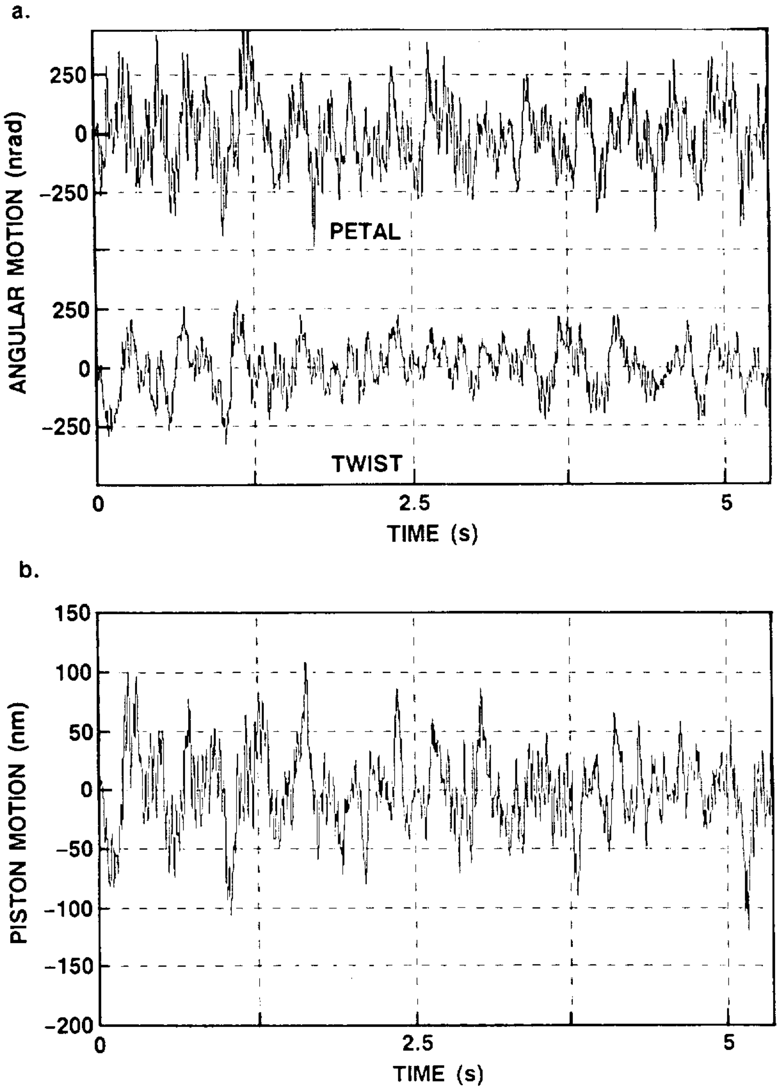

Figure 16. Segment tilt and piston errors corresponding to the same 5-sec period as actuator motion seen in Figure 15.