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DESIGN AND DEVELOPMENT OF A HIGH-STIFFNESS, HIGH-RESOLUTION TORQUE SENSOR

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ABSTRACT

The accuracy of precision pointing systems is often diminished by the inevitable presence of nonlinear drag torques resulting from rolling bearing friction and power/signal transfer cabling across rotary joints. These torques are difficult to characterize and impossible to predict analytically. However, the sensor described here provides torque knowledge that can be utilized by the controls designer to compensate for these nonlinearities. A prototype torque sensor has been built and tested, demonstrating that such a device is feasible for space-based precision pointing systems.

INTRODUCTION

Precision pointing applications require adequate knowledge of the system variables. Sensing torque directly in the precision motion control of spacecraft science platforms is recognized as a sound approach to significantly improving pointing performance. However, mechanical implementation and optimal control design remain challenges.

Previous torque-sensor designs are unacceptable for spacecraft science-platform articulation control. The problem is that the resulting devices are too flexible and of low resolution and low bandwidth. Existing designs today utilize displacement sensors configured on a flexible structure or shaft. Most designs use strain gauges as the sensing element, requiring rather flexible structures to obtain usable output signals. Other sensing elements suffer from the same flexibility and dynamic range limitations, or would require equipment too large or too complex to be incorporated practically.

A unique sensor has been designed and tested with encouraging results. The device uses a novel approach to sensing extremely small rotary motion, yet remains immune to cross-axis forces.

This paper presents a description of the hardware and design characteristics of the newly developed torque sensor, along with preliminary test data, a brief description of an integrated control methodology, and future applications.

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GENERAL DESIGN REQUIREMENTS

The following summarizes the requirements and the assumptions considered in designing the torque sensor. The primary design objective was to maximize stiffness in all nonrotational axes. In terms of dynamics, the device is required to provide extremely fine resolution over a wide torque range, to possess wide sensor bandwidth, to have high signal/noise electrical characteristics, and to have minimum hysteresis. Also it must be reliable in a space environment, i. e., designed to withstand launch loads, survive radiation exposure, and satisfy electronics qualification requirements. Finally, as in all space applications, devices must have low mass and low power consumption, and be inexpensive to manufacture.

The prototype torque sensor discussed in this paper was sized to fit existing hardware and designed to meet the following specifications, which reflect equivalent requirements for a representative science pointing application:

Torque Range	0.01 N-m - 10.0 N-m
Torque Resolution	0.001 N-m
Signal/Noise	10:1
Structural stiffness	>50Hz
Hysteresis	Minimum (10% Goal)

HARDWARE DESCRIPTION

The torque sensor consists of the sensing element, a flat-spoke support structure, interface plates, and associated signal conditioning and amplifier electronics.

Element

The heart of the torque sensor is the sensing element. Many types of load cells could be configured in the sensor, but to produce usable output signals, they must be mounted on a flexible structure or configured with a lever system to gain a mechanical advantage.

To obtain the highest displacement sensitivity, piezoelectric ceramic material was selected. The inherent characteristics of this material result in extremely high sensitivity, and the property of this material applied here is the electric polarization on its surface produced by mechanical strain. Conversely, when a field is applied to piezoelectric material, it changes dimensions in all three axes. The degree to which these dimensions change relative to the applied field is expressed as the d constant. This constant is the stress-free ratio of developed strain to applied field. The piezoelectric material selected for the torque sensor is from the lead-zirconate-titanate (PZT) family and has a d constant of approximately 110 C/N. A usable output signal must be obtained to resolve torque to the 0.001 N-m resolution specified as a design goal. Based on calculations using the assumed d constant, Young's modulus of 7.3 x 10^{-10} N/M^2, and a 2-mm thick, 5.07 x 10^{-4} m^2 area element, an output of 3.4 V would be achieved for 0.001 N-m of torque.

The required sensitivity relates to the extent to which the effects of coulomb friction from bearings, cables, and motor cogging must be reduced. This sensitivity is well within the capabilities of a torque sensor using a piezoelectric element. The torque sensor also has a large dynamic range that covers the maximum motor torque to the minimal error that must be corrected.

When purchased, the element was mounted to a brass baseplate to facilitate electrical connection, and the surfaces of the element were silvered for the same reason. One lead of a coaxial cable was soldered to the baseplate and the other to the element directly. Figure 1 shows the element placed between a mica insulator and a copper disk. Since the electric field is exposed at the surface of the element, the mica insulator isolates it from the mounting bracket. On the other side, the copper disk can pick off the electrical signal and distribute the preload force over a larger area of the element. The assembly is preloaded to remove compliance in the stack and creep in the assembly.

Flat Spoke Member

This member is a circular ring with thin, flat spokes machined radially along the circumference (see Fig. 2). It supports the sensor element along with its mounting brackets and provides structural stiffness. The flat spoke design provides a large aspect ratio to minimize deflection across the axis of rotation, and yet allows deflection about the rotation axis. The plate was machined from a single piece of 1.9-cm thick, 6061 T aluminum plate. A 15-cm hole is located at the center to lighten the component and, if necessary, allow passage of power and signal transfer cables through the device. The spokes measure 2-mm thick and approximately 2.5 cm in height. The goal was to make the spoke as thin as possible to maximize deflection in rotation and yet wide enough to resist moments across the axis of rotation. Maximum flexibility in rotation is needed to sense extremely small forces. This was accomplished by analyzing the spokes as simple cantilever beams with a very high aspect ratio to determine the optimum dimensions.

The end of each spoke has, parallel to the axis of rotation, a bolt hole for mounting to the interface plates. The diameter of the mounting pattern is 30 cm. Mounting consists of attaching alternating spokes to one plate, and the remaining spokes to the other plate. The equal mounting diameter maintains through-connection stiffness.

The use of multiple sensors positioned symmetrically around the device increases system stiffness and mechanical symmetry, and provides redundancy.

Only one element is needed to provide torque knowledge, so, in the event of a failure, any of the other elements could be activated.

Interface Plates (Fig. 3)

The interface plates serve two purposes. The first is to adapt the mechanical interfaces of the mounting structure to the spoke member described above. The second is to allow connection to alternating spokes. If the spoke member were mounted to a flat surface, rubbing would occur, restricting motion of the flat spokes. Protection against this is accomplished by machining standoffs on one side of each plate.

Launch Protection Assembly

The torque sensor must be rugged, reliable, and capable of withstanding launch vibration. The most sensitive component is the ceramic sensing element. Ceramic materials must be protected from shear and bending loads.

Due to the brittle nature of the ceramic material, a reliable method of protecting the device needs to be developed. A design concept for a launch protection assembly is presented. This device was not built during development of the prototype sensor. These materials are used most advantageously in a compressive loading condition.

The design shown in Figure 4 is believed to satisfy these requirements. The design shows an assembly that houses the brittle piezoelectric element so that shear and bending loads are eliminated and the element is subjected only to compressive loads. The drawing shows the fixed/floated combination for containing the element. The fixed side maintains the axial position of the element and carries part of the load. The other side is allowed to move axially in the other direction by means of a spring-loaded support. The spring's primary purpose is to relieve axial loads. It also relieves axial strains, such as those due to differentials in temperature or thermal expansion coefficients. The steel ball is used to alleviate loads and motion from the other degrees of freedom by allowing the element to roll when subjected to rotation or translation.

Electronics

A standard FET amplifier was used in this design and located as close to the sensor as possible. Sensor packaging must protect against thermal effects and interference from electromagnetic (EMI) sources such as the actuator motor.

PROTOTYPE TESTING

Testing of the prototype device was done to examine some of the fundamental design characteristics and to evaluate preliminary performance. The torque sensor was tested to determine the following:

- Cross-axis coupling
- Hysteresis
- Rotational stiffness
- Motor cogging.

Prototype testing of the torque sensor utilized existing hardware wherever possible to minimize development time and costs. The prototype sensor was sized to fit existing actuator hardware. However, the sensor could be made in any size to fit the application. A pointing control test-bed, located in JPL's inertial lab, was utilized to evaluate design characteristics and preliminary performance. The test-bed was designed for single-axis testing of precision actuators and pointing control algorithms. The test-bed adapts to different types of actuators and varying payload inertias. The actuator and payload are mounted on an air bearing to provide isolation and a frictionless rotary joint. The air bearing is configured with a calibrated spring connection between the levitated portion of the air bearing and ground, to simulate spacecraft boom rotational stiffness. The entire assembly is isolated from ambient noise by a concrete seismic pier. Test equipment includes dedicated microprocessor control electronics, a two-degree-of-freedom (DOF) rate gyro to measure platform motion, and data-acquisition equipment.

First calibration, sensor noise levels, and scale factor tests were performed to verify the sensor's operation and characterize its output signal.

Cross-axis coupling was determined by mounting the torque sensor on a horizontal test bench with the rotation axis parallel to the bench. Coupling from other axes would mean that forces not along the torque axis were detected by the sensor. This would corrupt the true torque knowledge to the controller and result in an incorrect torque command from the actuator. A rigid torque arm was bolted to one interface plate and the other plate secured to ground. A force was applied to the torque arm in different directions and the sensor output signal observed. It was found that cross-axis coupling significantly decreased with the steel-ball mounting arrangement, reducing the cross-axis signal to 10 percent of the rotation axis. The 10 percent cross coupling is felt by control analysts to be an acceptable value for three-dimensional pointing control to work properly.

Appraisal of hysteresis is important in all precision motion control systems. All mechanical systems exhibit hysteresis to some degree. Hysteresis represents lost motion that cannot be accounted for and therefore must be sensed and corrected. This is accomplished at the expense of additional hardware and control complexities. Every effort to minimize this lost motion should be taken. To determine hysteresis in the assembled device, the torque sensor was again mounted on the horizontal test bench with the rotation axis parallel to the bench. The rigid torque arm was mounted to one interface plate and the other plate secured to ground. Rotational motion was sensed by an electronic gauge. An incrementally increasing load was placed on the torque arm and the corresponding rotational motion recorded. Then the load was removed in the same increments and the resulting motion recorded. Results of this test indicate a maximum hysteresis of 4.9 percent over a torque range of 0 to 18 N-m.

Rotational stiffness of the torque sensor was tested next. The test configuration is shown in Figure 5, which represents the payload inertia oscillating at its natural frequency on the science-platform boom. The torque sensor must not noticeably increase the flexibility in the support structure. The sensor assembly stiffness should be at least an order of magnitude larger than the stiffness of the boom. A requirement of 50 Hz for the assembly's natural frequency was selected. One sensor element was installed between two spokes and preloaded by the mounting brackets. Tests were performed with jumper bars attached to the remaining open spokes to vary the overall stiffness and determine the minimum output signal from the sensor. Once firmly tightened, an impulse input was commanded to the actuator. Payload motion was sensed by the gyro located on top of the structure along the axis of rotation and recorded. Minimum stiffness about the rotation axis was found to be 63 Hz.

Finally, the motor cogging test was performed. Cogging is defined as the variation in torque due to the interaction of the armature magnets with the iron lamination. It is position-related and independent of excitation. For this test, the torque sensor was mounted between the base of a direct drive actuator and ground. The actuator motor was a two-phase, 24-pole-pair, permanent-magnet, brushless, dc type. The motor was designed to generate a sinusoidal back-EMF signal with minimum harmonic distortion for low ripple characteristics. Low cogging torque is achieved by the use of nickel-iron lamination material and skewing of the lamination to cover as much of the space between the permanent magnets as possible. The test was performed with the air bearing turned off, using quartz, a natural peizoelectric material, as the sensing element. A constant rate input of 0.39 rad/sec was commanded to the actuator. Figure 6 shows a plot of the torque sensor output. The variations in the output can be seen to correspond to the motor pole frequency at the input rate.

INTEGRATED CONTROL METHODOLOGY

Bridge-type feedback control is used extensively in electrical communication engineering with great success. Specifically, it greatly reduces the loop transfer function variations caused by uncertain conservative resonant loads, and thereby allows much higher feedback and better accuracy of control. Use of a similar control scheme in mechanical actuation systems, driving flexible structures, also provides enhanced control capability, but it necessitates using two sensors at the junction of the actuator and load simultaneously. One provides angular velocity and the other provides torque.

Recently, the balanced bridge control theory (BBT) was developed at JPL to take advantage of several nested bridge-type feedback loops. The BBT allows for large, wideband feedback around the actuator, greatly reducing the effects of imperfections caused by friction and cogging. In this way, a nearly ideal actuator can be implemented and used as a building block for precision pointing control.

OTHER APPLICATIONS

Sensor applications include spacecraft precision pointing and articulation control, distributed decoupling control of multilink systems (artificial limbs, manipulators, etc.), and large flexible structures.

SUMMARY

It has been demonstrated through design, development, and testing that the suggested torque sensor is feasible. The main design feature of the torque sensor that makes it unique is the novel configuration of the sensor support structure, which provides rotational compliance for the detection of small forces and cross-axis stiffness for isolation.

A prototype sensor has been built and tested to characterize its fundamental operating properties and has been used to measure motor cogging torques in a precision actuator.

This device provides increased control feedback knowledge for the precision science-platform pointing controls engineer without introducing "in-the-loop" flexibility. There are numerous applications for this technology in complex control systems and in precision motion control.

ACKNOWLEDGMENTS

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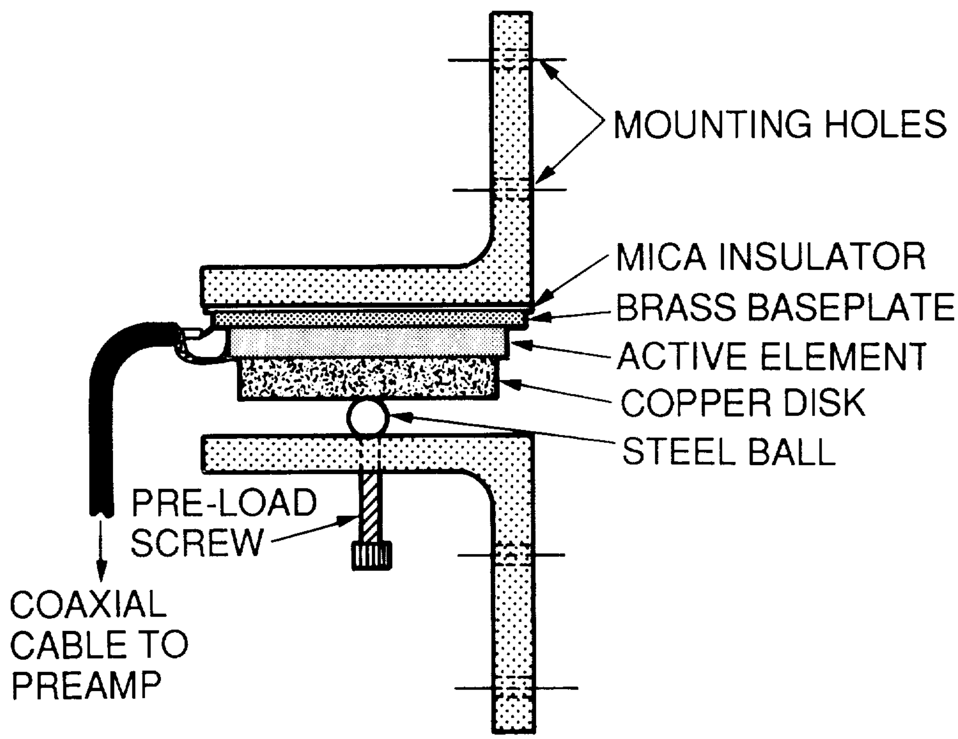

Figure 1. Piezo-ceramic sensor assembly.

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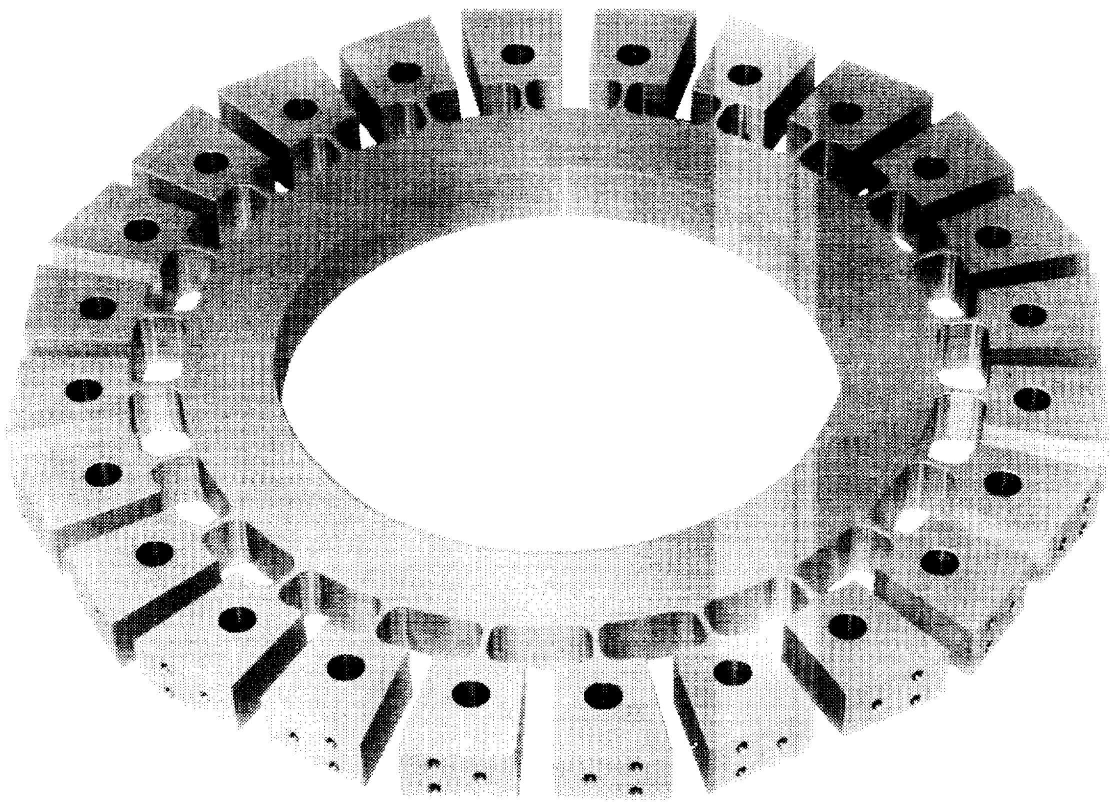

Figure 2. Flat Spoke Member

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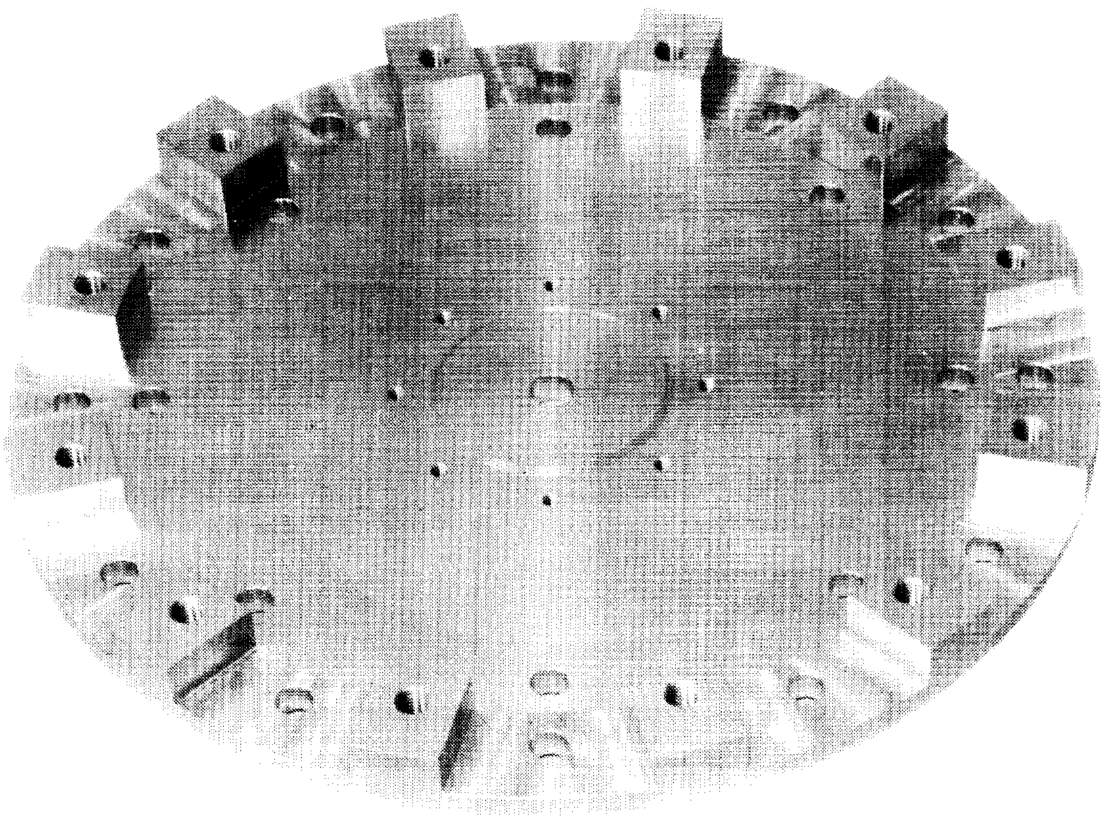

Figure 3. Interface Plate

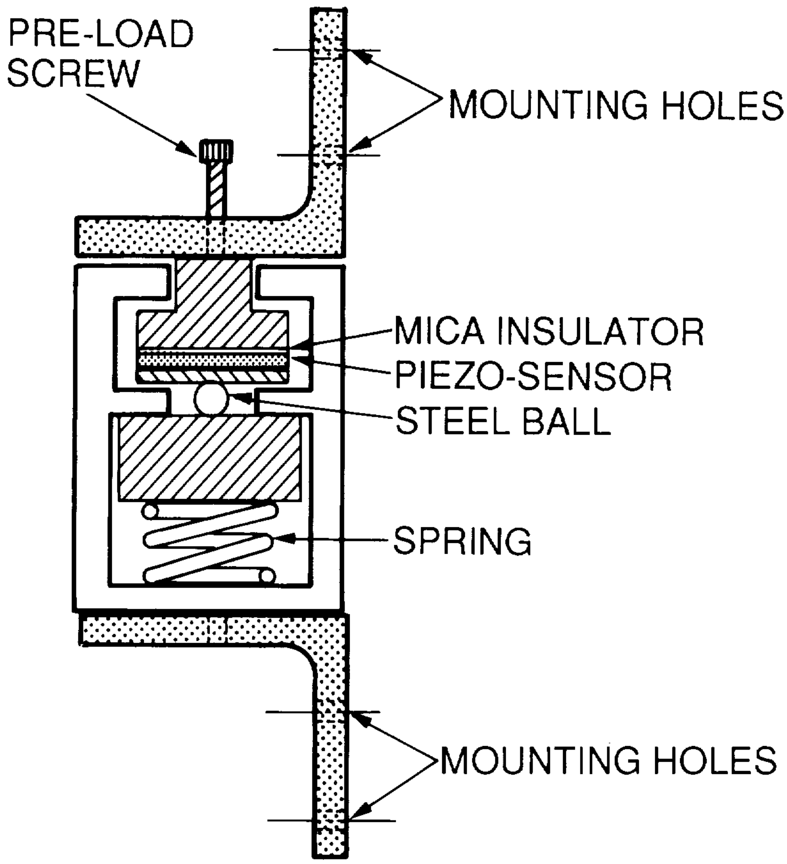

Figure 4. Launch Protection Assembly

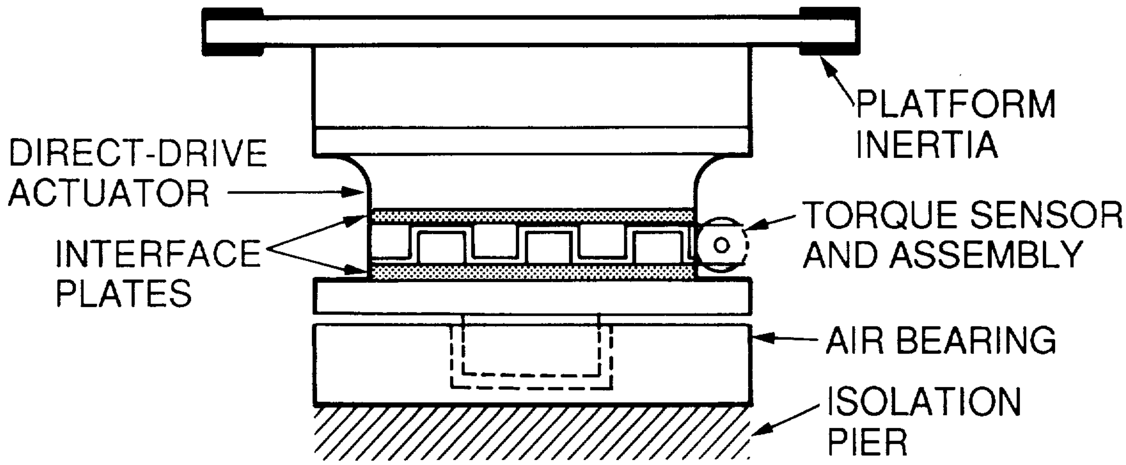

Figure 5. Torque Sensor Configured in Single-Axis Test Bed

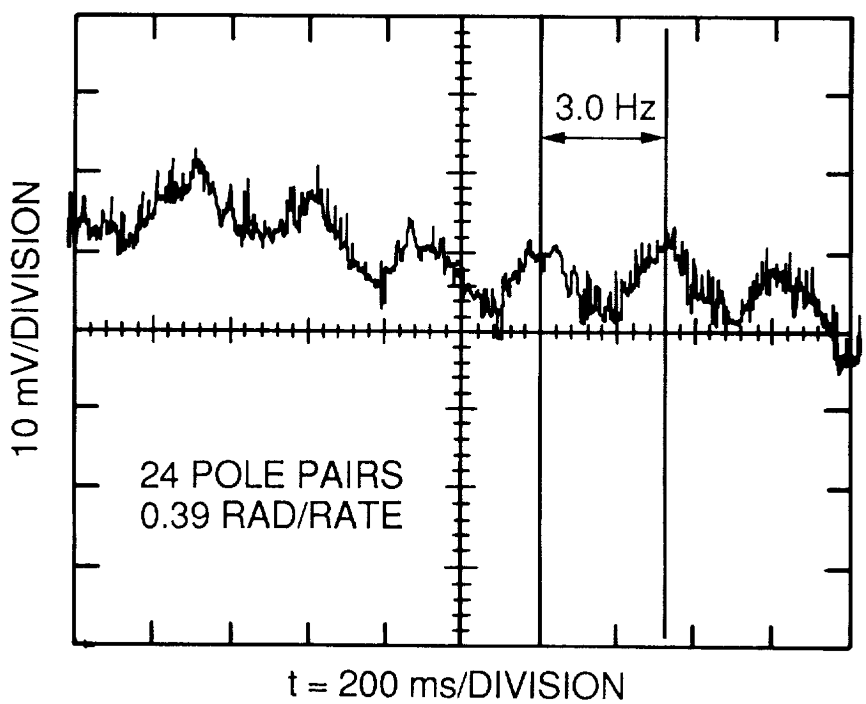

Figure 6. Motor Cogging