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THE DYNAMIC TORQUE CALIBRATION UNIT: AN INSTRUMENT FOR THE CHARACTERIZATION OF BEARINGS USED IN GIMBAL APPLICATIONS

Louise Jandura*

ABSTRACT

The Dynamic Torque Calibration Unit (DTCU), an instrument for the characterization of duplex ball bearing pairs used in gimbal applications, has been designed and built. The design and operation of the unit are described. Preliminary data from the instrument are presented to illustrate the kinds of experiments that can be performed with the DTCU.

INTRODUCTION

The Strategic Defense Initiative Organization (SDIO)-sponsored Tribomaterials Precision Gimbal Demonstration Program is an effort to develop technology for precision gimbals to support SDIO's pointing and tracking applications. The program's objective is the demonstration of enhanced performance of gimbal systems through the use of advanced tribomaterials in ball bearings. This approach recognizes that gimbal-bearing capabilities often drive the systems' conceptual-design requirements so that improvement in the bearings would lead to improved system performance.

Work funded through this program encompasses the range from development of new tribomaterial coatings to gimbal design. The Jet Propulsion Laboratory's (JPL's) role in the Tribomaterials Program is the evaluation of bearings, drawing upon the laboratory's experience as a designer and builder of precision-pointing systems. In contrast to many other members of the program whose primary role and interest are in developing new dry lubricants and in understanding the material properties of these films, JPL's contribution is in the evaluation and characterization of the coated bearings from a bearing user's point of view.

In keeping with its role as an evaluator of bearings, JPL has built a precision instrument designed to characterize a pair of test bearings in a single-axis test under carefully controlled conditions. This instrument is called the Dynamic Torque Calibration Unit (DTCU).

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* Member of Technical Staff, Guidance and Control Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

BACKGROUND

Other researchers have developed instruments to test bearings or bearing pairs under conditions appropriate for evaluating bearings for gimbal systems. These conditions include slow-speed operation and oscillatory operation, among others. Some of the instruments described in the literature are summarized below.

Greer and Mack [1] describe an instrument that tests a pair of angular contact ball bearings mounted back-to-back with a constant preload. A velocity servo drives the inner races of the pair at a constant speed while a position servo acts in a torque-rebalance servo loop to maintain the outer races at a null position. Torque measurements are made from the torque-balance servo loop. Results are presented on the spectral distribution of torque noise from the bearings as a function of various bearing parameters.

Leveille [2] describes tests performed in a slow-speed device that uses a single test bearing under a load. In this case, the test bearing's outer race is rotated at a constant speed while torque is measured by a strain-gage transducer mounted to the inner race.

In many papers [e.g., 3, 4] by researchers from the European Space Tribology Laboratory (ESTL), data are included from instruments capable of measuring bearing torque under both continuous and oscillatory motion. At ESTL, the test article is a preloaded duplex pair. The outer races of the test pair are driven and torque is measured at the inner races using an inductive torque transducer. These tests can be conducted in a vacuum.

Phinney et al. [5] conducted oscillatory life tests in a vacuum on lightly preloaded, face-to-face bearing pairs. The instrument accepts up to five bearing pairs at a time. The inner races are oscillated while torque is measured on the outer races through a strain gauge attached to a cantilever beam. Each bearing pair is instrumented separately.

The researchers listed above performed a variety of both performance and life tests. JPL set out to design an instrument specifically for performance testing (e.g., Dahl parameters [6], running torque, torque noise) of bearings coated with a dry lubricant and intended for use in a gimbal platform. The goal is to take very precise torque data while driving the test bearings with the same precision as that required in a gimbal application. This instrument's unique capability is in the precise position and rate control of the drive system. The torque-sensing capability, while significantly precise, is not unique. The desired test-item configuration is two angular contact bearings mounted back-to-back to form a duplex pair, because that is a common gimbal-bearing design.

DESIGN REQUIREMENTS

Given the scenario described above, the following design requirements for the DTCU were established:

- RATE TABLE:
    - Rate: 698 mrad/s (40°/s) maximum
    - Rate Error: < 3.5 mrad/s
    - Position Resolution: 12 μrad (19 bits)
    - Absolute Position Error: < 96 μrad
    - Modes of Operation: 1) continuous rotation in either direction, 2) oscillatory
- TORQUE SENSOR:
    - Torque Range: 0 to 2 N·m
    - Bandwidth: 0 to 100 Hz
    - Resolution: < 0.001 N·m
    - Accuracy: < ± 0.001 N·m

In addition to the specifications listed above, there were a few more requirements on the design task. The unit was required to operate in a vacuum. By necessity, the testing must be done in a dry environment (vacuum or nitrogen) to protect the integrity of the film. The instrument must be able to accept bearings of many different sizes that support a range of applications. The bearing test pair must be removed as a unit so it can be inserted into other test equipment as desired without disturbing the preload. The schedule was tight. All design, procurement, fabrication, and assembly was to be completed in six months.

The requirements on the drive system come directly from the sponsor's requirement to support a wide range of SDIO pointing and tracking applications. The desire is to exercise the test item with the same class of precision encountered in a gimbal application. The torque-sensor requirements flow directly from the drive-system requirements. Given the maximum drive system rate of 698 mrad/s or 0.11 Hz, the 100-Hz bandwidth of the torque sensor provides more than adequate frequency content. Moreover, we are most concerned with disturbances at frequencies within the typical gimbal-controller bandwidth, and this is at least an order of magnitude less than 100 Hz. The high end of the torque range requirement is set about an order of magnitude higher than that required for the kind of precision bearings used in gimbals. Further, the tribomaterial coatings are expected to produce lower levels of friction than typical liquid-lubricated bearings. This high-end requirement was maintained to give maximum flexibility in the types of bearings that can be tested.

DESIGN

The DTCU is composed of three major portions: a torque sensor or torque-rebalance loop, a drive system or rate table, and the bearing pair under test. It is similar to the instrument described by Greer and Mack [1]. DTCU operation is depicted in Figures 1 and 2.

A pair of test bearings is mounted back-to-back in a bearing cartridge under a known preload. The cartridge is then mounted on the DTCU shaft. The inner races of the bearing pair are precisely driven by the DTCU rate-table motor and its controller. The torque transmitted via the balls to the outer races of the bearing pair is measured by the torque-rebalance loop.

The operation of the torque-rebalance loop is shown in more detail in Figure 2. Two electrodynamic or voice-coil actuators are positioned to exert a pure torque couple to the outer races of the bearing pair. Two eddy-current differential position sensors mounted $\pi/2$ rad (90°) apart monitor the position of the outer races of the bearing pair. The advantage of this sensor configuration over a single sensor is that it reduces the effects of bearing runout and other drive eccentricities to an acceptable level. Three sensors mounted $2\pi/3$ rad (120°) apart would be immune to these effects but that option was too expensive. A torque-rebalance control loop drives the voice-coil actuators using the eddy-current sensors for feedback. This keeps the outer races of the bearing pair at a null position while the inner races of the bearing pair are driven by the rate table. The current developed in the voice coils to hold the outer race at a null position is proportional to the torque transmitted through the bearing pair.

Both the voice-coil actuators and the eddy-current sensors operate through an air gap; therefore, there is no direct mechanical contact between the test bearings and the measurement system. When properly aligned, this noncontacting system allows measurement without stray loads.

Rate Table

The mechanical rate-table design uses a 16-pole, brushless dc motor, an Inductosyn, two liquid-lubricated ABEC class 7 bearings, a flywheel, and a magnetic shield. An Inductosyn is a printed-winding pancake resolver. The magnetic shield prevents motor electromagnetic emissions from disturbing the Inductosyn operation. The flywheel was added after analysis revealed that more inertia would provide better rate stability. Tight tolerances are maintained on both the bearing mounting surfaces and the Inductosyn mounting surfaces in keeping with the desire for precise control of the position and rate of the shaft. The Inductosyn is mounted near the top of the shaft to provide more accurate knowledge of the portion of the shaft near the test-bearing pair. This lessens the effect of windup between the motor and the top of the shaft. Static o-ring and labyrinth seals are used to minimize contamination of the test article by the lubricants of the rate-table bearings.

Torque Sensor

The mechanical design of the torque-rebalance loop portion of the DTCU is intended to maintain the positions of the two linear voice-coil actuators and the two eddy-current sensors. The magnet portion of both voice-coil actuators and the sensor heads of both eddy-current sensors are positioned from a plate mounted on the top of the DTCU housing. The coil portion of the two voice-coil actuators and the targets for the two eddy-current sensors are mounted on the bearing cartridge and their weight is supported through the outer races of the bearing pair. This weight was designed to be minimal (less than 2.3 kg (5 lb)) and is statically balanced by appropriate counterweights to prevent the introduction of a moment load on the test article.

Bearing Cartridge

Although the bearing-cartridge design is not yet complete, it is being designed with the following features in mind. The cartridge will provide the preload for the bearing. Both hard and soft preloads can be accommodated. Once installed in its cartridge, the bearing pair can be removed from the DTCU so that it may be installed in other test equipment as necessary without disturbing the preload. The cartridge also aligns the bearing pair with the shaft. Finally, the cartridge will align and support the torque measurement equipment that is attached on the outer race of the bearing pair.

Figure 3 is a schematic diagram of the bearing-cartridge design. The two main challenges in this design are fixing the cartridge to the rate-table shaft and establishing the preload. Our interim design addresses the first problem, but does not yet completely answer the preload question. This will be resolved in the final version of the design.

The schematic shown in Figure 3 illustrates the means of attaching the bearing cartridge to the shaft. The split hub on the bottom of the bearing cartridge fits over the rate-table shaft and is clamped to the shaft. The tolerance and the fit of the split hub keep the bearing cartridge and therefore the test article concentric with the shaft. It is then ready to be mounted in other test equipment. Also shown in the figure are labyrinth seals on both the top and bottom of the test article. These are included to further minimize contamination of the test bearings by any outgassed lubricant that escapes from the labyrinth seal of the rate table.

Control Law Design

The electrical design of the DTCU consists of two major parts: a rate-table motor controller and a torque-rebalance loop controller. The rate-table motor controller is represented in Figure 4. To accomplish the required rate control, we have implemented what is fundamentally a precision position controller. The controller is not simple and is intended to give a class of performance similar to an actual spacecraft pointing platform. Although this is not completely possible without expensive inertial sensors, this performance is being approached by the use of a 12 μrad (19-bit) resolution Inductosyn position sensor. With this controller, difficult torque measurements, such as those associated with precision staring and controlled rate reversal, are possible.

The design challenge is to obtain 14.5 μrad pointing with this sensor. Conventional proportional-integral-derivative (P-I-D) compensation is inadequate to achieve this pointing stability, so a 3-state sequential least-squares estimator was created to obtain the necessary rate feedback. In Figure 4, the entire estimator is represented in the $K_r s$ block. The controller is a digital/analog hybrid design that performs all precision functions digitally (950 μs sampling time) and provides digital outputs for data logging. Both analog and digital input command signals are accommodated.

Figure 5 is a block diagram of the torque-rebalance loop controller. This is a standard P-I-D controller. No complications, as in the rate table controller, were necessary to obtain a tight 100-Hz bandwidth (-3 dB point) loop with current to the voice coils as the measure of torque. In this manner, the voice coils become the reference for torque and the eddy-current sensors serve only to close the loop.

ASSEMBLY

The most critical part of the DTCU rate-table assembly is the mounting of the Inductosyn. The positioning of this sensor is important in both the commutation of the motor and the precise control of the shaft. Tight specifications exist for parallelism, concentricity, and the gap between the rotor and stator pieces of the Inductosyn. Shims and spacers are used to create the correct gap and to level out the parts. The Inductosyn spacing was measured as shown in Figure 6. In this assembly, the top plate of the rate table is mounted on four posts designed specifically to allow access for measuring the Inductosyn gap. The entire assembly is fastened to a milling machine table where radial alignment of the top plate and the shaft to the bottom plate is established. This is necessary because the four posts provide only accurate axial spacing, not radial alignment. In the final assembly, the housing provides the radial alignment. The final gap was measured at 0.2 mm (0.007 in) and was uniform all around. Inductosyn rotor radial runout was measured as no more than 0.008 mm (0.0003 in) total indicator readout.

Accurate positioning of the torque-sensor mechanical assembly is necessary to achieve the desired sensor performance. This is done using a milling machine for measurements. The torque sensor is assembled with alignment rods to accurately position the magnet support, the voice-coil actuator, and the coil bracket. The voice-coil magnets are centered on the shaft center in two directions as described in Figure 7. The coil brackets are adjusted until the coils are concentric with the magnets. Finally, the position-sensor supports are shimmed so that the position-sensor targets are approximately centered in the position-sensor supports when the coils of the voice-coil actuators are centered in their magnets.

Figures 8, 9, and 10 show the DTCU completely assembled and integrated with the electronics. Figure 8 is an overview of the rack of electronics and the DTCU. Figure 9 is a view of only the DTCU. The connectors and sensor preamps mounted on the top plate of the instrument are visible. Also shown in Figure 9 and shown in closeup in Figure 10 is the torque sensor. The test-article mounting plate supports both the coils of the voice-coil actuator and the eddy-current sensor targets. Only one sensor pair and one actuator are visible in Figure 10. The voice-coil magnet and the position-sensor supports are attached to the torque-sensor base plate. One of the eddy-current sensor heads is seen between the sensor target and the right position-sensor support. The black box in the foreground is the eddy-current-sensor electronics for the sensor in the picture.

TEST RESULTS

Since the bearing-cartridge design is not yet complete, a substitute bearing was configured so that the DTCU could be tested. Figure 11 shows a schematic of the DTCU test setup using this substitute bearing. The bearing consists of a metal disk covered on its top surface with a 2-mm-thick disk of teflon. In this configuration, the substitute bearing is clamped to the shaft and the test-article mounting plate is placed on the teflon surface. Note that this is different than the mounting configuration used with a bearing pair in the cartridge. In the latter case, the bearing pair is mounted to the shaft as shown in Figure 3, and the test-article mounting plate is attached to the outer races of the bearing pair below the test article. However, for purposes of testing the operation of the DTCU, the substitute bearing configuration is functionally equivalent to the final mounting configuration. The rate-table shaft turns the substitute bearing, while the torque-rebalance loop maintains a null position against the friction torque transmitted through the teflon surface.

Figures 12 and 13 contain data taken with the DTCU using the substitute bearing. These experiments are meant to illustrate only the kinds of data that can be taken with the DTCU and to demonstrate its complete operation. The test conditions and data-collection parameters were chosen arbitrarily to illustrate the DTCU capabilities in both its higher and lower speed ranges. Different test profiles and higher rate sampling are possible. The values for torque presented in the figures are only an approximate calibration of the torque sensor. The final calibration has not yet been done.

Figure 12 is a plot of running torque taken with the substitute bearing running at 800 mrad/s in the counterclockwise direction. This rate is half the maximum rate of the DTCU and a little faster than the sponsor's specification for the maximum gimbal-slew rate. For this experiment, sampling was set for once every 17.5 mrad (1°) of position or approximately 46 Hz at this rate.

Figure 13 illustrates data from an experiment to measure Dahl friction parameters. The bearing was oscillated through about 1.75 mrad (0.1°) with a sine function of 0.1 Hz. Sampling was done at 10 Hz. The figure illustrates the hysteretic behavior found in this regime from which the bearing's Dahl parameters may be derived.

FUTURE WORK

The next steps in the DTCU development are to carefully validate the DTCU operation, to precisely calibrate the instrument and to complete the bearing-cartridge design. The evaluation of bearings can begin after these three steps are completed.

Another related area of DTCU development is adapting it for the torque characterization of other mechanical components such as motors, slip rings, and gear trains. The biggest technical challenge here is developing a scheme for mounting components other than bearing pairs.

CONCLUSIONS

The DTCU has been designed, fabricated, assembled, and tested. Experiments for running torque and Dahl parameters were performed using a substitute bearing. The initial testing indicates that the design requirements have been met or exceeded. The DTCU has the ability to test bearings under conditions similar to those of an actual spacecraft pointing platform. This test capability provides for precise torque characterization of duplex ball bearing pairs.

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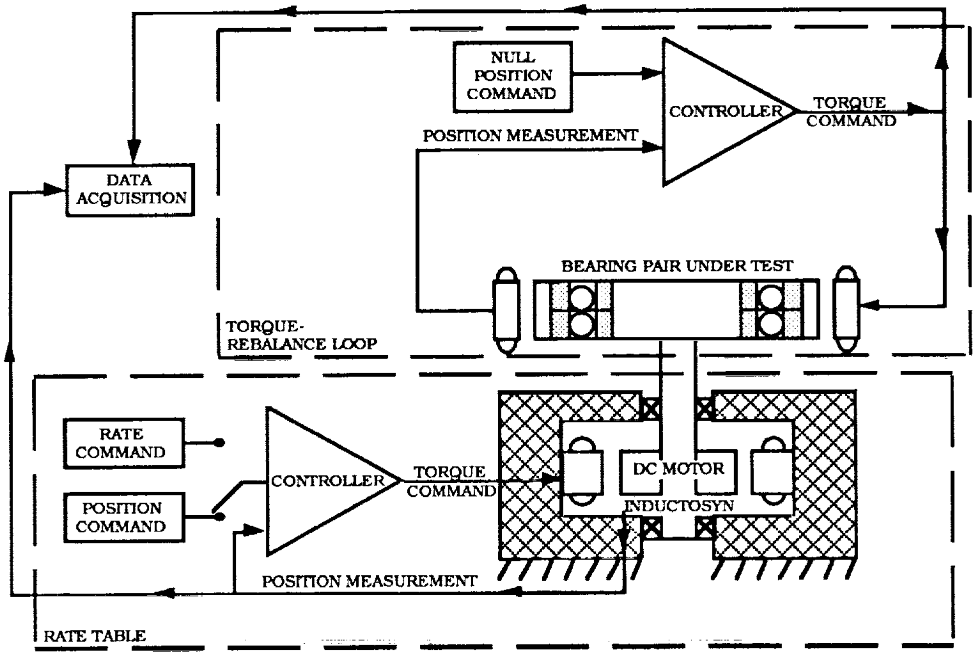

Figure 1. Schematic of the Dynamic Torque Calibration Unit (DTCU).

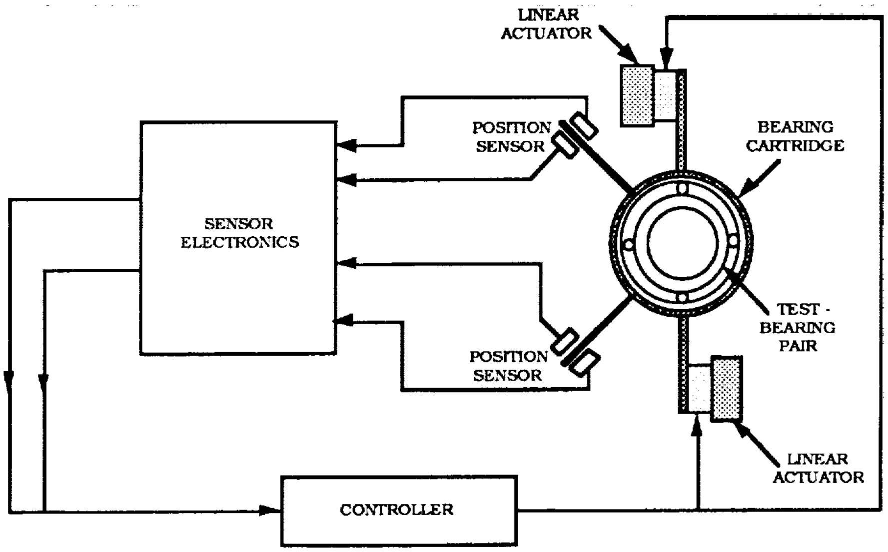

Figure 2. DTCU torque-rebalance loop operation.

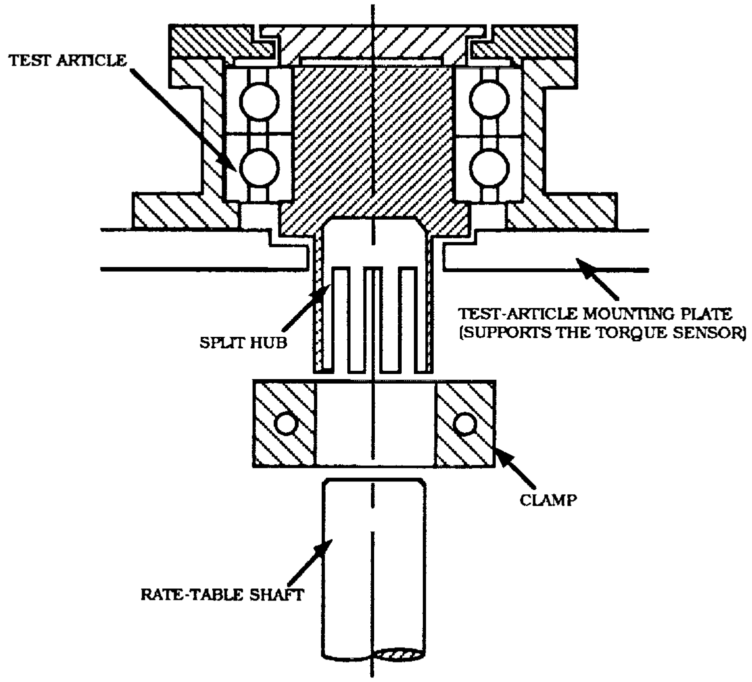

Figure 3. Bearing-cartridge design.

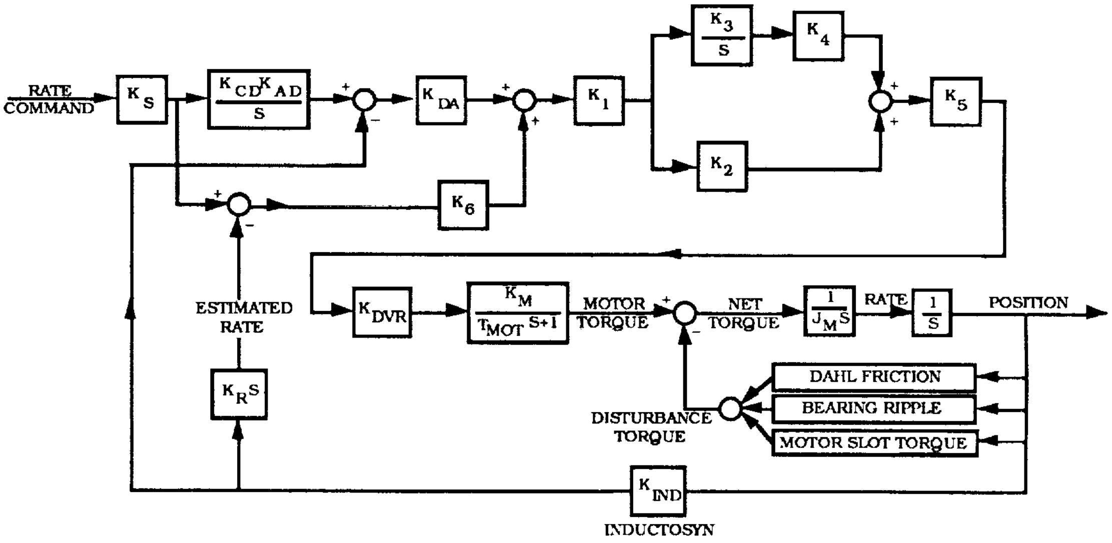

Figure 4. Rate-table controller.

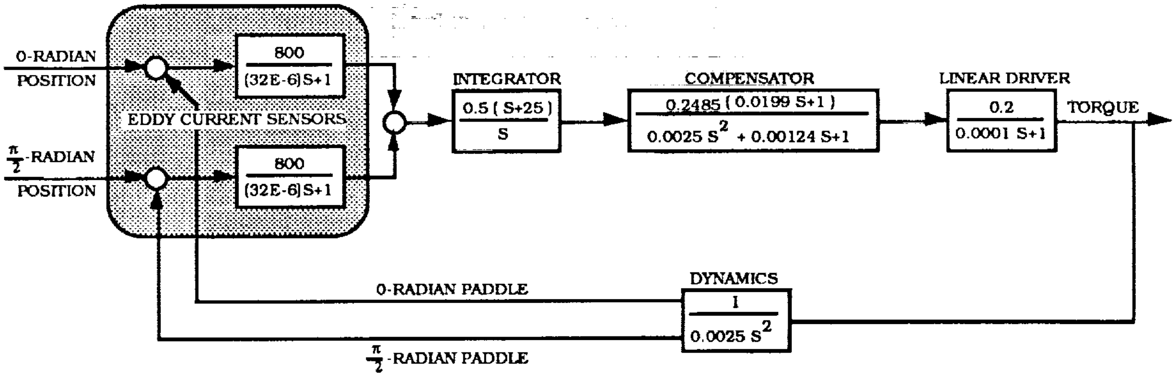

Figure 5. Torque-rebalance loop controller.

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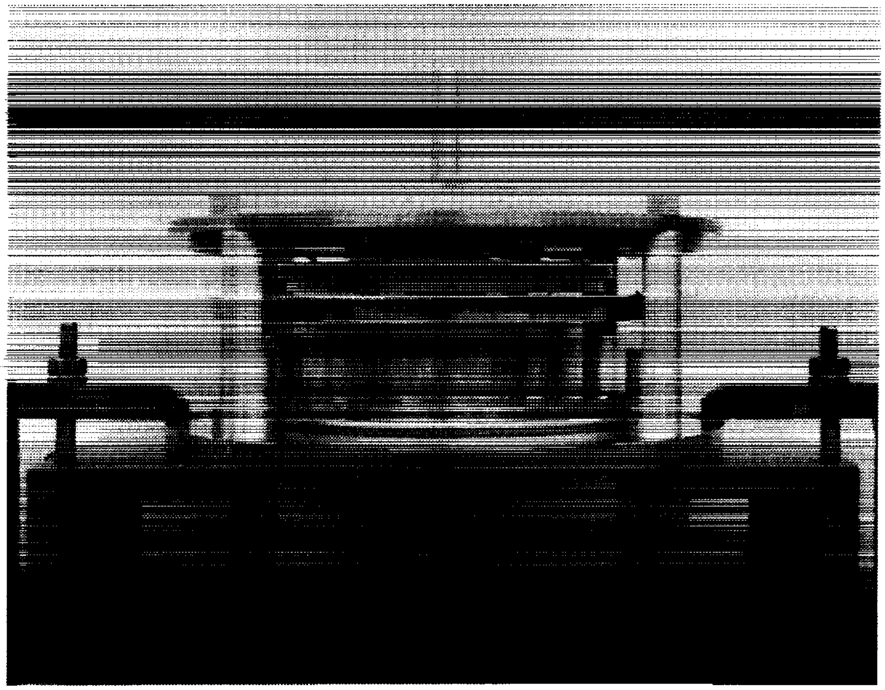

Figure 6. DTCU preliminary assembly mounted on a mill table.

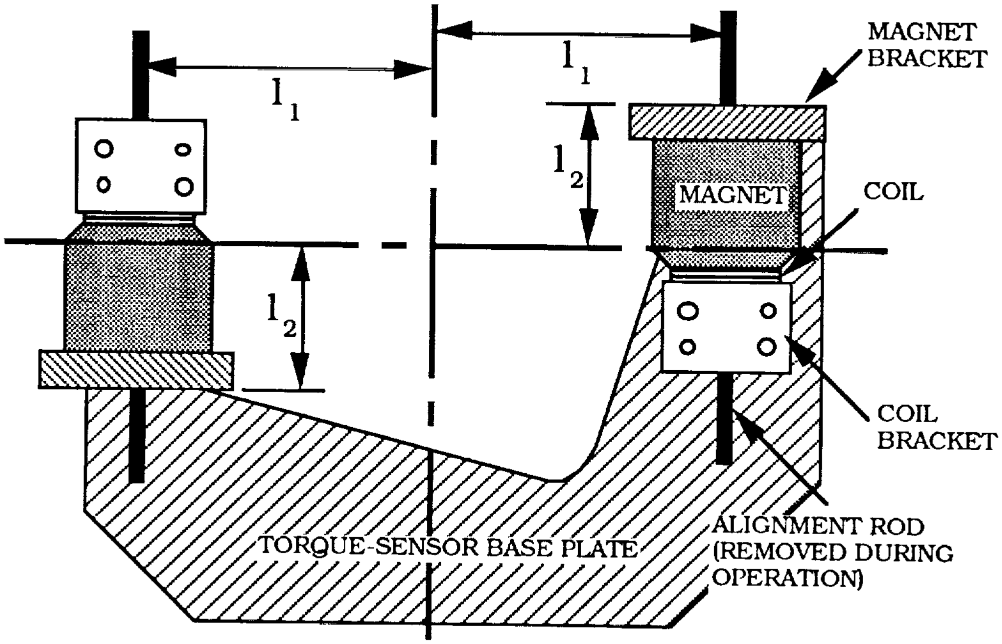

Figure 7. Torque-sensor alignment.

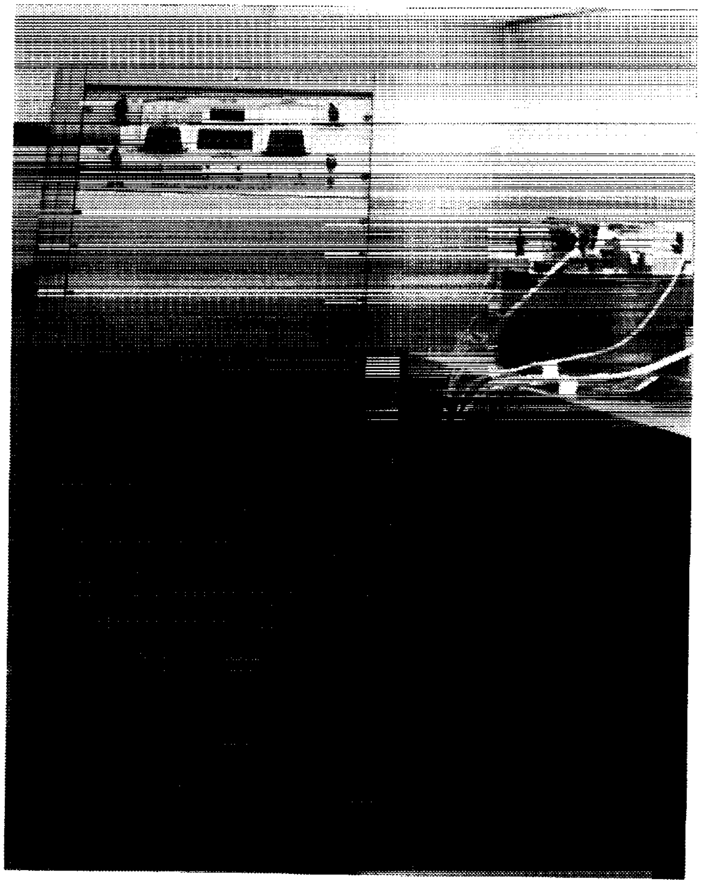

Figure 8. The DTCU and its electronics.

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Figure 9. The DTCU.

Figure 10. Closeup of the DTCU's torque sensor.

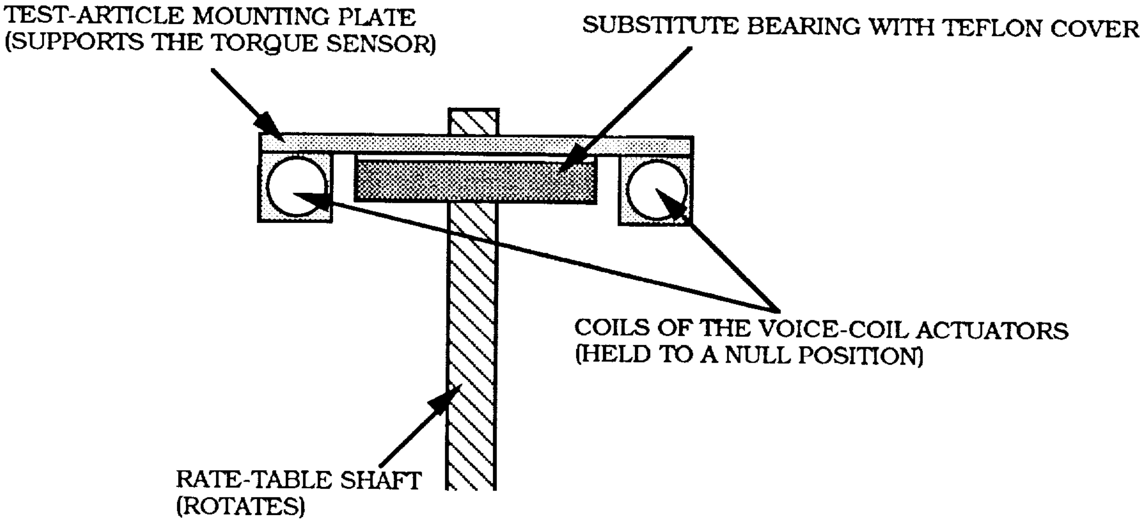

Figure 11. Test setup using a substitute bearing.

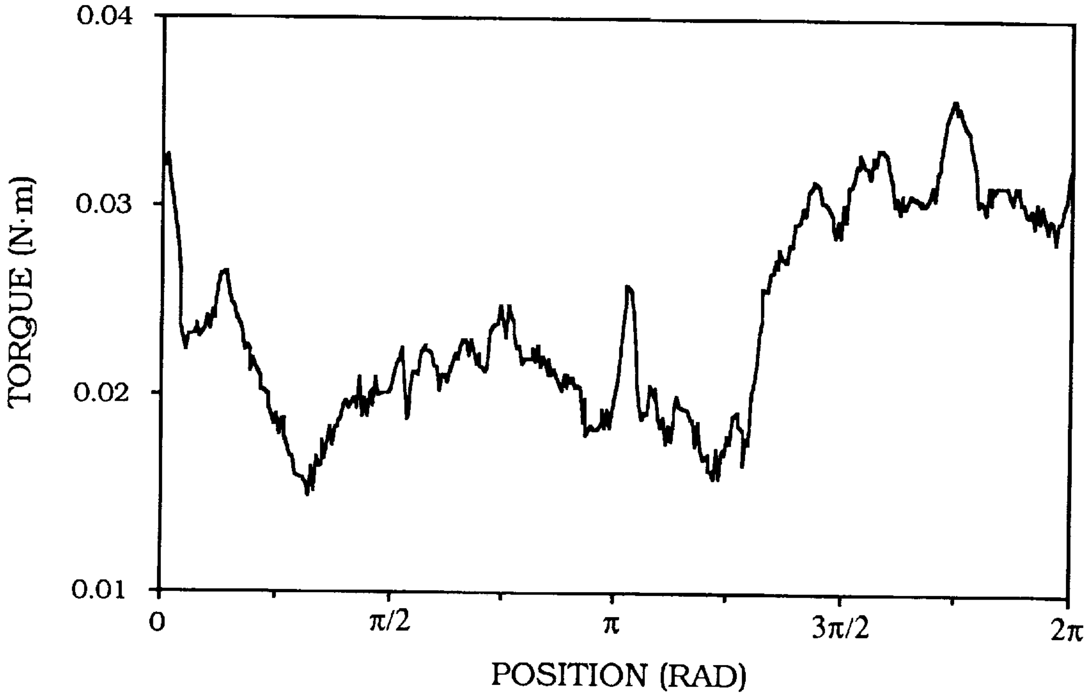

Figure 12. Running torque experiment using the substitute bearing.

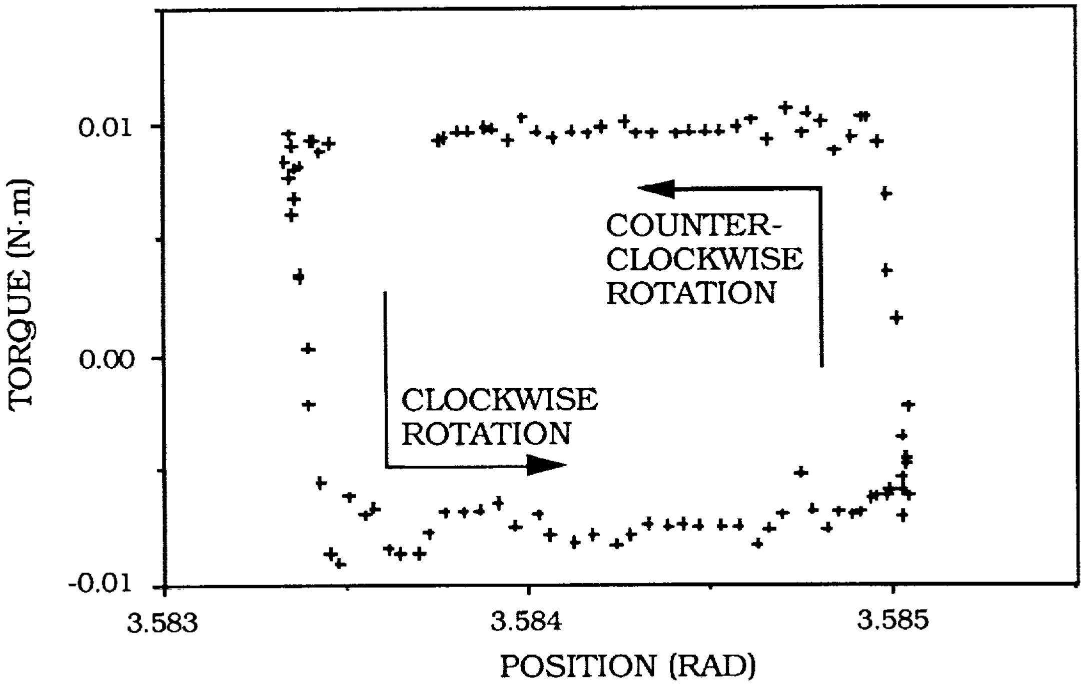

Figure 13. Dahl friction experiment using the substitute bearing.