NASA TECHNICAL NOTE

NASA TN D-3711

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A METHOD FOR THE MEASUREMENT OF EXTREMELY FEEBLE TORQUES ON MASSIVE BODIES

by J. C. Boyle and J. M. Greyerbiehl

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1966

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ABSTRACT

A method has been developed at the Goddard Space Flight Center for measuring torques generated by interaction between the magnetic dipole of a spacecraft and the ambient magnetic field. This report describes two torquemeters that have been developed and their calibration and performance tests. Also included is a discussion of the applicability of this method to the evaluation of attitude control systems that use magnetic torquing, as well as a number of other potential uses. There also appears a description of the successful use of one of these torquemeters in the evaluation of the spin control systems of the DME-A and AE-B spacecraft, which are GSFC scientific satellites of the Explorer series.

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LIST OF SYMBOLS

C	Damping factor
C_c	Damping factor at critical
H	Magnetic field intensity
I_c	Mass moment of inertia of calibration mass
I_t	Mass moment of inertia of torquemeter floated assembly
ΔI	Additional moment of inertia of the calibration mass
K_c	Torsional spring constant of calibration wire
K_ℓ	Torsional spring constant by laser beam deflection
K_t	Torsional spring constant of main torsion wire
L	Torque
M	Equivalent magnetic dipole moment
m	Calibration mass
M_i	Induced equivalent magnetic dipole moment
M_p	Permanent equivalent magnetic dipole moment
p	Angular frequency of applied oscillation
R	Distance from m to the torsion wire
T_1	Natural period of oscillation of the unloaded float
T_2	Natural period of oscillation of the float including ΔI
α	Calibration wire rotation angle
gamma	A unit of magnetic field intensity (**H**) equal to 10^{-5} gauss; and, with the permeability (μ) equal to 1 (cgs units), it is also equal to 10^{-5} oersted.
θ	Torquemeter rotation angle
θ_n	Peak amplitude of the n^{th} oscillation
θ_0	Peak value of sinusoidal oscillation of torquemeter
θ_{st}	Torquemeter rotation produced by a static torque
ϕ	Angle between the **M** and **H** vectors
ω	Angular frequency of free oscillation

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INTRODUCTION

Spacecraft are subjected to forces and moments caused by the presence of fields, particles, and electromagnetic radiation in their environment. The principal environmental factors are gravity gradients, solar radiation pressure, aerodynamic pressure, and magnetic fields.

The relative magnitudes of the torques produced by these factors are affected by orbit and spacecraft characteristics. Generally speaking, the torques are in the order of hundreds, or perhaps a few thousand, dyne centimeters for unmanned spacecraft in the NASA scientific satellite programs.

Because these torques tend to cause changes in spacecraft orientation, they can be sources of disturbance that must be countered by an attitude control system. On the other hand, attitude control systems can be designed to make positive use of such torques to stabilize the spacecraft. For example, magnetic torques are being used to unload momentum wheels of nonspinning satellites and to control the rotational rate of spin-stabilized craft.

This report discusses a method developed at the Goddard Space Flight Center for measuring magnetic interaction torques between a spacecraft and its ambient magnetic environment. It is a laboratory technique applicable to the measurement of the effective dipole moment, and to the evaluation of attitude control systems based upon magnetic torquing. Other methods have also been developed and are described in References 1 and 2.

GENERAL DESIGN CONSIDERATIONS

The principal problem involved is the measurement of very feeble torques applied to bodies that are relatively massive. This problem has prompted, as a first consideration, the uncoupling of the spacecraft's weight from its torsional compliance, so that weights of hundreds of pounds can be supported while, at the same time, providing enough torsional sensitivity to produce a measurable response to about ten dyne-centimeters of applied torque.

A second consideration is the dynamic response. A combination of high torsional compliance and large inertia will result in a system having a long natural period of oscillation. This implies insensitivity to rapidly changing inputs as well as a long settling-out time. The length of time required for the oscillation to damp to acceptable limits directly influences the time required to obtain a reading. If a large number of readings are required, the testing time may be quite long, which is usually inconsistent with the spacecraft schedule. In addition, errors which are functions of time will be greater for a slowly responding system. Thus, even if only static measurements are contemplated, the dynamic response becomes an important factor. For this reason, a design was sought in which the torsional element would be as stiff as possible, consistent with the measurement system used.

A third consideration is the amount of damping desired. It is desirable to be able to control the rate of decay of oscillation in order to obtain an optimum settling-out time. It is generally considered that a damping ratio C/C_c of about 0.7 will result in the minimum settling-out time. It may also be possible to anticipate the final value by estimating the null point of the double amplitude decay envelope for the first three or four cycles, without waiting for the oscillation to settle-out completely. Therefore, it seemed reasonable to design the meter to have an adjustable damping ratio up to at least 0.7 critical.

For measurement of magnetic torque the torquemeter is used within a coil system in which the magnitude and direction of the magnetic vector $\mathbf{H}$ can be controlled. In general, it is also possible to orient the spacecraft to any attitude desired. The combination of these two capabilities will permit the determination of all the dipole moment vector components with a single-axis torquemeter.

It is evident, however, that there are advantages in a three-axis system. Re-orientation of the spacecraft is time-consuming. In addition, some spacecraft must be maintained in one orientation only with respect to the earth's gravitational field. These considerations tend to make a three-axis torquemeter desirable. Such a meter, however, would be highly susceptible to error, due to temperature-induced drift of the center of gravity of the spacecraft.

MARK I TORQUEMETER

To satisfy the criteria of torsional sensitivity, dynamic response, and damping, developed in the preceding section, it was decided to design and build a single-axis torquemeter, in which the weight of the spacecraft and its support would be borne by a liquid. The advantage of the liquid is that it offers no shear resistance under static conditions. Thus, a static measurement of even a very feeble torque applied to a heavy object could theoretically be made under frictionless conditions.

To test the feasibility of this concept, an instrument known as the Mark I Torquemeter was designed and built. This instrument is shown schematically in Figure 1. Briefly, it consists of a doughnut-shaped pontoon floating in water in an annular basin. A vertically-oriented wire provides angular compliance to torques about the vertical axis. The wire is not required to support the test body, and, therefore, can be made to have any desired angular compliance. A reasonable amount of radial restraint can be imposed by pretensioning the wire. The torsion wire is attached to ground through a pair of parallel flexures, which permit some vertical motion of the floated assembly, but are relatively rigid in all other directions.

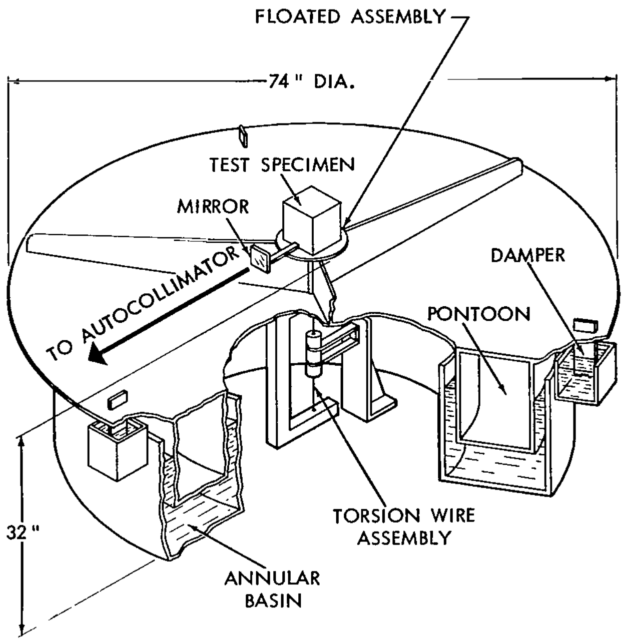

Figure 1—Mark I Torquemeter assembly.

The applied torque causes an angular deflection of the taut wire, whose motion is sensed by an optical autocollimator through the use of a target mirror attached to the floated assembly. The optical measuring system is sensitive to angular deflections of less than an arc second, thus permitting considerable torsional stiffness to be built into the taut wire.

Three dashpots, each utilizing a paddle immersed in a damping fluid, are deployed at 120° increments around the perimeter. The damping fluid is SAE 30 motor oil, and the percent critical is adjustable by varying the depth of immersion of the paddles.

The major design criteria for Mark I were:

Torque range	-	0 to ± 1000 dyne-cm
Angular compliance	-	8.8 dyne-cm/arc-sec
Taut wire pretension	-	15 lbs
Maximum test specimen weight	-	10 lbs
Transverse stiffness of taut wire	-	3 lb/in.
Damping rate	-	Approximately 0.7 critical (adjustable)
Total floated weight	-	150 lbs
Overall weight	-	360 lbs
Natural torsional period	-	84 seconds
Construction	-	Nonmagnetic

Preliminary testing of Mark I was done on the first floor of the Operations and Instrumentation Building at the Goddard Space Flight Center Magnetic Test Facility. Torques due to random air currents were found to be a major disturbance factor, and the meter oscillated wildly until the ventilation system was shut down and a crude plywood enclosure placed around it.

In addition to disturbances caused by equipment being installed in other parts of the building, deflections and vibrations of the floor were produced by people walking near the torquemeter and autocollimator. These seismic-type inputs resulted in a rather pronounced pitching motion of the floated assembly as measured by a two-axis autocollimator, but surprisingly little torsional disturbance was associated with them. This was possibly due to the relative absence of torsional inputs in the floor motion. Another factor is the very long period of the meter in torsion (84 sec), which would make it less responsive to normal disturbing frequencies than the pitching mode (period = 5 sec). It is also probably true that motion of the floor near the autocollimator could produce apparent disturbances which are not representative of movement of the torquemeter itself, but are motions of the autocollimator only.

Both aerodynamic and seismic-type effects were minimized by relocating the torquemeter from the first floor to the basement, where it was supported by a substantial concrete-slab floor and housed within a tight plywood enclosure.

Calibration of the Mark I meter was performed by using a relatively high-compliance torsion wire, whose spring constant had been determined by the torsional pendulum technique. This technique is described in the Calibration section of this report.

Several phenomena were noted during the calibration periods. Entering and leaving the enclosure produced a disturbance that required about half an hour to settle-out. The records taken show that the damped oscillation obtained from the initial disturbance generally diminished to a total amplitude of less than three arc-seconds within four minutes; however, a slow and usually unidirectional drift remained. It is believed that this was due primarily to an aerodynamic swirl, although the possibility of a persistent motion of the water has not been eliminated. It was assumed that settling-out had occurred when the motion of the float receded to within a two-arc-second band, and had remained within this region for at least fifteen minutes. On several occasions, this settling-out period was extended for an hour or more. Some additional drift, amounting to perhaps one or two arc seconds, was usually observed. The noise level achieved after settling-out was in the order of ±2 seconds of arc or ±18 dyne-centimeters. A difference in the trend of data points of the calibration curve between loading and unloading was also apparent; this suggested the presence of hysteresis in the calibration assembly and the main table wire.

Initially, the float chamber was filled with local well water from the tap. This procedure was satisfactory when the meter was located on the first floor, but, when the apparatus was relocated in the basement, the meter's behavior became quite unsatisfactory. Tests performed at this time gave extremely erratic results. Data were not repeatable, and at times the float would stick in position, even when displaced full scale (60 arc-seconds). It was noted that this "stickiness" would temporarily disappear when the instrument was rather violently disturbed by accidental jolts, such as occurred during checking of torsion wire clamps. Thereafter, the stickiness would gradually increase until, after about an hour, the instrument had once again become unresponsive. The float chamber was examined, and it was noted that a greasy-feeling, blue discoloration was present at the water line of both float and chamber. Float and chambers were emptied and thoroughly scrubbed, and the apparatus reassembled with fresh oil in the dashpots and distilled water in the float chamber. This completely alleviated the "stickiness" problem.

From a pragmatic viewpoint, the "sticky fluid" problem may be considered solved, although its cause has not been pinpointed. Regarding the difference in behavior of the meter in the two locations, one possible explanation is that the higher noise level incident to first floor operation prevented the fluid from "setting." It is also possible that between the first and second filling of the torquemeter, contaminants (solder flux, grease, pump packing compound) may have been introduced into the water system by mechanical work on the well pump and associated piping.

MARK II TORQUEMETER

On the basis of the results achieved with Mark I, it was decided to go ahead with the design and construction of a torquemeter capable of testing spacecraft up to the maximum size and weight that can be handled by the Delta launch vehicle. This torquemeter has been designated Mark II.

The torquemeter was located within the 22-foot-coil system of the GSFC Magnetic Fields Component Test Facility, where the magnetic field can be controlled to any desired static magnitude and direction within the range 0 to 60,000 gamma, and can also be rotated about any desired axis at angular velocities up to 100 radians per second. This latter capability allows magnetic simulation of a spacecraft spinning in a magnetic field by rotating the field rather than the spacecraft. This introduces the possibility of making static torque measurements in the laboratory which are representative of dynamic torques encountered by a spinning satellite in orbit.

The Mark II Torquemeter (Figure 2) was designed and built by the Martin Company of Baltimore, Maryland, and is similar in principle to the Mark I. It differs, however, in one important respect; it is constructed entirely of nonconductive materials to eliminate induced electric eddy currents in the presence of dynamic fields.

The characteristics of the Mark II are:

- Maximum test specimen weight, 600 lbs;
- Maximum test specimen dimensions, 4 ft dia × 5 ft long;
- Restricted torque range, using autocollimator, 0 to ±3000 dyne-cm;
- Maximum torque range, using laser beam, 0 to $\pm 6.6 \times 10^4$ dyne-cm;
- Torsional stiffness, 23 dyne-cm/arc-sec;
- Natural period, unloaded, 66 seconds;
- Damping, adjustable;
- Construction, nonmagnetic and nonconductive.

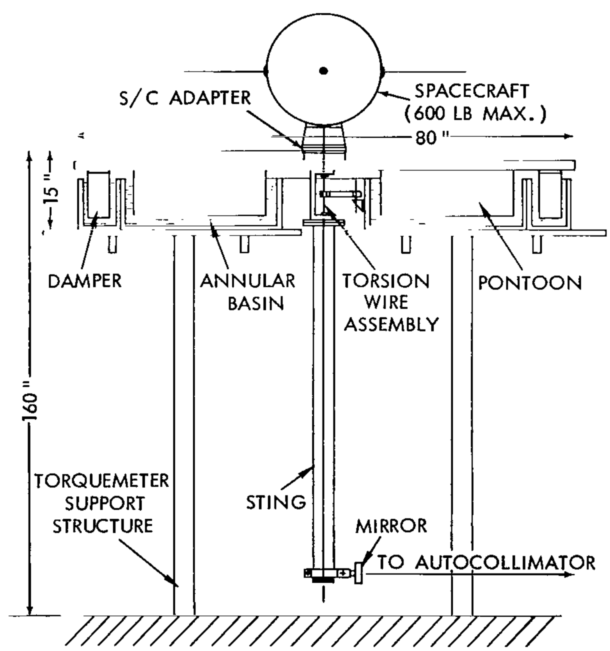

Figure 2—Mark II Torquemeter assembly.

CALIBRATION

The calibration of the torquemeter is essentially the measurement of the torsional spring constant of the instrument. Three different methods were found satisfactory for determining the spring constant, (a) a static mechanical technique, (b) a dynamic mechanical technique, and (c) a static magnetic technique.

Static Mechanical Calibration

This method employs a torsional pendulum as a calibrator and makes use of a spoked disc of known moment of inertia, I_c, a calibration torsion wire of measured spring constant, K_c, and a rotating gear head to apply and measure the angle α, through which the calibration torsion wire is twisted (Figure 3).

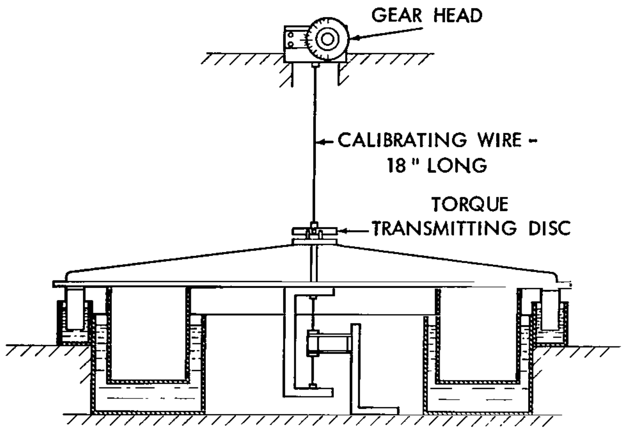

Figure 3—Mark I calibration assembly.

The spring constant of the calibrator torsion wire is determined by measuring the natural period of the torsional pendulum. Its value is computed from

$$K_c = \frac{(2\pi)^2 I_c}{T^2} .$$

The torque applied by the calibrator is then

$$L = K_c \alpha .$$

The torquemeter torsional element is twisted through a measured angle θ by the torque L. By this procedure, the straight line calibration curves appearing in Figures 4 and 5 have been obtained for the Mark I and Mark II Torquemeters, respectively. Evaluation of the Mark I curve yields a K_t = 8.8 dyne-cm/arc-sec. Data from the Mark II curve yield a K_t = 23.1 dyne-cm/arc-sec.

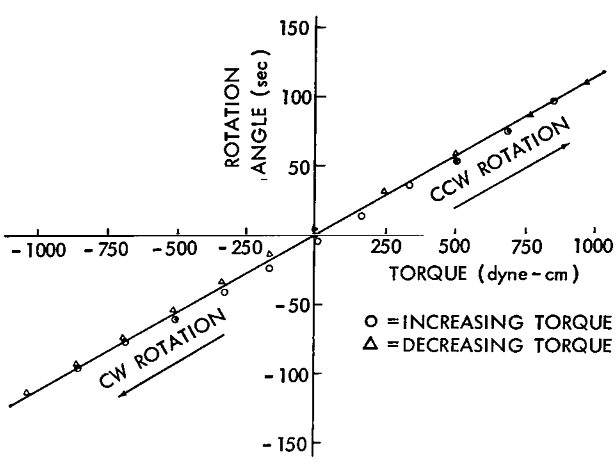

Figure 4—Mark I Torquemeter calibration curve.

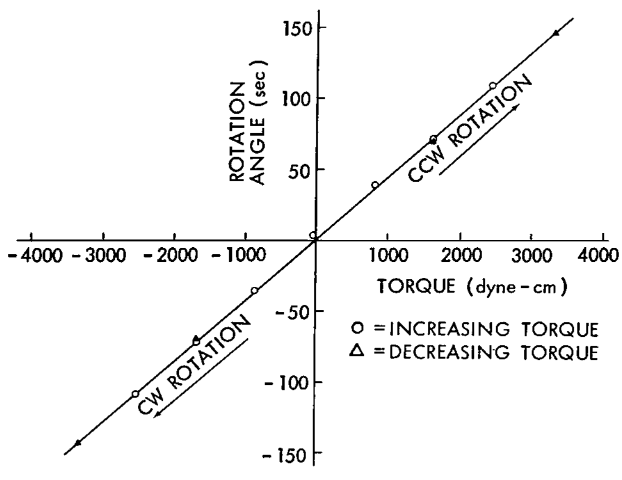

Figure 5—Mark II Torquemeter calibration curve.

Dynamic Mechanical Calibration

The second method employed in determining K_t for the torquemeter is the differential inertia technique; it was used on the Mark II Torquemeter only. The torquemeter spring constant is determined by observing the free oscillation of the float and torsion wire as a torsional pendulum and is expressed by

$$K_t = \frac{(2\pi)^2 I_t}{T_1^2} .$$

There are, however, two unknown constants, K_t and I_t. If the moment of inertia of the float (I_t) is changed by a known inertia (ΔI), consisting of equal masses placed diametrically opposite on a circle whose center is the torsion wire, K_t can be determined by measuring the periods of both systems. Therefore,

$$K_t = \frac{(2\pi)^2 \Delta I}{T_2^2 - T_1^2} ,$$

where

$$\Delta I = I_c + m R^2 .$$

The torsional spring constant measured by this method was 22.95 dyne-cm/arc-second. A diagram of the configuration used appears in Figure 6.

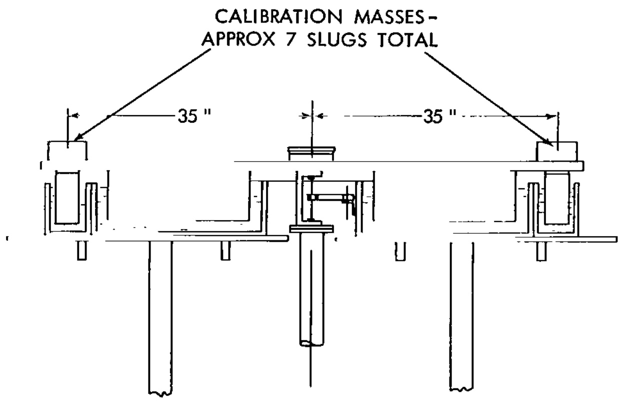

Figure 6—Mark II differential inertia calibration.

Static Magnetic Calibration

The third calibration technique employed uses the moment produced when a magnet of known strength is subjected to a known magnetic field.

When a magnet of equivalent dipole moment, M, is placed in a magnetic field of intensity, H, and the angle between the field and the magnet is ϕ, then a torque is developed, the magnitude of which is given by

$$L = M H \sin \phi .$$

This phenomenon provides an additional method for calibrating the torquemeter. A magnet of known dipole moment, M, is attached to the torquemeter and is subjected to a field of intensity, H, at an angle $\phi = 90°$.

The applied torque is then

$$L = MH = K_t \theta .$$

In order to ensure an accurate calibration, a permanent magnet made of Alnico II was encapsulated in plastic and standardized by the Fredericksburg Geomagnetic Center. Its magnetic moment was measured as 5450 dyne-cm/oersted. The magnet was then mounted horizontally on the torquemeter float and subjected to orthogonal magnetic field vectors of strengths up to ±50,000 gamma. The resultant angular deflection was measured by the autocollimation system, and the torsional spring constant was computed to be 23.02 dyne-cm/arc-sec.

For torques above 3000 dyne-cm, a magnet rated at 98,000 cgs was used to calibrate a laser-beam assembly acting as an optical lever. The linear movement of the reflected laser beam is directly proportional to the rotation angle of the torquemeter float. When average values of K_t obtained for the torquemeter were used, the calibration constant (K_ℓ) was determined to be 5530 dyne-cm/cm of deflection along a scale 14 feet from the torquemeter centerline.

Table 1

Calculated Values of K_t (Mark II).

Method	Torsional Spring Constant, K_t, (dyne-cm/arc-sec)
Static Mechanical	23.10
Dynamic Mechanical	22.95
Static Magnetic	23.02

The values of K_t obtained from the various calibration methods were averaged, yielding a torsional constant of 23.02 dyne-cm/arc-sec for the Mark II Torquemeter. A summary of all values of K_t obtained are listed in Table 1.

As a matter of interest, the spring constant of the torsion element was computed from its nominal dimensions and mechanical properties and found to be 20.1 dyne-cm/arc-sec.

Frequency Response

In addition to the determination of K_t, measurements were made of the frequency response of Mark II. The forcing function was provided by attaching an 1116 cgs magnet to the float with its moment vector horizontal, and by energizing the coil system so that the field intensity vector rotated at selected frequencies in the horizontal plane. The result was a sinusoidally varying torque at the frequency of rotation of the field vector.

Selected frequencies from static to $p/\omega = 16$ were generated, and the response was measured. Figure 7 shows the normalized frequency-response curve obtained. Data from this and later tests indicate the peak magnification ratio to be 10.05. Because the Mark II is a single-degree-of-freedom system in the torsional mode, the damping ratio may be expressed as

$$\frac{C}{C_c} = \frac{1}{2} \frac{\theta_{st}}{\theta_{0(resonance)}} .$$

For a magnification ratio of 10.05, this yields

$$\frac{C}{C_c} = 0.048 .$$

Alternatively, the damping ratio may be calculated on the basis of the decay rate of free oscillations. For small damping

$$\frac{C}{C_c} = \frac{1}{2\pi} \ell n \frac{\theta_n}{\theta_{n+1}} .$$

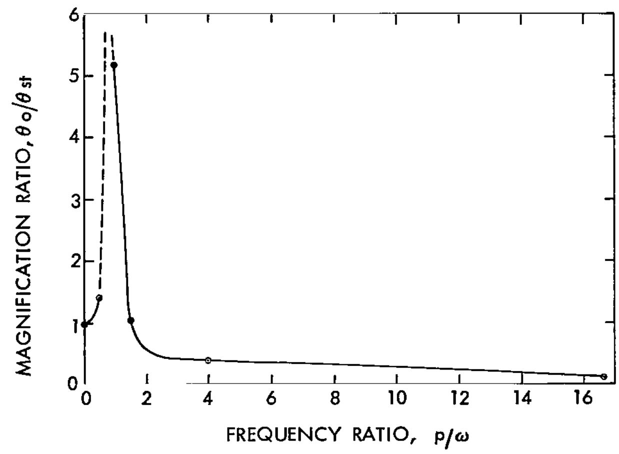

Figure 7—Mark II Torquemeter frequency response.

Examination of free-oscillation records reveals the ratio of successive peaks to be 1.39, corresponding to $C/C_c = 0.052$. This is in good agreement with the value of 0.048 obtained from frequency response data. In the Mark II Torquemeter water is being used in the dashpots, but it would be easy to substitute a more viscous fluid and to achieve a higher damping ratio, if desired.

Error Analysis of Mark II Torquemeter

An effort has been made to analyze the three calibration techniques, (1) static mechanical, (2) dynamic mechanical, and (3) static magnetic, from the point of view of the accuracy viewed.

(1) The static mechanical calibration of the Mark II Torquemeter is subject to error from the following sources:

Spring constant (K_c)

The spring constant of the calibrating wire was obtained by the torsional pendulum technique, and its accuracy is dependent upon both the period and mass moment of inertia determination.

Calibration wire twist (a)

System backlash produced discrepancies in the measurement of the angle of twist.

Measurement of torquemeter rotation angle (θ)

The accuracy of the angle measurements depends upon the autocollimation system used.

Zero shift

A slow zero shift was observed over an extended period and introduced an uncertainty in the angle measured.

Noise

This problem was common to all calibration techniques and includes inputs from several sources.

The maximum error possible may be estimated by considering the influence of the above on any particular reading. In percent full scale,

Error in K_c	±2.0%
Error in α	±0.5%
Error in θ	±0.2%
Zero Shift	±1.0%
Noise	±1.0%
Total Error	±4.7%

(2) Based upon these two sources of error, the spring rate, as determined by the differential inertia method, is estimated to be accurate to ±6%.

A comparison of the accuracy achieved by the three calibration methods is shown in Table 2.

Table 2

Accuracy Comparison.

Method	Maximum Error (% full scale)
Static Mechanical	±4.7
Dynamic Mechanical	±6
Static Magnetic	±3.72

(3) The accuracy of results achieved with the static magnetic calibration technique is dependent upon autocollimator error, noise, and drift, as in the static mechanical method. In addition, it is dependent upon the:

Magnetic dipole moment of the test magnet

The Fredericksburg Geomagnetic Center is a prominent authority in magnetic measurements and routinely performs standardization of permanent magnets. In addition, the use of Alnico II and the encapsulation in plastic promote high magnetic stability.

Magnetic field vector

Measurements were made of the magnetic influence of the autocollimator and its ancillary electronics and recording equipment. This was determined to affect the magnetic intensity in the vicinity of the test specimen by less than 4 gamma. The GSFC coil system is compensated for diurnal variations and controls the variations in magnetic intensity to within 0.5 gamma of the set value.

Orientation of the magnet

A plumb line aligned to the magnetic meridian was used to orient the magnet with respect to the coil system.

It is evident that the errors present are not amenable to rigorous analysis. The following is an estimate in percent of full scale.

Maximum error in M	±1.00%
Maximum error in H	±0.02%
Maximum error due to misorientation	±0.50%
Maximum error due to drift	±1.00%
Maximum error due to noise	±1.00%
Maximum error due to autocollimator	±0.20%
Total Maximum Error	±3.72%

Accuracy of calibration by means of the differential inertia technique involves two factors: (1) the accuracy with which ΔI is known; this depends in turn upon I_c, M_c and R, and (2) the accuracy with which the period is measured.

The foregoing percentages represent estimated maximum errors, rather than probable errors. In view of the close agreement in calibration results between the three techniques (total variation of less than 0.7%), it is believed fair to state that the calibration is accurate to ±1% of full scale.

EVALUATION

As stated in the previous section, the calibration error is believed to be less than 1% of full scale. The principal sources of error in measurement are random noise and drift, which were found to be more severe when testing an actual spacecraft (DME-A) than during calibration.

Several possible physical mechanisms have been postulated to account for the random inputs. These may be divided into four categories.

Aerodynamic Effects

Air currents impinging on the float or test object may cause torque fluctuations. Although precautions have been taken to minimize this effect by shutting down the ventilation system and by using a plywood enclosure to surround the instrument, convection currents may still be generated within the enclosure, from temperature differences in the enclosure walls and from heat-dissipating sources on board the test object. In addition, the enclosure itself is not air-tight; thus, the torquemeter may also be influenced by air movements originating outside the enclosure.

Hydrodynamic Effects

These are water currents in either the main float chamber or in the damper chambers. Such currents may arise from temperature differentials or from relative motion between the float chamber and the float. Pitching, heaving, and rectilinear motion of the float may be coupled into the torsional mode.

Surface Tension Effects

Water has a surface tension of about 73 dynes per centimeter; hence, it is quite possible to produce a sizable torque by uneven wetting of the float, if there are irregularities in the wetted perimeter. In addition, surface disturbances may alter the wetting, thus producing torque variations.

Seismic Effects

Earth tremors may transmit forces to the torquemeter float. Factors involved are mode and frequency spectrum of the input motions, eccentricity of the mass center of the floated assembly, and the transmission mechanism between float and chamber through both the water and the taut wire.

As previously noted, the noise problem was more severe when testing DME-A than during the calibrations. It was most severe during the night; but, even during the day, it was necessary to take advantage of periods of relative calm to obtain data.

Subsequent to the DME-A test, several steps were taken which were intended to minimize the aerodynamic noise contribution. These were:

(1) Boarding up the windows with insulating board. The windows were perceptibly colder than the building walls (particularly at night), and were suspected of promoting convection.

(2) Mounting a cylindrical pressed-board enclosure on the torquemeter table so as to surround the test specimen. This "high hat" was intended to eliminate turbine torques due to local warm spots on the test specimen.

(3) Sealing the base of the torquemeter supporting structure with masking tape, and placing a loose-fitting baffle around the torquemeter sting to inhibit air motion.

(4) Turning on all lights within the coil building and leaving them on day and night. This was intended to nullify thermal down drafts due to cold walls, particularly at night. The building has nine 300-watt ceiling lights and twenty-six 150-watt wall lights.

Application of these measures produced a marked reduction in noise level, particularly during the nighttime period. The facility schedule did not permit individual evaluation of each of the above measures, but enough data were obtained to show that the greatest reduction in noise occurred when the taping and baffling were done simultaneously with the maximum use of the building lights. This noise reduction was quite drastic, going from a double amplitude of 180 arc seconds during the noisiest nighttime period to less than 5 seconds double amplitude. The drift rate was on the order of 1 arc second per hour. Adding or removing the high hat had no significant effect.

An unexpected opportunity to obtain information on the seismic response of the torquemeter was occasioned by the occurrence of a Chinese earthquake on the night of March 21, 1965. This happened to be the same date that the torquemeter noise tests were begun. Seismic records were obtained from Georgetown University (about 15 miles from GSFC), which showed that the quake began at approximately 4:30 a.m. on the morning of March 22 and lasted until 7:45 a.m. This did indeed correspond with a period of high noise level, but it is difficult to draw the conclusion that the earthquake was responsible, since the torquemeter record was already at a high noise level by 10:30 p.m., at which time the Georgetown seismic record was still quiet. Furthermore, the noisy nighttime behavior of the torquemeter had been observed previously during the DME-A tests, at which time there was no earthquake activity evidenced by the Georgetown records.

The atmospheric explorer satellite (AE-B), which uses a magnetic spin control system, was tested on April 7 and 8, 1966. The noise during this test remained at the same low level that was achieved in the noise tests of the previous month.

To sum up, the Mark II Torquemeter is considered to be quite satisfactory for the direct measurement of control or disturbance torques of the magnitude commonly encountered by scientific satellites.

APPLICATIONS

There are several interesting applications for the Mark II.

Evaluation of Attitude Control System

In October, 1965, the Mark II Torquemeter was used for the first time in an actual spacecraft test. It was used in conjunction with the GSFC 22-foot-coil system to test the spin control system of the DME-A spacecraft (Figure 8). This spacecraft incorporates a magnetic spin control device, which may be commanded to increase or decrease the spin rate of the spacecraft, or to seek automatically a predetermined

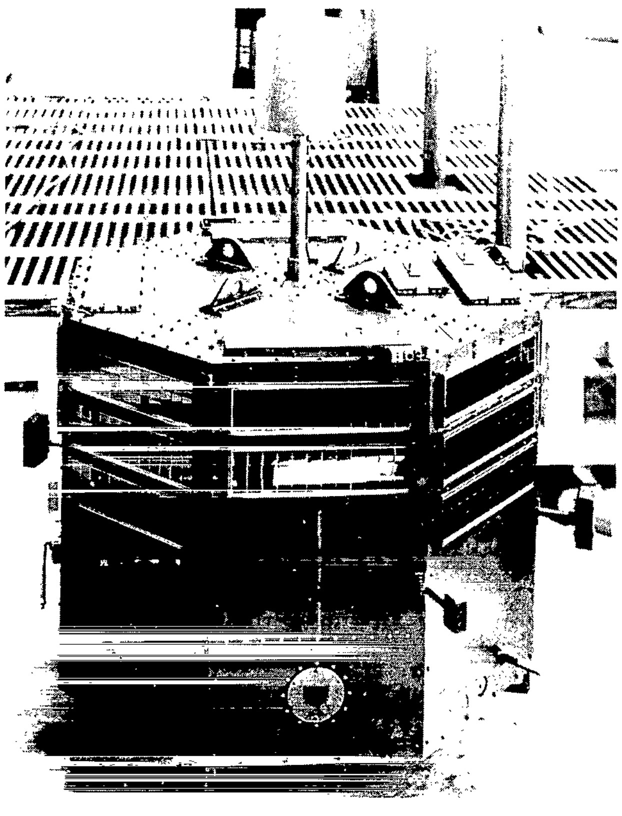

Figure 8—DME-A mounted on Mark II Torquemeter.

rate. The coil system was energized so that it produced a rotating magnetic vector, thus simulating the rotation of the spinning spacecraft in relation to the ambient magnetic field. The magnitude and sense of the interaction torque between the dipole moment produced by the spacecraft's automatic control system and the ambient vector were measured by the Mark II. All modes of operation were successfully demonstrated. Figure 9 presents data obtained in the automatic control mode, in which the predetermined spin rate was 3 rpm.

In April, 1966, the Mark II Torquemeter again demonstrated that it could be used effectively in a spacecraft test to determine spin control torques. The AE-B spacecraft, which also uses a magnetic spin control system to spin up or down upon command, was successfully tested at this time. The magnitudes and sense of the spin torques generated for various simulated rotation rates of the AE-B spacecraft were measured. Figure 10 presents the data obtained for this test.

The Mark II may also be used to evaluate systems associated with nonspinning spacecraft, such as momentum-wheel magnetic-dumping, systems and magnetic torque systems used in stabilization of gravity gradient satellites.

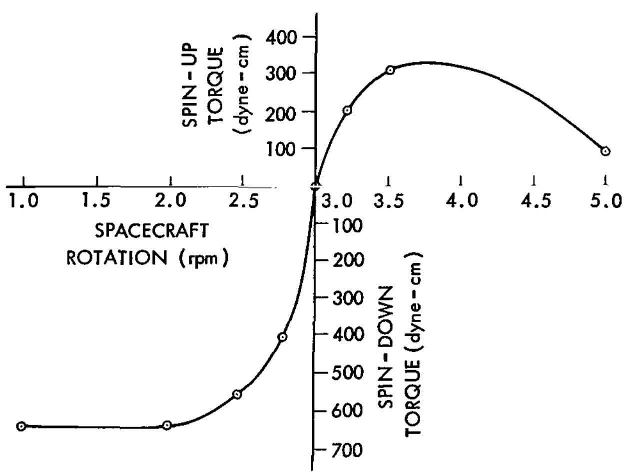

Figure 9—DME-A spin rate control system automatic mode torque vs. rpm.

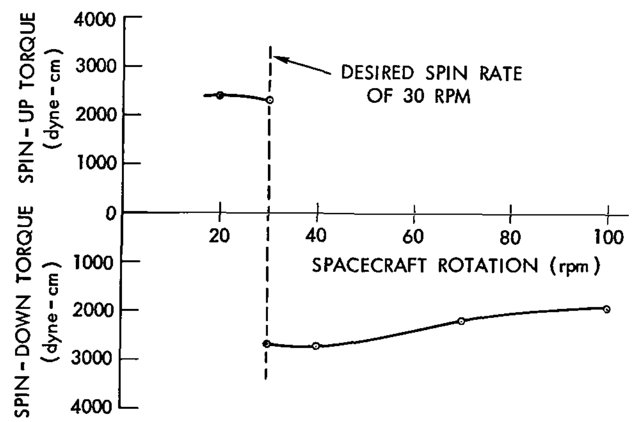

Figure 10—AE-B spacecraft spin torque vs. rpm.

Dipole Moment Measurements

The equivalent permanent dipole moment of a spacecraft is a vector that can be resolved into components along the body axes. Each of these components can be determined from the torque generated about a vertical axis, when the spacecraft is so oriented that the body axis of interest lies in a horizontal plane and the magnetic field vector is horizontal. It is also preferable that the field vector be directed at right angles to the body axis. This requires two orientations of the spacecraft on the torquemeter.

In general, both a permanent and an induced dipole moment will be present. Barring saturation effects, these can be separated by the following two-measurement technique.

Suppose a torque measurement was to have been taken. The corresponding total magnetic moment is

$$M_1 = \frac{L_1}{H} = M_p + M_i \ .$$

If the direction of the magnetic field vector is reversed, the torque due to the permanent dipole moment will reverse, but the torque due to the induced moment will not. Thus,

$$M_2 = \frac{L_2}{H} = -M_p + M_i \ ,$$

which yields

$$M_p = \frac{M_1 - M_2}{2} = \frac{L_1 - L_2}{2H} \ ,$$

$$M_i = \frac{M_1 + M_2}{2} = \frac{L_1 + L_2}{2H} \ .$$

Static values of both permanent and induced equivalent dipole moments were measured on the DME-A spacecraft. With the spin axis vertical, two orthogonal components of the transverse moment were measured. The spacecraft was then re-oriented so that the spin axis was horizontal; the moment about this axis was measured.

It is common procedure to measure magnetic dipole moments by magnetometer measurement of the field strength in the vicinity of the body. If the body can be considered to approximate a simple dipole, as in the case of a small bar magnet, it is a simple matter to relate the dipole moment to the field strength at a given position. Relative to this point, a comparison was made between the dipole moment of several magnets, as determined by the Mark II Torquemeter and by a fluxgate magnetometer; agreement within a few percent was obtained, as shown in Table 3.

If, however, the source is a complex multipole, near field magnetometer measurements cannot be interpreted easily in terms of an equivalent dipole; it becomes desirable to make measurements at distances great enough so that the assemblage closely resembles a simple dipole.

Table 3

Comparison of Magnetic Moments.

Magnet Number	Mark II (cgs units)	Magnetometer (cgs units)	% Difference
1	1,152	1,130	1.91
2	1,998	2,055	2.85
3	2,736	2,835	3.62
4	5,453	5,321	2.42
5	113,800	118,500	4.13

A limitation of this technique is reached when the measurements must be made at such a great distance that the field intensity is too low to be accurately determined. This is the case where compensation magnets are used to minimize the net dipole moment of a spacecraft. A direct measurement of the interaction torque obviates these fundamental difficulties.

Eddy Current Torque Measurements

Eddy currents are generated in the conductive elements of a spacecraft that spins in a magnetic field. These eddy currents produce a magnetic field, which interacts with the ambient field to produce a retarding torque to the spin of the spacecraft. This condition can be simulated by rotating the magnetic field vector instead of the spacecraft; the net retarding torque will be the average value measured by the torquemeter.

Potential Applications

In addition to magnetic torque measurements, the Mark II meter is potentially adaptable to the measurement of torques and forces stemming from a variety of sources. Among these are (1) measurement of electromagnetic pressures due to transmission or reception of rf and optical frequencies, (2) measurement of electromagnetic torques due to transmission of circularly-polarized energy, (3) determination of electric dipole moments by measuring the interaction torque produced between the electric dipole moment of a spacecraft and a known ambient electric field, which is analogous to the measurement of the magnetic dipole moment by interaction with a known magnetic field, and (4) determination of micro-thrusts by offsetting the thrust vector a known distance, and by measuring the resultant torque.

(Manuscript received March 30, 1966)

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2. Wooley, R. P. and Smith, Jr., J. E., "Magnetic Balance of the OSO-C," Ball Bros. Research Corp., Boulder, Colorado: July 8, 1965.

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