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TORSIONAL MEASUREMENTS OF SATELLITE BOOMS

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16. Abstract

This report presents the experimentally determined torsional parameters of several different satellite booms currently in use. Included is a detailed description of the procedure used in making these measurements along with the test data and the resultant graphs. Also described is a device that has been developed by the author to measure and plot the torsional characteristics of booms.

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INTRODUCTION

As more advanced designs for satellite booms evolved, it became clear that the torsional characteristics of these booms should be defined experimentally. Theoretical expressions defining the torsional and warping rigidity for open-section booms of the STEM type can be found in Reference 1.* These expressions, however, have not been verified in the laboratory for the actual booms being used on existing satellites. Theoretical descriptions of the torsional parameters of booms with zipper mechanisms or tabs have not been attempted. These parameters are needed to determine whether or not a particular boom attached to an orbiting spacecraft will exhibit a thermal-flutter instability when exposed to direct sunlight (References 2 and 3). Hence, a test program to experimentally define the torsional-stiffness and torsional-damping parameters of the various booms was initiated. Tests were performed on sections of booms having lengths of approximately 3, 10, and 20 ft to determine if boom length had any unexpected effect upon torsional characteristics.

Several different types of fixtures were developed to hold the various boom sections during the tests (Figure 1). Booms were secured to these fixtures with clamps or pins or by passing a yoke fitting through slots cut into either end of the boom. The yoke fitting allowed the ends of the open-section booms to be free to warp. In some tests, the deployer, the basic structure of which is shown in Figure 2, was used to hold one end, while the other end was either clamped, pinned, or held by a yoke.

*Also found in Harold P. Frisch, "Determination of the Undamped Torsional Normalized Modes and Frequencies of a Thin-Walled Cylinder of Open Section", NASA-Goddard Space Flight Center Stabilization and Control Branch Report No. 160, Goddard Space Flight Center, Greenbelt, Maryland, March 1, 1967.

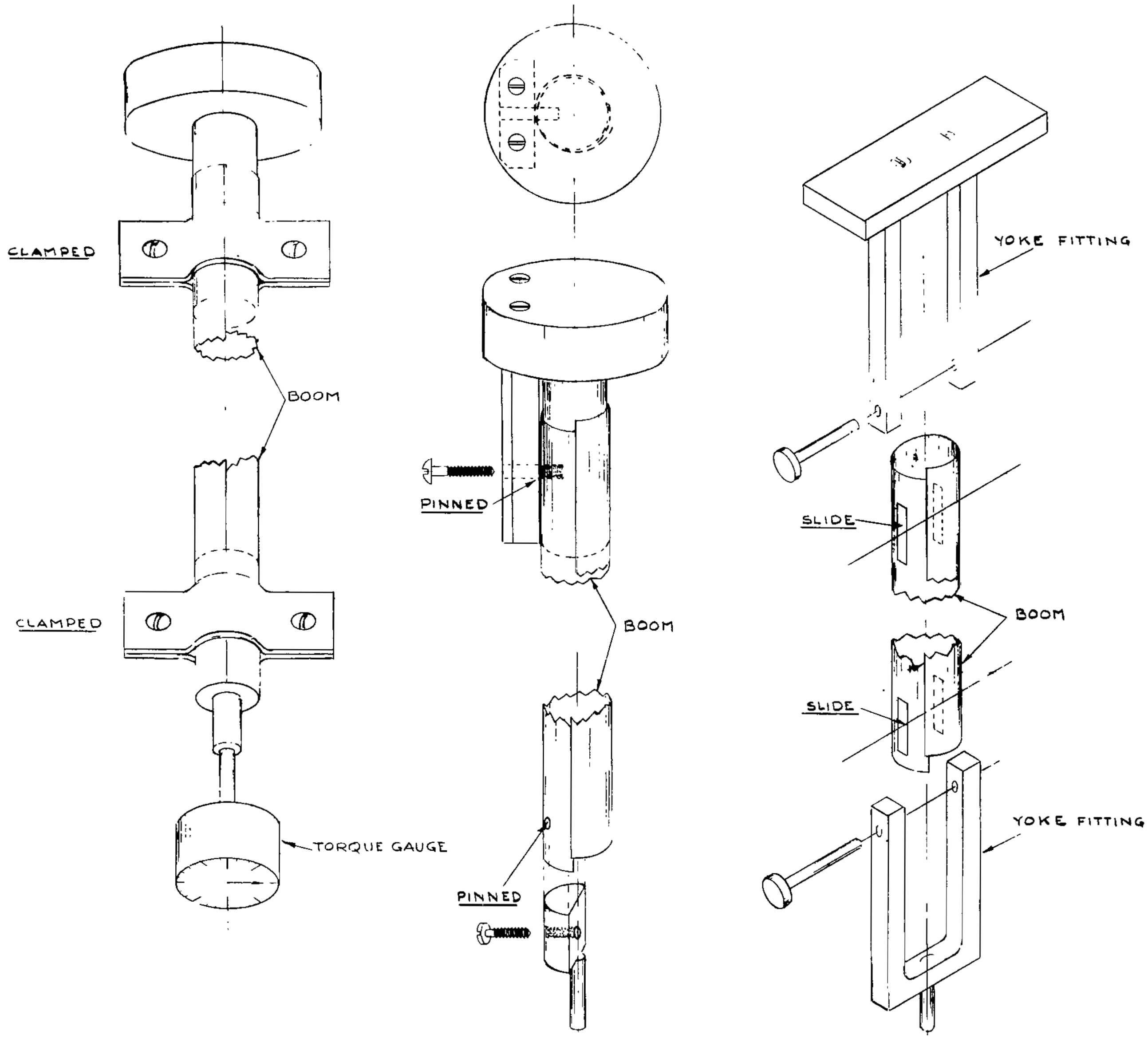


Figure 1–Boom test fixtures.

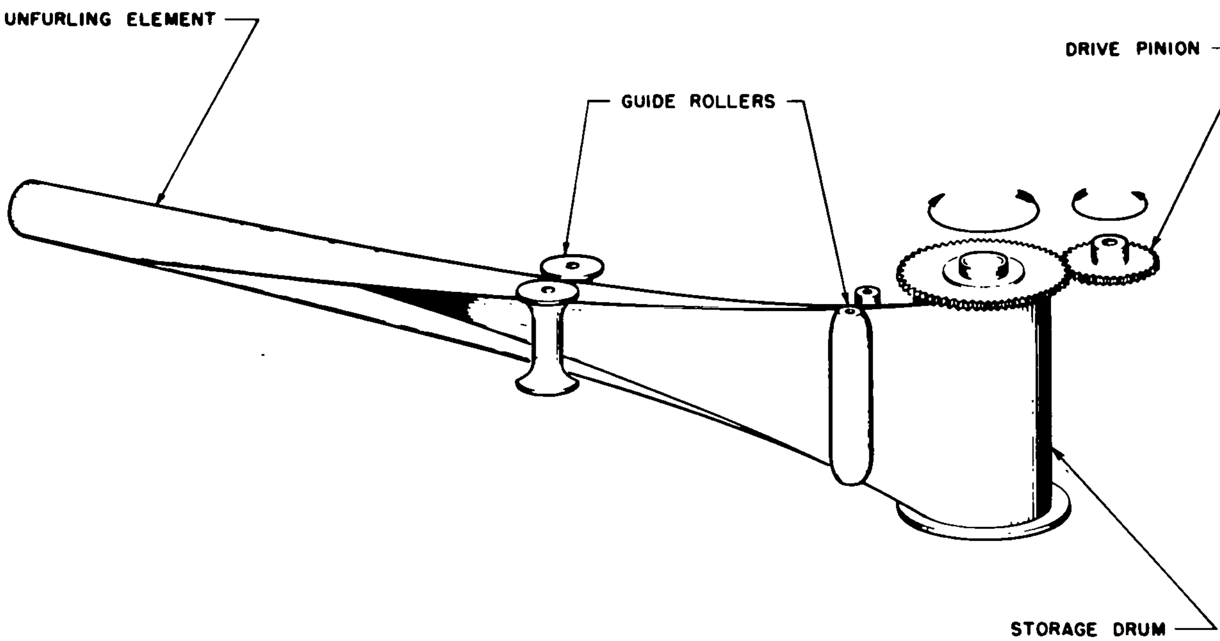


Figure 2—The "stem" principle (basic deployer structure).

During tests, the upper end of the boom section was held by either a deployer or some other fixture that prevented the boom from rotating about its own axis. The lower or free end of the boom was constrained in bending by passing it through a hole in the center of a rigidly mounted disc calibrated to read from 0 to 360 deg. A fine wire pointer was fixed to the boom immediately above this angular-readout disc (Figure 3). As the boom was rotated about its longitudinal axis, the angular displacement in each direction could be determined from the calibrated disc.

The applied torque required to twist the lower end (tip) of the boom in either direction was measured in oz-in. by means of a torque gauge secured to the lower end of the boom with a fitting. The "dead space" of a boom was defined to be the distance the boom could be rotated in either direction without exhibiting an angular change upon being released.

In measurements of torsional rigidity for open-section booms, both ends should be free to warp. When measurements are made of the warping rigidity, the boom should be reasonably short, and the ends should be constrained so that they are not free to warp. In open-section booms, these constraints must be observed in order to obtain meaningful measurements.* Booms with zippered or interlocking tab features have effective torsional-stiffness characteristics that approach those of a closed-section tube. For these booms, warping rigidity is ignored and the torsional rigidity is measured with neither end free to warp; this configuration is called "clamped-clamped" (Figure 1).

*Harold P. Frisch, "Determination of the Undamped Torsional Normalized Modes and Frequencies of a Thin-Walled Cylinder of Open Section", NASA-Goddard Space Flight Center Stabilization and Control Branch Report No. 160, NASA-Goddard Space Flight Center, Greenbelt, Maryland, March 1, 1967.

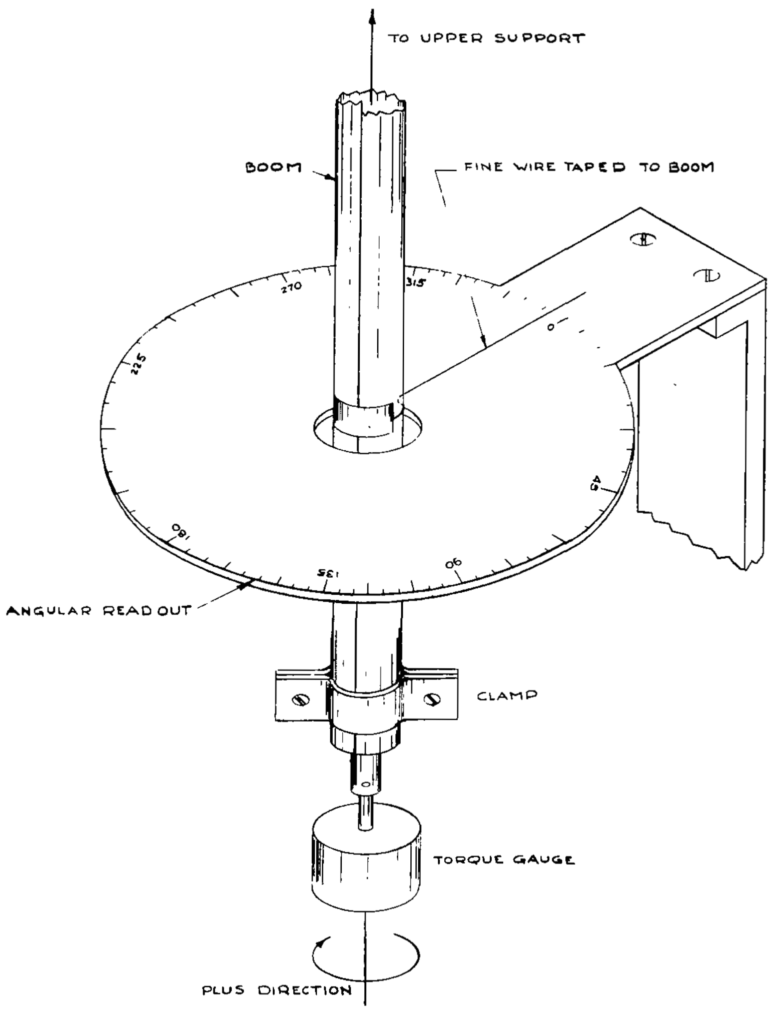


Figure 3—Angular-readout assembly.

The torsional rigidity of the boom (in lb-in.^{2}) was determined by plotting the applied torsional torque at the tip versus the angular tip rotation. The tip spring rates (in oz-in./deg) were found from the slope of these plots. The torsional rigidity C of the boom was then found by multiplying the tip spring rate by the length of the boom section and converting oz-in./deg into lb-in.^{2}/rad. We define—

S_T = tip spring rate in oz-in./deg,

and

l = length of boom in in.

Then,

$$C = \frac{57.3}{16} S_T l.$$

All torque-gauge measurements are made in equal increments in both the positive and negative directions. As seen from the end of the boom, facing the deployer, motion in the positive direction is counterclockwise and would tend to tighten the seam, and motion in the negative direction is clockwise and would tend to open the seam (Figure 3).

TORSIONAL-MEASUREMENT PROCEDURES

The angular-readout disc was first positioned as shown in Figure 3. The center of the boom dead space was found. The boom pointer and the zero-degree position of the angular-readout disc were aligned with the dead-space center. A torque gauge was secured to the lower end of the boom with one of several fittings (Figure 1) depending on the particular configuration being tested.

The breakaway torque, the amount of torque applied by the torque gauge that is required to break static friction, was measured and recorded. Measurements of the dead space were made in both directions between the breakaway-torque readings and the torque readings obtained at the point of maximum twist where no angular change was exhibited upon being released. Torque measurements were also made on locked booms, beginning at a point where the torque gauge readings started to increase rapidly. This occurs when the teeth or tabs of the zippered or tabbed booms lock in either direction. Measurements were made in increments of 10 deg and continued until it was decided that any additional force would damage the boom.

Typical Torsion Graph

A typical and somewhat idealized graph of the torsional torque at the tip versus angular tip rotation of a Westinghouse zippered mono-stem boom is shown in Figure 4. As can be seen from this graph, the boom has a dead space of ± 450 deg, a breakaway torque of 0.16 oz-in., a tip spring rate in the dead-space region of 2.7×10^{-4} oz-in./deg, and a tip spring rate of 0.11 oz-in./deg after the teeth lock.

The torsional rigidity of this boom is computed simply by multiplying the tip spring rate in the locked condition by the length. Thus, a torsional rigidity of 85 lb-in.^{2} is obtained for this particular boom section as compared to 750 lb-in.^{2} for a completely closed tube.

A 7-ft section of this same boom was measured for comparative analysis. With all conditions remaining the same except the length, it was found that the spring rates varied inversely with the length (similar to a normal torsional spring). The dead space varied directly with the length, and the breakaway torque (T_0) was independent of the length.

Torsional Parameters of Open-Section Mono-Stem Booms

The torsional parameters of open-section mono-stem booms were investigated. On the first test of a 226-in. section of a silver-plated beryllium copper boom (nominal diameter, 0.5 in.), measured under clamped-clamped conditions, the tip spring rate was found to be 0.1333 oz-in./rev. This yielded a torsional-rigidity value of 0.3 lb-in.^{2} This value differs considerably from the theoretically expected value of torsional rigidity defined by the equation $C = 1/3\ t^3\ PG$, where t = thickness, P = perimeter of cross section, and G = shear modulus. It has been shown that as boom length increases from zero to infinity, an applied torque is countered first by the boom's resistance to warping (short booms) and then by its resistance to pure torsion (long booms).* For the booms of the length tested (226 in.) in the clamped-clamped configuration, the applied torque was resisted by both warping and torsional rigidity to such a degree that neither constant can be easily extracted from the test data. The data and graph of this test are shown in Figure 5. The same boom was tested again with the boom section pinned rather than clamped to the end fittings (Figure 1). This allowed the boom freedom to warp and was referred to as a "pinned-pinned" condition. Measurements made under this condition gave an average tip spring rate of 0.026 oz-in./rev and a torsional rigidity of 0.059 lb-in.^{2} (which agreed well with the theoretical value for torsional rigidity). The data and graph of this test are shown in Figure 6.

A 36-in. segment of this open-section boom was tested while another method of holding the boom to the end fittings was used. This test configuration allowed the boom complete freedom to warp and was referred

*Harold P. Frisch, "Determination of the Undamped Torsional Normalized Modes and Frequencies of a Thin-Walled Cylinder of Open Section", NASA-Goddard Space Flight Center Stabilization and Control Branch Report No. 160, Goddard Space Flight Center, Greenbelt, Maryland, March 1, 1967.

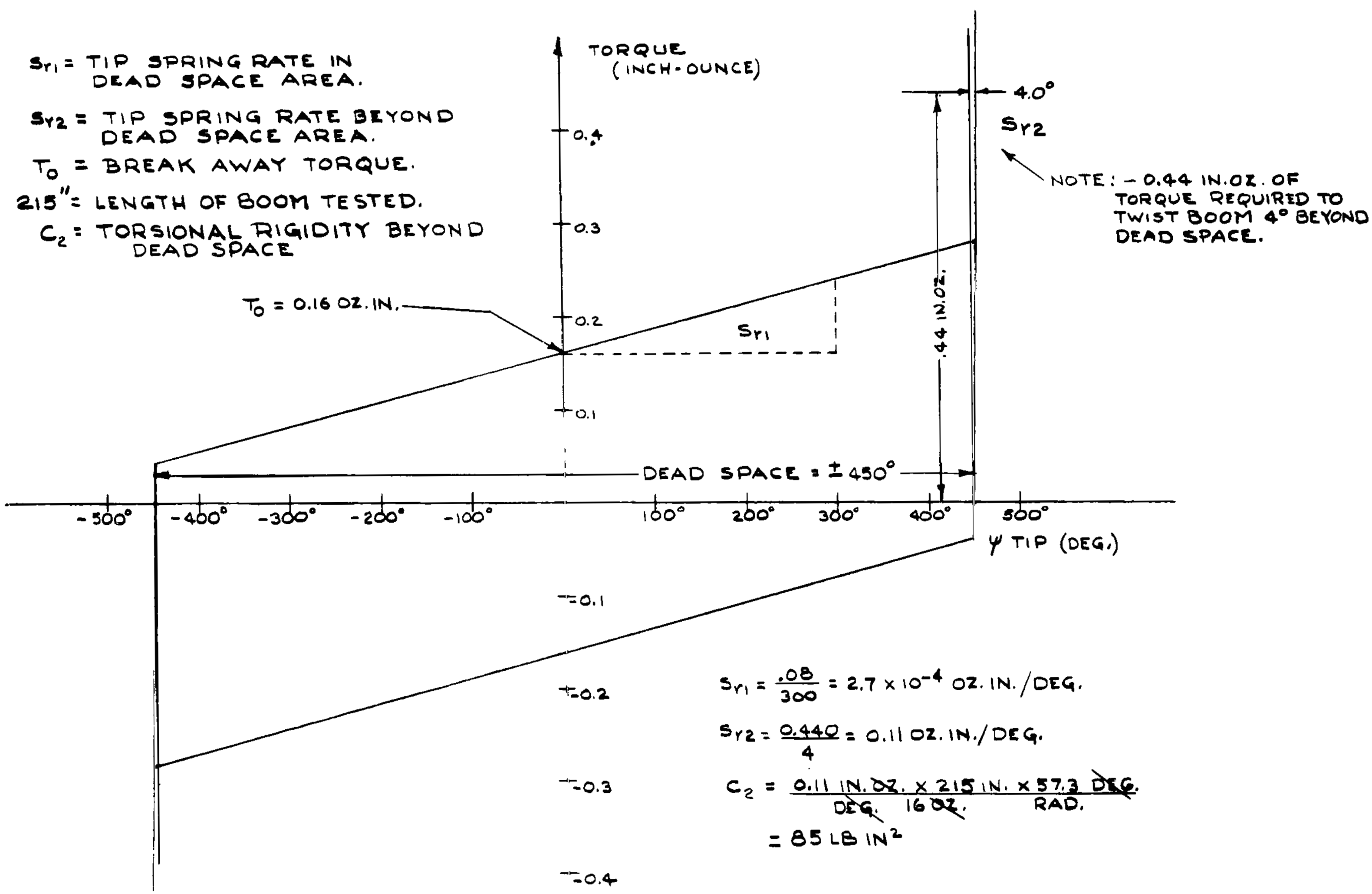


Figure 4—Torsional characteristics of a Westinghouse zippered mono-stem boom tested in clamped-clamped configuration.

ANGULAR OFFSET ψ REVOLUTIONS	TORQUE (IN. OZ.) +	TORQUE (IN. OZ.) −
½	0.075	0.075
1	0.175	0.15
1½	0.225	0.25
2	0.25	0.3
2½	0.3	0.4
3	0.45	0.425
3½	0.45	0.5
4	0.5	

AVG. TIP SPRING RATE $= \frac{0.3 \text{ IN. OZ.}}{2.23 \text{ REV.}} = .00037$ IN. OZ./DEG.

TEST CONFIGURATION – CLAMPED-CLAMPED

TORSIONAL RIGIDITY $C = .00037 \frac{\text{IN.}\cancel{\text{OZ.}}}{\cancel{\text{DEG.}}} \times \frac{1 \text{ LB}}{16 \cancel{\text{OZ.}}} \times 57.3 \frac{\cancel{\text{DEG.}}}{\text{RAD.}} \times 226 \text{ IN.}$

$= .3 \text{ LB. IN}^2$

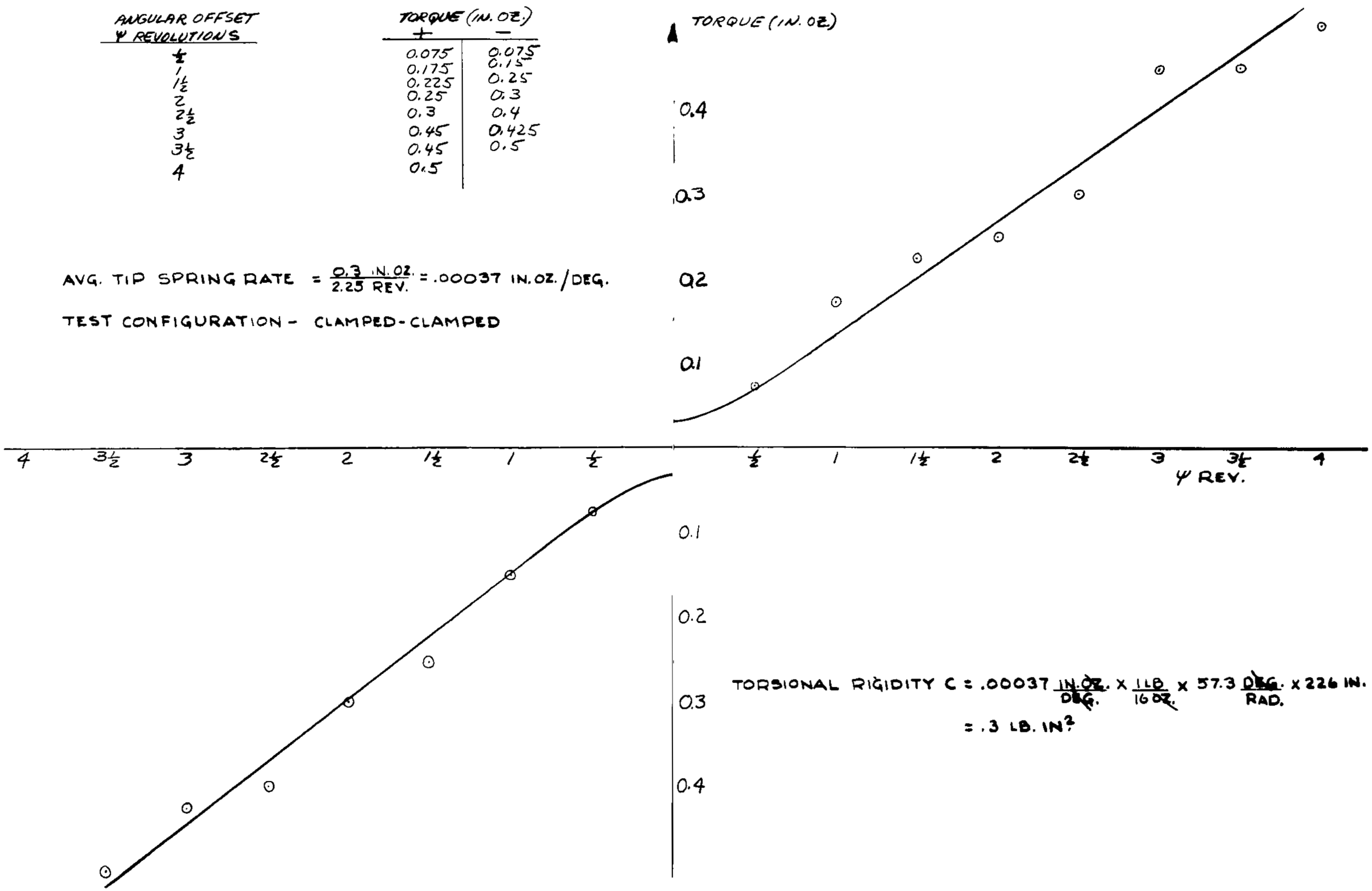
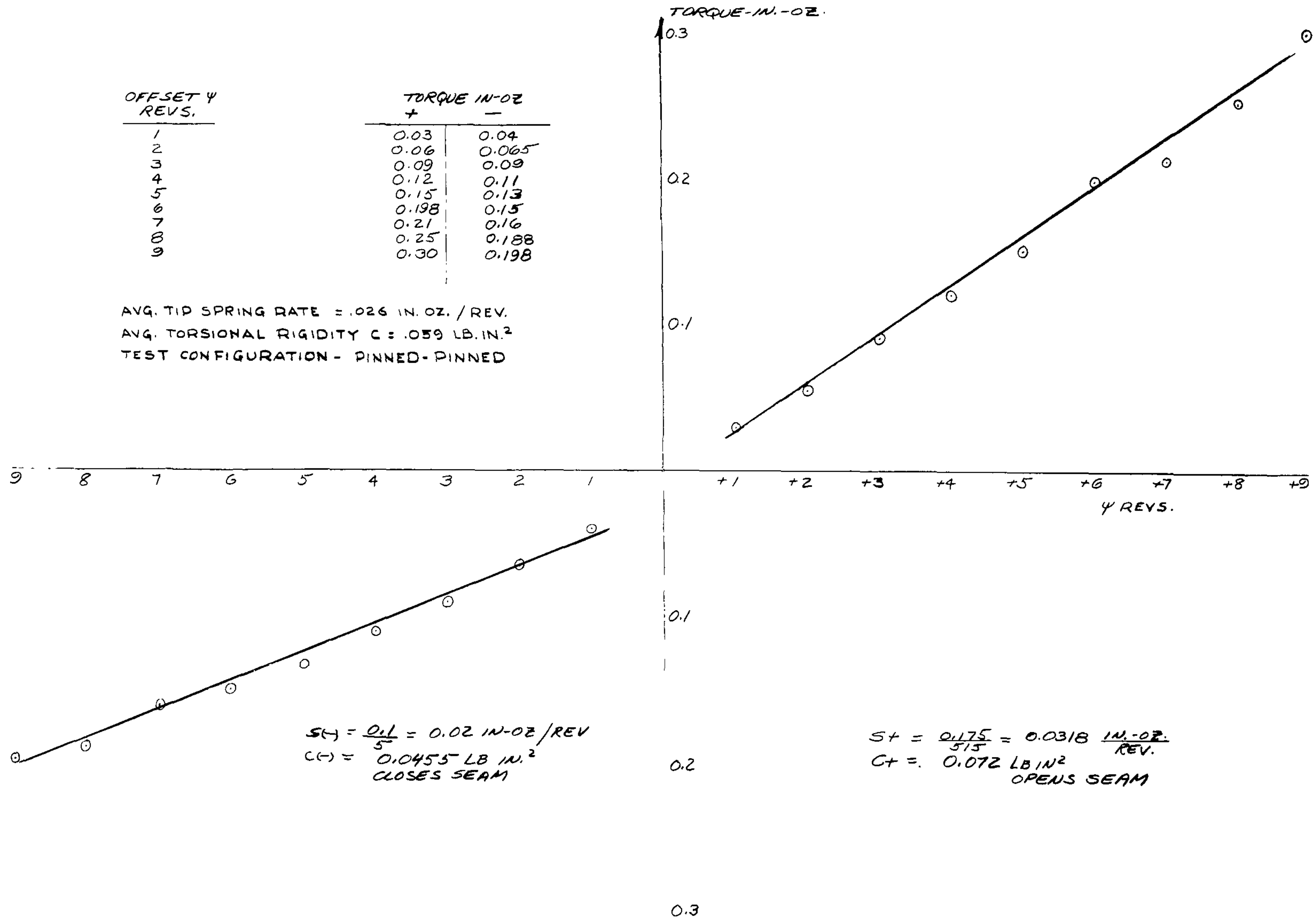


Figure 5–Measured torsional characteristics of a 226-in. silver-plated (tarnished) open-section boom.



OFFSET ψ REVS.	TORQUE IN-OZ +	TORQUE IN-OZ −
1	0.03	0.04
2	0.06	0.065
3	0.09	0.09
4	0.12	0.11
5	0.15	0.13
6	0.198	0.15
7	0.21	0.16
8	0.25	0.188
9	0.30	0.198

Figure 6—Measured torsional characteristics of a 226-in. silver-plated (tarnished) open-section boom.

to as the "slide-slide" condition. This holding arrangement is brought about by providing yoke fittings secured by pins passed through diametrically opposed slots in each end of the boom (Figure 1). Measurements of this specimen gave a torsional rigidity of 0.0578 lb-in.^{2} The data and graph of this test are shown in Figure 7. It can be seen from the above tests that the torsional-rigidity measurements made under slide-slide conditions are in close agreement with those made under pinned-pinned conditions.

Torsional-Damping Measurements

In addition to the torsional characteristics that were measured, it was also pertinent to this study to measure the torsional-damping characteristics of the open-section mono-stem boom. This was done by securing a weight (to provide inertia) to the lower end of a boom section that had its upper end secured to a ceiling beam. The boom was given an angular rotation ψ and was then released and allowed to oscillate. The positive peaks of the decaying oscillations were recorded and plotted on a graph versus the number of cycles n.

The actual test was conducted as follows:

A 226-in. length of open-cross-section boom 0.5 in. in diameter was suspended from the ceiling. The boom was clamped at both ends so that it was not free to warp. A circular plate following specifications was secured to the lower end of the boom:

Thickness, $t = 1/4$ in.;

Radius, $r = 1/2$ ft;

Mass, $M = 2.875$ lbs $= 0.089$ slug;

and

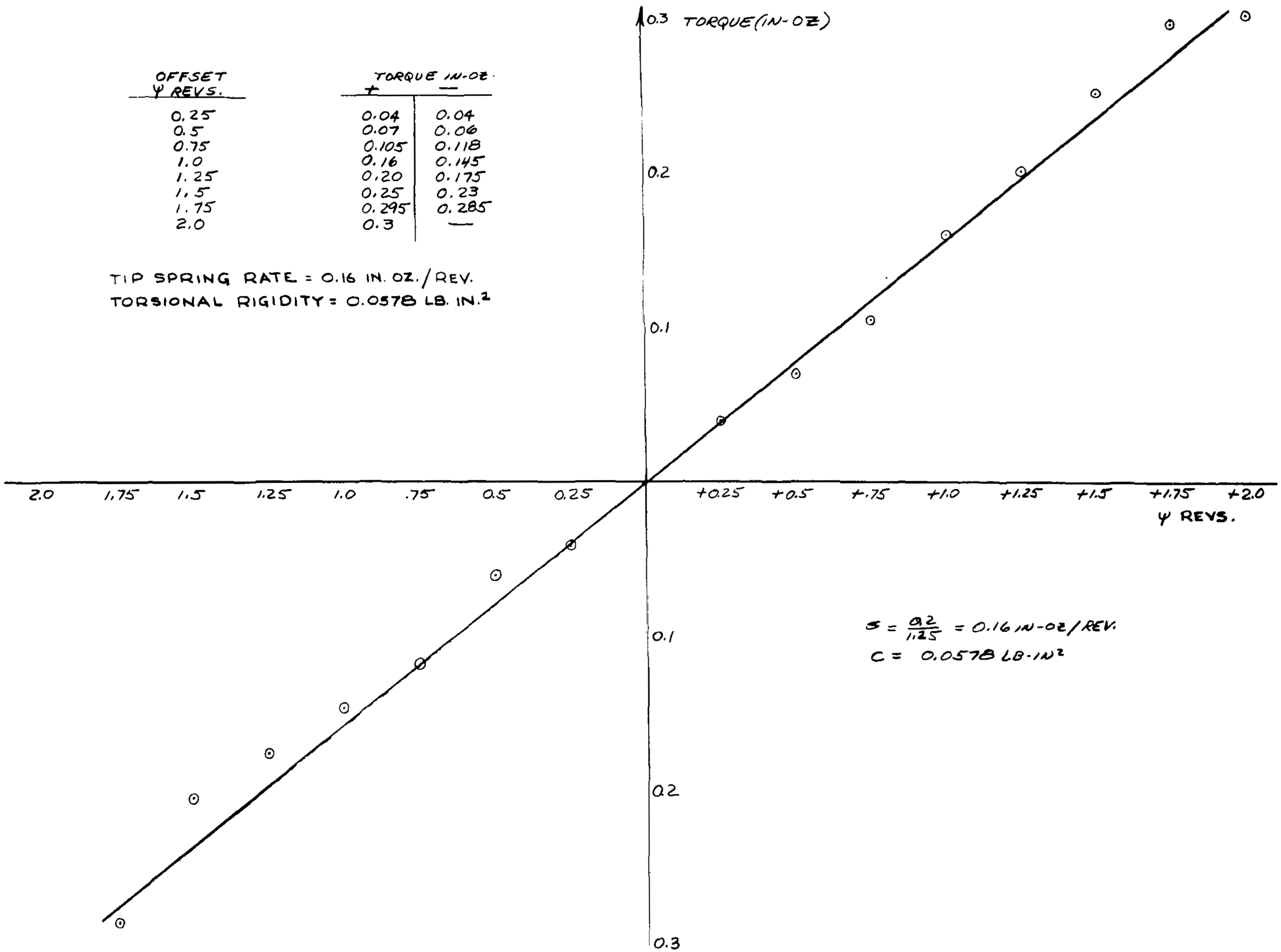
Moment of inertia, $I = \frac{Mr^2}{2} = 0.0111$ slug-ft^2.

The boom was given various initial angular rotations from 180 to 1080 deg in both the positive and negative directions before it was released and allowed to oscillate. As the oscillations decayed, the angular position of each positive peak was recorded. The period (approximately 50 s) was about the same for all values of initial rotation. The data and graph drawn from this test are shown in Figure 8. From the linear decay characteristics shown, it can be inferred that the damping is strongly governed by the effect of Coulomb friction between overlapping surfaces.

Equivalent Viscous Damping

For purposes of comparison, a curve based on the logarithmic decrement equation used for viscously damped systems was superimposed over Plot A of the graph of test data in Figure 8. The initial damping ratio ζ of this curve, represented as a dotted line, was based on

$$\zeta = -\frac{1}{2\pi n} \ln \frac{\psi_n}{\psi_0},$$



OFFSET ψ REVS.	TORQUE IN-OZ +	TORQUE IN-OZ −
0.25	0.04	0.04
0.5	0.07	0.06
0.75	0.105	0.118
1.0	0.16	0.145
1.25	0.20	0.175
1.5	0.25	0.23
1.75	0.295	0.285
2.0	0.3	—

Figure 7—Measured torsional characteristics of a ½-in. (diameter) by 36-in. silver-plated open-section mono-stem boom.

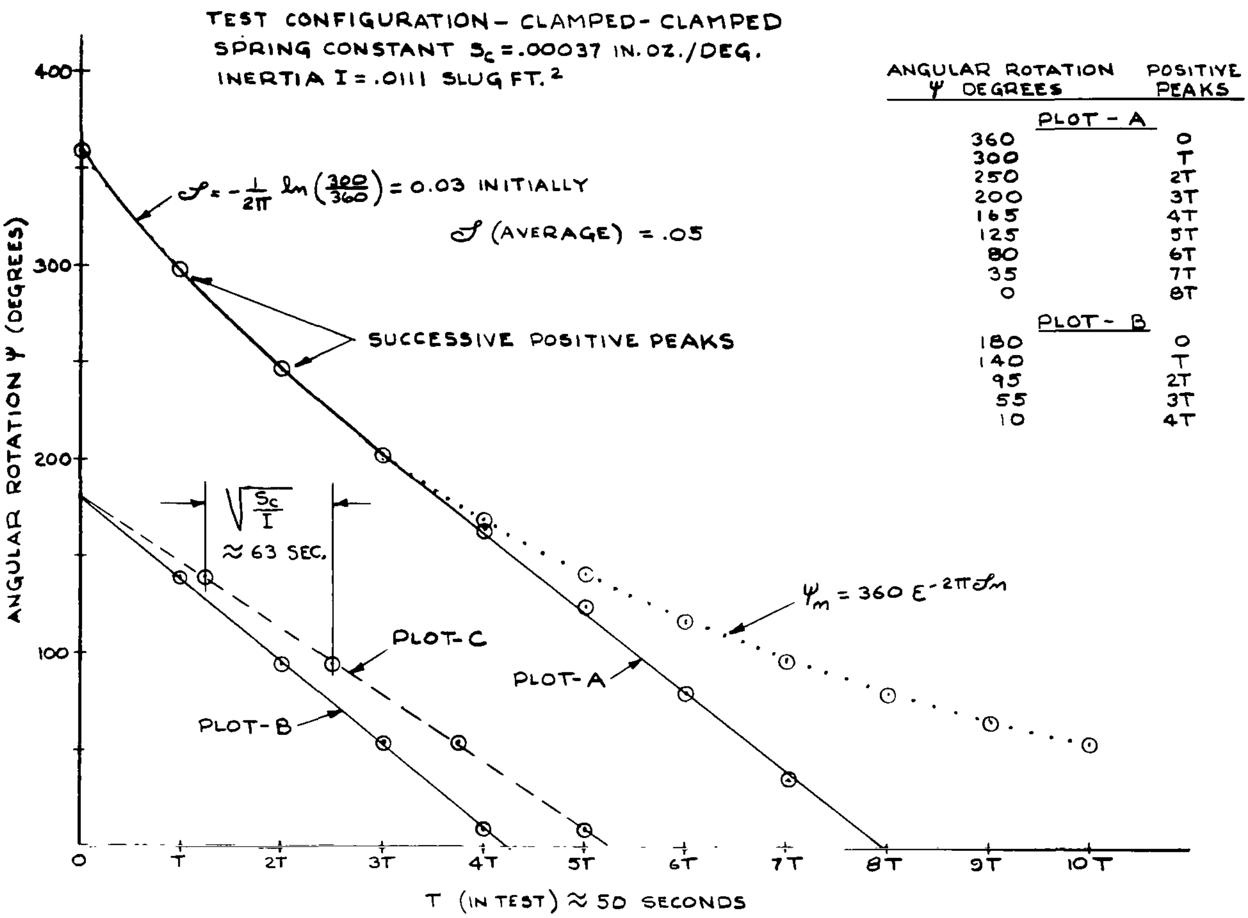


Figure 8—Torsional damping characteristics—positive peaks versus time—of a ½-in. by 226-in. open-section boom.

where

ζ = damping ratio,

n = number of positive peaks,

ψ_n = angular effect at end of n cycles in deg,

and

ψ_0 = initial offset in deg.

From the above, ζ was found to be 0.03 initially. The angular offset ψ_n at the end of each positive peak of oscillation was then determined from

$$\psi_n = 360\, e^{-2\pi\zeta n},$$

where initial offset was 360 deg.

The dotted curve in Figure 8 deviates from the test results after the first two positive peaks. Consequently, equivalent-damping ratios for viscously damped systems cannot be applied to accurately describe the torsional damping of open-section booms.

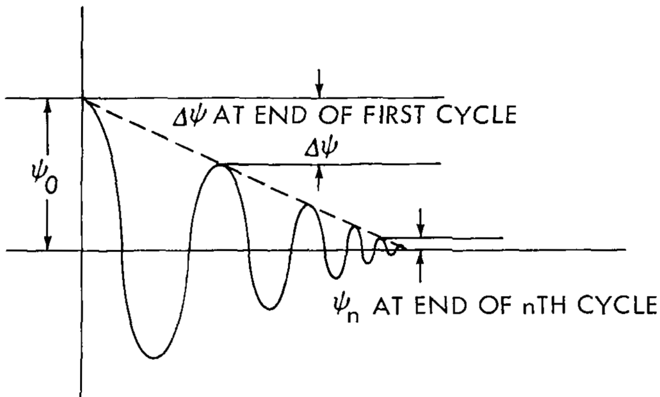
Torsional-Damping Equation

An equation was developed from a phase-plane plot representing Coulomb- (dry-) friction damping based on the graphed test data shown in Figure 8. This equation for torsional damping in oz-in. is

$$T_d = \frac{S_c \Delta\psi_n}{4n} ,$$

where S_c is the spring constant in oz-in./deg and

$$\Delta\psi_n = \psi_0 - \psi_n .$$



COULOMB-FRICTION DAMPING DECAY

For purposes of comparison, an additional plot representing Coulomb friction is superimposed over Plot *B* of Figure 8 and is shown as a dashed line.

The spring constant from the test data shown on Figure 5 was found to be 0.00037 oz-in/deg. Then, from plot C of Figure 8,

$$\Delta\psi = 180 - 140 = 40 \text{ deg.}$$

The torsional-damping equation then gives

$$T_d = 0.0037 \text{ oz-in.}$$

at the end of the first cycle.

Theoretical Boom Frequency

As a check on the above calculations, the theoretical frequency was compared with the measured frequency, with the former defined as

$$\omega = \sqrt{\frac{S_c}{I}} \ ,$$

where

$$S_c = 0.00037 \text{ oz-in./deg}$$

and

$$I = 0.0111 \text{ slug-ft.}^2$$

The theoretical frequency produced a period of approximately 63 s, whereas the measured period was approximately 50 s. The difference between the two frequencies is accounted for chiefly by gravitational forces which prevent the tip weight from being raised and lowered freely as the boom winds up and unwinds in torsion. The spring constants measured and presented previously were determined with no weight attached to the end of the booms; thus, these constants approach those expected in a zero-g field.

Since these frequency differences exist, the balance of this report will give simply the average damping rate of the boom under test and present the result as a ratio against critical damping. In the case of the boom test of Figure 8, the average damping rate produced a damping ratio ζ of 0.05.

Kinetic Damping During First Cycle

The kinetic damping T_k of a 1/2-in. bi-stem boom with no tabs (Figure 9) during the first cycle of oscillation was determined as follows:

A weight of 2.875 lb, 1 ft in diameter, was attached to the lower end of the boom. The boom was given an initial deflection of 1080 deg (3 revolutions), and the first positive peak was measured 54 s later at 495 deg. Thus,

$$\omega = 0.1163 \text{ s}^{-1},$$

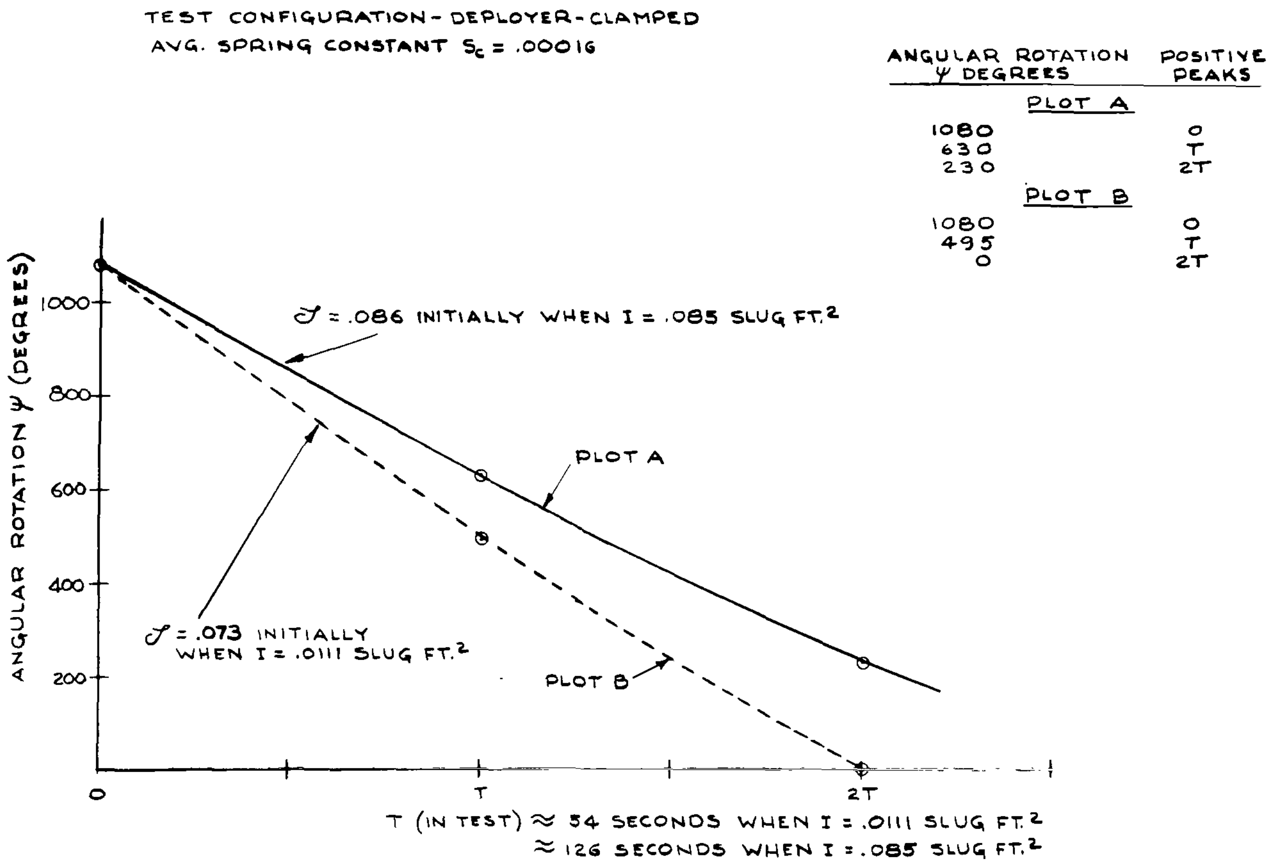


Figure 9—Torsional damping characteristics—positive peaks versus time—of a ½-in. by 244-in. untabbed bi-stem boom.

and the kinetic damping during the first cycle was

$$T_k = \frac{Mr^2}{2} \frac{(\psi_0 - \psi_n)}{4} \omega^2$$

$$= 0.000385 \text{ ft-lb}$$

$$= 0.074 \text{ oz-in.}$$

Minor-Hysteresis Curves

It was observed during tests that some booms, when deflected 5 deg or less, exhibited torsional characteristics that approximated those of a closed tube having the same dimensions. Therefore, additional graphs showing minor-hysteresis curves are given in the section of this report that deals with these booms.

BOOM TESTS

The balance of this report contains descriptions of each boom tested, including pertinent resultant test data and graphs. Table 1 gives the results of the following tests in condensed form.

Measurement of a Westinghouse Zippered Mono-Stem Boom

A 215-in. length of boom section was selected from the front end of a production run and was considered to be typical of the standard Westinghouse product with the following nominal parameters:

Construction	mono-stem
Length	215 in.
Nominal diameter	0.5 in.
Closed (zippered) diameter	0.510 in. normal to the seam 0.495 in. in the seam
Open (unzippered) diameter	0.432 in. normal to the seam 0.440 in. in the seam
Material	1.750-in.-wide, 0.002-in.-thick, preformed beryllium copper, with 0.011 lb/ft weight, 17 percent of the surface as holes, oxidized black inside, vapor-deposited aluminum on the outside, and bending stiffness of 1000 lb-in.^{2} in the weakest plane
Pretwist	1 turn in 16 ft, counterclockwise

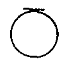
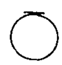
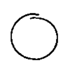
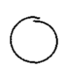
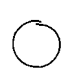
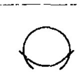
Short nylon fittings were inserted and clamped to each end of the boom section. One of these fittings was used to suspend the upper (fixed) end of the boom from a ceiling beam. The fitting at the lower (free) end of the boom was machined to hold a torque gauge. Since both ends of the boom section were firmly clamped with neither end free to warp; i.e., the boom was in clamped-clamped condition (Figure 1). The data and graph produced from measurements of this boom are shown in Figure 10.

Measurement of Fairchild-Hiller Booms Used on RAE

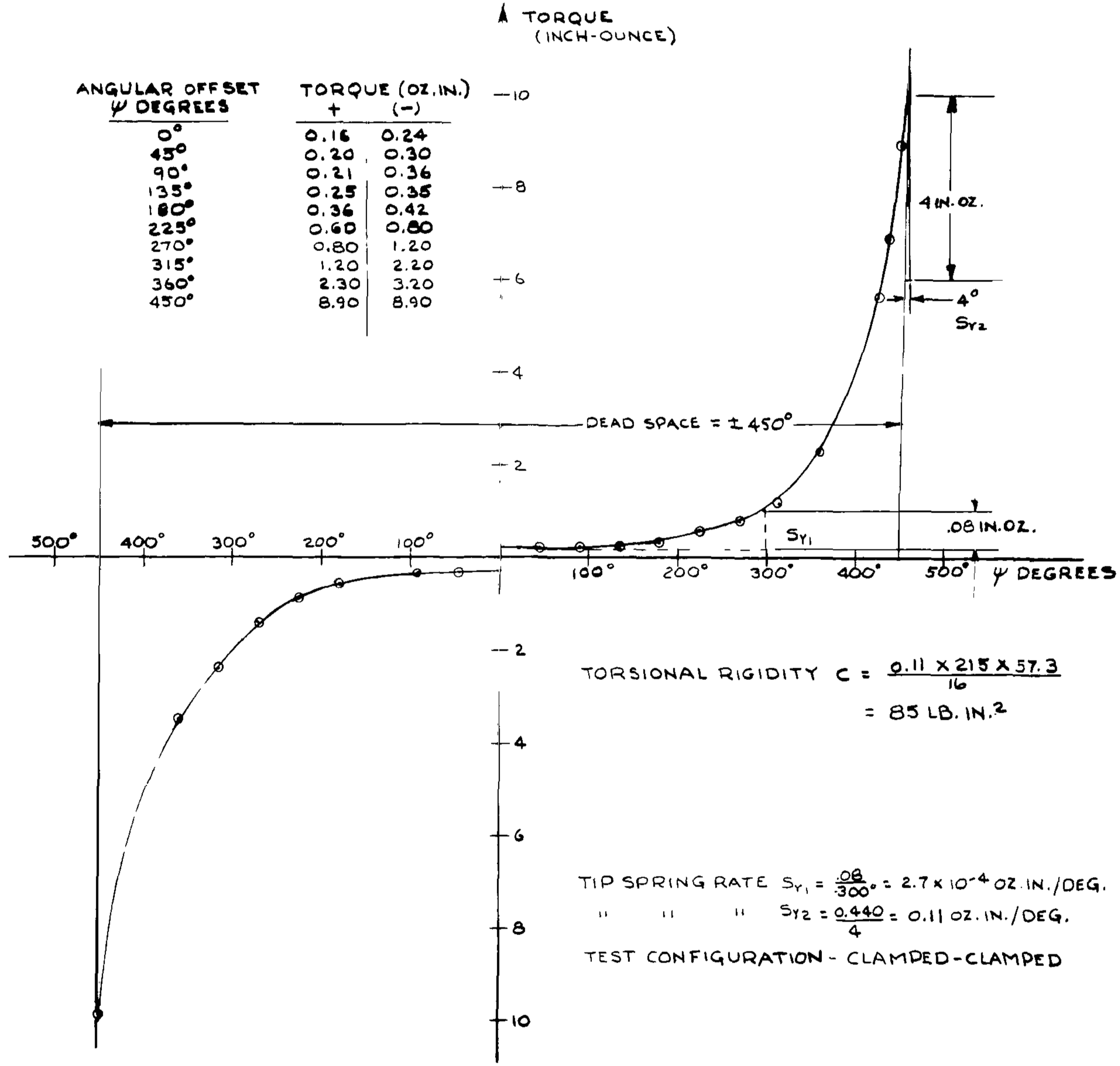
The parameters of the Fairchild-Hiller RAE booms tested were the following (each column represents a different boom):

Length	96 in.	229 in.
Nominal diameter	0.57 in.	0.57 in.
Measured unzippered diameter		
(opposite seam)	0.54 in.	0.525 in.
(in seam)	0.54 in.	0.524 in.

Table 1—Boom chart.

Type	Style	Construction	Figure	Thickness of Material (in.)	Coatings	Diameter (in.)	Length Tested (in.)	Tab Spacing (in.)	Test Condition	Dead Space (deg)	Breakaway Torque (oz-in.)	Torsional Rigidity C (lb-in.^{2})	Warping Rigidity C_1 (lb-in.^{4})	Damping Ratio ζ
Westinghouse	Zippered mono-stem		10	0.002	Vaporized aluminum outside, black oxide inside	0.50	215	0.750	Clamped clamped	± 450	0.16	85	–	–
Fairchild-Hiller	Zippered mono-stem		11	0.002	Silver plate outside, black paint inside	0.50	96	1.00	Clamped clamped	± 10	0.15	32.7	–	–
Fairchild-Hiller	Zippered mono-stem		12	0.002	Silver plate outside, black paint inside	0.50	229	1.00	Clamped clamped	± 7.5	0.20	34.0	–	–
SPAR*	Tabbed bi-stem		13	0.002	Silver plate outside, uncoated inside	0.250	215	0.50	Deployer clamped	± 2160	0.04	0.0162	–	–
Fairchild-Hiller	Double hingelock		14	0.002	Uncoated	0.50	122	0.312	Clamped clamped	± 4.5	1.20	185.5	–	–
SPAR*	Open section mono-stem		6	0.002	Silver plate inside and out	0.50	226	–	Pinned pinned	< 0.1	< 0.1	0.059	–	0.05
SPAR*	Open section mono-stem		7	0.002	Silver plate inside and out	0.50	36	–	Slide slide	< 0.1	< 0.1	0.058	–	0.05
SPAR*	Tabbed bi-stem		16	0.002	Silver plate inside and out	0.50	244	24	Deployer clamped	< 0.1	< 0.1	0.157	–	0.10
SPAR*	Open bi-stem		18	0.002	Uncoated	0.50	244	–	Deployer clamped	< 1.0	< 0.1	0.140	–	0.075
Fairchild-Hiller	Double hingelock		19 and 20	0.002	Silver plate inside and out	0.50	233	0.312	Deployer clamped	± 150	5.0	278	–	–
Nimbus	Tabbed mono-stem		21 and 22	0.004	Uncoated	1.00	161	1.375	Deployer clamped	± 60	5.0	1033	–	–
SPAR* Nimbus	Open section mono-stem		15	0.004	Uncoated	1.00	84.5	–	Slide slide Clamped clamped	< 0.1	< 0.1	0.79	35,203	–
SPAR*	Interlocked bi-stem		23	0.002	Silver plate inside and out	0.50	235	1.00	Deployer clamped	± 150	0.45	147.28	–	–
SPAR* Instrumented Test	Interlocked bi-stem		26 and 27	0.002	Silver plate inside and out	0.50	231	1.00	Deployer clamped	150 ccw 40 cw	0.40	145 ccw 124 cw	–	–

*Formerly De Havilland.



ANGULAR OFFSET ψ DEGREES	TORQUE (OZ. IN.) +	TORQUE (OZ. IN.) (−)
0°	0.16	0.24
45°	0.20	0.30
90°	0.21	0.36
135°	0.25	0.35
180°	0.36	0.42
225°	0.60	0.80
270°	0.80	1.20
315°	1.20	2.20
360°	2.30	3.20
450°	8.90	8.90

Figure 10–Measured torsional characteristics of a 215-in. Westinghouse zippered mono-stem boom.

Dead Space	± 10 deg	± 7.5 deg
Breakaway torque	0.15 oz-in.	0.2 oz-in.
Torsional rigidity	32.7 lb-in.^{2}	34.0 lb-in.^{2}

Both samples were constructed of 2-in.-wide, 2-mil-thick beryllium copper, silver plated on the outside and painted black on the inside, with a bending stiffness of 2000 lb-in.^{2} in the weakest plane. The sample weight was 0.014 lb/ft, and holes constituted 8 percent of the surface.

There was no correlation between dead space and length on the two samples tested; the breakaway torques increased somewhat with length, and the effective spring constant scaled properly, i.e., inversely with length. When the teeth of this type of boom lock, they tend to rise up at their centers as the torsional stress is increased (Figures 11 and 12).

Measurement of a ¼-Inch Tabbed Bi-Stem Boom

The ¼-in. (diameter) tabbed bi-stem boom (tube-within-a-tube construction) had alternate tabs (teeth) every 4 ft. The deployer was secured to a ceiling beam, and 215 in. of this boom were deployed. The lower end of the boom was clamped so that it was not free to warp. Thus, the test conditions were "deployer-clamped". The tip torsional spring rate was found to be 2.1×10^{-5} oz-in./deg, and the torsional rigidity was computed to be 0.01620 lb-in.^{2} The data and graph of these measurements are shown in Figure 13.

Measurement of a Fairchild-Hiller Double-Hingelock Boom

The specimen of a Fairchild-Hiller double-hingelock boom (tested in clamped-clamped configuration) was a very rough piece of an initial design that was supplied to allow a quick look at the torsional parameters. The nominal diameter was ½ in., and the length of the specimen supplied was 122 in. The boom was uncoated beryllium copper with 8 percent holes. The measured dead space was ± 4.5 deg and the frictional breakaway torque was 1.2 oz-in. The tip torsion spring constant was 0.035 oz-in./deg. The torsional rigidity that corresponds to this spring constant and length is 185.5 lb-in.^{2} The data and graph of these measurements are shown in Figure 14.

Torsional- and Warping-Rigidity Tests of the SPAR Nimbus Boom

Calculations for both torsional and warping rigidity for the SPAR Nimbus boom were performed, based on test measurements made on an 84.5-in. section of this boom. Torsional rigidity was measured using the "slide-slide" configuration described earlier, which gives the boom freedom to warp. The torque gauge was attached and the angular-readout disc was positioned as previously described. The data and graph resulting from these measurements are shown in Figure 15. The tip spring rate determined from the graph was

$$S_r = 0.00273 \text{ oz-in./deg.}$$

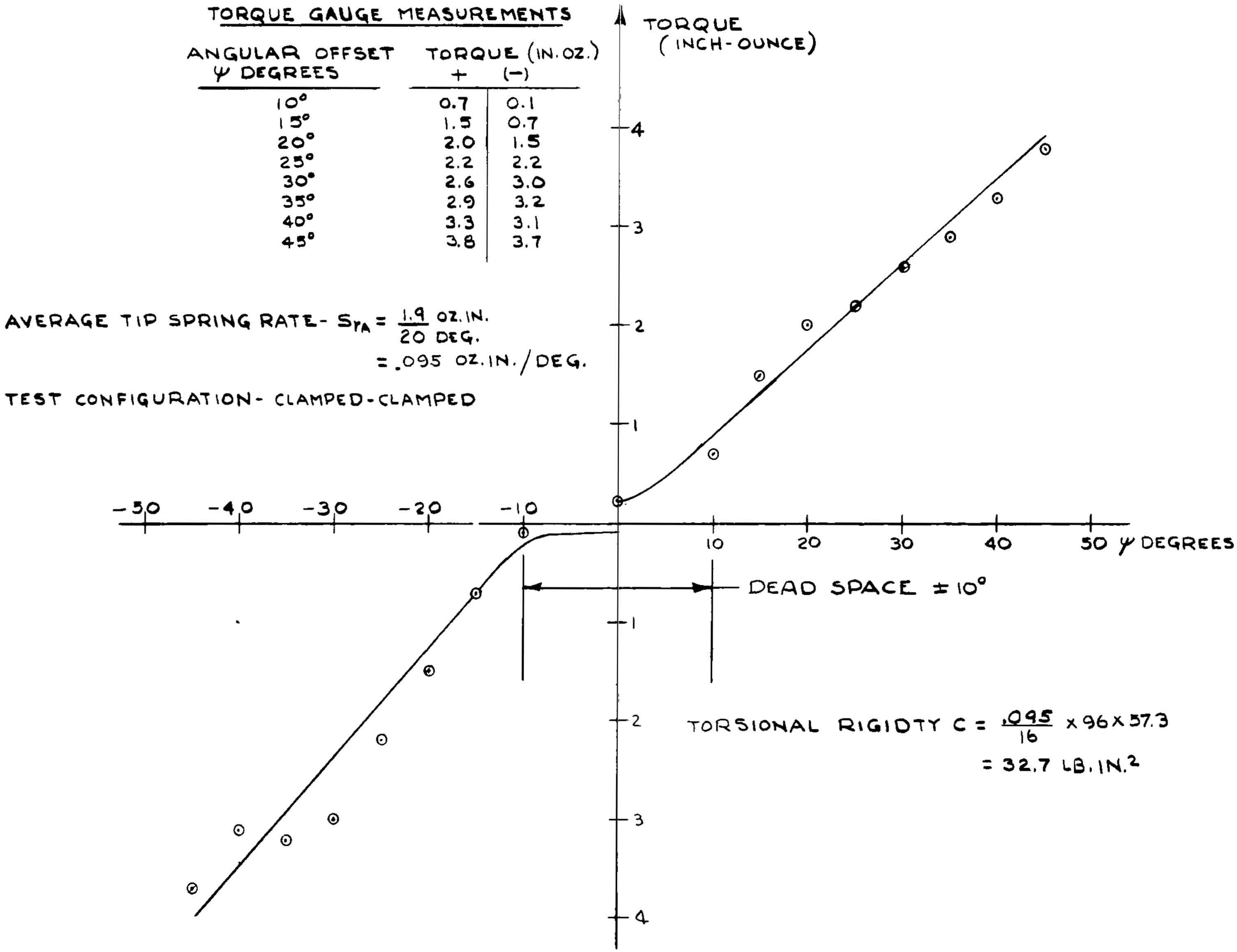
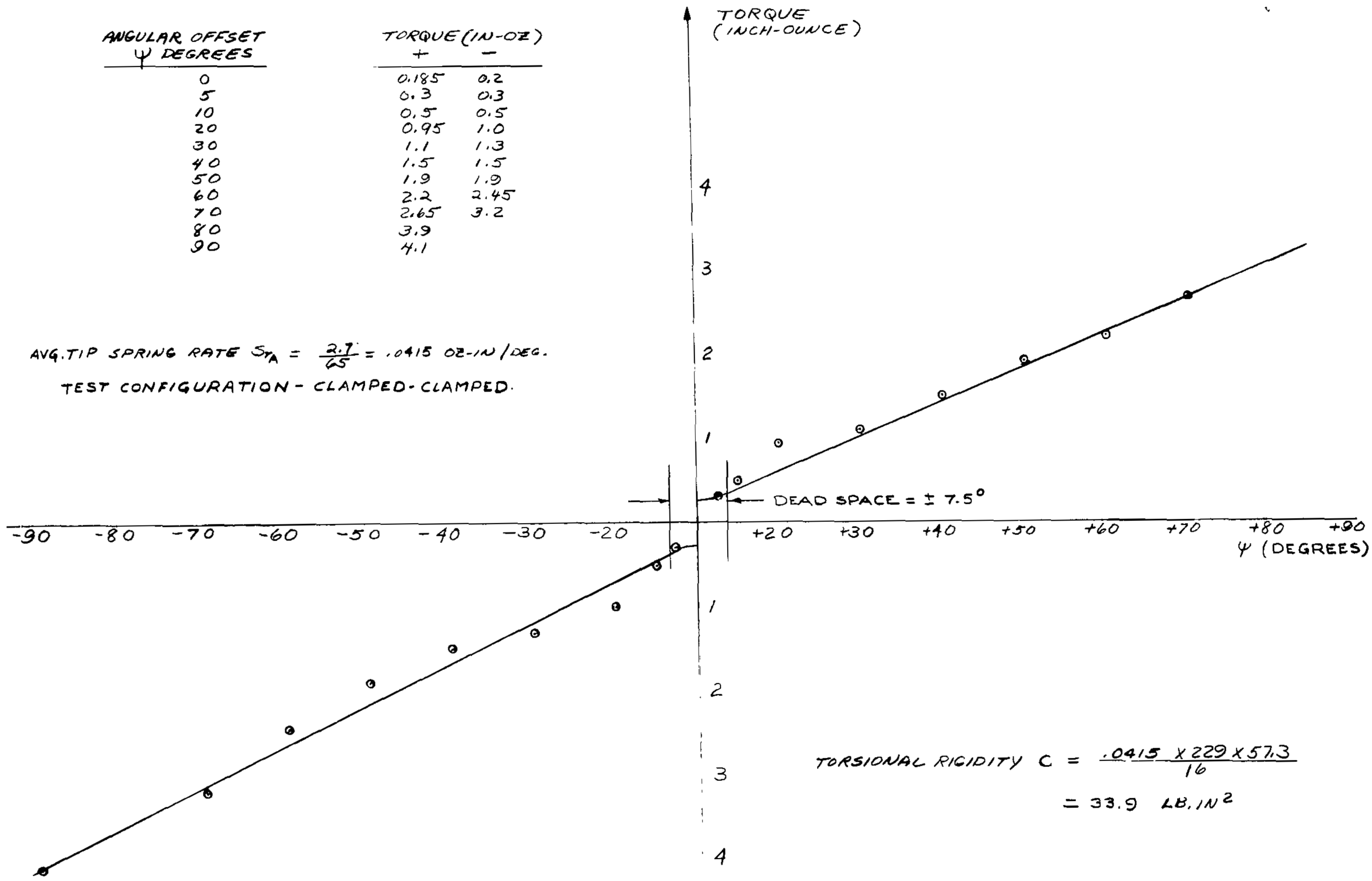


Figure 11–Measured torsional characteristics of a 96-in. Fairchild-Hiller zippered mono-stem boom.

ANGULAR OFFSET ψ DEGREES	TORQUE (IN-OZ) +	TORQUE (IN-OZ) −
0	0.185	0.2
5	0.3	0.3
10	0.5	0.5
20	0.95	1.0
30	1.1	1.3
40	1.5	1.5
50	1.9	1.9
60	2.2	2.45
70	2.65	3.2
80	3.9	
90	4.1	

AVG. TIP SPRING RATE $S_{T_A} = \frac{2.7}{65} = .0415$ OZ-IN/DEG.

TEST CONFIGURATION – CLAMPED-CLAMPED.



TORSIONAL RIGIDITY $C = \frac{.0415 \times 229 \times 57.3}{16}$

$= 33.9$ LB. IN^2

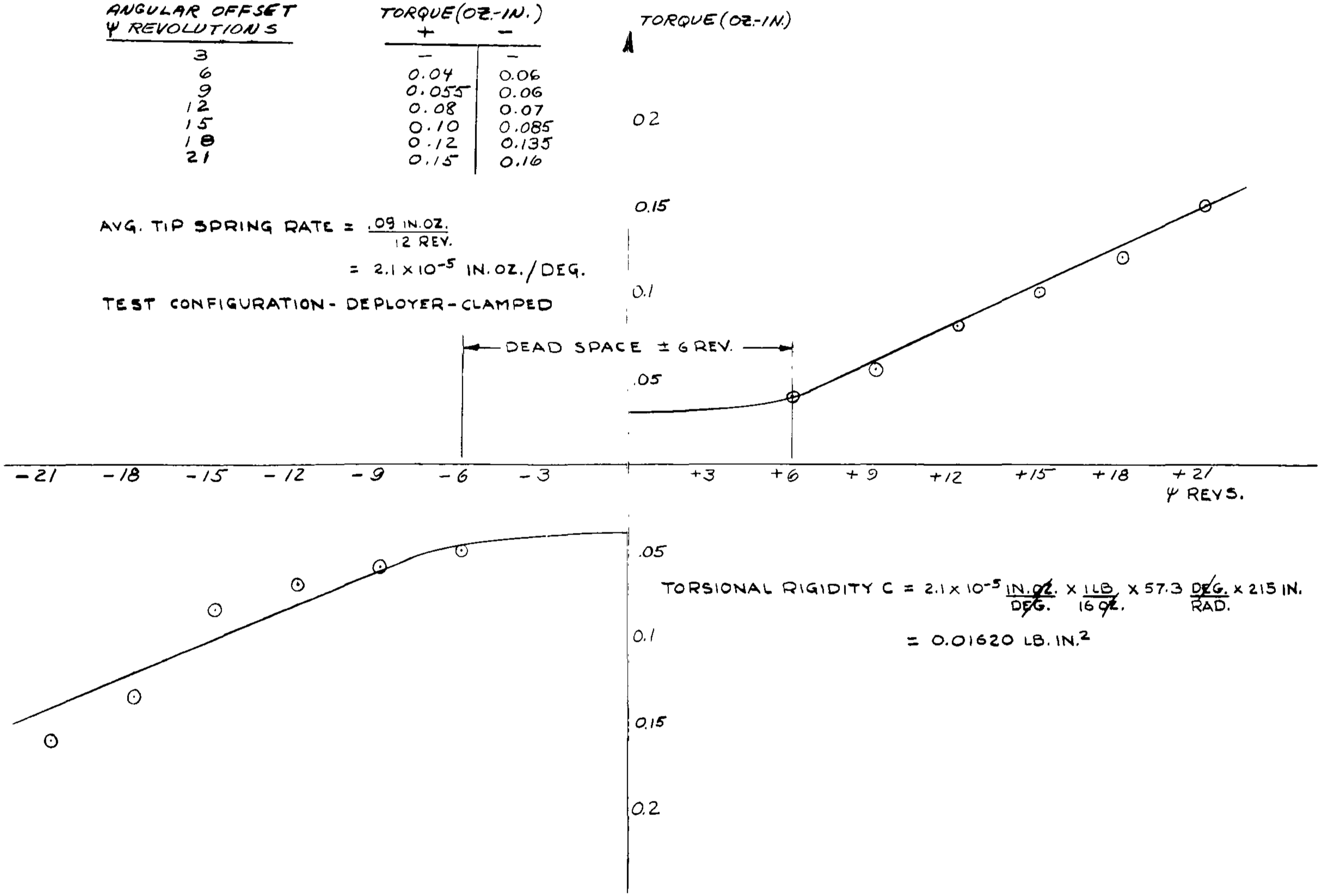
Figure 12–Measured torsional characteristics of a 229-in. Fairchild-Hiller zippered mono-stem boom.

ANGULAR OFFSET ψ REVOLUTIONS	TORQUE (OZ.-IN.) +	TORQUE (OZ.-IN.) −
3	—	—
6	0.04	0.06
9	0.055	0.06
12	0.08	0.07
15	0.10	0.085
18	0.12	0.135
21	0.15	0.16

AVG. TIP SPRING RATE = $\frac{.09 \text{ IN.OZ.}}{12 \text{ REV.}}$

$= 2.1 \times 10^{-5}$ IN.OZ./DEG.

TEST CONFIGURATION - DEPLOYER - CLAMPED



TORSIONAL RIGIDITY $C = 2.1 \times 10^{-5} \frac{\text{IN.}\cancel{\text{OZ}}.}{\cancel{\text{DEG}}.} \times \frac{1 \text{ LB}}{16 \cancel{\text{OZ}}.} \times 57.3 \frac{\cancel{\text{DEG}}.}{\text{RAD.}} \times 215 \text{ IN.}$

$= 0.01620 \text{ LB. IN.}^2$

Figure 13—Measured torsional characteristics of a ¼-in. by 215-in. SPAR interlocked tabbed bi-stem boom (tabs spaced every 4 ft).

ANGULAR OFFSET ψ DEGREES	TORQUE (IN. OZ.) +	TORQUE (IN. OZ.) (−)
4	1.3	1.7
6	2.0	2.2
8	2.6	2.5
10	3.4	4.0
12	5.0	5.2
14	6.2	6.0
16	7.1	7.1
18	7.7	8.2
20	9.9	8.9
22	9.8	9.8

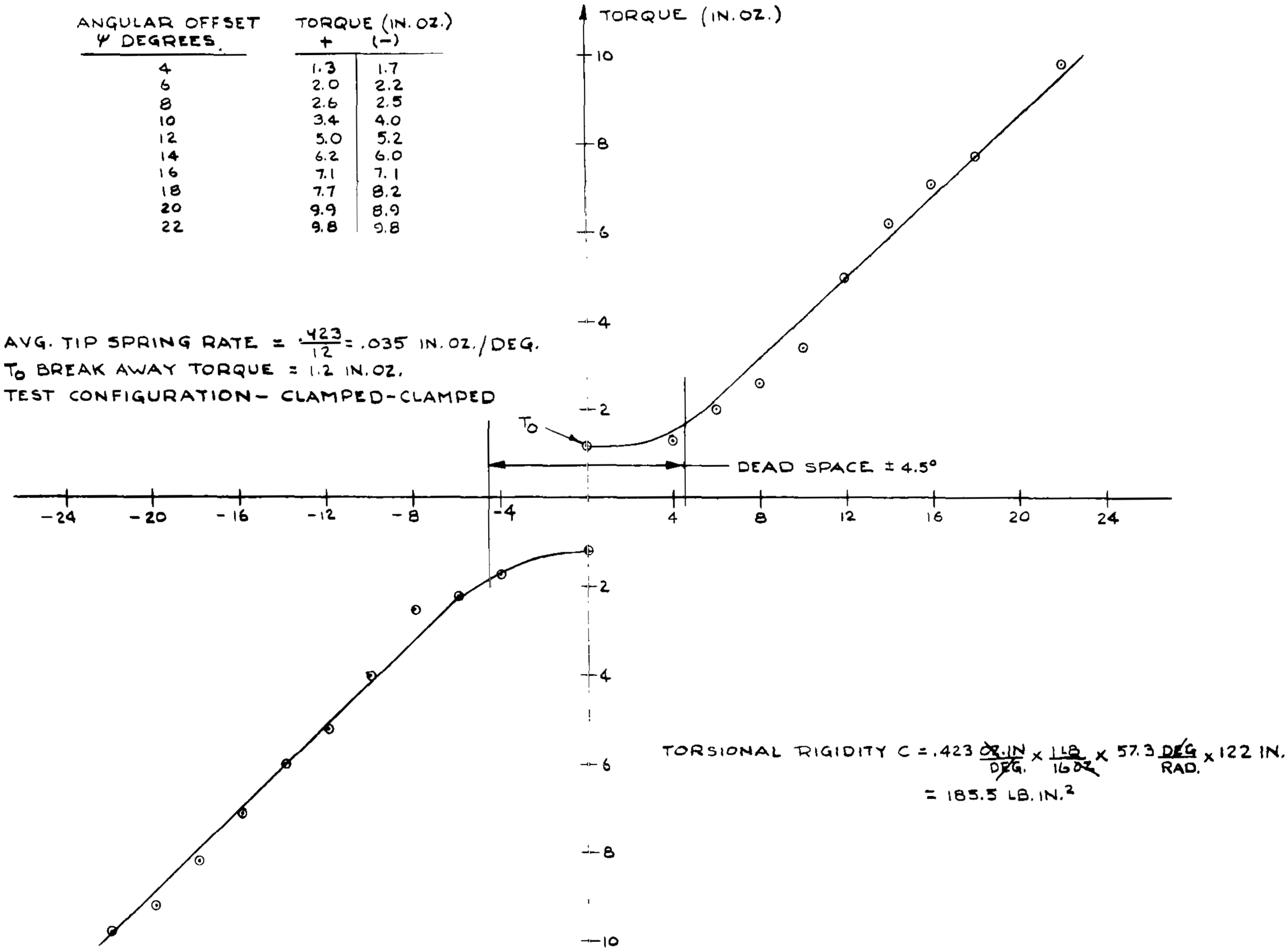


Figure 14–Measured torsional characteristics of a 122-in. Fairchild-Hiller double-hingelock boom (with tab centers spaced 5/16 in. apart).

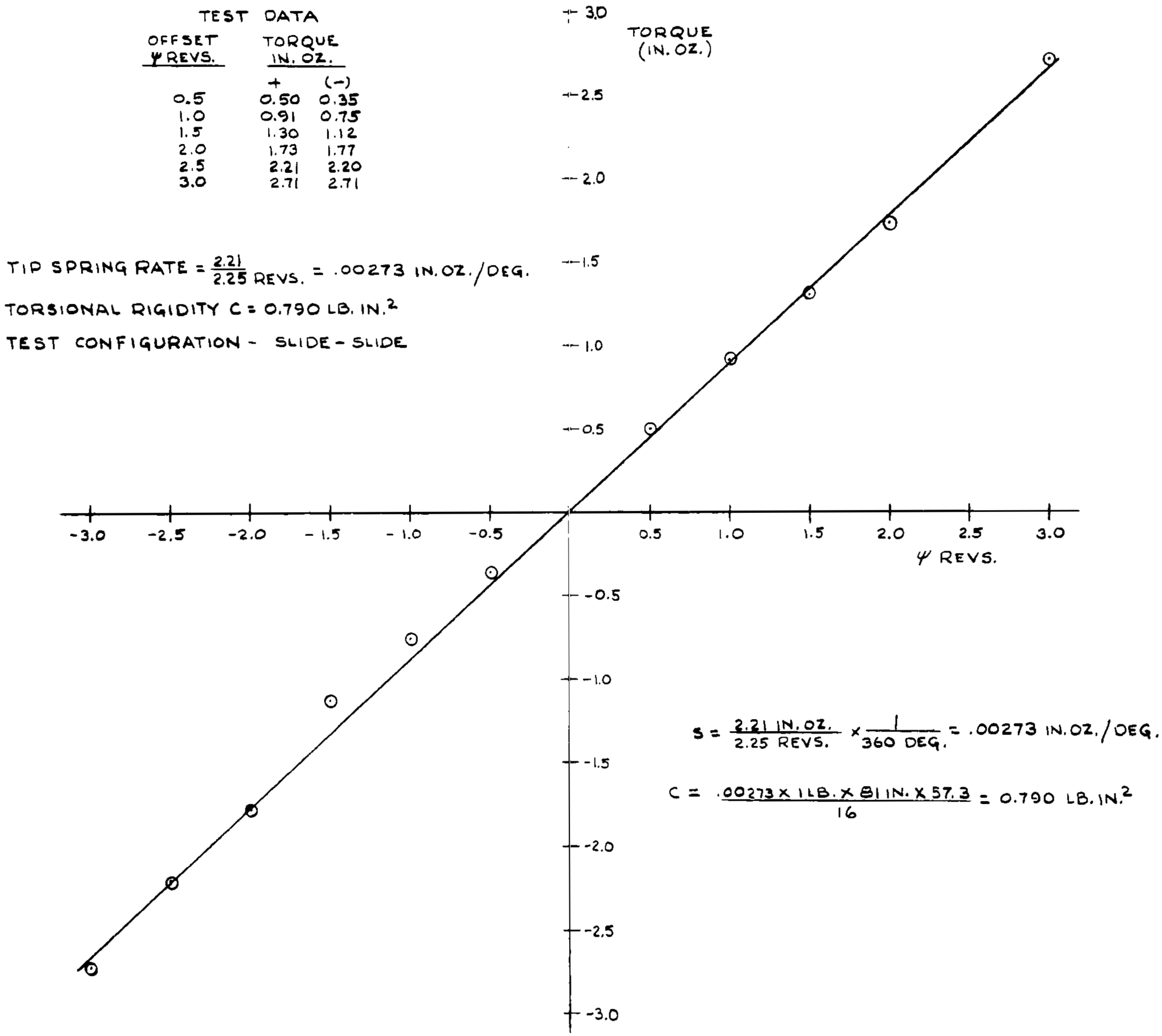


Figure 15–Measured torsional characteristics of a SPAR Nimbus boom (81 in. between slots).

The torsional rigidity was determined to be

$$C_o = 0.790 \text{ lb-in.}^2,$$

where 81 in. (the distance between the slots cut in the boom for the slide-slide configuration) was used for the length. The theoretical value for the torsional rigidity is 0.45 lb-in.^{2}

The warping-rigidity C_1 measurements were made with both ends of the boom firmly clamped. A circular plate with a moment of inertia of 0.10688 slug-ft^2 was attached to the lower end. The boom was given various angular rotations and allowed to oscillate. The period was found to be 8.5 s. With this information and the equation for warping rigidity,*

$$C_1 = \frac{\pi^3 \omega^2}{12},$$

the computed warping rigidity for a length of 84.5 in. was 35,203 lb-in.^{4} The associated theoretical value is 41,111 lb-in.^{4}

Test of a ½-Inch Tabbed Bi-Stem Boom

The test data and torsional characteristics for a ½-in. tabbed bi-stem boom, 244 in. long and made of 0.0025-in.-thick Kapton-coated beryllium copper with tabs 2 ft apart, tested in the deployer-clamped configuration, are shown in Figure 16. The damping curves for this test are shown in Figure 17.

Test of a ½-Inch Bi-Stem Boom With No Tabs

The torsional characteristics for an uncoated ½-in. bi-stem boom 244 in. long and with no tabs, tested in the deployer-clamped configuration, are shown in Figure 18. The damping characteristics for this test are shown in Figure 9.

Test of a ½-Inch Fairchild-Hiller Double-Hingelock Boom

The torsional characteristics for a ½-in. Fairchild-Hiller double-hingelock boom constructed of 0.002-in.-thick beryllium copper, silver plated inside and out, 233 in. long, with tabs 5/16 in. apart, and tested in the deployer-clamped configuration, are shown in Figure 19.

It was observed during the test that this boom was comparatively stiff. When the boom was deflected 5 deg or less, its torsional characteristics approached those of a closed tube of the same dimensions. Therefore, an additional graph is given in Figure 20 showing minor hysteresis curves that developed when the boom was deflected 5 deg in either direction.

*Harold P. Frisch, "Determination of the Undamped Torsional Normalized Modes and Frequencies of a Thin-Walled Cylinder of Open Section", NASA-Goddard Space Flight Center Stabilization and Control Branch Report No. 160, Goddard Space Flight Center, Greenbelt, Maryland, March 1, 1967.

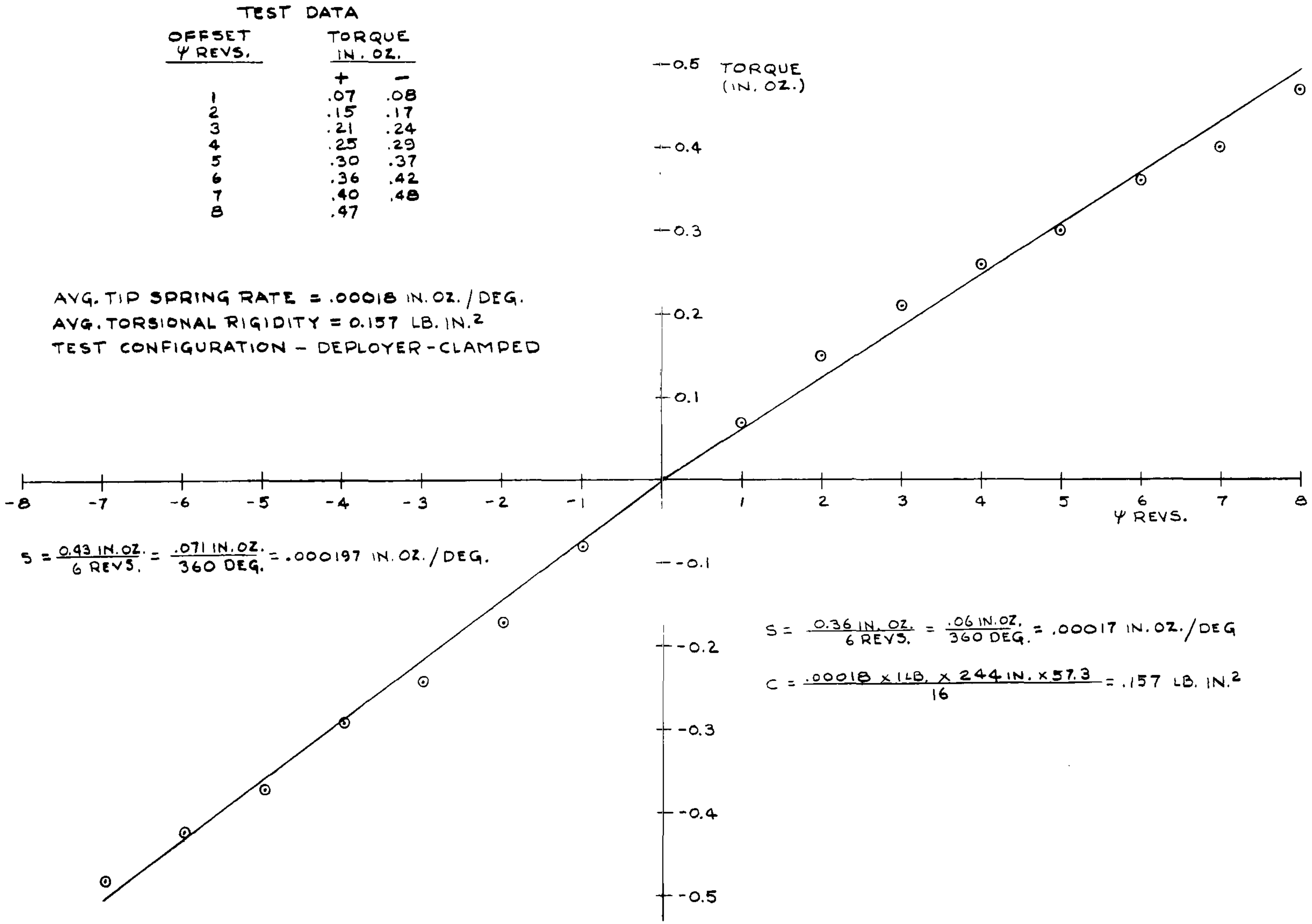


Figure 16–Measured torsional characteristics of a ½-in. by 244-in. tabbed bi-stem boom (tab centers spaced 24 in. apart).

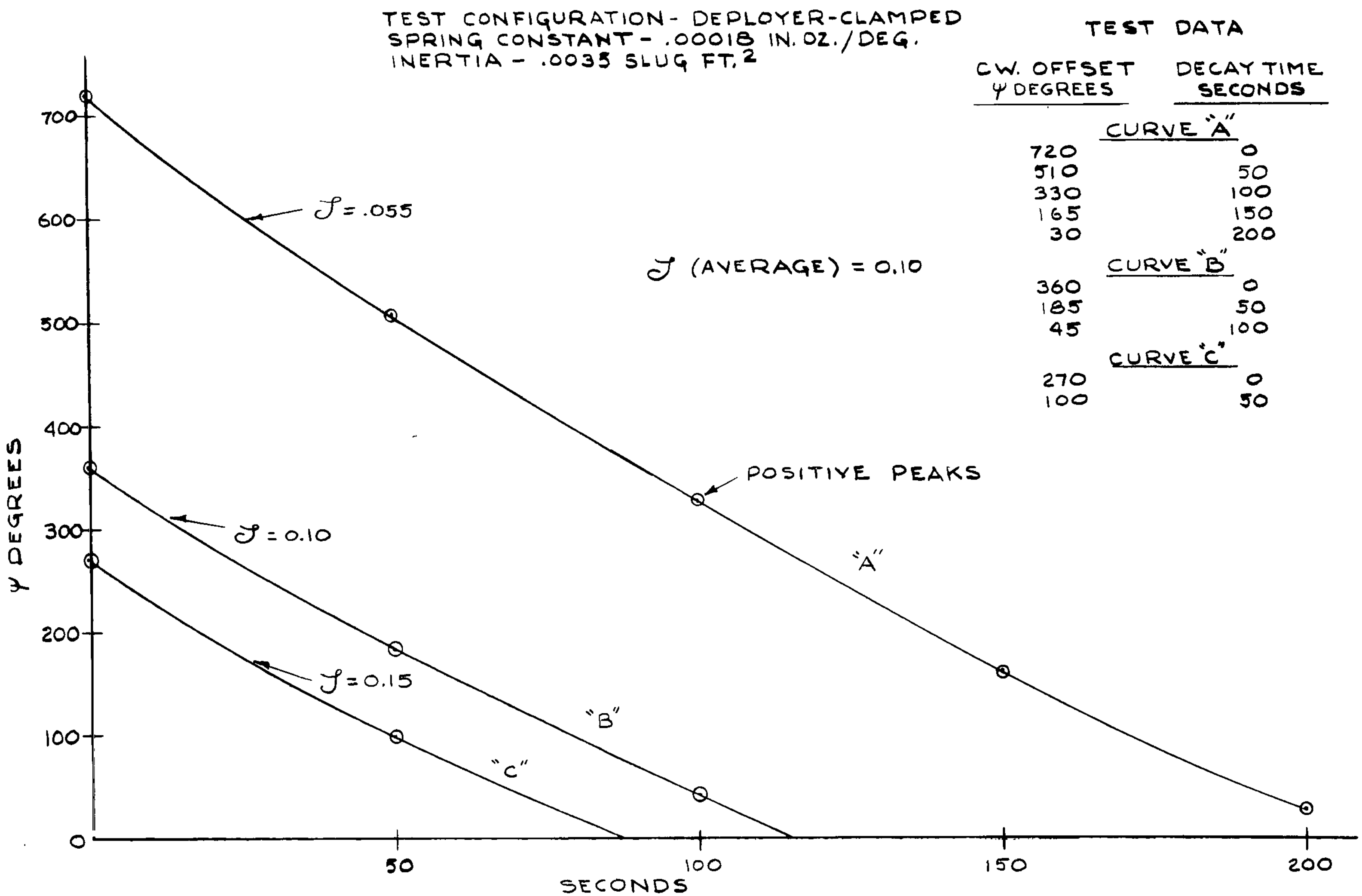
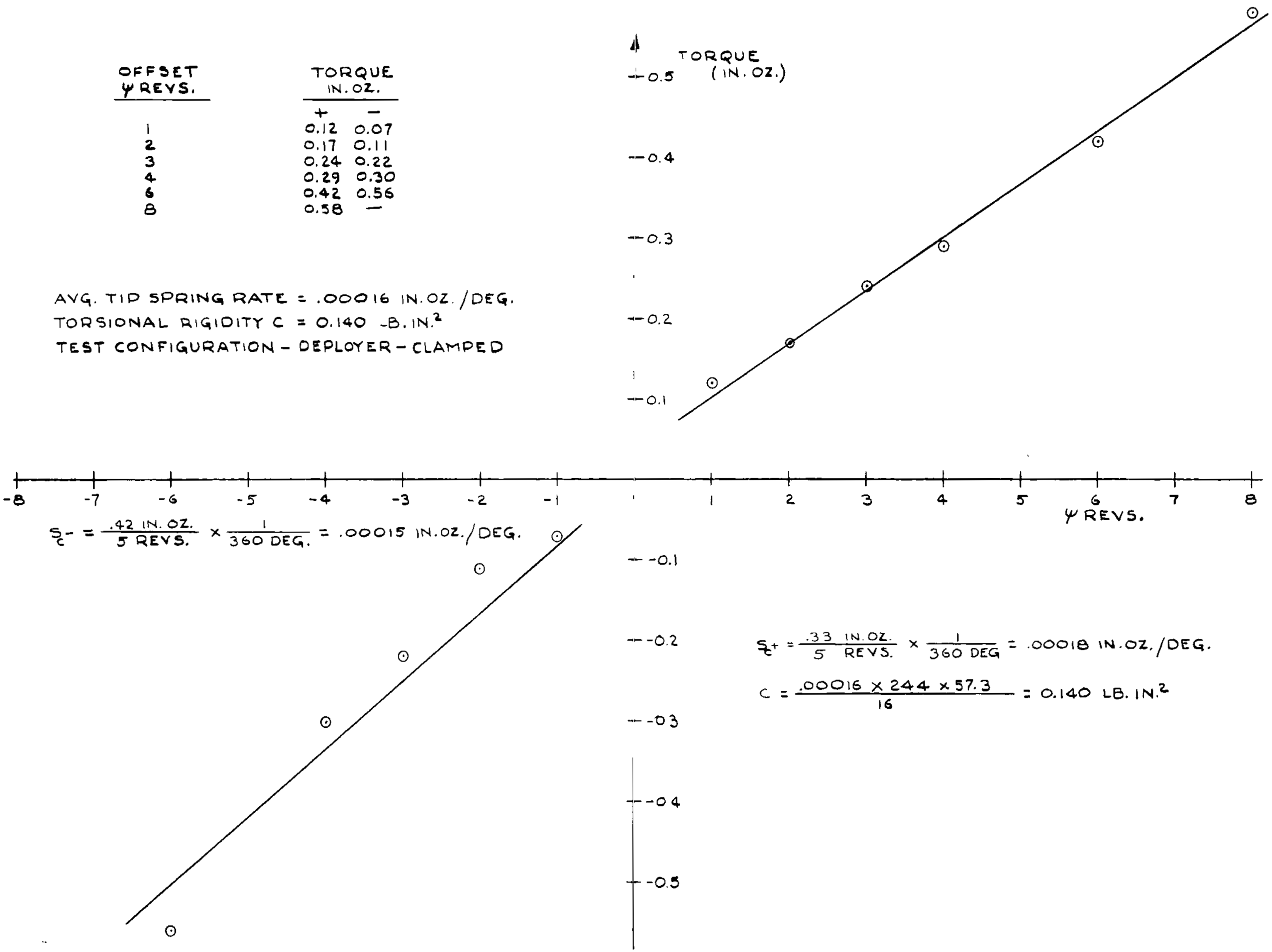


Figure 17–Measured damping characteristics of a ½-in. by 244-in. tabbed bi-stem boom.



OFFSET ψ REVS.	TORQUE IN. OZ. +	TORQUE IN. OZ. −
1	0.12	0.07
2	0.17	0.11
3	0.24	0.22
4	0.29	0.30
6	0.42	0.56
8	0.58	—

AVG. TIP SPRING RATE = .00016 IN. OZ. /DEG.
TORSIONAL RIGIDITY C = 0.140 LB. IN.^{2}
TEST CONFIGURATION – DEPLOYER – CLAMPED

$$S_{c^-} = \frac{.42 \text{ IN. OZ.}}{5 \text{ REVS.}} \times \frac{1}{360 \text{ DEG.}} = .00015 \text{ IN.OZ./DEG.}$$

$$S_{c^+} = \frac{.33 \text{ IN. OZ.}}{5 \text{ REVS.}} \times \frac{1}{360 \text{ DEG}} = .00018 \text{ IN.OZ./DEG.}$$

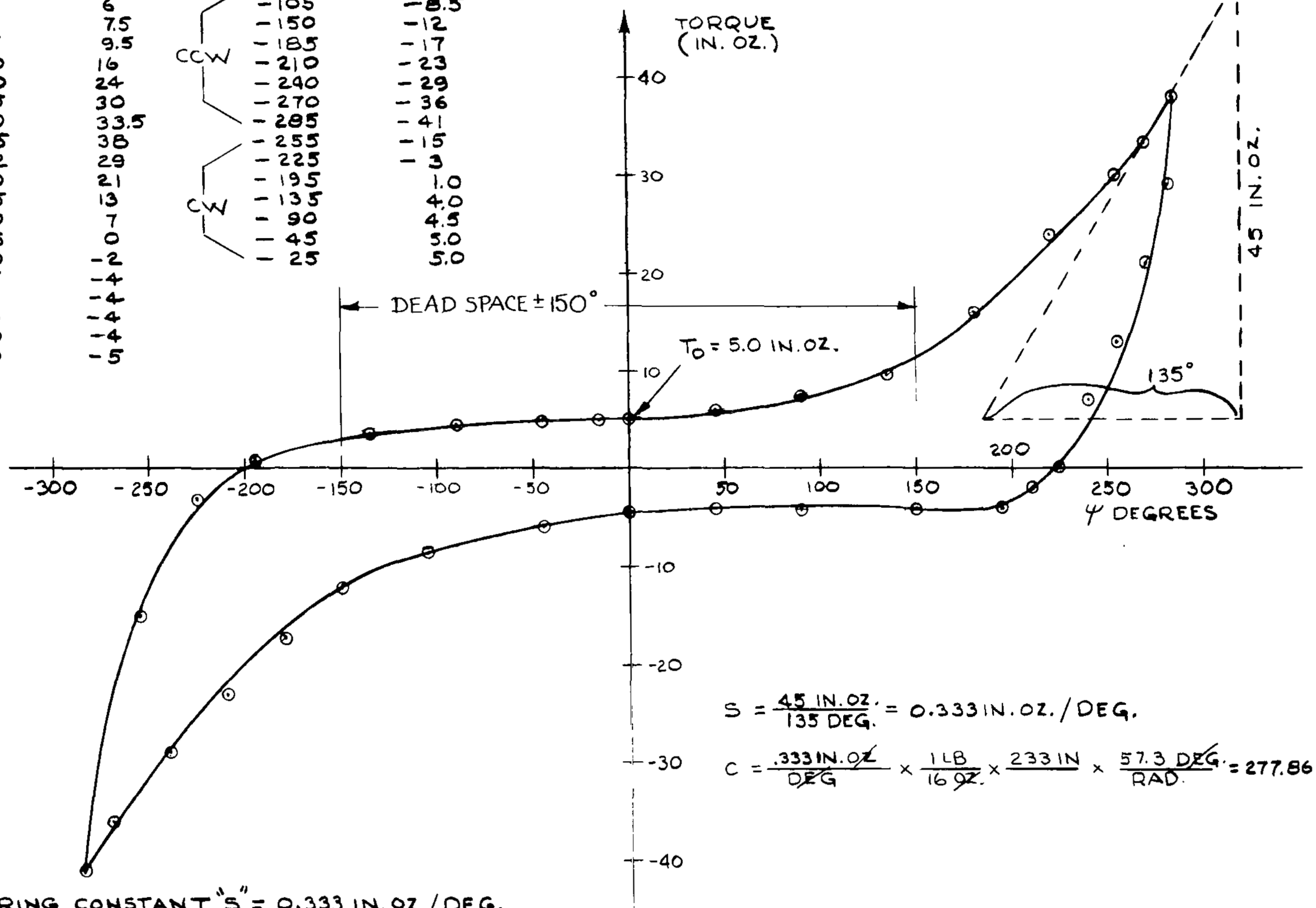
$$C = \frac{.00016 \times 244 \times 57.3}{16} = 0.140 \text{ LB. IN.}^2$$

Figure 18–Measured torsional characteristics of a ½-in. by 244-in. untabbed bi-stem boom.

TEST DATA

	ANGULAR OFFSET ψ	TORQUE (IN. OZ.)
	0	5
CW	45	6
CW	90	7.5
CW	135	9.5
CW	180	16
CW	220	24
CW	255	30
CW	270	33.5
CW	285	38
CCW	282	29
CCW	270	21
CCW	255	13
CCW	240	7
CCW	225	0
CCW	210	-2
CCW	195	-4
CCW	150	-4
CCW	100	-4
CCW	50	-4
CCW	0	-5

	ANGULAR OFFSET ψ	TORQUE (IN. OZ.)
CCW	-45	-6
CCW	-105	-8.5
CCW	-150	-12
CCW	-185	-17
CCW	-210	-23
CCW	-240	-29
CCW	-270	-36
CCW	-285	-41
CW	-255	-15
CW	-225	-3
CW	-195	1.0
CW	-135	4.0
CW	-90	4.5
CW	-45	5.0
CW	-25	5.0



$$S = \frac{45 \text{ IN. OZ.}}{135 \text{ DEG.}} = 0.333 \text{ IN. OZ./DEG.}$$

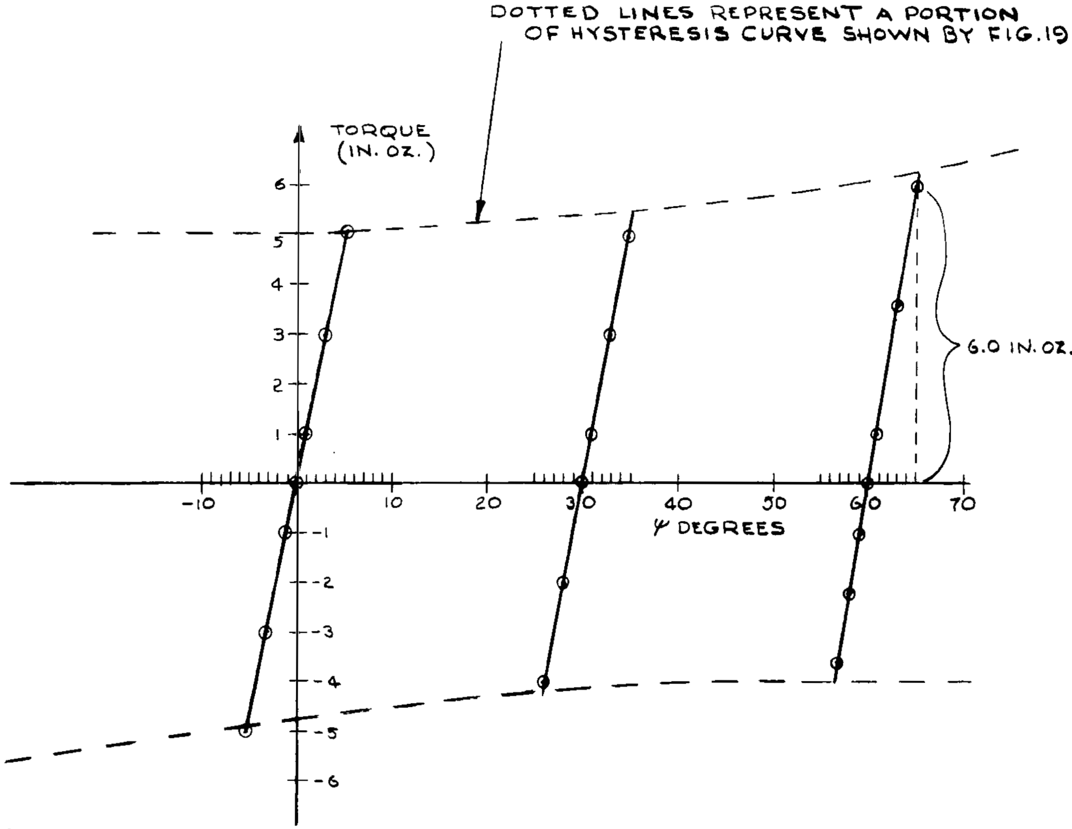
$$C = \frac{.333 \text{ IN. } \cancel{OZ}}{\cancel{DEG}} \times \frac{1 \text{ LB}}{16 \cancel{OZ}} \times \frac{233 \text{ IN}}{} \times \frac{57.3 \cancel{DEG}}{RAD} = 277.86 \text{ LB IN.}^2$$

SPRING CONSTANT "S" = 0.333 IN. OZ./DEG.
TORSIONAL RIGIDITY "C" = 277.86 LB. IN.^{2}
TEST CONFIGURATION — DEPLOYER — CLAMPED

Figure 19—Measured torsional characteristics of a ½-in. by 233-in. Fairchild-Hiller silver-plated double-hingelock boom (with tabs spaced 5/16 in. apart).

TEST DATA
TAKEN AT 0°, 30°, AND 60°

ANGULAR OFFSET (ψ DEGREES)	TORQUE (IN. OZ.)
0	0
1	1.0
3	3.0
5	5.0
-1	-1.0
-3	-3.2
-5	-5.3
30	0
31	1.0
33	3.0
35	5.0
28	-2.0
24	-4.0
60	0
61	1.0
63	3.6
65	6.0
59	-1.0
58	-2.2
57	-3.6



AT 60° OFFSET

SPRING CONSTANT $S_c = \frac{6.0 \text{ IN. OZ.}}{5 \text{ DEG.}} = 1.2$ IN. OZ./DEG.

TORSIONAL RIGIDITY

$$C = \frac{1.2 \text{ IN.} \cancel{\text{OZ.}}}{\cancel{\text{DEG.}}} \times \frac{1 \text{ LB}}{16 \cancel{\text{OZ.}}} \times \frac{57.3 \cancel{\text{DEG.}}}{\text{RAD.}} \times 233 \text{ IN.}$$

$$= 1001.3 \text{ LB. IN.}^2$$

Figure 20–Minor-hysteresis curves of a ½-in. Fairchild-Hiller double-hingelock boom.

The spring constant and torsional rigidity at zero-degree angular rotation of this boom are also shown in Figure 20. If a minor hysteresis slope is measured for a 60-deg offset of the boom, it is found that the spring constant and torsional rigidity, respectively, at this point are:

$$S_c = 2.2 \text{ oz-in./deg}$$

$$C = 1001 \text{ lb-in.}^2$$

The theoretical torsional rigidity of a closed tube having the same dimensions as this boom is found with the equation

$$C = 2\pi t r^3 G ,$$

where G, the shear modulus, is 6×10^6 lb/in.^{2} (Reference 1). For the respective values of thickness and radius of 0.002 and 0.25 in., C is found to be 1176 lb-in.^{2}

Thus, it can be seen that the torsional rigidity of the boom at this point agrees rather closely with the torsional rigidity of a closed tube of the same dimensions.

Test of a 1-Inch Nimbus Boom

Specifications for the 1-in. Nimbus boom tested were the following:

Length	161 in.
Tab spacing	1.375 in. center to center
Material	0.004-in.-thick beryllium copper
Test configuration	deployer-clamped
Measured diameter	0.940 in.

The torsional characteristics of the 1-in. Nimbus boom are shown in Figures 21 and 22. The hysteresis curve in Figure 21 gives a spring constant S_c of 1.79 oz-in./deg after the teeth lock up. This, in turn, gives a torsional rigidity of 1033 lb-in.^{2} Static friction will effectively prevent all warping for applied torques of up to 5 oz-in., and in this area the boom will be structually equivalent to a closed tube having the same dimensions. Also, in this region, the slopes of the minor hysteresis curves shown in Figure 22 indicate that the torsional rigidities will be in excess of 6000 lb-in.^{2}

Measurement of a ½-Inch Interlocked Bi-Stem Boom

The ½-in. diameter interlocked bi-stem boom tested had the specifications which follow:

Length	231 in.
Material	0.002-in.-thick beryllium copper, silver plated inside and out

TEST DATA

	ANGULAR OFFSET ψ	TORQUE (IN. OZ.)	
	0.0	5.0	
	25.5	7.0	
	39.5	8.0	
	45.0	9.0	
	55.5	10.0	
	63.0	11.0	
	72.0	14.0	
	81.0	17.0	
	84.5	20.0	
	90.5	25.0	
	94.5	29.0	SEAM CLOSING CW
	96.5	31.0	
	97.0	33.0	
	98.0	34.0	
	98.5	35.0	
+	99.0	36.0	
	99.5	37.0	
	100.0	38.0	
	101.0	39.0	
	101.0	40.0	
	101.0	35.0	
	100.5	30.0	
	100.0	25.0	
	99.5	20.0	
	97.0	10.0	
	94.5	5.0	
	89.0	0.0	
	68.0	3.0	
	31.0	4.0	
	0.0	5.0	
	43.0	6.0	
	53.0	7.0	
	58.0	8.0	SEAM OPENING CCW
	64.0	10.0	
	74.5	15.0	
	82.5	20.0	
	87.5	25.0	
	91.0	30.0	
	91.5	32.0	
	92.5	34.0	
	93.5	36.0	
	94.5	38.0	
(−)	96.0	40.0	
	96.5	42.0	
	96.0	35.0	
	95.0	30.0	
	94.5	25.0	
	93.0	20.0	
	92.0	15.0	
	90.0	10.0	SEAM CLOSING CCW
	88.0	5.0	
	83.0	0.0	
	72.0	2.0	
	55.5	3.0	
	36.5	4.0	
	7.5	5.0	

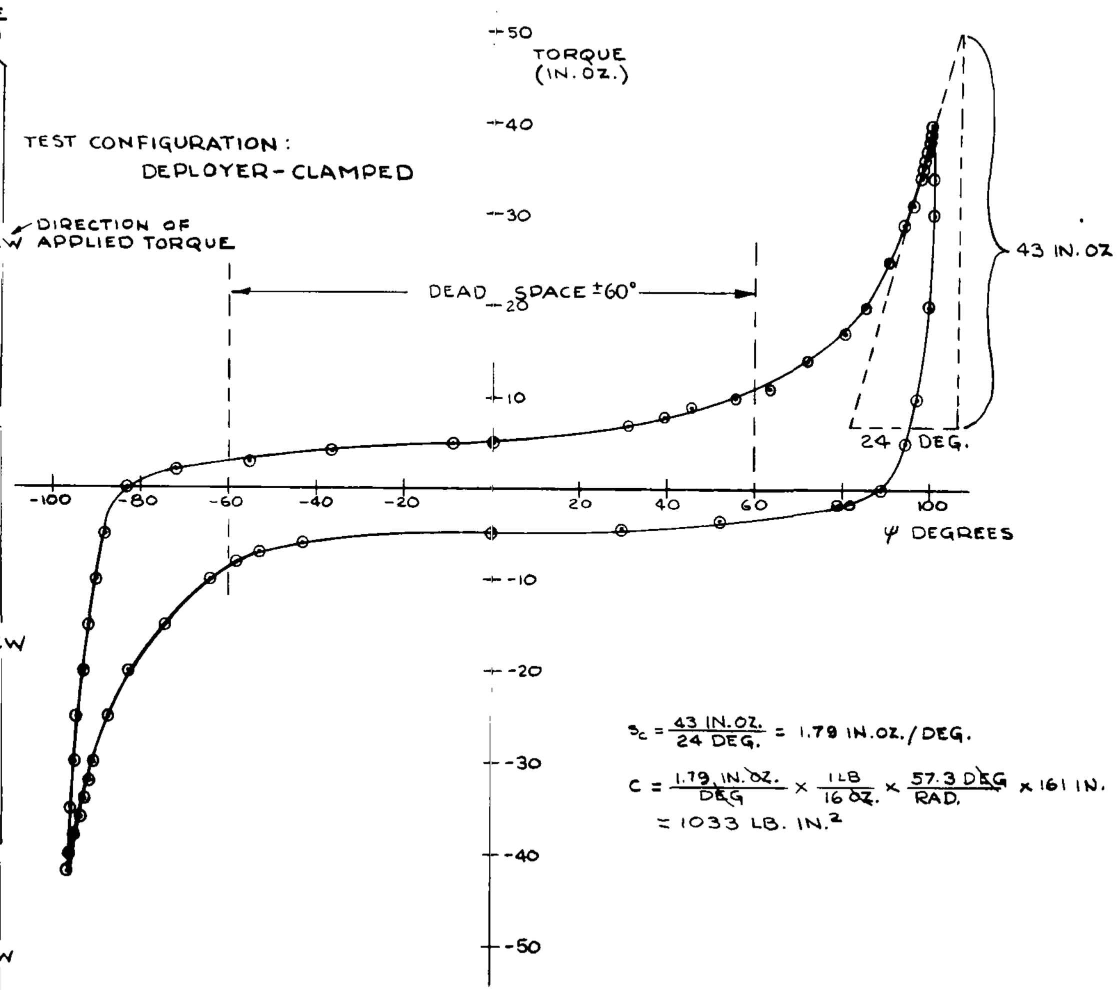


Figure 21–Measured torsional characteristics of a 1-in. by 161-in. tabbed Nimbus boom (tabs spaced 1.375 in. apart). The boom was constructed from 0.004-in.-thick unplated beryllium copper.

TEST DATA

	ANGULAR OFFSET ψ	TORQUE (IN. OZ.)	
+	0.0	5.0	SEAM CLOSING CW
	20.0	5.5	
	33.0	6.0	
	42.0	6.5	
	48.5	7.0	
	52.5	7.5	
	55.5	8.0	
	58.5	8.5	
	61.0	9.0	
	61.0	7.0	SEAM OPENING CCW
	61.0	5.0	
	61.0	3.0	
	60.5	0.0	
	60.0	2.0	
	55.5	4.0	
	45.0	5.0	
	26.0	5.5	
	14.0	6.0	
	5.0	6.5	
(−)	8.0	7.0	
	37.5	7.5	
	44.0	8.0	
	48.5	8.5	
	52.5	9.0	
	52.5	6.0	SEAM CLOSING CW
	52.5	2.0	
	52.0	0.0	
	51.5	2.0	
	50.0	3.0	
	46.0	4.0	
	21.5	5.0	
	3.0	5.0	

DIRECTION OF APPLIED TORQUE

TEST CONFIGURATION: DEPLOYER-CLAMPED

TEST DATA

DEGREES	ANGULAR OFFSET / 10 IN. OZ. (SHOWN BY DASHED LINES)
0	0.7 DEG.
+20	1.0 DEG.
+40	0.6 DEG.
−20	1.0 DEG.
−40	1.0 DEG.

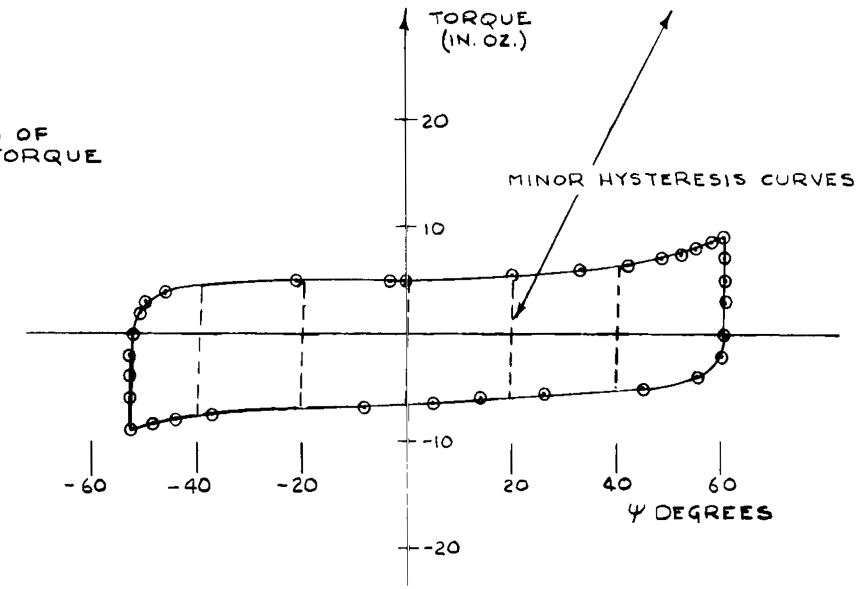


Figure 22–Minor-hysteresis curves of a 1-in. by 161-in. tabbed Nimbus boom (tabs spaced 1.375 in. apart). The boom was constructed from 0.004-in.-thick unplated beryllium copper.

Tabs	both sides and spaced 1 in. apart
Pretwist	approximately 270 deg

The torsional characteristics of this boom are shown in Figure 23. As seen from the end of the boom, facing the deployer, the positive direction is counterclockwise, in opposition to the pretwist direction; the negative direction is clockwise, in the same direction of the pretwist. Hand measurements show this boom to have a spring constant of 0.175 oz-in./deg and a torsional rigidity of 147.28 lb-in.^{2} in the positive direction.

Deflection in the negative direction produced a spring constant of 0.151 oz-in./deg and a torsional rigidity of 127.0 lb-in.^{2} These results may be compared with the instrumented torsional measurements of this boom discussed in the following section.

INSTRUMENTED HYSTERESIS-LOOP PLOTTING

System Design and Operation

A device has been developed by the author to instrument the plotting of angular deflection versus torque (Figure 24). An electromechanical system was designed to feed angular-deflection and torque signals to an *xy*-plotter that would produce resultant hysteresis curves for various boom sections under test. This system consists of the following basic units:

(1) A mechanical device to hold and twist the free ends of booms in torsion, including a mechanized centering feature that provides a means of exactly aligning the measuring device with the suspended boom section to be tested. A variable multiple-turn potentiometer is mounted on this device to indicate the degree of angular deflection of the boom in the form of an electrical output. A torque gauge indicating torsional twist in oz-in. provides a means of measuring the torsional twist in the form of an electrical output.

(2) A control unit (schematic diagram shown in Figure 25) that provides (a) limit controls for both angular and torque limits, (b) phone jacks to receive angular and torque signals from the multiple-turn potentiometer and the torque gauge, respectively, (c) indicating lights to show the extent of limit adjustment, (d) centering controls to operate the mechanized *xy*-axis movement, (e) a motor switch and speed controls to adjust the rate of rotation, (f) a cycle counter, (g) a provision for safety-limit switches, and (h) built-in power supplies.

The output of the potentiometer controlled by angular deflection has been trimmed to 1 mV/deg. Thus, a digital voltmeter placed in this circuit may be used to indicate degrees of rotation. The readout provided with the torque gauge will indicate torsion applied to the boom in oz-in.

A fitting that provides a means of securing one end of the torque gauge is clamped to the free end of the boom to be tested. The other end of the torque gauge is held by the rotating arm of the deflection device. The extent of angular rotation of the boom is controlled by limit settings of either the applied torque

ANGULAR OFFSET ψ DEGREES	TORQUE (IN.OZ.) +	TORQUE (IN.OZ.) (−)
0°	0.45	0.45
30°	0.50	0.60
50°	0.55	0.92
70°	0.71	1.22
100°	1.20	2.00
130°	2.40	2.60
150°	3.75	4.80
180°	7.80	8.70

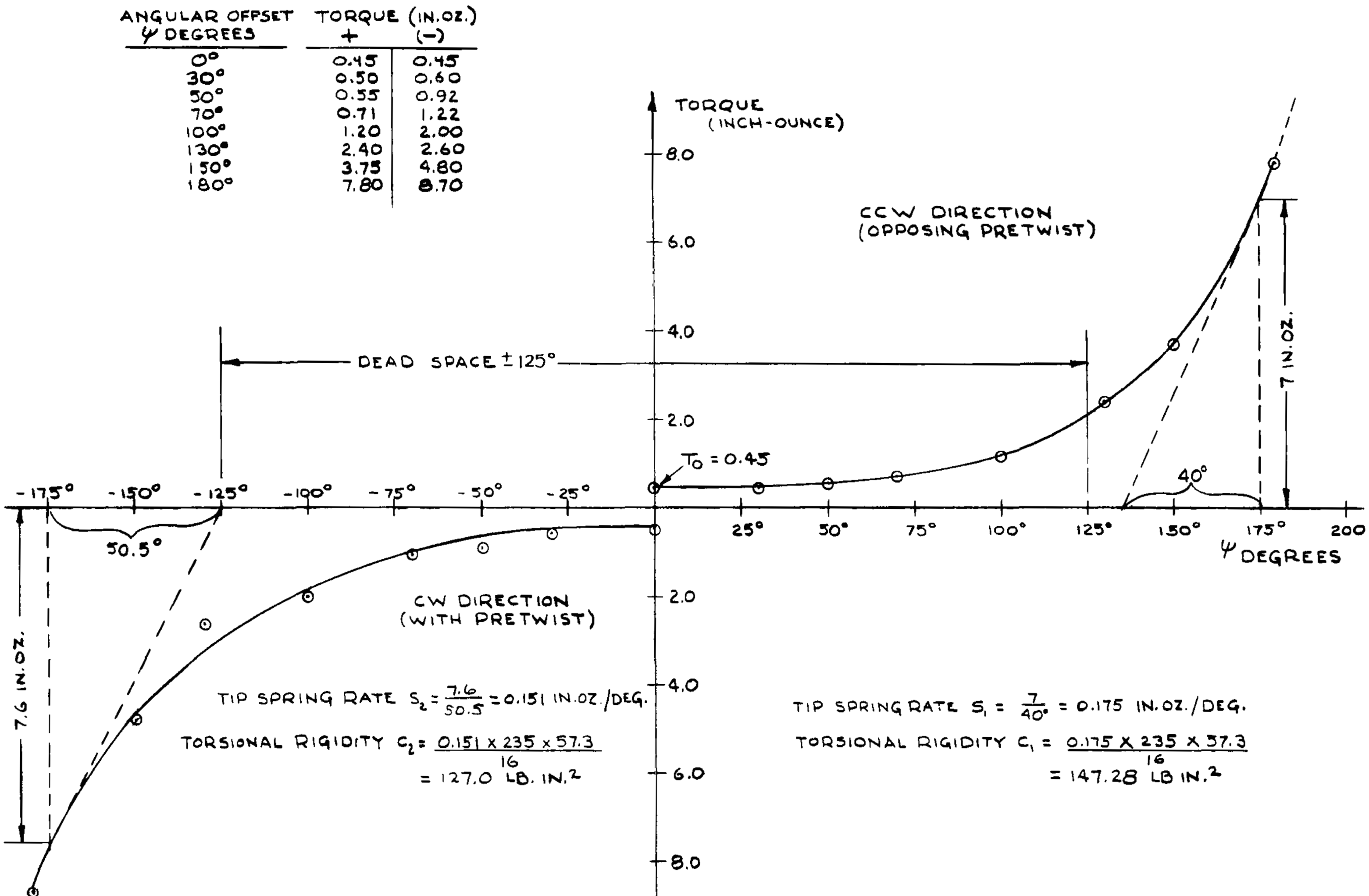


Figure 23–Measured torsional characteristics of a ½-in. by 235-in. interlocked tabbed bi-stem boom (1-in. spacing between tab centers) silver plated inside and out, with 270 deg pretwist.

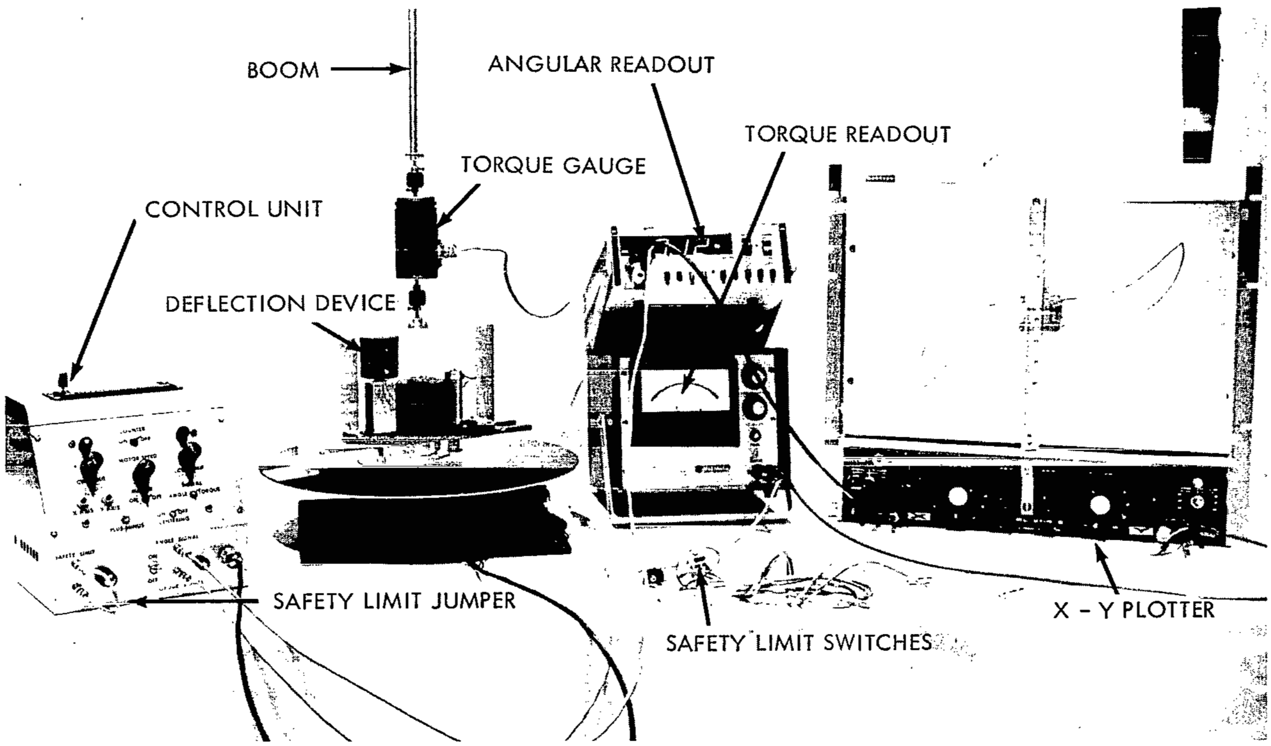


Figure 24—Torsion measuring device.

or angular deflection of the rotating arm. If a limit setting of 2 oz-in. clockwise and counterclockwise has been preset with the signal switch in the "torque" position, turning the device on will cause the boom to be twisted in one direction until a torque of 2 oz-in. has been attained. At this point, the motor controlling the rotating arm will reverse direction and will continue to twist the boom until it has reached 2 oz-in. in the opposite direction, at which point the motor will again reverse direction. Since both the torque gauge and the angular deflection device have electrical outputs, the information developed through each oscillation of the boom is fed to an xy=plotter that prints out the resultant hysteresis curve. The hysteresis curve may be plotted by controlling either the torque limits or the angular limits.

The device will continue to rotate the boom between limits until it is shut off. A counter has been added to record cycles of oscillation if fatigue tests are to be conducted.

Instrumented Hysteresis Plot of a ½-Inch Interlocked Bi-Stem Boom

A 231 in. length of ½-in. interlocked bi-stem boom was played out from a deployer secured to a ceiling beam. The tabs of this boom are spaced 1 in, from center to center, and the pretwist over this length is approximately 270 deg.

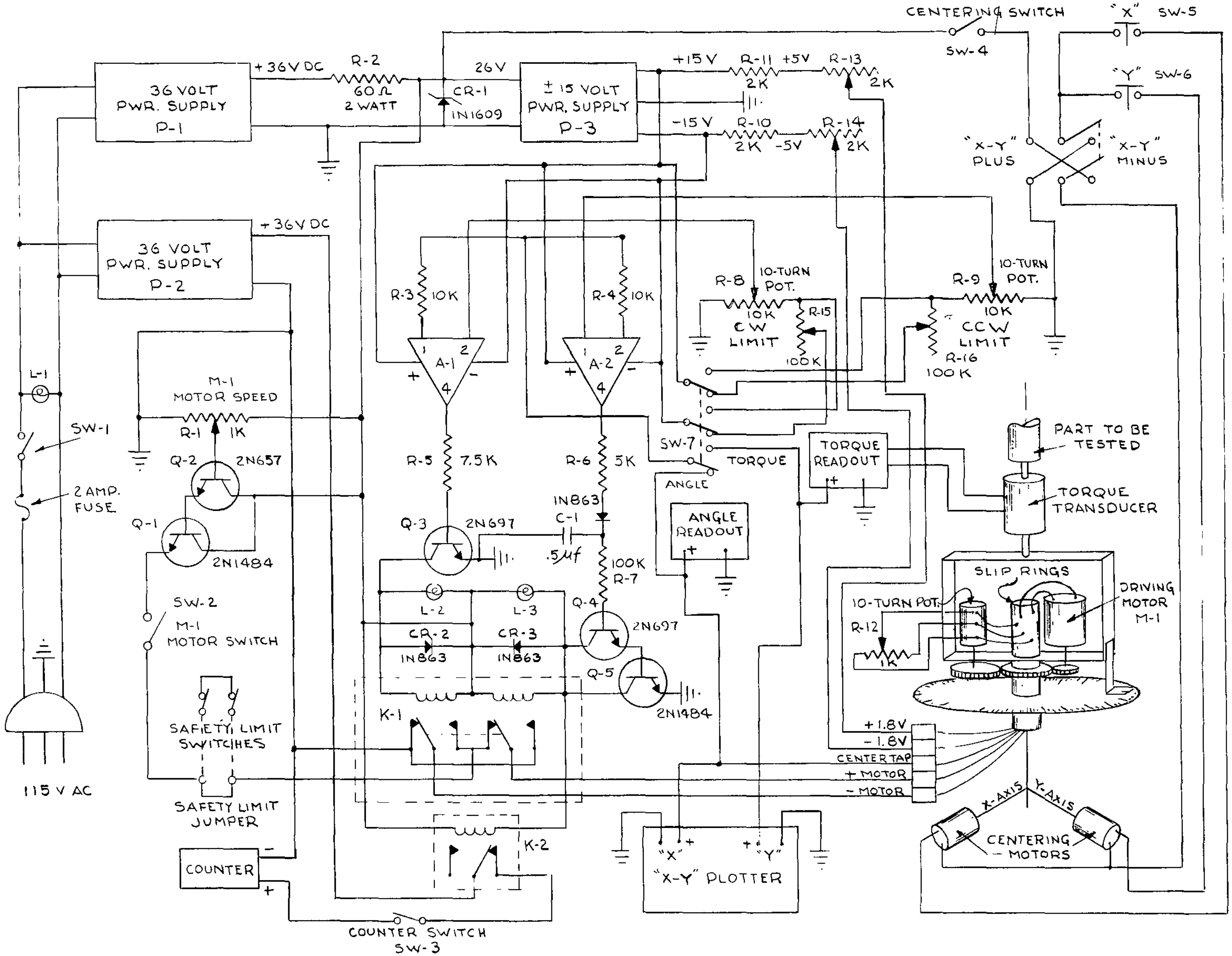


Figure 25–Schematic of torsion measuring device.

The angular-deflection device and torque gauge (Figure 24) were centered beneath the free end of the boom. The torque gauge was secured to the holding fixture which was clamped to the end of the boom. The center of the boom dead space was located, and the rotating arm of the deflection device was centered there. Torque limits of 2 oz-in. were preset both clockwise and counterclockwise.

The measuring device produced the curve shown in Figure 26 which indicates a breakaway torque of 0.4 oz-in. The 2-oz-in. torque limit was reached before the boom had sufficient angular deflection to determine the total dead space. Therefore, the torque limits were increased to 10 oz-in. The resultant curve is given in Figure 27 which shows a dead space from + 150 to − 40 deg, or a total of 190 deg. Comparison of the hand-measured torsional characteristics of the ½-in. interlocked bi-stem boom shown in Figure 23 with the instrumented measurements of a similar section of boom shown in Figure 27 indicates that the torsional characteristics of the two similar sections are remarkably consistent.

The torque gauge used when the breakaway-torque measurements were made had a full scale reading of 3.2 oz-in. Thus, the torque settings of ± 2 oz-in. would take advantage of the full electrical output, resulting in a rather smooth plot. However, the gauge used for the plot shown in Figure 27 had a full-scale reading of 100 oz-in.; hence, the torque settings of ± 10 oz-in. (a small portion of the full electrical output) made it necessary to set the torque axis control of the xy-plotter to a level of high sensitivity to give adequate deflection in this direction. In this highly sensitive range of the plotter, the bearing noise of the torque gauge is reflected in the plot as a sinusoidal frequency of low amplitude.

If preset torque limits require an output voltage close to the maximum of the gauge, then the xy-plotter will have sufficient deflection along the torque axis without requiring the plotter to be set to a sensitivity range such that bearing noise is produced on the plot.

CONCLUSIONS

The most important features of this report may be summarized as follows:

(1) The torsional rigidity of booms can be considerably increased by the addition of tabs or interlocking teeth. Increasing the number of tabs per foot of boom length tends to increase the effective torsional rigidity.

(2) As expected, it was found that the torsional rigidity is independent of the length (similar to a normal torsion spring). The dead space varies directly with the length, and the breakaway torque is independent of the length of the boom.

(3) Measurements made by the methods outlined in this report agree with previous theoretical predictions.

(4) Instrumentation of the torsional measurements produced approximately the same results as hand-held torque-gauge measurements. However, the instrumented hysteresis plots present more detailed information.

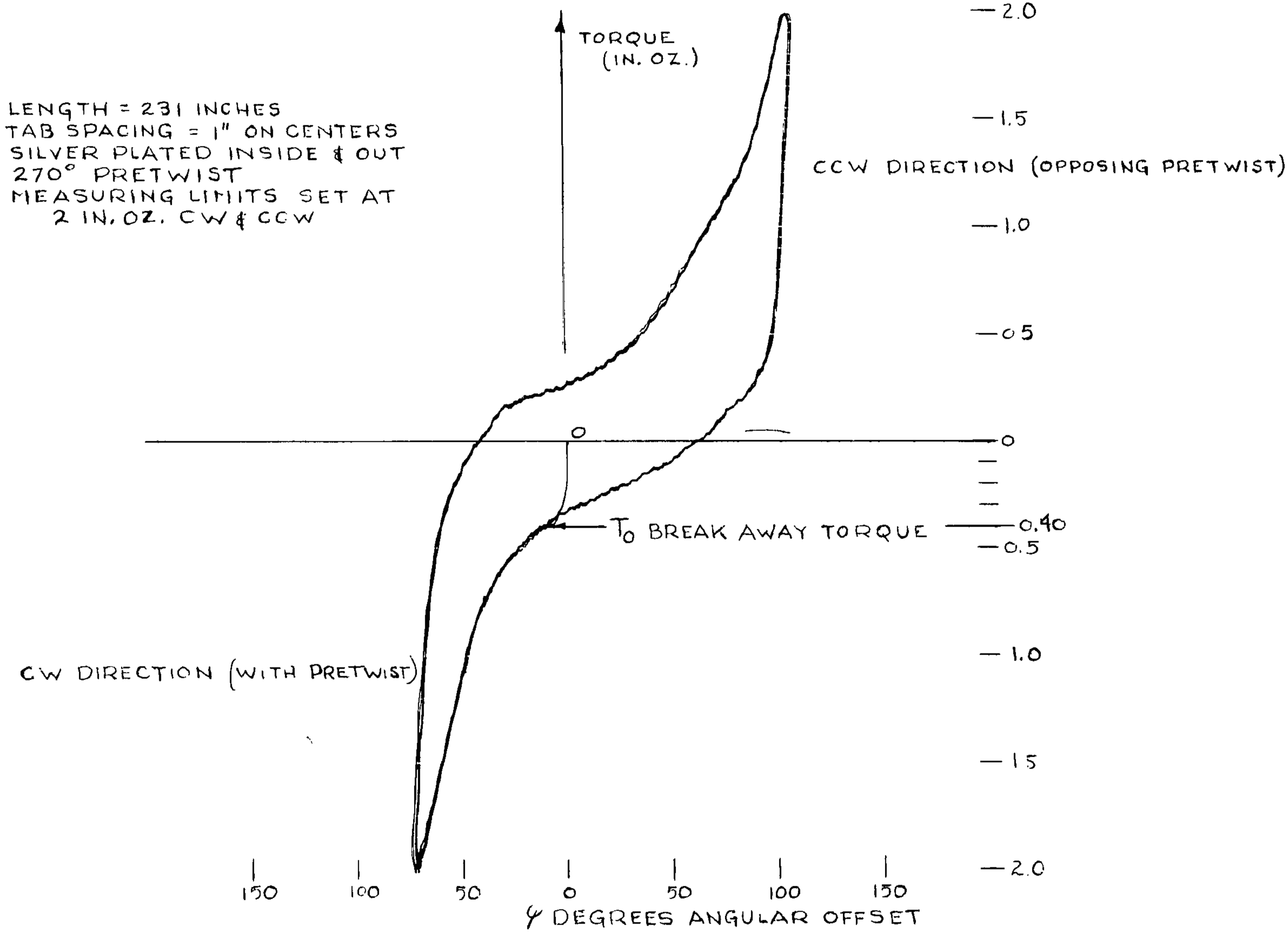


Figure 26—Instrumented breakaway-torque measurement of ½-in. interlocked bi-stem boom.

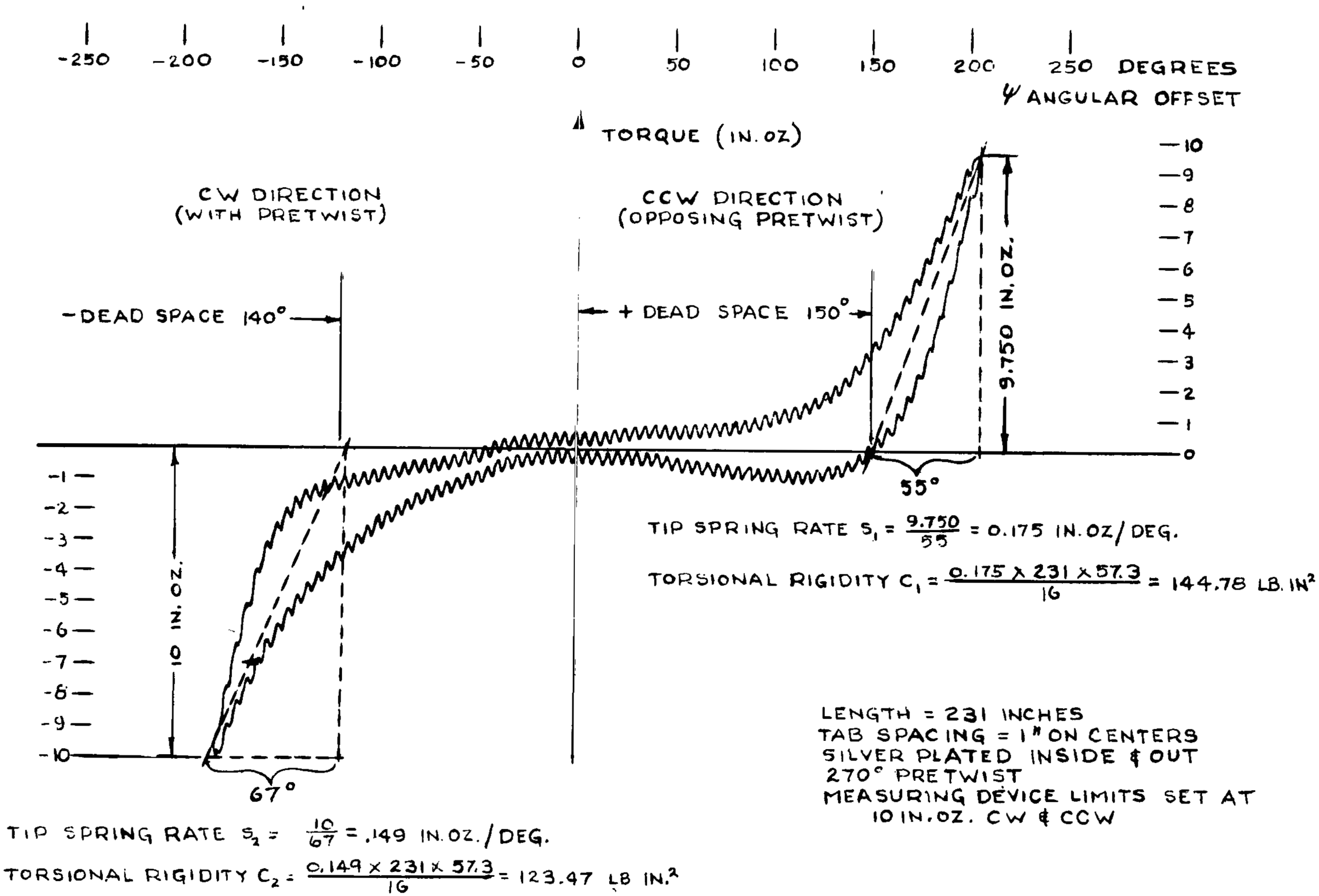


Figure 27–Instrumented measurement of torsional characteristics of ½-in. interlocked bi-stem boom.

(5) Gravitational forces represent a major factor when dynamic torsional measurements are made in a gravitational field. However, static measurements used in determinations of various boom spring constants are not affected by gravitational forces.

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National Aeronautics and Space Administration
Greenbelt, Maryland, November 24, 1970
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REFERENCES

1. Frisch, Harold P., "Thermal Bending Plus Twist of a Thin-Walled Cylinder of Open Section with Application to Gravity Gradient Booms", NASA Technical Note D-4069, National Aeronautics and Space Administration, Washington, D.C., August 1967.

2. Donohue, James H., and Frisch, Harold P., "Thermoelastic Instability of Open Section Booms", NASA Technical Note D-5310, National Aeronautics and Space Administration, Washington, D.C., December 1969.

3. Frisch, Harold P., "Coupled Thermally-Induced Transverse Plus Torsional Vibrations of a Thin-Walled Cylinder at Open Section", NASA Technical Report R-333, National Aeronautics and Space Administration, Washington, D.C., March 1970.

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