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CAROUSEL DEPLOYMENT MECHANISM FOR COILABLE LATTICE TRUSS

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ABSTRACT

AEC-Able Engineering Company, Inc. (ABLE) has developed a unique mechanism for instrumentation and solar-array deployment by combining two technologies. The first technology (initiated by the Jet Propulsion Laboratory and later developed by Lockheed Missiles and Space Company [1]) is the "smart" motor which can operate in either an analog mode to provide high speed and torque, or in a stepper mode to provide accurate positioning. The second technology is a mechanism developed by ABLE, where a coilable lattice mast is deployed then rotated about its axis with a common drive system, thus eliminating the need for a second drive system. A prototype unit has been designed, built, and tested. A review of the design and function of this system is presented along with structural and thermal test data.

BACKGROUND

In the early 1960s, a triangular lattice truss made of unidirectional fiberglass rods was developed which was capable of retracting and extending. Retraction is accomplished by the coiling of the continuous longitudinal element, which then acts like a spring to deploy the mast. This type of mast has been used extensively for space application because it is lightweight, strong, and stiff, and stows to a small fraction of its (deployed) length (Fig. 1).

Lanyard Deployment

A key to using this structure is the deployment mechanism which controls the extension and retraction. The simplest and lightest way to control deployment is by running a cable or "lanyard" down the middle of the mast. This lanyard is attached to the top plate at one end and to a motor or rate limiter at the other (Fig. 2A). In this way, the lanyard is paid out gradually so that the mast deploys at a controlled rate. The mast is very strong and stiff when fully deployed, but it does have some disadvantages. This is because during deployment the mast has a relatively weak and flexible transition section which may be undesirable. Also, during deployment and retraction, the top of the mast rotates with respect to the base about the mast centerline. This rotation is unacceptable for some applications.

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Elevating Nut Deployment

A second deployment method was developed where the mast is enclosed in a large, thin-walled tube or canister, and deployment is controlled by a large rotating nut at the top (Fig. 2B). The most important change to the mast is the addition of roller lugs which enable the mast to be constrained at a deployed section rather than at the flexible root. This greatly increases strength and stiffness during deployment. The motorized elevating nut continuously transports the rollers up or down to deploy or retract the mast. The mast is prevented from rotating as it deploys by guide rails inside the nut, and the stowed mast is allowed to rotate at the base.

The elevating nut method has several advantages. The mast has nearly full stiffness and strength throughout deployment, and the tip deploys without rotating. There are, however, some disadvantages to this system. The elevating nut is a relatively heavy, complex component supported by large bearings. Weight reduction can be accomplished only by more complex and costly machining or by using more exotic materials. The elevating nut also increases the envelope of the system and, at full deployment, the mast is subject to free-play due to the clearances required at the roller-lug-to-elevating-nut interface.

Carousel Deployment

The subject of this paper is an alternate method called "carousel," which has some of the advantages of the other methods and offers unique features of its own. The carousel method is similar to the elevating nut method, except that the nut has been removed and the motor drives a turntable at the base. During deployment, the mast tip does not rotate, and the mast has significant strength and stiffness. The system weighs less than the elevating nut-method but more than the lanyard method, and the packaging volume is slightly more than that of the lanyard method.

Unique to this system is the fact that once the mast is fully deployed, it changes smoothly from axial deployment to rotational movement (Fig. 3). The outstanding advantage of the carousel system is that when combined with the smart motor technology, the same drive mechanism used for deployment may also be used for tracking. The turntable/drive system is common to both functions, thus eliminating the need for a second drive system.

THE MOTOR

The Carousel Deployment System takes advantage of "smart" motor technology [1]. The basic elements of this technology are a brushless dc motor and a control circuit which operates the motor in either an analog or stepper mode. To deploy the mast, the motor operates in the analog mode to provide the speed and power required to deploy the mast and, if needed, to extend a solar array. Once the mast is fully deployed, the motor operates either in the analog mode to rapidly slew the mast into position or, more importantly, in the stepper mode to accurately rotate the mast at a constant rate.

A "dual-drive" gear box is used to complete the drive system. The dual-drive was developed by JPL as a reliable, redundant drive system for aerospace applications. This system uses harmonic drives to provide independent load paths from two motors to a common output. (This technology was presented at the 16th Aerospace Mechanisms Symposium in 1982.)

CAROUSEL DEPLOYMENT SYSTEM DESCRIPTION

The carousel deployment system consists of a thin aluminum cylindrical shell which contains three principle functional areas: turntable, storage section, and transition section.

Turntable

The turntable at the base of the system is a rotating platform which is driven by the motor. The platform is supported by large-diameter duplexed bearings which are preloaded against each other to eliminate any free-play or dead band over the required temperature range (Fig. 4). The bearings are supported by thin-walled shells to accommodate thermally-induced distortion without greatly increasing bearing preload. The radial flexibility designed into the system allows thermal deflection without sacrificing overall system stiffness. The bearing supports are designed with radial interference at room temperature and are assembled by heating one bearing seat while cooling the other, then slipping the bearing in place. The base of the mast is mounted to the turntable platform, which is open in the center to provide space for a slip ring assembly if needed. A large-diameter internal gear is used so that room is available to add encoders or potentiometers, depending on the application's telemetry requirements.

Storage Section

Above the drive area is the storage section which contains the stowed mast when the system is retracted. There is enough clearance between the mast and the storage shell to allow mast rotation, but not enough to allow excessive excursions during vibration or launch.

Transition Section

Immediately above the storage section is the transition section, where the mast smoothly changes from the stowed to the deployed state. This operation is the key to carousel system success. Transition guides are curved rails which control the transition shape of the mast and thus control the deployment of the system. Rollers are attached to the mast at each batten frame and protrude into the rails to constrain and guide the mast during deployment.

The mast shrinks in diameter as it goes through the transition section. For the elevating nut method, this problem is solved by contouring the rails to match the mast (Fig. 5). For the carousel system, however, this is not feasible due to interference between the guides and the mast when the system is in the tracking mode. A slightly larger-diameter canister and longer rollers are used and the transition rails are of a constant thickness, so that there is clearance for the mast to rotate once the mast is fully deployed and no rollers are engaged.

Mast axial strength is increased by using guide rails on both sides of the roller lugs. The mast diameter is smaller when it goes through transition so that the transition section is of asymmetrical hour-glass shape. The roller lugs must be long enough to accommodate the change in mast radius and still adequately engage in the transition guide.

FUNCTIONAL DESCRIPTION

When power is applied to the motor the turntable rotates, uncoiling the mast by driving it up through the guide rails. Deployment continues until the mast is almost fully deployed and only the last roller lug is left in the guide rail (Fig. 6). The last amount of deployment extends the last roller lug out of the guide so that it is only constrained by a gate. By continued rotation of the turntable the last roller leaves the gate, and the mast begins to rotate on the turntable about its centerline. The gate must close for the mast to continue rotating. In this rotation mode, the motor is switched to the stepper mode to provide accurate rotational movement.

BASELINE DESIGN

To verify the carousel deployment concept, ABLE designed and built a full-size demonstration unit which incorporated an existing mast design with the following properties:

Mast Diameter	0.254 m	10 in.
Mast Length	5.5 m	18 ft
Longeron Diameter	3.8 mm	0.150 in.
Batten Diameter	2.3 mm	0.090 in.
Diagonal Diameter	0.8 mm	0.032 in.

The mast was constructed of unidirectional S2 glass/epoxy fiberglass elements, aluminum fittings (6061-T6), epoxy adhesive (EA 934), and stainless steel fasteners.

One of the design goals was to provide room for a payload within the volume defined by the transition guides. A mechanism at the top of the mast enables it to pass smoothly through the transition guides and to fully retract by allowing the top attachment points to move radially inward as well as to pivot.

STRUCTURAL TESTING

Various tests were run to characterize the system. The test program was divided into performance and deployer torque determination. Bending tests were performed to determine strength and low-load stiffness characteristics. Low-load stiffness was targeted because it normally defines a system's natural frequency. The general procedure used was to apply a lateral tip-shear load to the horizontally-mounted mast. Lateral tip deflections were then recorded for loading and unloading. The test loads, deflections, and set-up geometry were used to deduce equivalent system stiffnesses. The mast's shear and root deflections were included in this equivalent stiffness.

Bending strength and equivalent stiffness are given as:

$$M_{CR} = V_{MAX} L$$

$$EI = \Delta V / \Delta\delta \; L^3/3$$

where

M_{CR} = maximum bending strength (in.-lb)

V_{MAX} = maximum applied lateral tip shear (lb)

L = boom deployed length (in.)

EI = bending stiffness (in.-lb^2)

ΔV = change in lateral tip shear loading (lb)

$\Delta\delta$ = change in lateral tip deflection (in.) .

Various mast system configurations were tested and characterized. The test parameter variations were deployed length, mast axial compressive load, mast root condition, and transition guide extensions. A total of 108 system configurations were examined.

For most partially-deployed configurations of the carousel mast, the maximum bending moment the system can withstand is dictated by the loads at the roller-lug-to-transition-guide interface. Typically, the lateral tip load can be increased to the point where the local side load at the roller lug overcomes the internal preload provided by the mast. The lug then escapes from the transition guide. The mast's maximum moment strength could be increased over the tested design by incorporating a captured roller lug design.

Table 1A gives maximum bending strengths for various configurations. The values shown are averaged from various tests to highlight trends. Transition guide extensions improved maximum bending strength during the deployment phase by a factor of 3.8. However, with transition-guide extensions installed, bending strength during deployment is about 1/4 of fully-deployed bending strength. Maximum bending strength was not greatly influenced by the mast's end condition. Axial mast compression had only a slight effect on bending strength. As axial compressive load was increased, bending strength slightly decreased (by about 1 percent per pound of axial load). These data are presented in Figure 7.

Bending stiffness data are presented in Table 1B for various test trends. The average values indicate that there is negligible variation due to axial compressive load variation. Transition guide extensions improve bending stiffness performance during deployment by a factor of about three. But even this improved stiffness was only 3 percent of the fully-deployed value. This marked difference, shown graphically in Figure 7, is due to the difference in the mast longeron-end conditions. When the mast is fully deployed, the longerons terminate directly into the turntable with zero curvature. Loads are reacted axially, which is an inherently stiff load path. In the partially-deployed mast condition, the longerons have curvature which causes some of the load reaction to be in bending, a less stiff load path.

Torsional tests were performed to determine the carousel deployer's characteristics under torsional loading. The mast system was again mounted horizontally at both half and full deployment. The mast tip was supported with a pinned-end-bearing mechanism. In this way, end-shear deformation was minimized while allowing full torsional deflection. A torque was applied and angular deflections were measured and recorded at multiple load points.

Table 2 summarizes torsional performance as a function of both axial compressive load and transition-guide-extension configuration. An unexpected trend can be observed in Figure 8. For test set-ups where transition guide extensions were installed, increasing axial mast load increased torsional stiffness. Conversely, for cases without transition guide extensions, increasing axial load decreased torsional stiffness. Another expected trend that was observed was greater stiffness under counterclockwise loading than clockwise loading for the partially-deployed test configurations. This effect is due to longeron curvature in the mast transition zone. A clockwise torque twists the mast in the same direction as the transition shape. A counter-clockwise torque loads against this shape. This effect is accentuated by the addition of axial compressive loading.

To characterize the carousel drive actuator and control system design, mast axial load and ambient temperature were varied. An additional test was run which focused on drive torque variation during the terminal phase of deployment, when the deploying mast shape changes from its standard helix to a straight, stiff configuration.

The tests where mast axial compressive load was varied were done at room temperature with the system mounted horizontally. The mast tip was supported by a bridle mounted to an overhead track. In this way variations in mast bending load were kept to a minimum. A weight pan, cable, and load cell arrangement maintained a constant axial compression load as the mast deployed. Axial loads were varied between 0 and 26.7 N (0 and 6 lb).

Figure 9 presents the test results in a graphic format. Results are nearly linear for all three test conditions. As indicated in Figure 9, with no compressive load the system requires a 0.35 N-m (3.1 in.-lb) torque to restrain the system against its inherent self-deploying force. However, with a 71.2 N (16 lb) axial preload, the system requires 0.51 N-m (4.5 in-lb) of torque to drive the system out.

The system was placed in a thermal chamber and mounted to deploy vertically upward, causing a gravity load which varied with the length of boom deployed. This load proved manageable. Since it would not affect the qualitative results, a variable counterweight system was not installed.

The system was tested at room temperature [approximately 21°C (70°F)] at -51°C (-60°F), and at 68°C (140°F). System motor-drive torque was indicated by an in-line torque transducer. Tests were conducted after the mechanism reached the prescribed test temperature and had soaked for a minimum of one hour.

In order to isolate the drive torque characteristics from those due to the mast's self-deploy force, the carousel was run at test temperatures and voltages with the mast fully extended. In this way the mast rotated as a rigid body, and its strain energy did not affect the indicated torque values. Any variations observed were due only to turntable-torque-requirement changes.

Table 3 gives a summary of the results. Figure 10 presents the data graphically. Torque required to deploy the system varied from a 0.41 N-m (3.65 in.-lb) driving torque at -51°C (-60°F) to a 0.22 N-m (1.95 in.-lb) restraining torque at 140°F. At low temperatures the mast's self-deploy force is not enough to overcome the internal bearing drag. At high temperature the bearing drag drops to near zero and the self-deploy force dominates the system requiring a restraining torque. Retraction must be motor driven as both bearing drag and mast self-deploy force inhibit retraction at all temperatures. The variation in retraction torque is from 1.21 N-m (10.75 in.-lb) at -51°C (-60°F) to 0.69 N-m (6.10 in.-lb) at 140°F. The variation is almost entirely due to changes in bearing drag, as the self-deploy force is almost independent of temperature. Since observed torque variations were small, the bearing-support-skirt design performed satisfactorily. The radial compliance built into the system satisfactorily isolated the bearings from the thermal loads in the stiff mounting rings over a wide temperature range. It is estimated that the torque variations are in the range associated with changes in bearing lubrication viscosity.

CONCLUSION

The test program has shown that the carousel deployer concept is a viable technique with sufficient maturity to consider for flight development and certification. The components exhibited mechanical stability and minimal torque variations during deployment under various thermal and mechanical loading conditions. The tests showed that, as in nut-deployment technique, the transition guide shape and size are the critical factors contributing to smooth deployment. Their successful design is a critical undertaking for proper operation.

The thermally-compliant, dual-bearing support concept proved to be successful over a wide temperature range. No binding or low-load deadband was observed at either hot or cold temperatures. This design concept is generic enough to apply to various thermal/mechanical conditions.

The existence of moderate bending and torsional structural stiffness and strength during deployment was verified by the test program. The carousel-deployed mast may be used to deploy, pretension, and track payloads such as solar arrays or antennae. Structural performance is improved during deployment by the use of transition guide extensions.

It is recommended that if additional structural stiffness and strength are required during deployment, future carousel development programs implement the transition-guide extension design option and captivated rollers. To maintain the smallest package volume, the transition guide extensions can be designed to articulate into position or to be part of a payload support structure. This test program has provided a database from which system designers can make application-specific structural design choices.

REFERENCE

1. 18th Aerospace Mechanisms Symposium, NASA Conference Publication 2311.

TABLE 1A. BENDING STRENGTH TEST RESULTS

			Transition Guide Extension			
Deployed	Load		Installed		Removed	
Position	(N)	(lb)	(N)	(in.-lb)	(N)	(in.-lb)
Last Roller Disengaged						
1/4	0	0	24.9	220.3	6.2	54.9
	22.2	5	25.7	227.3	9.1	80.4
	44.5	10	27.4	242.8	--	--
1/2		0	22.8	201.9	6.6	58.7
	22.2	5	20.3	180.1	7.2	63.8
	44.5	10	19.6	173.6	--	--
1/1	0	0	74.1	655.7	68.0	602.2
	22.2	5	74.1	656.3	63.5	562.1
	44.5	10	66.6	589.2	62.0	548.5
Last Roller Engaged						
1/4	0	0	27.8	245.8	5.7	50.3
	22.2	5	26.5	234.6	5.9	51.9
	44.5	10	25.0	220.9	--	--
1/2		0	29.5	260.9	7.9	70.3
	22.2	5	26.2	232.1	7.4	65.8
	44.5	10	25.7	227.5	6.5	57.7
1/1	0	0	--	--	--	--
	22.2	5	--	--	--	--
	44.5	10	--	--	--	--

TABLE 1B. BENDING STIFFNESS TEST RESULTS

	Load		Transition Guide Extension			
			Installed		Removed	
Position	(N)	(lb)	(N-m^2)	(lb-in.^{2})	(N-m^2)	(lb-in.^{2})
Last Roller Disengaged						
1/4 Depl.	0	0	165.9	5.78×10^4	69.4	2.42×10^4
	22.2	5	148.4	5.17×10^4	29.8	1.07×10^4
	44.5	10	147.2	5.13×10^4	--	--
1/2 Depl.	0	0	522.3	1.82×10^5	147.2	5.13×10^4
	22.2	5	487.9	1.70×10^5	--	--
	44.5	10	476.4	1.66×10^5	--	--
1/1 Depl.	0	0	1.52×10^4	5.29×10^6	1.43×10^4	4.98×10^6
	22.2	5	1.27×10^4	4.41×10^6	1.43×10^4	4.97×10^6
	44.5	10	1.32×10^4	4.60×10^6	1.37×10^4	4.79×10^6
Last Roller Engaged						
1/4 Depl.	0	0	324.3	1.13×10^5	76.9	2.68×10^4
	22.2	5	324.3	1.13×10^5	68.3	2.38×10^4
	44.5	10	238.2	8.30×10^4	--	--
1/2 Depl.	0	0	485.0	1.69×10^5	205.2	7.15×10^4
	22.2	5	450.6	1.57×10^5	212.7	7.41×10^4
	44.5	10	516.6	1.80×10^5	--	--
1/1 Depl.	0	0	1.43×10^4	4.98×10^6	--	--
	22.2	5	1.43×10^4	4.97×10^6	--	--
	44.5	10	1.37×10^4	4.79×10^6	--	--

TABLE 2. TORSIONAL TEST RESULTS: STIFFNESS, GJ

			Loading Direction			
	Load		Clockwise		Counter-Clockwise	
Test Set-Up	(N)	(lb)	(N-m^2)	(lb-in.^{2})	(N-m^2)	(lb-in.^{2})
During Deployment						
Transition Guides Installed						
	0	0	215.8	$7.52x10^4$	301.3	$1.05x10^5$
	22.2	5	255.1	$8.89x10^4$	367.3	$1.28x10^5$
	44.5	10	244.8	$8.53x10^4$	344.6	$1.20x10^5$
Transition Guides Removed						
	0	0	37.6	$1.31x10^4$	29.3	$1.02x10^4$
	22.2	5	17.2	$5.99x10^3$	23.8	$8.31x10^3$
	44.5	10	12.7	$4.44x10^3$	22.1	$7.70x10^3$
Fully Deployed						
Transition Guides Installed						
	0	0	272.9	$9.51x10^4$	321.4	$1.12x10^5$
	22.2	5	283.8	$9.89x10^4$	364.5	$1.27x10^5$
	44.5	10	262.9	$9.16x10^4$	373.1	$1.30x10^5$
Transition Guides Removed						
	0	0	244.5	$8.52x10^5$	228.7	$7.97x10^4$
	22.2	5	221.8	$7.73x10^5$	228.7	$7.97x10^4$
	44.5	10	210.1	$7.32x10^5$	242.5	$8.45x10^4$

TABLE 3. TORQUE VERSUS TEMPERATURE RESULTS

		Turntable (N-m)		System (N-m)	
Temp. (°C)	Volts	Mean	Band	Mean	Band
Deployment					
-51	28	-0.47	0.08	-0.41	0.28
21	28	-0.11	0.06	0.19	0.25
60	28	-0.07	0.05	0.22	0.21
Retraction					
-51	28	0.41	0.09	1.21	0.45
21	28	0.13	0.06	0.78	0.26
60	28	0.10	0.06	0.69	0.25

		Turntable (in.-lb)		System (in.-lb)	
Temp. (°F)	Volts	Mean	Band	Mean	Band
Deployment					
-60	28	-4.18	0.75	-3.65	2.5
70	28	-.99	0.54	+1.70	2.2
140	28	-.65	0.44	1.95	1.9
Retraction					
-60	28	3.60	0.80	10.75	4.0
70	28	1.16	0.56	6.90	2.3
140	28	0.89	0.50	6.10	2.2

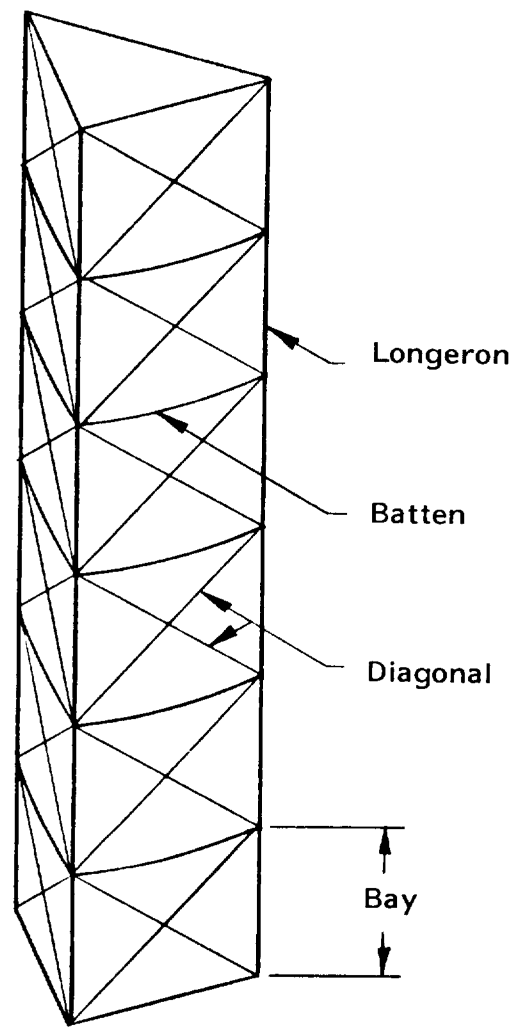

Figure 1. Triangular lattice structure.

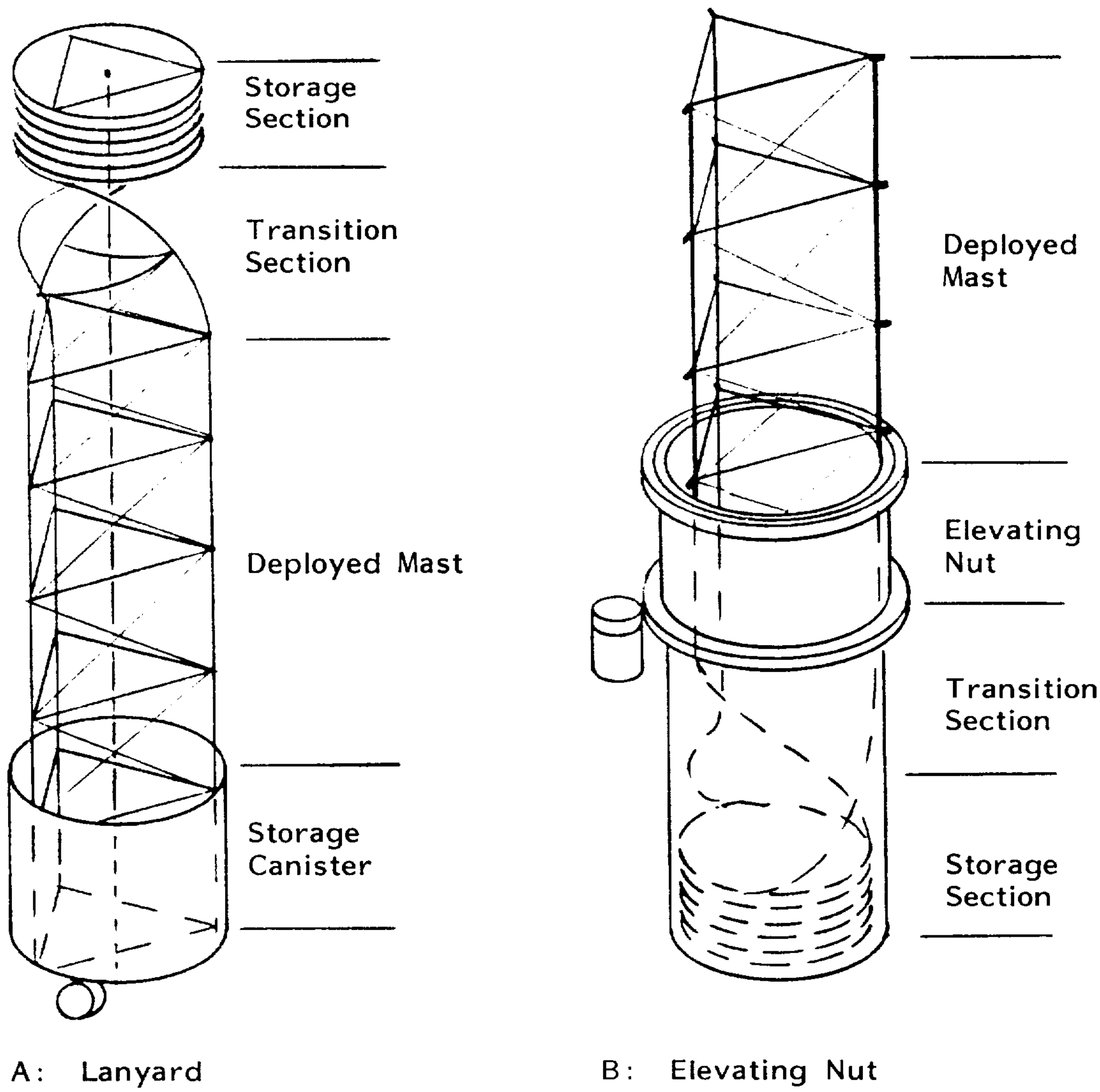

Figure 2. Lanyard and elevating nut deployment schematics.

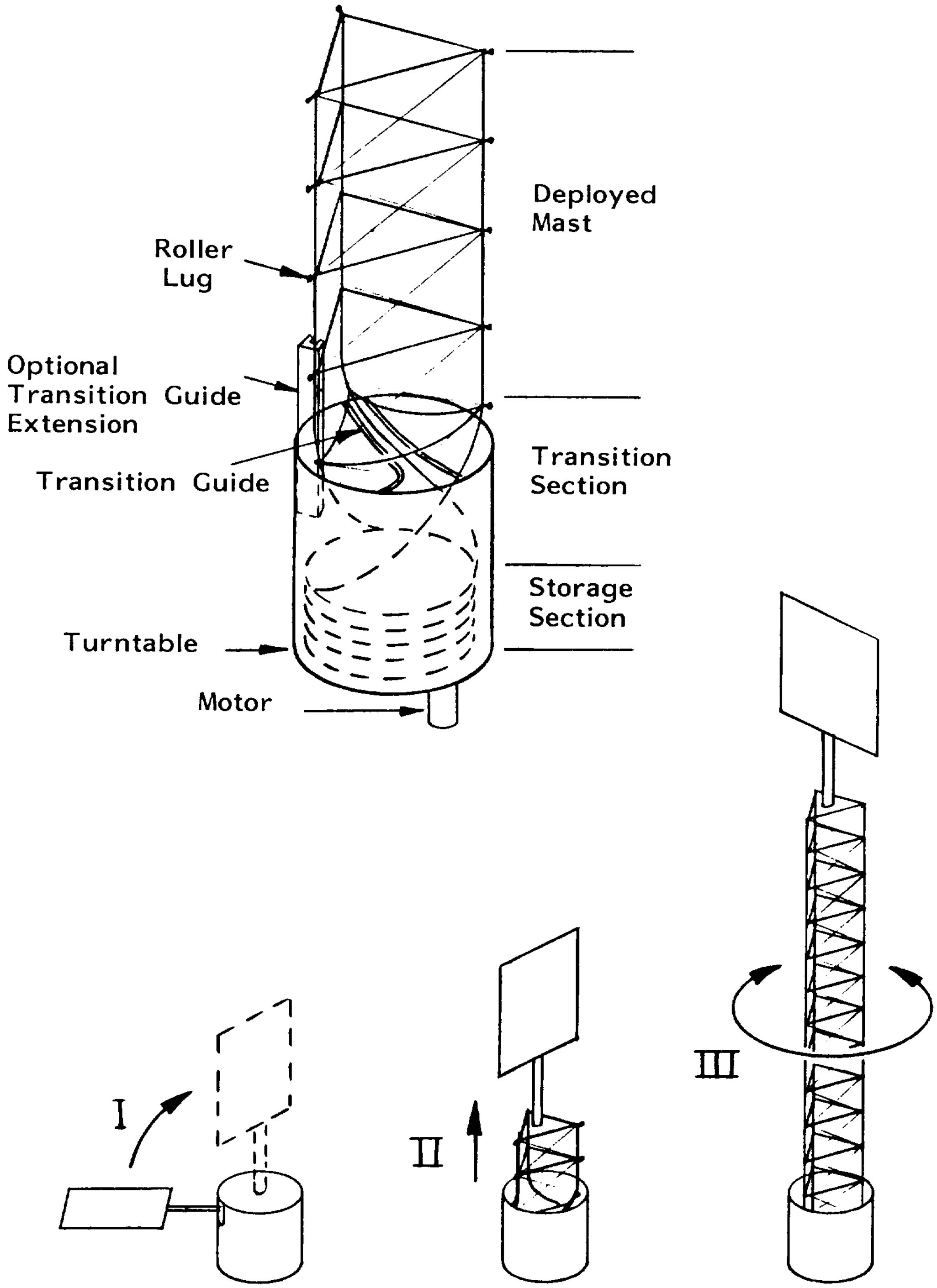

Figure 3. Carousel deployment schematic.

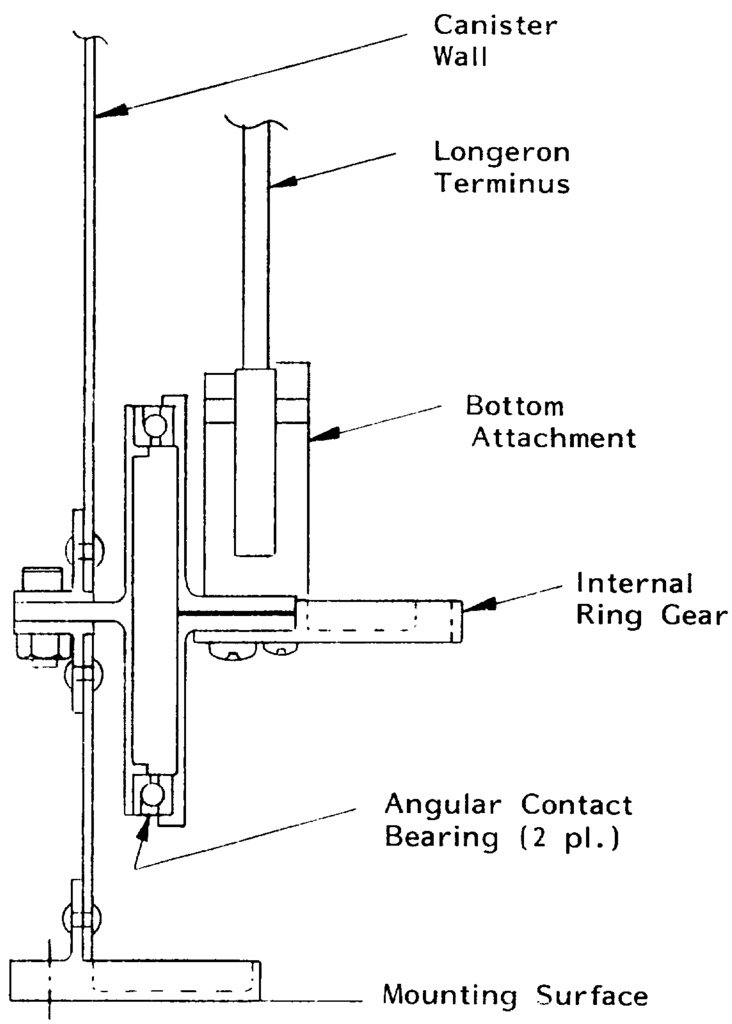

Figure 4. Turntable bearing detail.

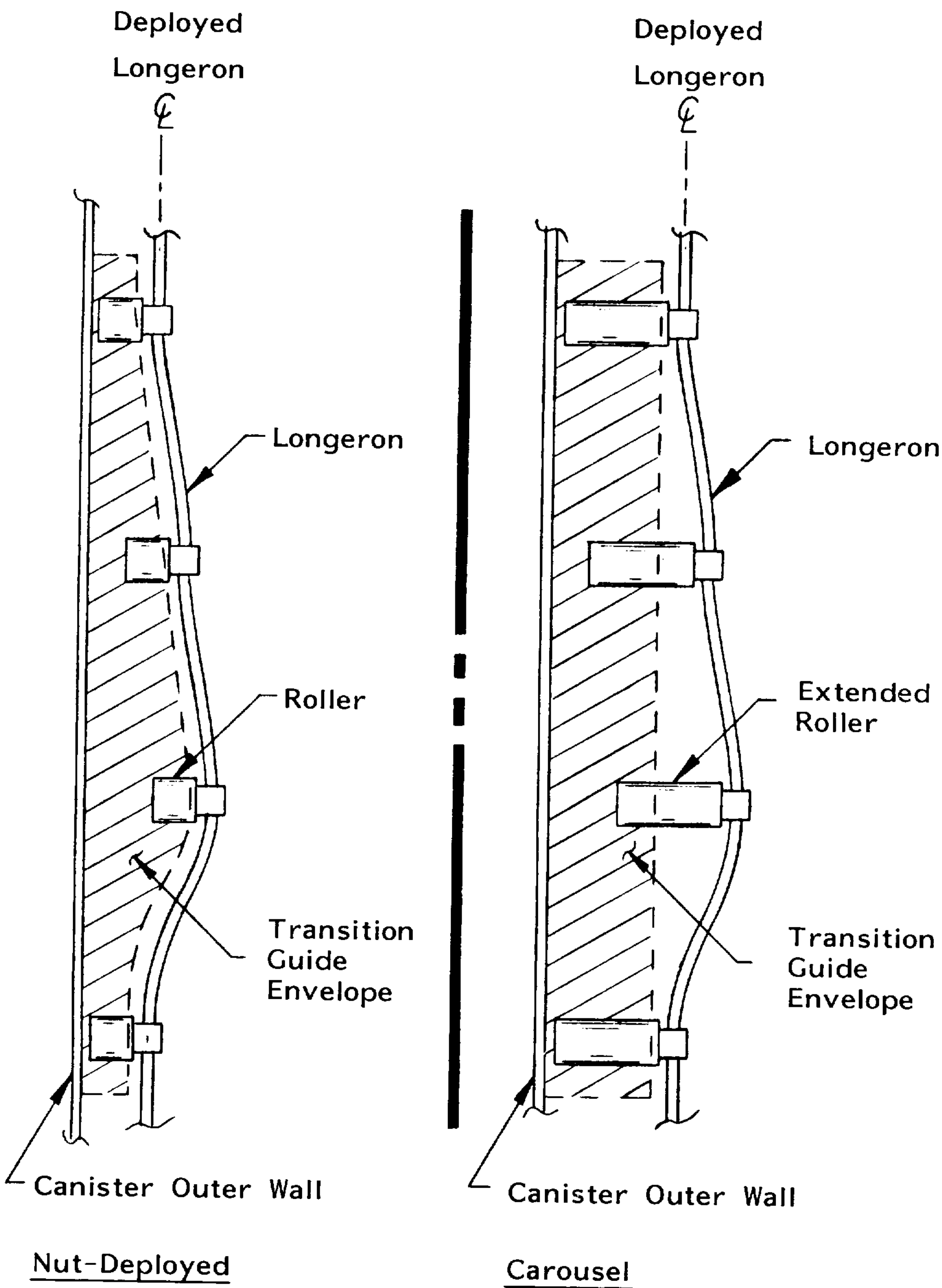

Figure 5. Transition section guides.

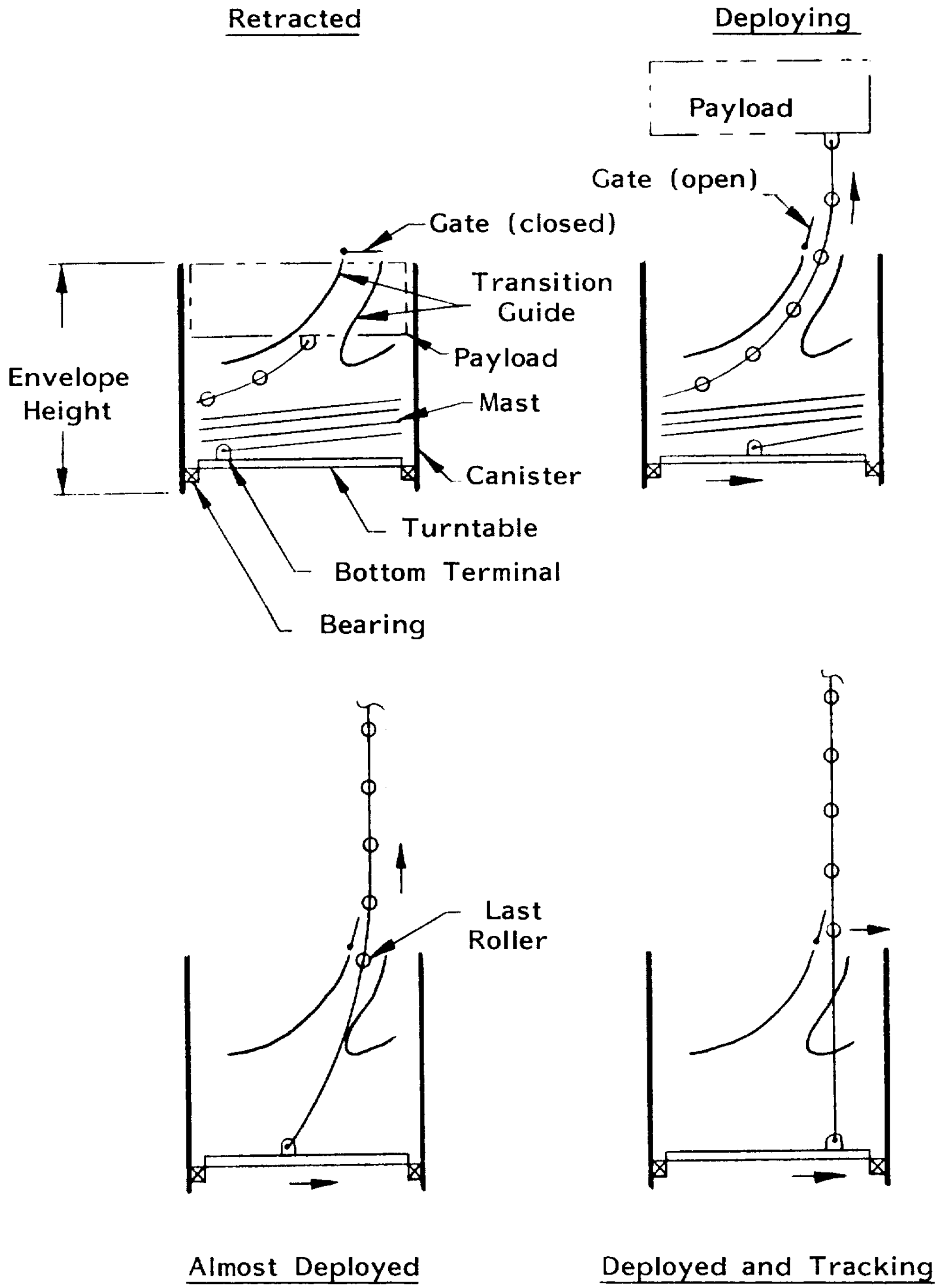

Figure 6. Functional sequence.

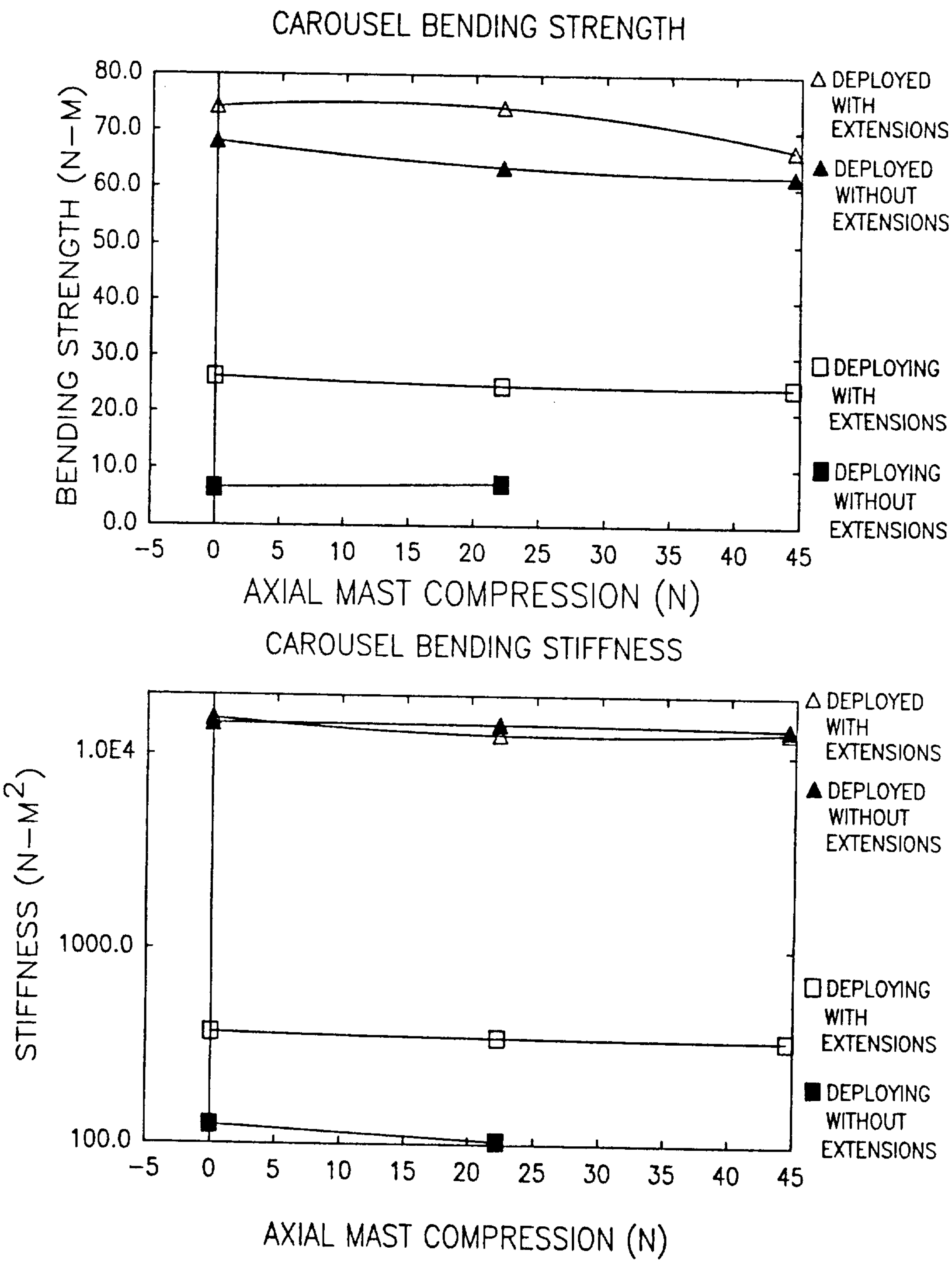

Figure 7. Bending test results.

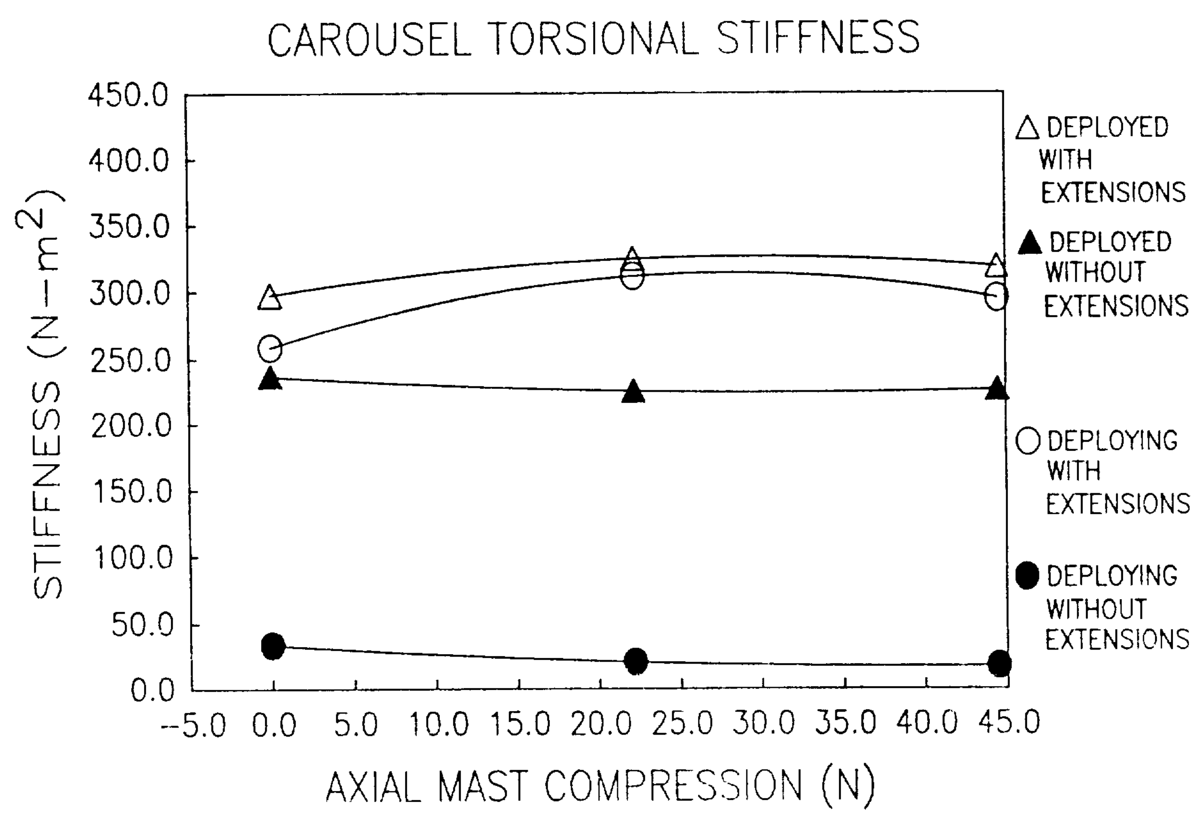

Figure 8. Torsional test results.

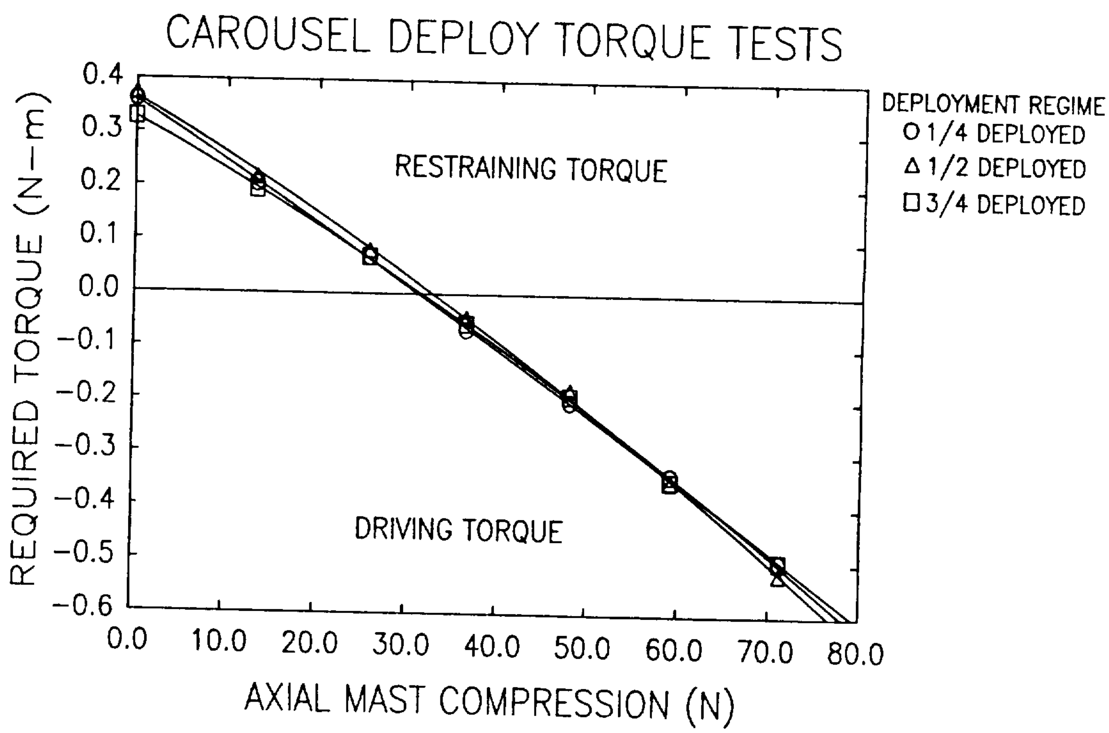

Figure 9. Deployment torque-versus-axial-compression test results.

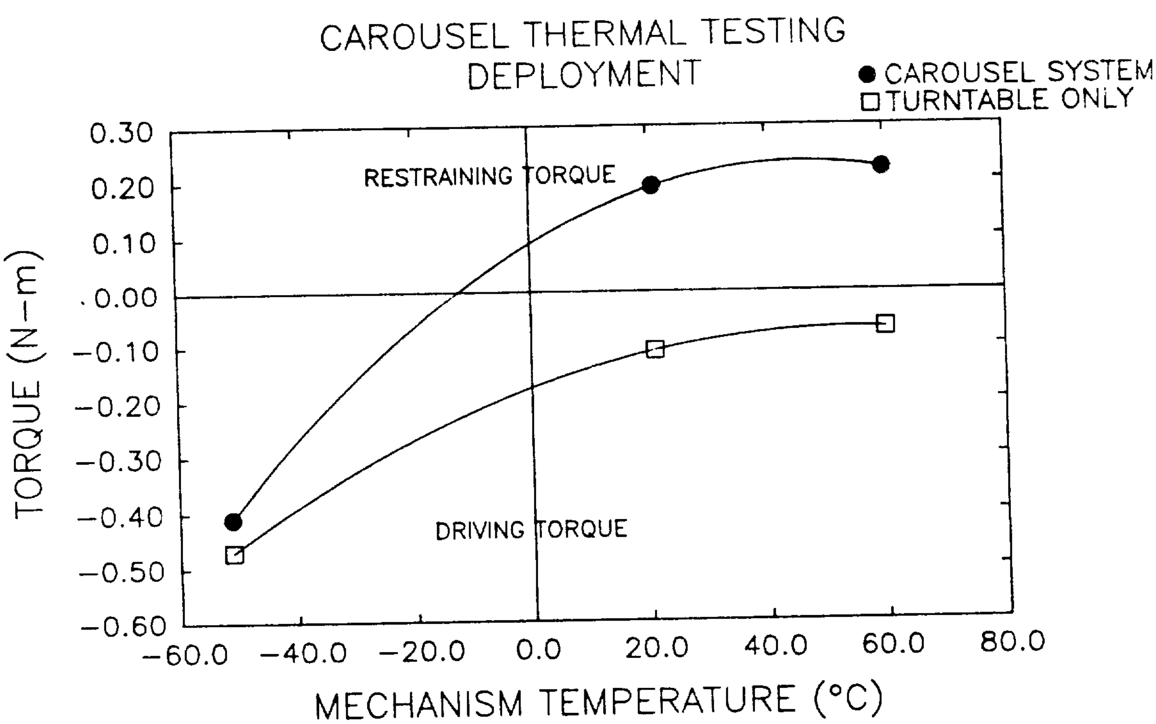

Figure 10. Carousel deployment torque versus temperature.

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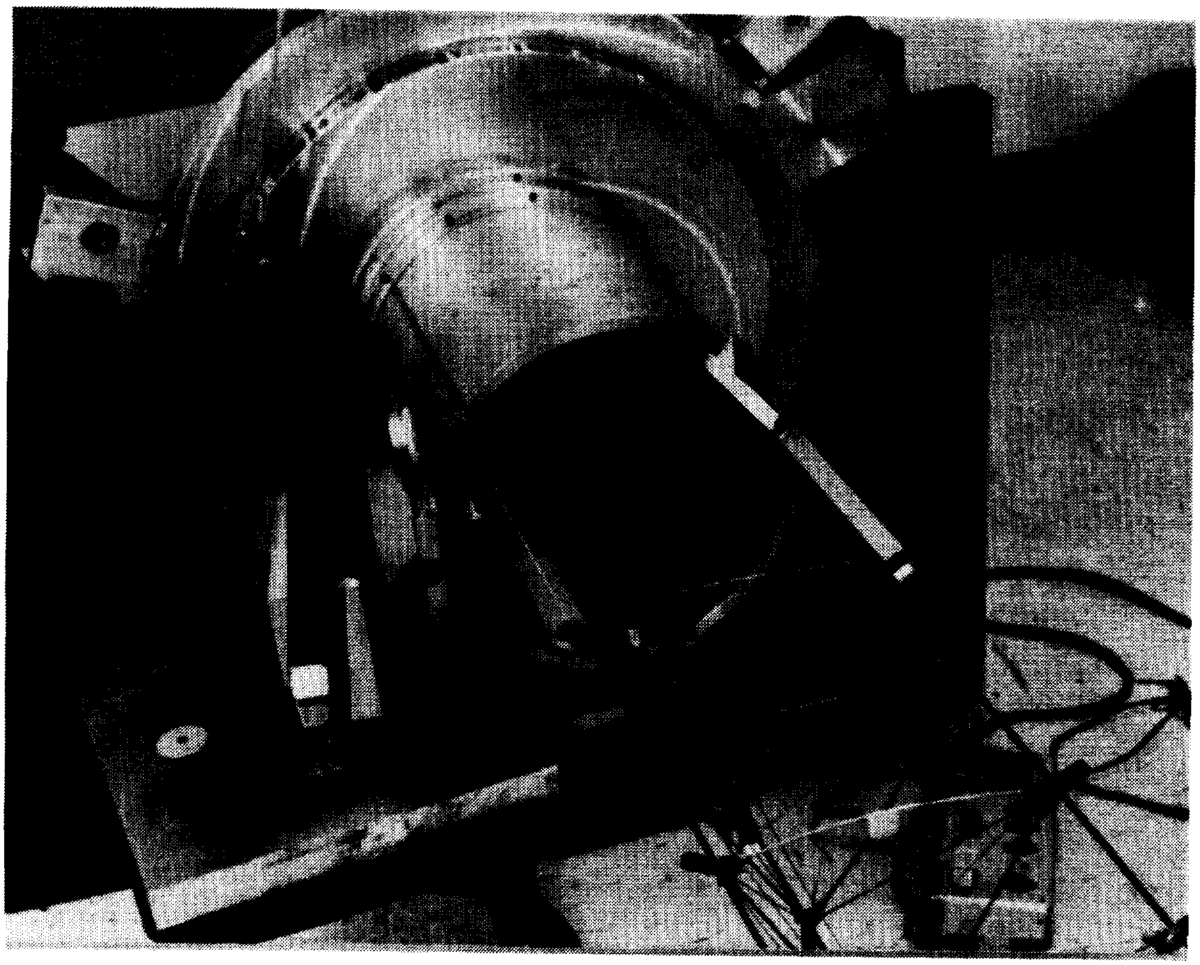

Figure 11. Structural test photo.

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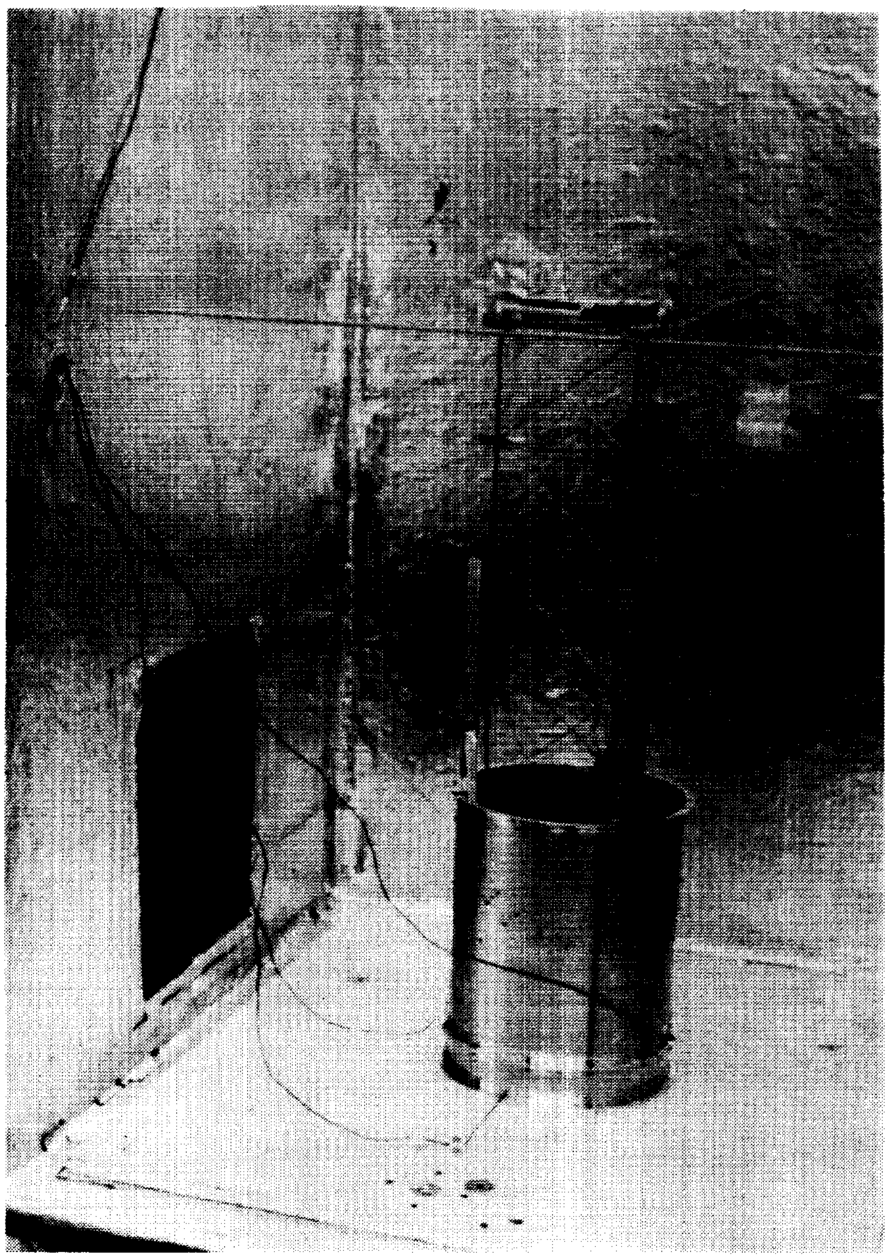

Figure 12. Thermal test photo.