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MOTION SYNCHRONIZATION OF A MECHANISM
TO DEPLOY AND RESTOW A TRUSS BEAM

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ABSTRACT

The functions of the Control of Flexible Structures I (COFS I) deployer and retractor assembly (DRA) are primarily to deploy and retract the Mast 1 beam, and secondarily to latch, unlatch, and restow the DRA mechanism. The objective of this paper is to present the problems associated with the diagonal folding mechanism that retracts the beam, discuss the synchronization requirements critical to the process of restowing the beam, and to present a proposed solution to the problem of synchronization between the mechanical systems. In addition, this paper presents a detailed description of the design and functioning of the DRA.

INTRODUCTION

Future space missions are anticipated to require large truss platforms and beams for a number of structural applications. Under a Control/Structures Interaction (CSI) effort, there is being developed a validated technology data base which includes the areas of controls and structures interaction, deployment dynamics, and system performance for large flexible spacecraft.

The NASA initiated COFS Program, a major element of the CSI effort (figure 1), provides focus for the research and technology base activities in structural dynamics and controls. These activities address technology needs through the development and validation of analytical tools, extensive ground testing of representative structures, and performance of in-space experiments for verification of analysis and ground test methods.

Under COFS, the COFS I Project, involving the space structures and controls research community, consists of a series of planned ground and flight activities that progressively build from large space systems modeling and dynamic characterization to evaluating the more complex issues of flexible-body control.

As a subset of COFS I, the Mast Flight System (MFS), figure 2, incorporating a reusable, generic deployable-restowable truss beam as a test bed, was conceived to bridge the gap between ground and on-orbit verification, and validation of structure and control methodologies. This single test article was planned for use

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in the ground test and two flight tests. The objectives of the two flight tests were to evaluate system identification open-loop dynamics and distributed flexible-body closed-loop controls, respectively.

The sections that follow describe the Mast subsystems involved with the various motion synchronization issues and their possible improvement.

DESCRIPTION

Several subsystems comprised the MFS which was being developed by the prime contractor, the Harris Corporation (figure 3). These were designated as the Integrated Mast Subsystem (IMS), Mast Support Subsystem (MSS), Modular Distributed Instrumentation Subsystem (MDIS), Excitation and Damping Subsystem (EDS), and Power Distribution Subsystem. The IMS was composed of four functional components: the beam, parameter modification device (PMD), motor controller (MC), and deployer and retractor assembly (DRA). The beam, PMD and DRA were to be provided under subcontract by Astro Aerospace Corporation. The MFS's DRA, containing a large deployable and restowable "next-generation" truss beam, was to be attached in a cantilever fashion to the carrier. The carrier was the Spacelab Enhanced Multiplexer Demultiplexer/Space Technology Experiments Program pallet (EMDM/STEP). The carrier would, in turn, be attached within the Space Transportation System (STS) Orbiter payload bay. A detailed discussion of the IMS beam and DRA follows.

Beam

The Astro Aerospace Corporation's Articulating Astromast beam, also referred to as the Z-beam, is shown in figure 4. The beam was a statically determinate, 60.7m long, non-redundant, truss structure that incorporated single degree-of-freedom (d.o.f.) hinges for deployment and retraction. Longitudinal members (longerons) provided bending stiffness and were hinged only at their ends. Alternating diagonal members (diagonals) provided torsional and shear stiffness and were hinged at their ends and near their centers. Transverse members (battens) were positioned at regular intervals along the beam to assure longeron stability. The "B" frame battens were hinged at their ends and near their centers while the "A" frame battens were rigidly attached to the beam nodal (corner) bodies. All beam elements were composed of graphite/epoxy tubes bonded to titanium end fittings. The beam design consisted of a triangular cross section with the longerons located at the vertices of an equilateral triangle. The truss structure repeated itself in two-bay segments. There were 27 repeatable two-bay (bay-pair) segments for a total of 54 bays. Pertinent beam specifications are listed in Table I. This design was specifically chosen for low member loads induced during the deploy and restow process.

The single d.o.f. hinges were designed for low compliance and minimum free play. These hinges also provided control over the kinematics of the structure during deployment and retraction. For this truss configuration, single d.o.f. joints produced strains, derived from moments (figure 5), during deployment and restow, and this effect was quantified and accounted for in terms of induced loads and sizing of members. When compared to other possible configurations, the unique design and folding geometry of the Z-beam minimized the induced strains and eliminated the need for swivel joints. The spatial motions of a typical pair of diagonal hinges, a "B" batten hinge and a "B" corner body are shown on figure 6. Astro's kinematic modeling efforts involved in-house developed code while Langley's verification efforts have utilized ADAMS* code.

The beam was deployed two bays at a time by rotating the longerons of a bay-pair approximately 90° to their upright position. Simultaneously, the diagonals unfolded and were locked in place by mid-span spring-loaded hinges. No net beam rotation was experienced during deployment and restow due to the alternating directions of the diagonals in a bay-pair.

During the process of deployment and restow, the design of the Z-beam necessitated that the "B" batten frame experience large deformations. Mid-span hinges were incorporated in the "B" batten members to permit these large deformations with relatively low strain being induced in the truss members (the diagonals being strained more than the other beam members). The geometry of the truss beam allowed its members to be strain free in the deployed and stowed configurations.

The beam stowed efficiently with symmetric (alternating clockwise and counter-clockwise) folding of the longerons about the longitudinal axis. The diagonals and "B" batten frame members were folded at mid-span to allow packaging. The basic packaging of the beam reduced the length to 3.51 percent of the deployed length.

Actuators, instrumentation, and avionics necessary for excitation, measurement, and control of the low-frequency modes of this structure were an integral part of the flight system. The truss beam also contained a PMD at the tip which provided the capability of changing the tip inertia during on-orbit testing. This allowed alteration of the frequency spacing and cross axis coupling between modes.

The effective stiffness, coefficient of thermal expansion (CTE) and buckling loads for the truss member assemblies are listed in Table II.

Deployer and Retractor Assembly (DRA)

The DRA was a mechanical device to deploy and retract the beam during orbital operations. The design consisted of a structural container for the beam, an upper drive assembly containing the mechanisms necessary for deployment and restow, a diagonal fold-arm retractor mechanism, telescoping support tubes attached to a base plate, and latch cluster assemblies (not shown) (figure 7). The deploy and restow mechanism (lead-screw drive system) and diagonal fold-arm mechanism (bell-crank linkage system) were housed in the DRA upper drive assembly (figure 8). The stiff, reinforced tubular structural framework (figure 9) was to be covered by a honeycomb shell.

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The DRA had to execute four different operations (DRA extension, beam deployment, beam retraction, and DRA restow). There were basically five different mechanisms incorporated in the DRA to perform these operations and the mechanisms incorporated a total of eleven pairs of D.C. motors. Both motor windings of any pair of motors were powered by independent driving sources so that a single failure in the MC (or MDIS computer) would not prevent retraction and restow of the beam.

The DRA deployment and retraction mechanism consisted of a deployer drive motor and gear box, a continuous loop gear and shaft power transmission system, three lead-screw drive assemblies and lead-screws, and a stowed beam stack lifting assembly (not shown). The lead-screws were driven by an assemblage of gearing and six shafts (figure 8)--the latter identified as a recirculating gear arrangement. At each alternate bevel gear cluster, a power take-off drove the lead-screw. This recirculating arrangement of gears and shafts was selected to minimize backlash and permit redundancy in the power transmission path from the deployer drive motor to the lead-screws.

The three synchronized lead-screws engaged partial nut fittings at the beam "A" batten cluster hinge assemblies (corner bodies). Constant rotation of the lead-screws caused bay-pairs to be sequentially deployed and deployment and retraction were continuous. Each deployed bay-pair achieved full structural integrity before exiting the DRA. The deployment process could be stopped at any two-bay increment and the beam locked in place to provide a direct load path through the MSS to the carrier. To minimize the overall height of the experimental MFS package, the DRA itself was stowed and extended using the same lead-screw mechanism.

Deployment of the Mast

Illustrated in figure 10 is the general sequence for deployment of the beam. All DRA functions would be checked prior to committing the DRA or beam to deployment. During deployment, all beam electronics would be active thereby enabling ground personnel to monitor beam acceleration. The sequence was as follows:

> The first operation in the deployment was the release of the DRA from its preloaded, stowed configuration by functioning the stowage latch. This swivel latch (figure 11), which holds down the upper drive and tip assemblies, would translate while rotating 90° (using a cam action). This released the preload and provided clearance between the upper drive and beam tip canister assemblies during deployment. Functioning the stowage latch only released the upper drive assembly as the tip canister assembly was still being held down by the tube latch.
>
> The deployer drive motor was operated to start turning the lead-screws in a direction that would elevate the upper drive assembly while simultaneously extracting the lead-screws from the stacks of stowed beam partial nut fittings. This operation extended the DRA's telescoping tubes (figure 10). At maximum extension, the deployer drive motor would stop and the tube latches (figure 12) would lock-up the telescoping tubes. Functioning of the

tube latch would also unlock the beam tip canister assembly retention latch, thereby freeing the stowed beam tip canister assembly.

To raise the tip canister assembly and initiate beam deployment, the deployer motor was reversed and began lifting the beam's first set of "A" corner bodies. When the tip canister assembly reached a position near the top of the DRA's upper drive assembly, the longerons of the first deployed bay-pair were vertical. Contined deployer motor operation caused the extended longerons to pull the next set of "A" corner bodies past detents (figure 13) and onto the bottom of the lead-screws. As will be described later, the spring loaded diagonal hinges acted as energy stowage devices which assisted beam deployment, therefore some space was provided between the detent and stowed beam to allow for this final bay-pair deployment action. Each detent was designed to release the "A" corner body at about 100N of force. The DRA then, in a continuous manner, extended the first deployed bay-pair out of the DRA while the next bay-pair was being deployed within the DRA. Bay-pairs were deployed until the required number of extended bays was reached.

During deployment and retraction, a device called an off-loader (stack lifter) (figure 14) would move the stack of stowed bays toward or away from the deployment and restow mechanism, respectively. The stack lifter, being mechanically slaved to the lead-screw, would prevent partial bay deployment within the stowage canister.

When the required even number of bays had been deployed, the beam latch (figure 15) would be engaged. This latch would transfer any loads from the beam directly into the DRA base structural tube and hence to the Orbiter through the MSS structure and the carrier.

Retraction of the Mast

For retraction, the process was essentially reversed from that for deployment except the diagonal folding mechanism was activated to unlatch and initiate the opening of the diagonal hinges.

Retraction of the Mast began with unlocking the beam latch and operating the lead-screws in the opposite direction from that of deployment. While this operation was under way, the separate diagonal folding mechanism (figure 8) activated the upper and lower diagonal fold-arms to initiate unlatching and opening of the diagonal mid-span hinges and also began simultaneously folding the six diagonals. A compressive load was introduced into the "B" batten member which, in turn, caused the batten to fold at its mid-span hinge.

The fold-arms initiated the diagonal hinge folding action by releasing a secondary mechanical hinge latch and then they began pressing inwards on the hinges. This hinge is a separate mechanism and will not be described in this paper. The fold-arms were most effective only during the initial stages of restow of a given bay-pair, then they were recycled to their retracted position. In figure 8, the diagonal folding mechanism drive motor activated the diagonal fold drive gear which in turn functioned a continuous loop of bell-cranks and coupler links. At every other bell-crank, linkages led to the upper and lower diagonal fold-arms (a typical set of fold-arms is shown for clarity). These fold-arms pressed on the diagonal hinges during the initial stages of each bay-pair's retraction process.

At the final stage of restow, the tip canister assembly would be retracted. The tube latches would unlock the tubes and simultaneously lock the stowed tip canister assembly. The direction of lead-screw rotation would then be reversed to return the DRA to the stowage position. This final motion would also pull the upper drive assembly down toward the stowed tip canister. Stowage latch actuation subsequently would lock the upper drive and tip canister assemblies.

Table III presents a listing of the status monitoring instrumentation signals that were to be passed to the MDIS computer and which were needed to synchronize and control functioning of the DRA.

If allowable limits were exceeded at any time during deployment or restow, the process would have been automatically interrupted by the MDIS/MC combination. Retraction could be reinitiated at any time by the flight crew. Starting the retraction process would require that the diagonal folding mechanism be cycled back to its retracted position, had it moved, and that the beam would have to be deployed to the next even bay-pair. Once fully retracted, the packaged beam would have been preloaded within the DRA by the clamping action of the stowage latches.

ON THE PROBLEM OF SYNCHRONIZATION DURING RESTOW OF THE BEAM

Conceptually, beam bay-pair restow could have been accomplished by any of three methods, used singly or in combination. The three methods were: rotation of the "B" batten frame with respect to the "A" batten frames (required large displacement mechanisms and would produce high member loads), forcing the upper three "A" corner bodies downwards (required introduction of excessively high loads in the members sufficient to affect diagonal hinge opening), and pushing inwards or applying a torque across the six diagonal mid-span hinges (required large displacement mechanisms and would produce low member loads). A combination of the latter two methods was selected for simplicity and minimum energy expenditure.

It was analytically determined that the fold-arm mechanism required the least amount of energy to affect bay-pair restow during the first 25° of diagonal hinge rotation. This mechanism was designed to apply the necessary forces at the proper point of contact on the diagonal hinge while tracking the path of required spatial motion. Figure 16 presents the torque required to open the diagonal hinge. It was necessary to synchronize the movement of this mechanism with the restowing beam bay-pair member spatial motion that would be associated with the constant rotation of the lead-screws. At the beginning of bay-pair retraction, the lead-screws started turning to push the "A" corner bodies downward while the lower set was being restrained by the detent device. Simultaneously, the upper and lower diagonal fold-arms began to press on the diagonal hinges. This combined action continued for the first 25° of diagonal hinge rotation. At the 25° position, the constant drive lead-screw mechanism became the most energy efficient restow method; therefore, the fold-arms were disengaged to be recycled back to their retracted position while the lead-screws continued to press downward on the "A" corner bodies. Once the upper and lower "A" corner bodies came together, continued lead-screw rotation drove the lower set of corner bodies past the detent. At that point, a new set of "A" corner bodies was engaged at the top of the lead-screws and the process repeated itself. The synchronization of these functions is extremely crucial.

Suppose, for example, the diagonal fold-arms were not synchronized kinematically and began pushing on the diagonal hinges before lead-screw motion began reducing the distance between the upper and lower sets of "A" corner bodies--the lower set being either still on the lead-screws or restrained by the detents. Conceivably the joints and/or members within the retracting bays could become subject to high loads and hence, the possibility of failure. On the other hand, if the diagonal fold-arms were late in pushing on the diagonal hinges, the downward force on the "A" corner bodies could cause excessive loadings leading to buckling of the longerons or could force the lower set of corner bodies past the detents.

This problem of synchronization arises from the fact that two independent displacement inputs into a single d.o.f. mechanism are being specified. A simple equivalent illustration (figure 17) follows:

> Suppose one wishes to apply two displacement inputs into a four-bar linkage. Since a four-bar linkage has only a single d.o.f., a specification of angle θ will give rise to an angle $\hat{\phi}$. If ϕ were specified as well and is different from $\hat{\phi}$, excessive loadings on the joints, buckling of the coupler link, or even bending of the other links may result. In the MFS, such excessive loading could cause failure in any of the beam members or any element of the deployment and restow or diagonal fold-arm mechanisms.
>
> In the same manner, for the lead-screw and diagonal hinge motion synchronization, there exists a 1:1 kinematic relationship between the rotation of the lead-screw and the displacement of the diagonal hinge. If the motion of the diagonal folding arm does not coincide with the displacement of the diagonal hinge for a given lead-screw rotation, then either:
>
> 1. The fold-arms are not pushing on the diagonal hinges (and may cause buckling of the longerons at the initial stages of retraction) or
>
> 2. The fold-arms are pushing with an excessive force (and may cause failure of the pin joints or bending of some of the battens or longerons).

A SOLUTION TO THE SYNCHRONIZATION PROBLEM

In this writer's opinion, it is highly improbable that such closely synchronized motions between lead-screw rotation (and hence, "A" body translation) and fold-arm actuation of the diagonal hinges can be achieved. Based on a combined kineto-elastostatic model of the Mast Z-beam and DRA design, optimization techniques should first be applied to the model to minimize the differences between the desired fold-arm motion and the actual motion. Subsequently, to account for these differences, it is recommended that a flexible member (such as a constant-load spring) be incorporated at the point (area) where the diagonal fold-arm pad is to contact the diagonal hinge such that the remaining differences between the motions do not result in excessive joint and member loadings. This approach would prevent the problems stated above. The theoretical basis follows:

> Using the four-bar linkage analogy illustrated earlier (figure 17), one would specify the displacement θ to the input link and a displacement $\hat{\phi}$, not equal to the displacement, ϕ, of the output link. However, the shaft that is connected to the output link is flexible such that $\hat{\phi}$ and ϕ, though different, are taken up by the flexibility. This flexibility of a member is equivalent to that to be attached to the diagonal fold-arm.

A proposed solution would be to design into the flexible element of the diagonal fold-arm, preferably a constant-load spring effect, then one would not be loading up the beam elements excessively, thereby increasing reliability. Furthermore, it is recommended that an optimized system design be performed to ensure that diagonal fold-arm movement and diagonal hinge motion are sufficiently close to each other.

SUMMARY

In a complicated mechanism such as the DRA, it is desirable to simplify the general essence of the mechanical movements of subassemblies. For the particular case of the beam retractor linkage, the motion of the "A" corner bodies and the synchronized motion of the diagonal fold-arms in relation to the spatial motion of the diagonal hinges may be difficult or impossible to achieve. With an analogy to a four-bar linkage (also a single d.o.f. system), a simple approach (such as use of a constant load spring) may minimize the loads due to motion errors during the retraction synchronization process. This constant load spring may relax the synchronization dimensional accuracy requirements to allow a practical and feasible design.

Table I: Pertinent Beam Specifications

Number of Bays:	54
Deployed Bay Length:	44.250 inches (1.124m)
Total Deployed Length:	2389.500 inches (60.693m)
Beam Diameter:	55.118 inches (1.400m)
Angle between Deployed Diagonal/Batten:	42.831 degrees
Stowed Bay-pair Height:	3.000 inches (0.076m)
Stowed Beam Height:	84.000 inches (2.134m)
Packing Ratio:	0.035
Maximum Tube Diameters:	Longeron - 0.900 inch (22.86mm)
	Diagonal - 0.945 inch (24.00mm)
	Batten A - 0.625 inch (15.88mm)
	Batten B - 0.500 inch (12.70mm)

Table II: Beam Members, Effective Structural and Thermal Properties

	Effective Axial Stiffness, 10^6 lb (N) Max.	Design	Min.	Effective CTE 10^{-6} in/in/°F	Local Buckling Loads
Longeron 1	10.7(47.6)	9.7(42.9)	9.3(41.3)	+0.082	5935 lb (26,400 N)
Longeron 2	9.0(40.1)	8.2(36.4)	7.9(35.2)	+0.082	5070 lb (22,560 N)
Diagonal 1	1.0(4.4)	0.9(3.9)	0.8(3.7)	+1.13	264 lb (1175 N)
Diagonal 2	1.0(4.4)	0.9(3.9)	0.8(3.7)	+1.09	264 lb (1175 N)
Batten A (axial load)				-0.32	343 lb (1525 N)
(frame, 3 radial loads, ea)					594 lb (2640 N)
Batten B				+0.372	201 lb (894 N)

Table III: DRA Status Monitoring Instrumentation

Stowage and tip latch limit switches -- each stowage and tip latch motor actuates a redundant limit switch at each end of travel. Activation of a switch element is an event and is monitored by the MDIS.

Telescopic tube limit switches -- each telescopic tube latch motor actuates a redundant limit switch at each end of travel. Activation of a switch element is an event and is monitored by the MDIS.

Deployed bay-pair encoder -- provides the deployed bay-pair count.

Diagonal latch verification switches -- an optical switch is employed to verify that each of six diagonal mid-span hinges of a bay-pair are latched before any portion of the bay-pair exits the DRA.

Beam lock limit switches -- each beam lock motor actuates redundant limit switch at each end of travel. Activation of a switch element is an event and is monitored by the MDIS.

Diagonal folding encoders -- provide the position of the diagonal folding mechanism.

Diagonal folding stow limit switch -- the diagonal folding motor actuates a single limit switch at a fully stowed position.

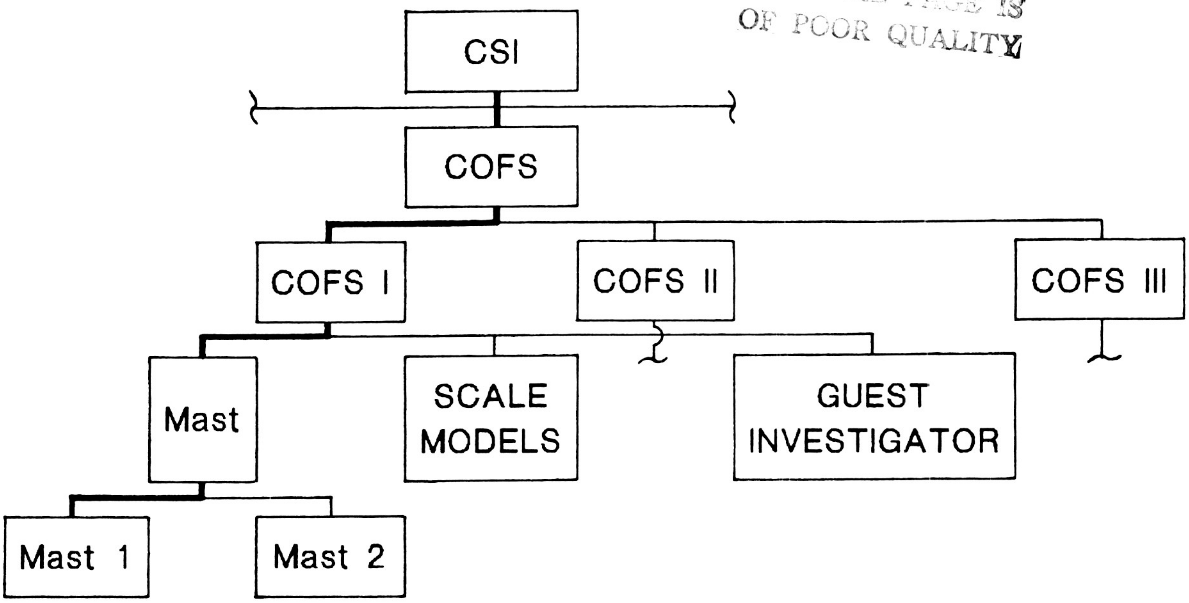

Figure 1. Control/Structures Interaction (CSI) effort.

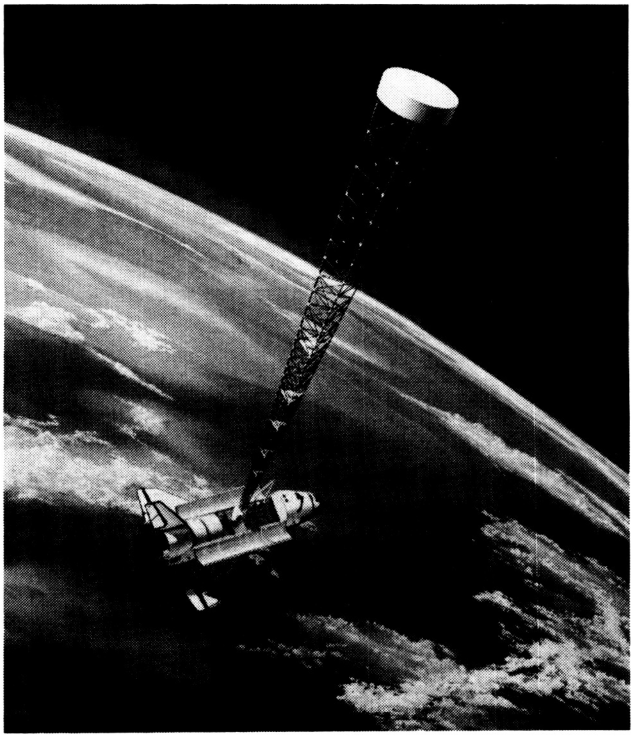

Figure 2. Deployed 60-meter Mast beam.

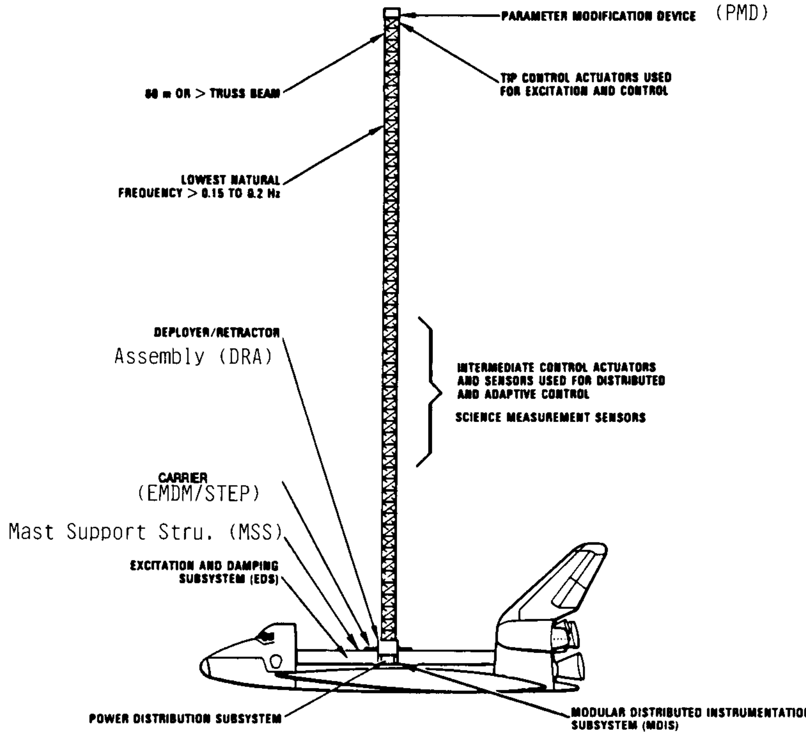

Figure 3. Mast Flight System (MFS).

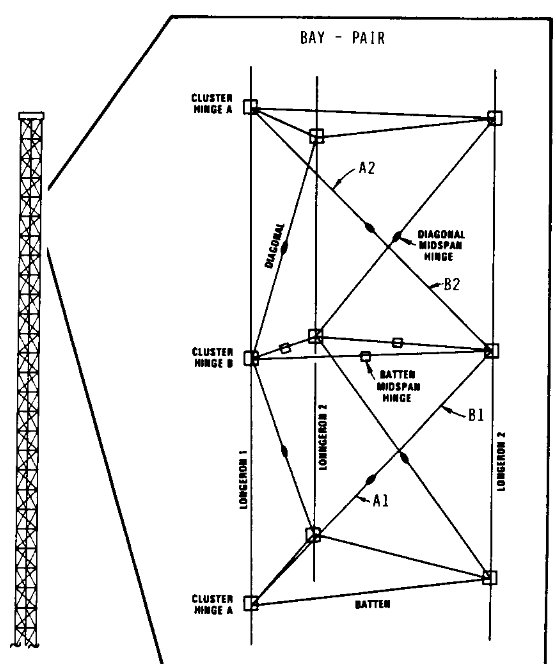

Figure 4. Articulating Astromast beam concept.

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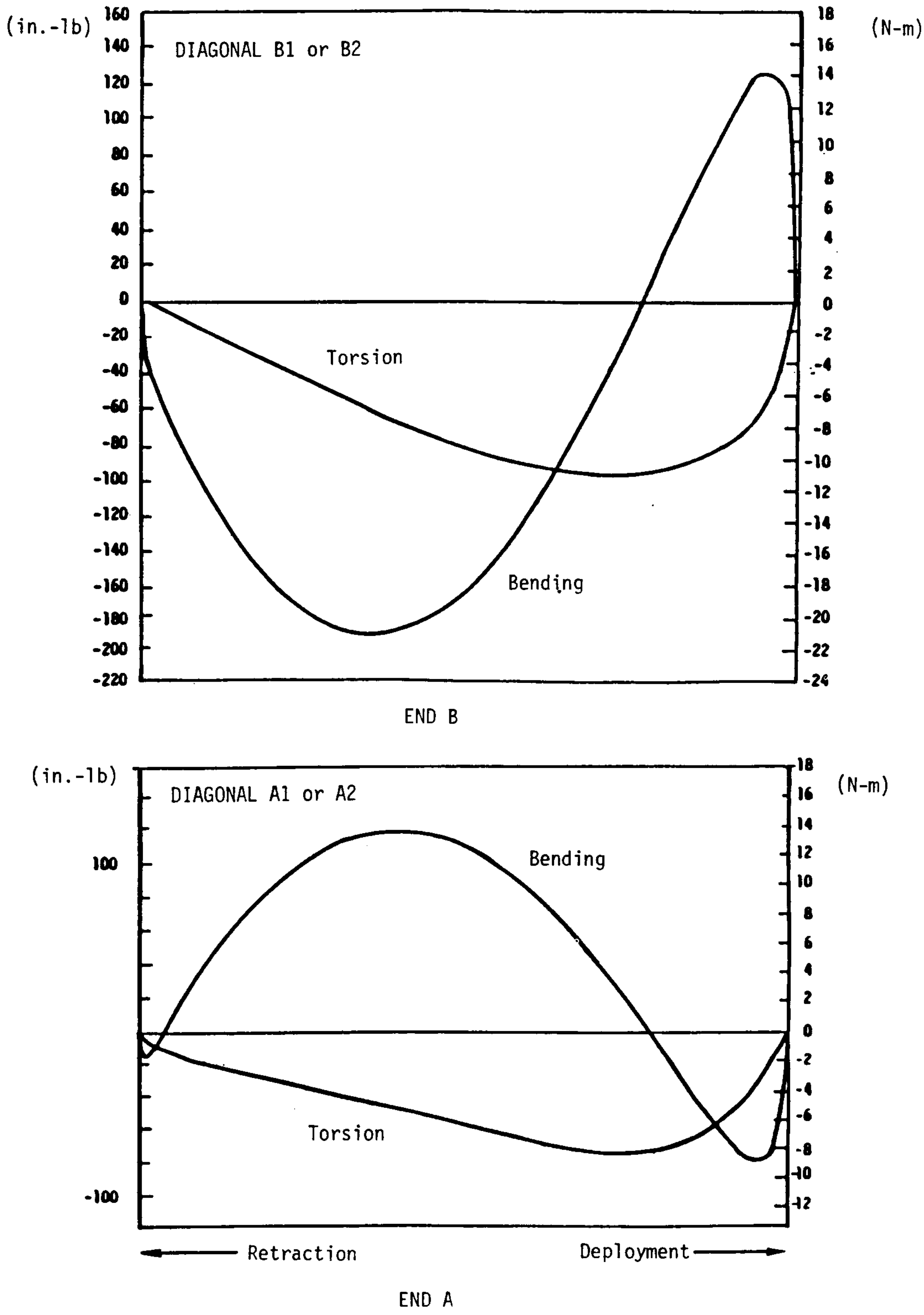

Figure 5. Moments at ends A and B during deployment/retraction cycle.

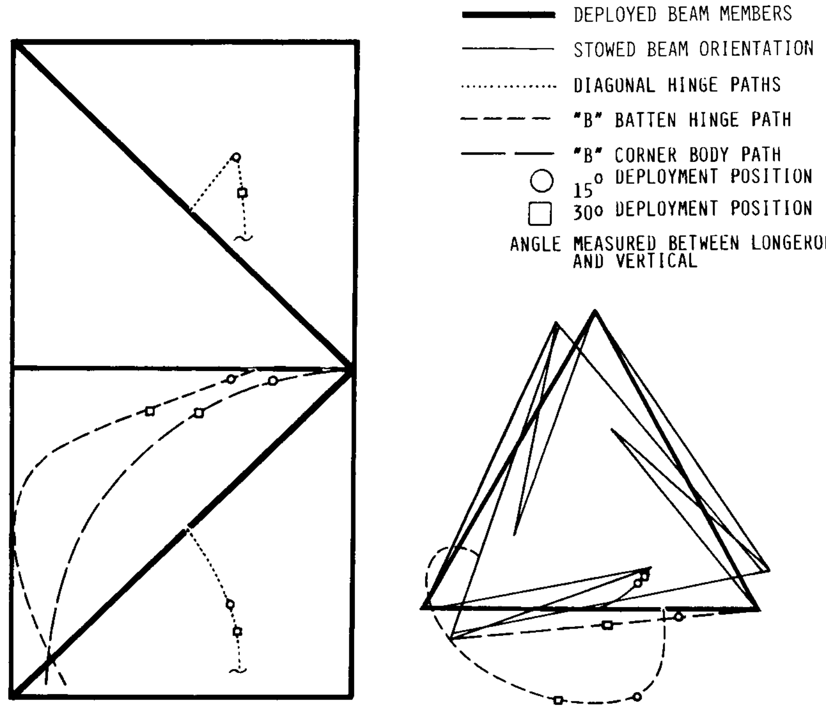

Figure 6. Spatial motion of typical beam members.

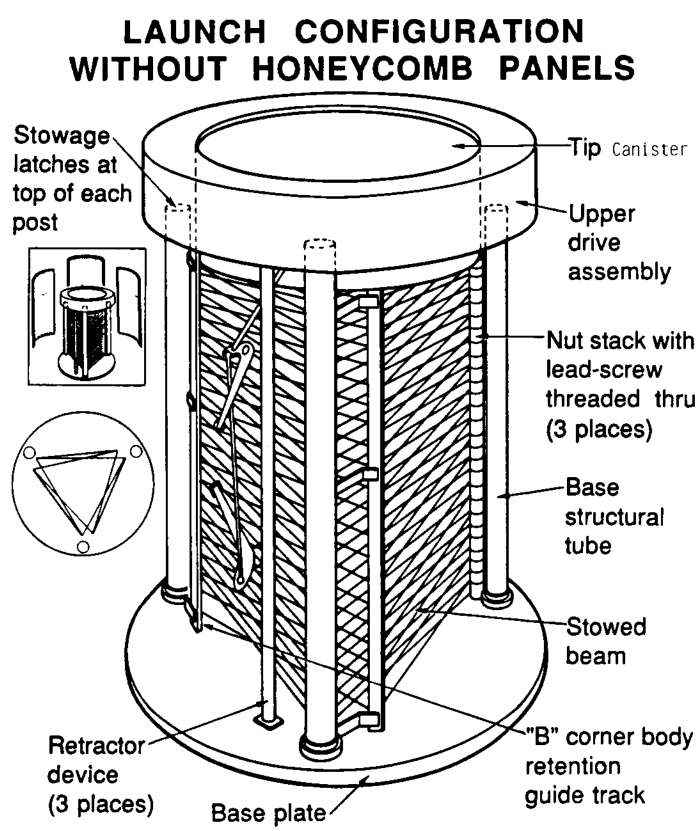

Figure 7. Mast flight system - stowed.

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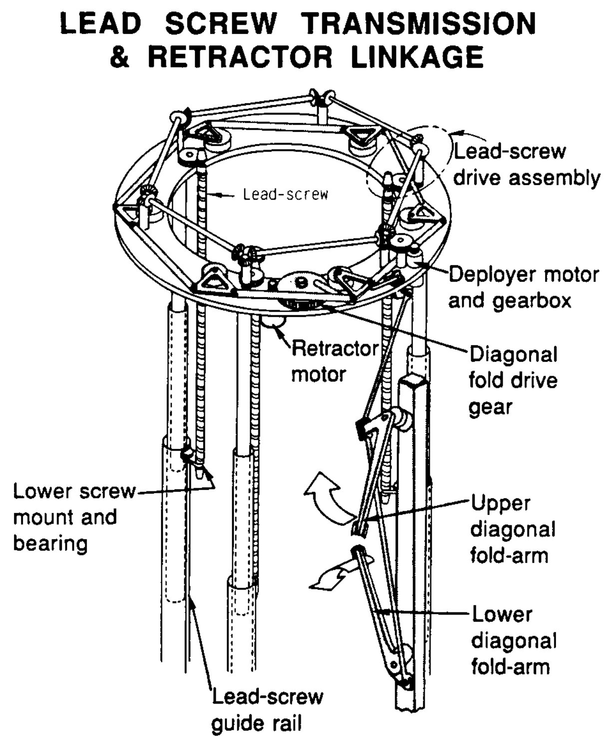

Figure 8. Lead-screw and fold-arm mechanisms.

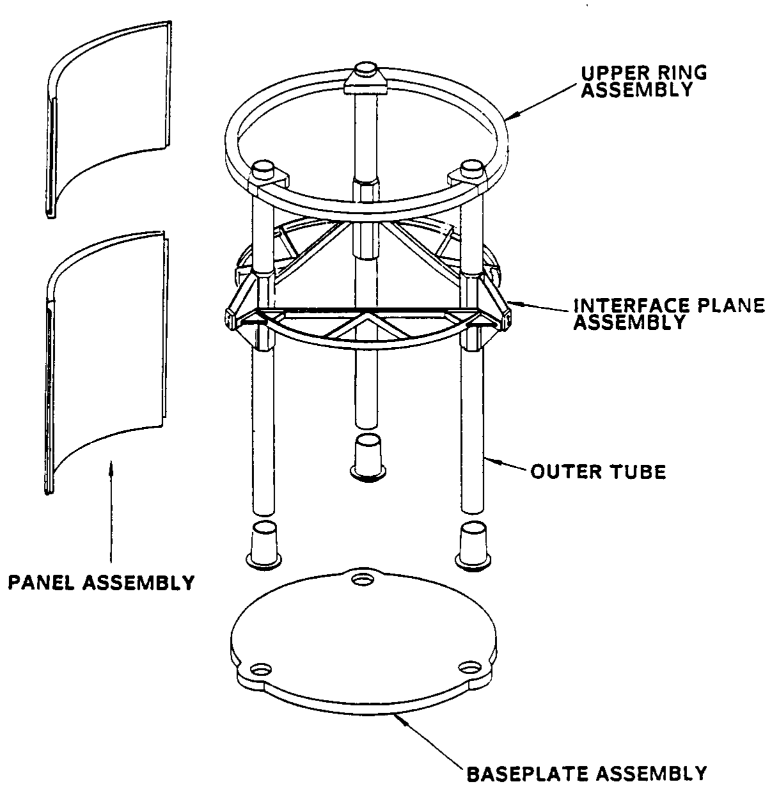

Figure 9. Fixed DRA support structure.

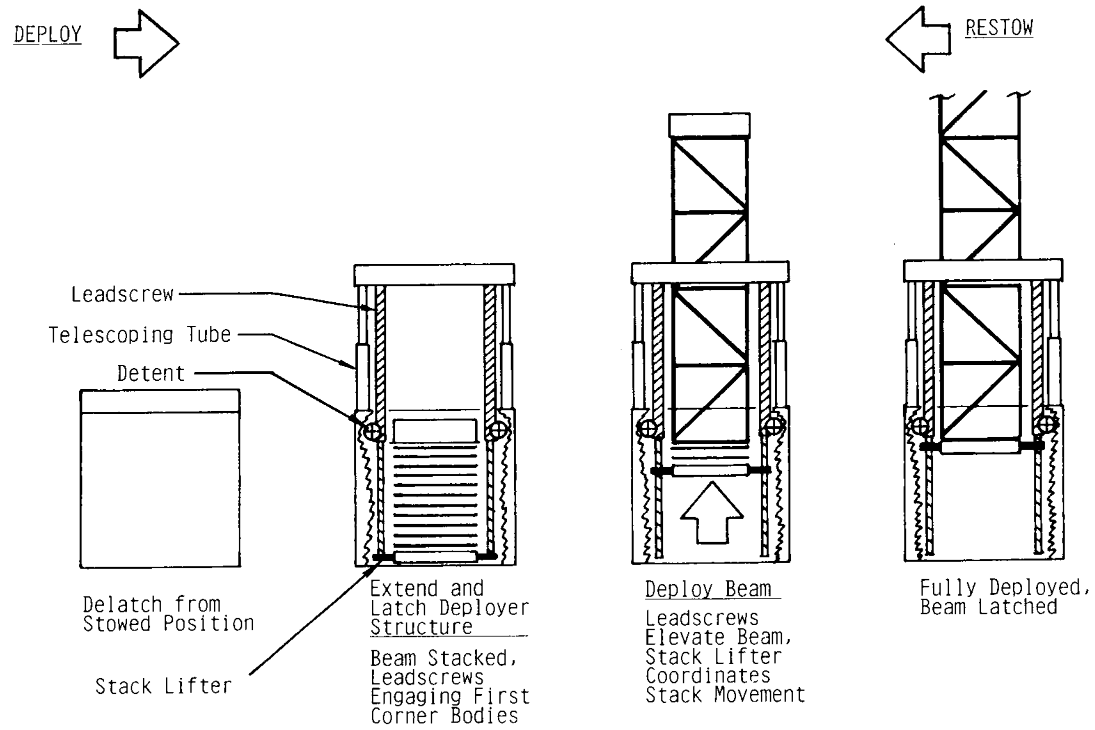

Figure 10. Deployment/retraction sequence.

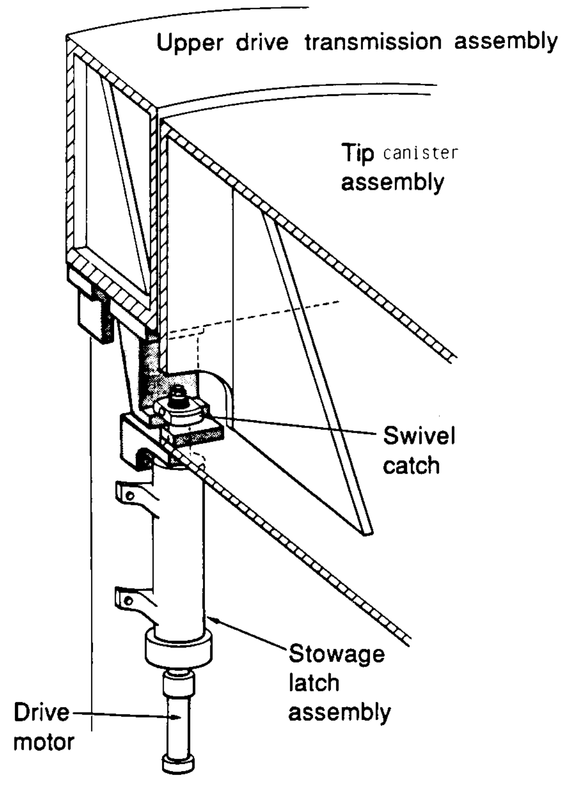

Figure 11. Stowage latch.

TUBE LATCH, UNLOCKED

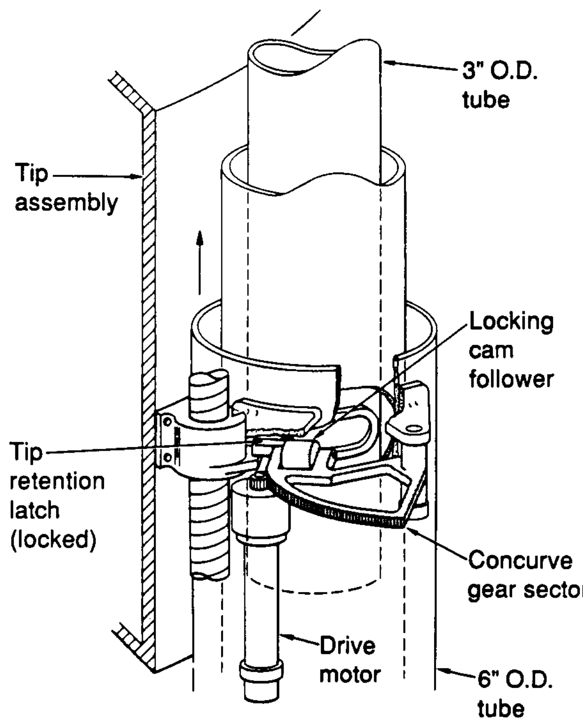

Figure 12. Telescoping tube latch mechanism.

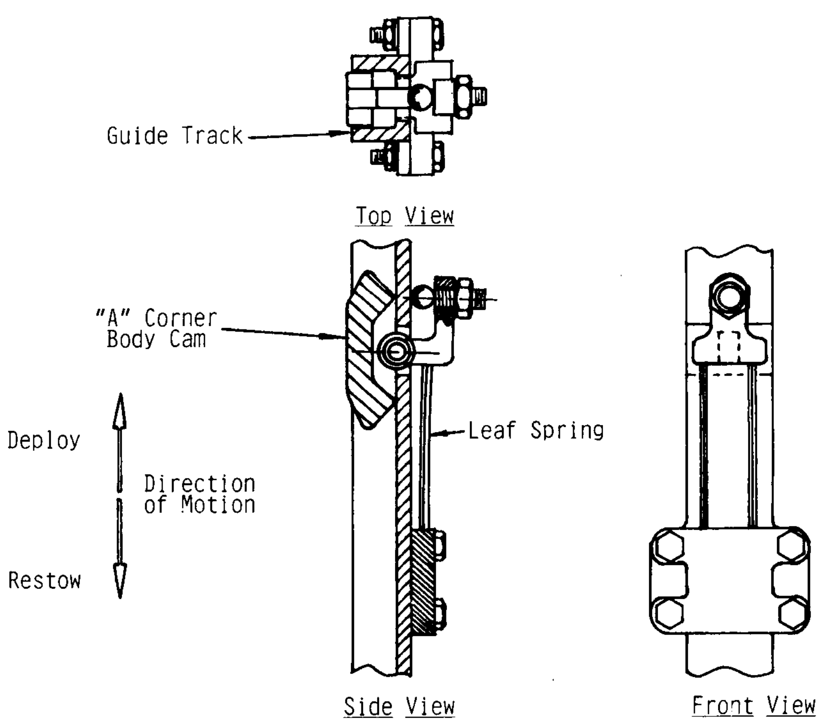

Figure 13. Detent device.

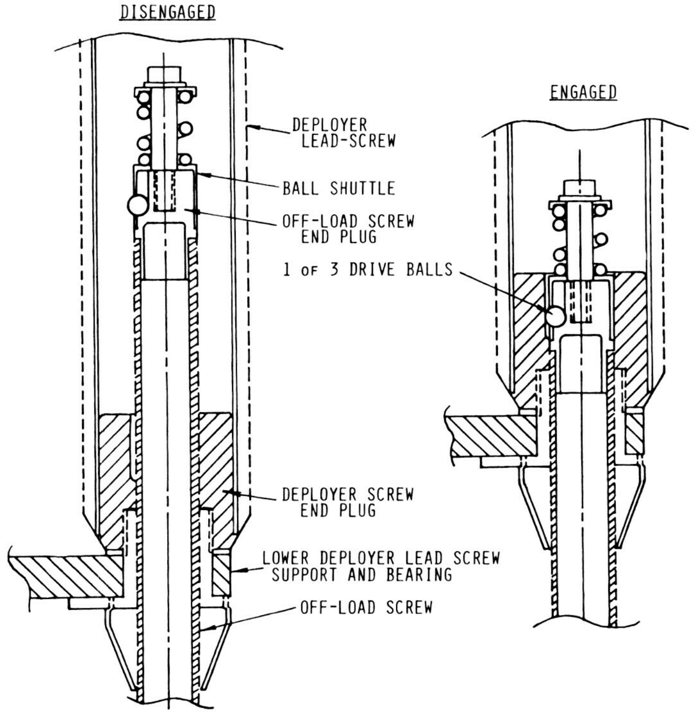

Figure 14. Stack lifter (off-loader).

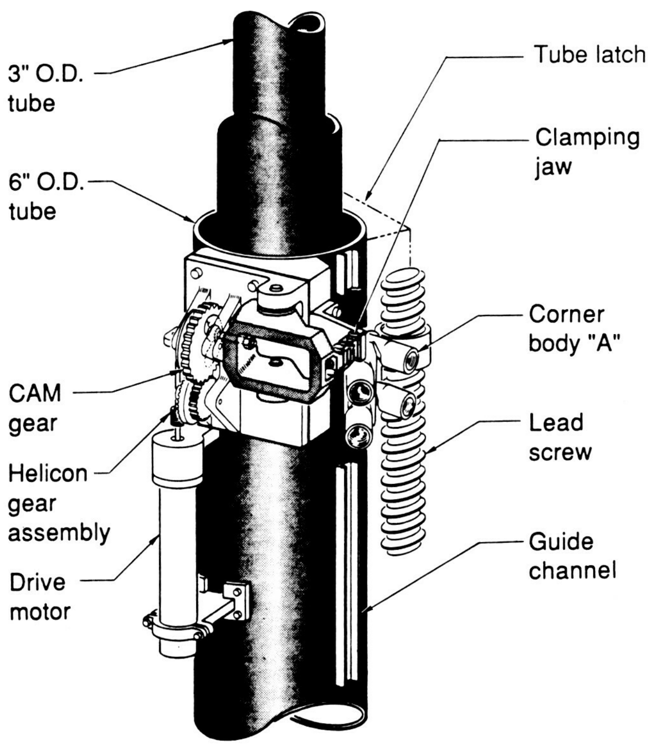

Figure 15. Beam latch mechanism.

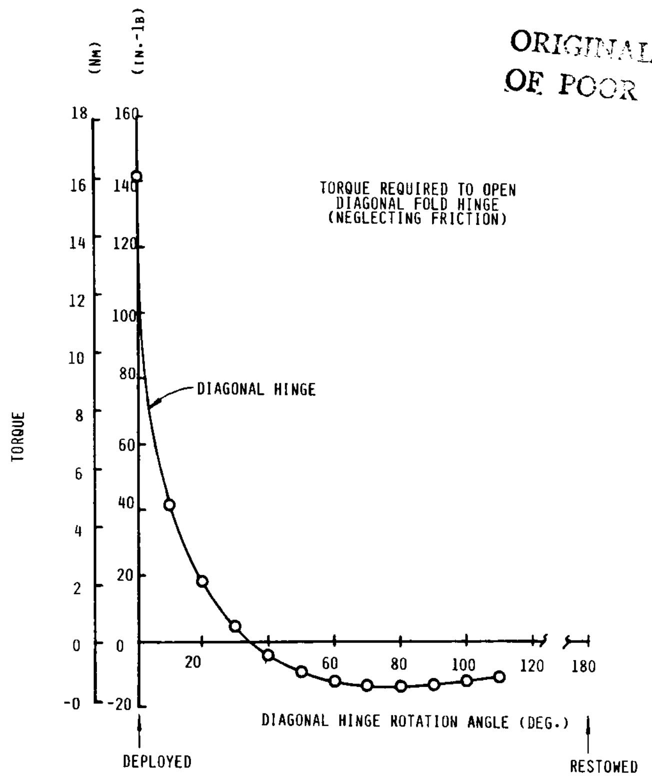

Figure 16. Torque required to open diagonal hinge.

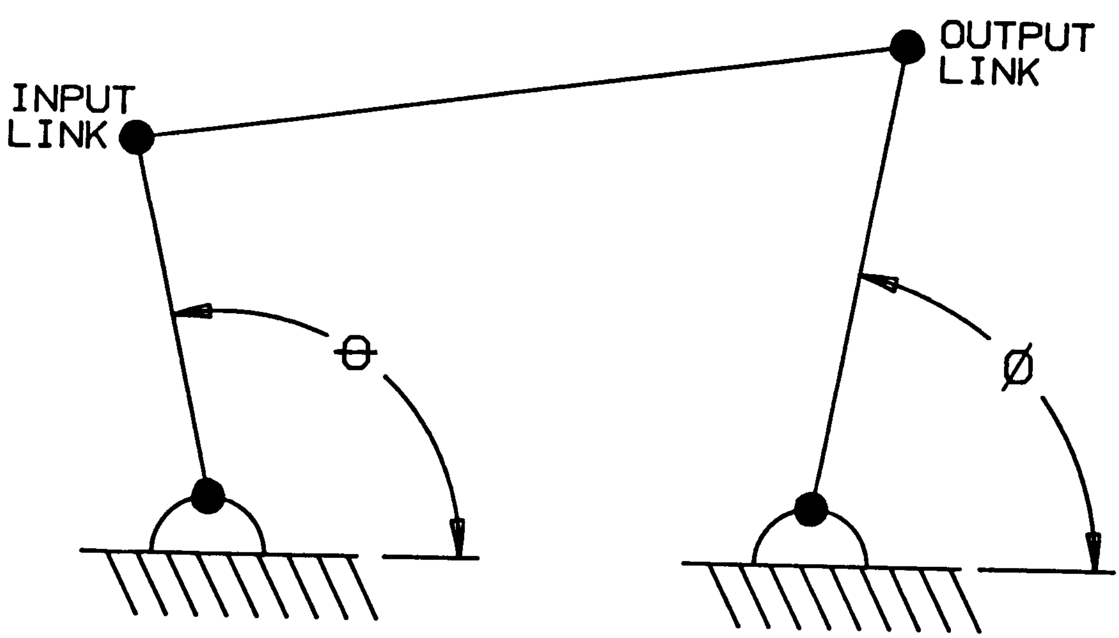

Figure 17. Equivalent four-bar linkage.