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DEPLOYABLE AND RETRACTABLE TELESCOPING TUBULAR STRUCTURE DEVELOPMENT

M.W. Thomson
Astro Aerospace Corporation
Carpinteria, California

ABSTRACT

A new deployable and retractable telescoping boom capable of high deployed stiffness and strength is described. Deployment and retraction functions are controlled by simple, reliable, and fail-safe latches between the tubular segments. The latch and a BI-STEM (Storable Tubular Extendible Member) actuator work together to eliminate the need for the segments to overlap when deployed. This yields an unusually lightweight boom and compact launch configuration.

An aluminum space-flight prototype with three joints displays zero structural deadband, low hysteresis, and high damping. The development approach and difficulties are discussed. Test results provide a joint model for sizing flight booms of any diameter and length.

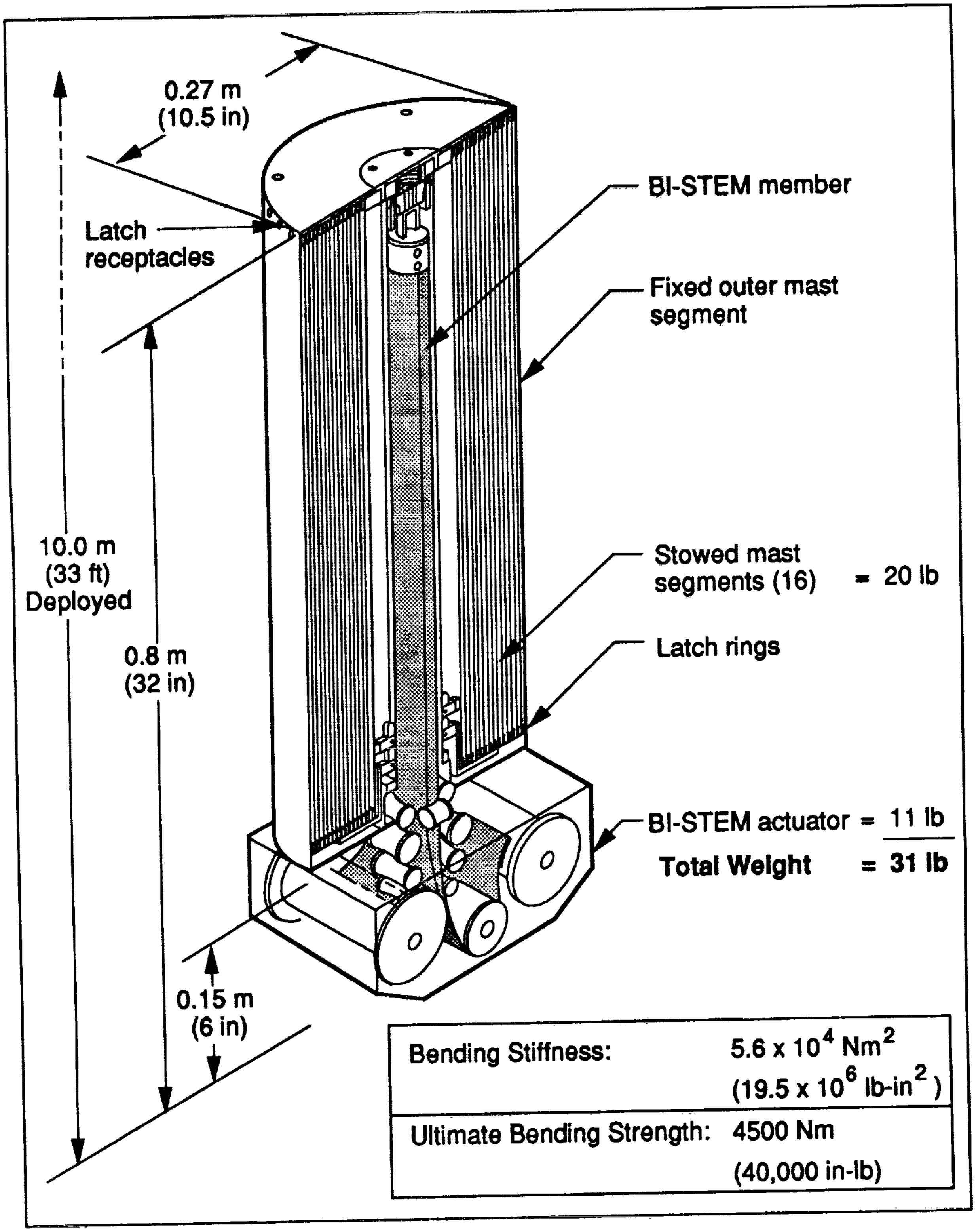
INTRODUCTION

The new telescoping boom was developed to service recent spacecraft requirements for lightweight, high strength and stiffness deployable and retractable boom structures. An example of the new design is shown stowed and cutaway in Figure 1.

Telescoping booms have tapered section properties, which makes them ideal for most cantilevered boom systems, and thin wall tube segments can be stowed very compactly. Telescoping booms have few parts and simple deployment kinematics and are therefore intrinsically reliable [Ref. 1]. They are also exceptionally resistant to structural failure from micrometeoroid or other bombardment. The nested tubes of a telescoping boom can be fabricated from metallic or composite materials depending on the structural performance that is required, and they may be perforated to minimize weight and thermal gradients.

BACKGROUND

One problem that must be addressed in the design of compact telescoping booms is the need for stabilization during deployment and retraction. Tube segments that are in relative motion can easily bind inside one another, particularly during retraction.



Bending Stiffness:	5.6×10^4 Nm^2 (19.5×10^6 lb-in^2)
Ultimate Bending Strength:	4500 Nm (40,000 in-lb)

Figure 1. Telescopic Boom Unit—Stowed.

A compact boom that is deployed from the root needs a high degree of stabilization. The forces required to stabilize root deployment are proportional to the ratio of boom length to deployer length, which may be as high as 20, so stabilization is an important issue. Furthermore, any play between the deploying boom and the stabilizer is exaggerated at the boom tip by the same ratio. This intensifies dynamic nonlinearities and the loads thereof.

Stabilization is usually provided by overlapping adjacent deployed tube segments. More overlap is needed if the tube walls are thin or have surface irregularities or relatively soft coatings. Designs that depend upon precisely nesting diameters to reduce overlap are prone to jam from elastic or thermal deformations. The amount of overlap needed can be as much as three tube diameters [Ref. 1]. Overlap increases not only the deployed nonstructural weight, but also the number of tube segments required to fit the total boom length into a given launch envelope. The loss of structural efficiency can be significant for designs with many segments, particularly if the ratio of stowed length to maximum tube diameter is less than about eight.

Play in the latches between deployed tubes is a common problem with telescoping booms, particularly those with numerous joints [Ref. 1]. Latch designs that have both high stiffness and autonomous retractability can be complex and heavy. It is essential that the latches be lightweight and of simple design if high structural efficiency and reliability are to be achieved.

Finally, the axial thickness of the latches at the joints of telescoping booms often end up stacked when stowed. This staggers the tube lengths and reduces the potential length of the boom. The amount of lost boom length is magnified by the number of tube segments. For instance, a stack of 20 tubes successively staggered by 1 centimeter loses 2 meters of potential deployed length.

DESIGN GOALS

The primary goal was to design new deployment and latching mechanisms that eliminate the compromises that can detract from the structural efficiency of telescoping booms. The new design should be able to sequentially deploy and retract from the tip, instead of from the root, to minimize the stabilization needed and to maximize the stiffness of the system at all extended lengths. All functions should be achieved with minimum complexity so that the design can be readily and cost-effectively scaled to a variety of sizes. Some reduction of stiffness due to latch compliance will be inevitable, but the goal is to keep the joint knockdown factor below 25 percent and to eliminate structural deadband.

An additional goal was a well-rounded design that is easily adapted to a wide range of applications. The design of the tubes should be simple and compatible with metallic and composite materials. Deployment and retraction should be tolerant of dynamic loads and the loads exerted by payloads such as flexible solar array blankets. The boom should be capable of precise positioning and of deployment and retraction forces up to 450 N (100 lb). The ability to retract autonomously in 1 g would reduce the expense of qualification whether or not retraction is required in orbit.

GENERAL DESIGN APPROACH

It was decided that the BI-STEM, (a pair of Storable Tubular Extendible Members) would actuate and stabilize sequential tip deployment to eliminate the need for the tubes to overlap. A veteran of space flight, the BI-STEM consists of two "C" sections of thin formed metal that are flattened so they can be rolled onto separate spools for launch, as shown in Figure 2. Deployable booms in the STEM family are simple and extremely lightweight; they have been successfully deployed over 300 times in space without any known failures.

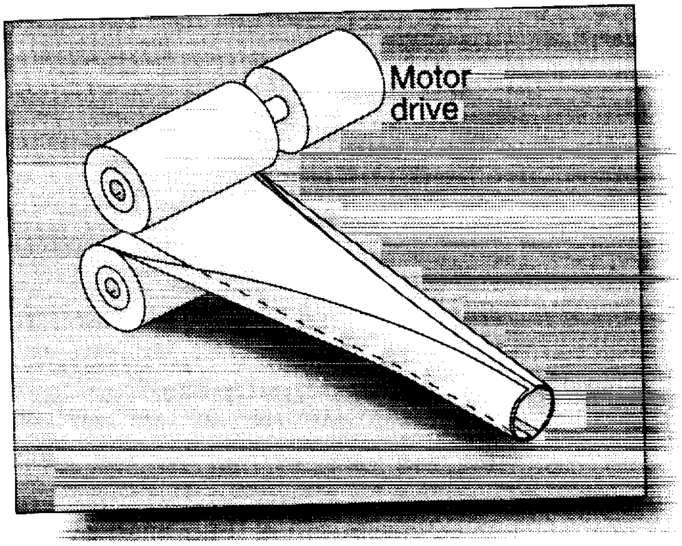


Figure 2. BI-STEM.

The payload and package of stowed tube segments are pushed from the inside of the fixed external root segment by the BI-STEM. When the package reaches the end of the fixed segment, the outer tube in the package latches to it, as shown in Figure 3. This tip deployment process repeats sequentially until all tubes are latched into place. The same sequence is reversed to retract.

The innermost of the undeployed tubes is fixed to the tip of the BI-STEM in order to stabilize the moving package of tubes. An ample diametral clearance is provided between the tubes and their neighbors so that the BI-STEM can deflect moderately without the tubes binding. Because the BI-STEM actuator does not need to be exceptionally stiff, its diameter and weight can be low. The clearance between tubes reduces the impact of any thermal distortions or imperfections in the walls so that larger tubes can be made at a lower cost than previously thought possible [Ref. 2].

BI-STEMs can exert 450 N (100 lb) of compressive deployment force in the largest common diameter of 51 mm (2 inches) and can be accurately positioned. Tubes that have been latched into structure behind the deploying tip of the boom can brace the BI-STEM element laterally to enhance its ability to react tip loads or to reduce the size of the element. Lightweight annular supports can be deployed periodically as shown in Figure 3. The supports can be spaced as close as one tube length apart, which may be necessary so that the BI-STEM can exert high deployment forces without buckling the element.

To minimize the number of tubes, they are all the same length and are stowed coincident with each other, as shown in Figure 1. Larger booms can further minimize stowed volume if the BI-STEM can be placed inside the smallest tube, as shown in Figure 4. The latches fit in the annular gap between adjacent tubes in a stiffening ring at the lower end of each tube. The adjacent larger tube in turn necks down to a thin stiffening ring at the upper end. The stiffening ring helps to center and align the adjacent smaller tube and to lessen local deformations between the latched segments in bending. The consequent step in successive tube diameters creates a moderate taper that can be tailored to optimize structural performance.

The ultimate success of the boom is centrally reliant upon a simple, lightweight and structurally linear latch between the tube segments. Although the BI-STEM offers a novel option for deployment, it is designed to push, pull, and position the boom tip. The latch must, therefore, provide fail-safe control of the deployment and retraction sequence without—as a goal—any additional components.

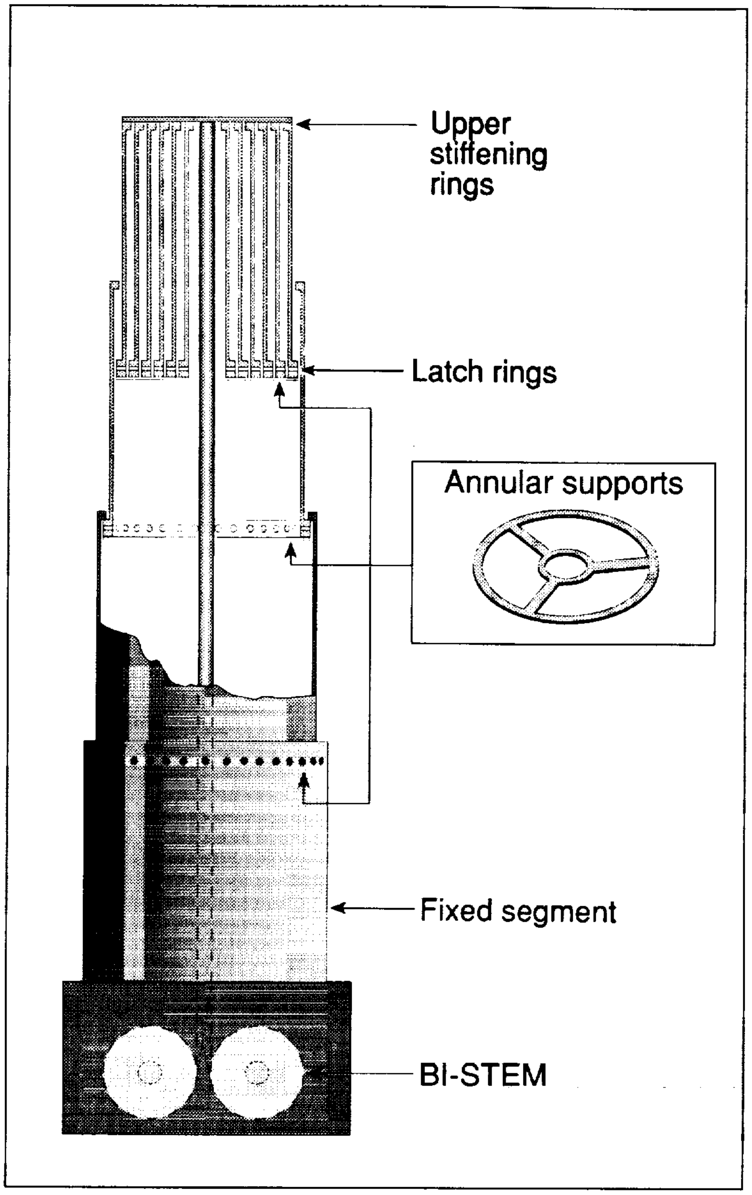


Figure 3. Telescopic Boom Unit Tip Deployment.

LATCH DESIGN

To eliminate structural deadband, there must be a preloaded latch at the joints between segments. It was decided that small tapered pins would be distributed circumferentially in the stiffening ring at the lower end of each tube. The pins are loaded radially outward by short springs to engage with tapered holes at the upper end of each larger adjacent tube, as shown in Figure 5. When stowed, the springs and pins are compressed by the interior surface of the adjacent larger tube. During deployment, the tips of the pins slide on the surface until they pop into the tapered seats to latch.

The included angle of the taper avoids a locking taper geometry that would make retraction difficult. The preload is sufficient to prevent the pin from squeezing out of the seat as a result of boom bending. It was reasoned that numerous smaller pins would increase redundancy, stiffness, strength, and linearity by evenly loading

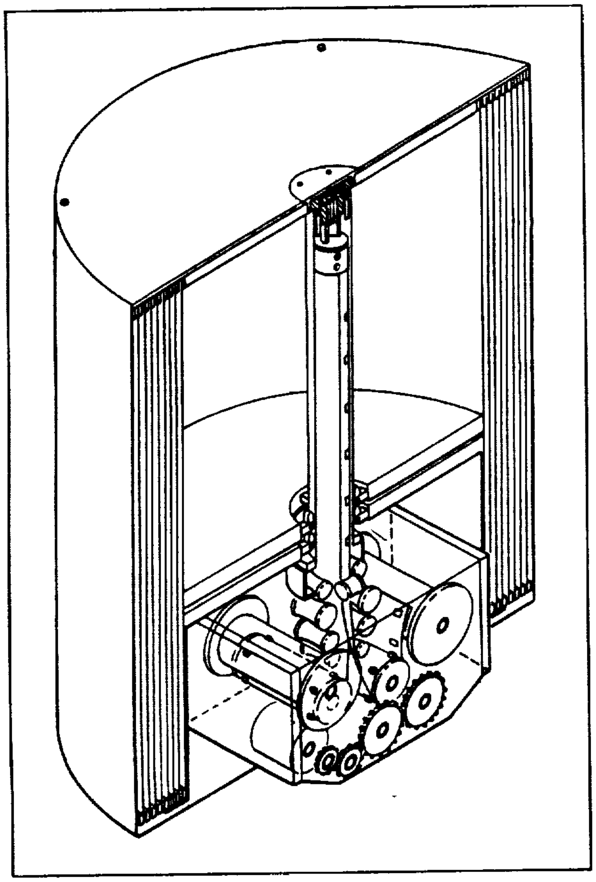


Figure 4. Large Diameter Compact Telescoping Boom.

the thin tubular walls. The taper of the pins also makes it easy for them to "find" the seats during deployment despite any mismatch between pins and receptacles. Coarse torsional alignment up to the point of latching is maintained by a key or "clocking strip" that is affixed to the exterior of each tube. The clocking strip engages a notch on the inner diameter of the upper stiffening rings.

Getting to this stage of the concept during the design process was relatively easy. Satisfactory solutions to the remainder of the design goals, sequencing and autonomous retractability, were not as easily achieved.

SEQUENCING

Numerous complex variations of the basic tapered pin latch were conceived to cause it to sequence and retract the boom. The designs did not seem sufficiently robust and would have been costly to manufacture.

After repeated trial and error, an elegant solution emerged. It was realized that because the tubes are stowed coincident to each other, each ring of compressed latch pins can engage the adjacent smaller ring with simple detents as shown in Figure 5. All the nested tubes are thus locked together so that they can be pushed as a package during deployment. When the latch ring in the outermost tube of the package locks it into deployed structure, the detents retaining that tube to the moving package of tubes are released. The now smaller package of moving tubes continues without interruption.

The male component of the detent on the interior end of the latch pin is conically shaped to make the latching function fail-safe. If one or more springs fail, the affected pin is forced out of the way by the female side of the detent, which acts as a ramp, as shown in Figure 5. Without the spring to preload the pin in the tapered receptacle that pin cannot contribute to the deployed stiffness of the boom, however, deployment will not be impeded.

RETRACTION

The sequencing concept provides a direct means for coordinating the movement of each tube with its neighbors. To retract a given tube, its latch pins are pulled

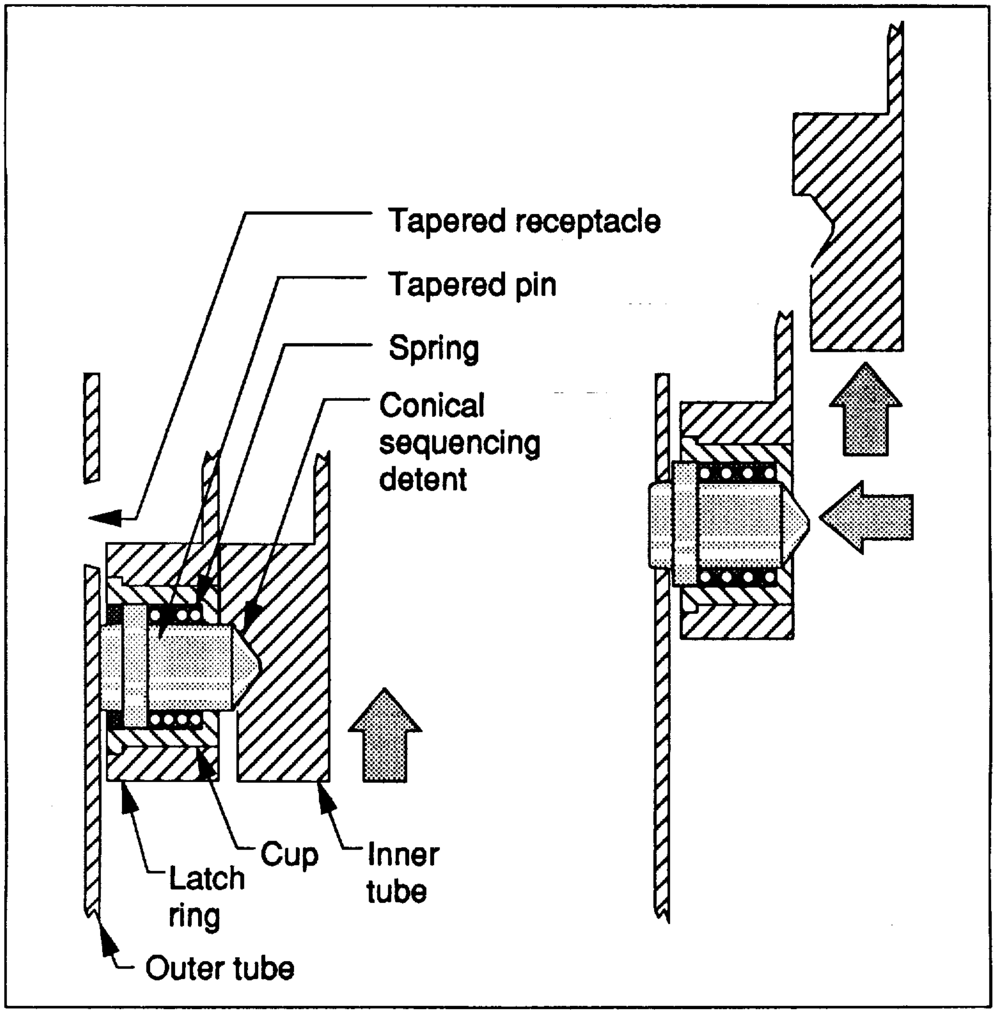


Figure 5. Tapered Pin.

from engagement with the next larger tube by ramps in the next smaller tube. The ramps are hollowed out of the latch rings to engage conical rims at the male detent end of the latch pins, as shown in Figure 6.

The BI-STEM is attached to a short piston located in the smallest tube segment at the boom tip. The piston provides end fixity in bending for the deployment stabilization function yet affords axial motion. The lower end of the piston has retraction ramps and female sequencing detents but no latch pins. The BI-STEM is reversed to pull the piston toward the latch ring of the tip tube to release it, which initiates retraction. Retraction continues until the retraction ramps in the latch ring of the tip tube releases the next larger tube, and so forth, as the sequencing detents bind the package of stowed tubes together in reverse.

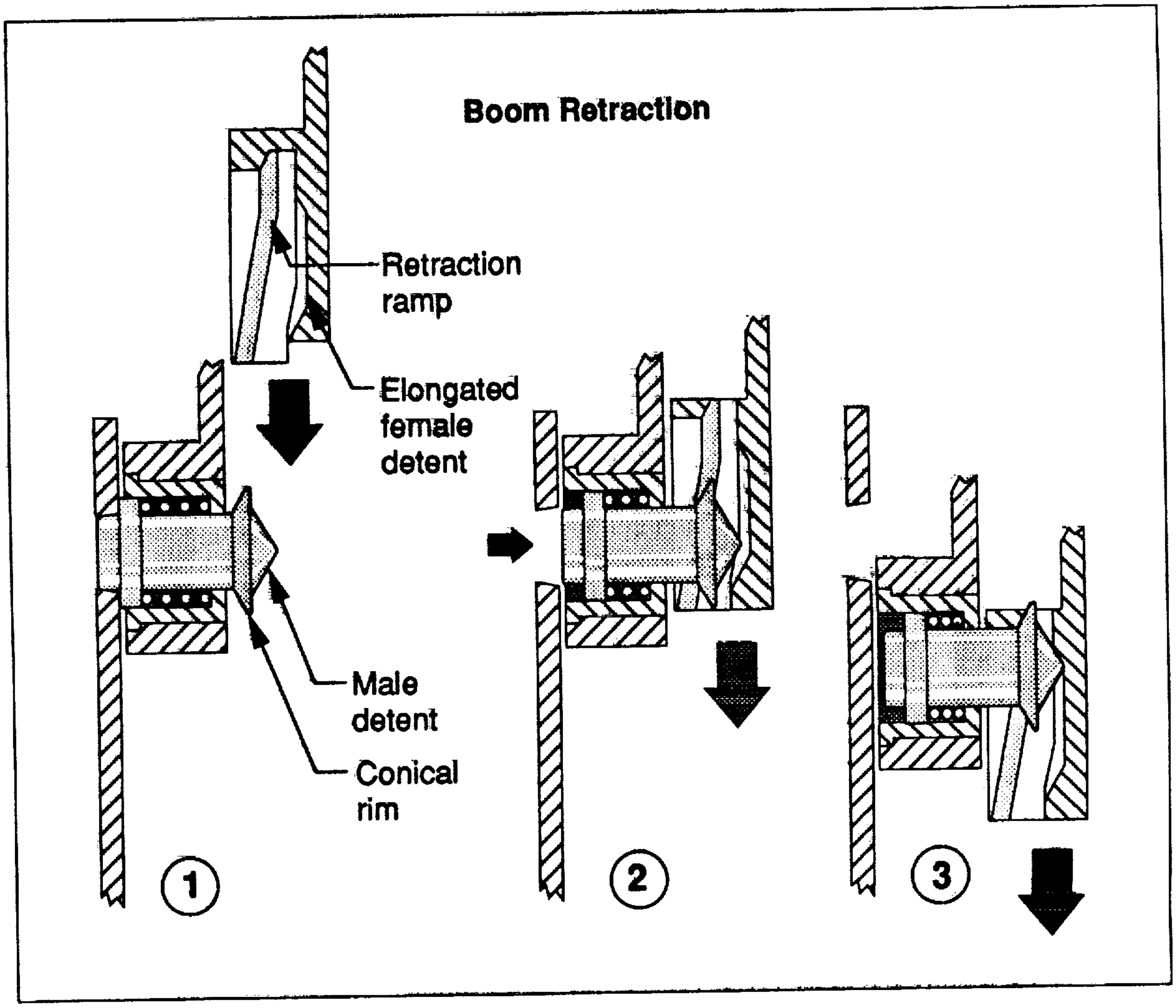


Figure 6. Boom Retraction.

Latch pins are alternated with retraction ramps and detents in increments around the circumference of each ring. Each successive tube in the assembly is indexed by one such increment relative to its neighbors so that everything meshes properly, as shown in Figure 7. Figure 7 also shows the clocking strips that maintain precise rotational alignment between adjacent tubes.

The sequencing function of the detents is not affected by retraction if the female portion of the detent is elongated into a trough, as shown by the first inset of Figure 6. This accommodates the axial motion between the latch and the adjacent smaller ring as the pins are pulled. The length of the trough is controlled so that the detents will engage before the deployed tube is unlatched, as shown in the second inset of Figure 6. The failure of one or more latch springs will not impede retraction so that fail-safe functionality is retained.

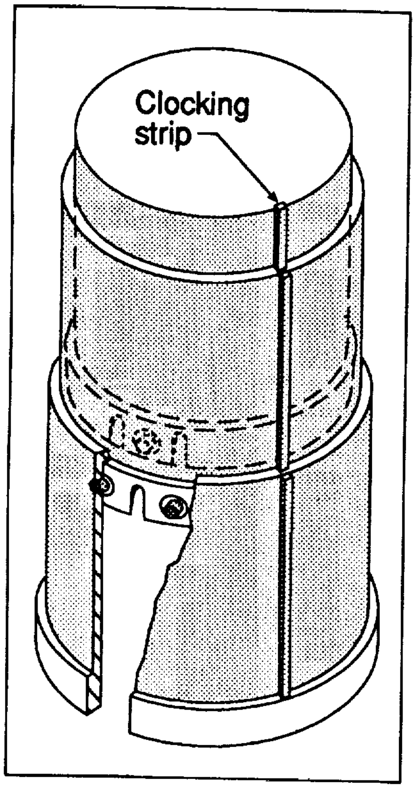


Figure 7. Latch Pins and Retraction Ramp.

LAUNCH RESTRAINT

A launch restraint mechanism is shown in Figure 8. A cap plate is preloaded over the end of the stowed boom by a ball detent latch. The latch engages a tube that is fixed to the BI-STEM housing on the inside of the stowed boom. The cap plate is released when the BI-STEM begins to deploy. This feature eliminates the need for pyrotechnic or other active devices to unstow the boom.

FLIGHT PROTOTYPE DESIGN

A flight quality aluminum prototype, shown deployed in Figure 9, was built to prove the feasibility of the boom concept. The model has a length of 2.3 m (91 inches) with a 12 cm (4.7 inch) average diameter. The four segments range in diameter from 14 to 10 cm (5.5 to 4.0 inches) and all have wall thicknesses of 0.64 mm (0.025 inch). The boom is actuated by a 3.4 cm (1.34 inch) diameter BI-STEM actuator.

The diametral pitch between tube segments was set at 1.27 cm (0.5 inch) to provide a moderately tapered configuration. A larger pitch

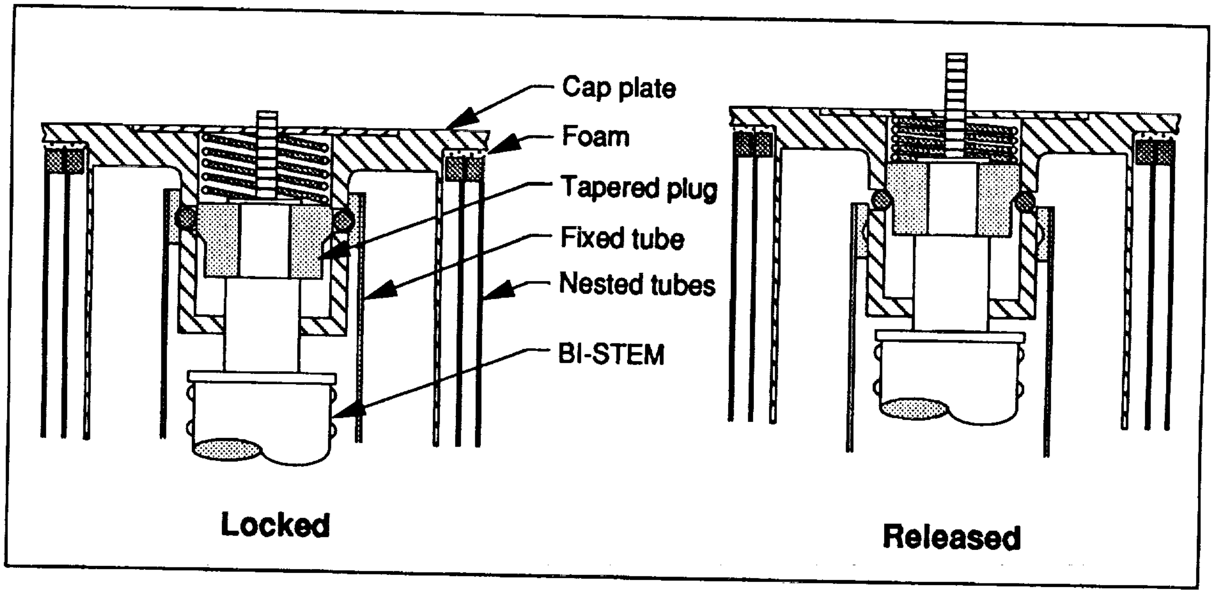


Figure 8. Launch Restraint.

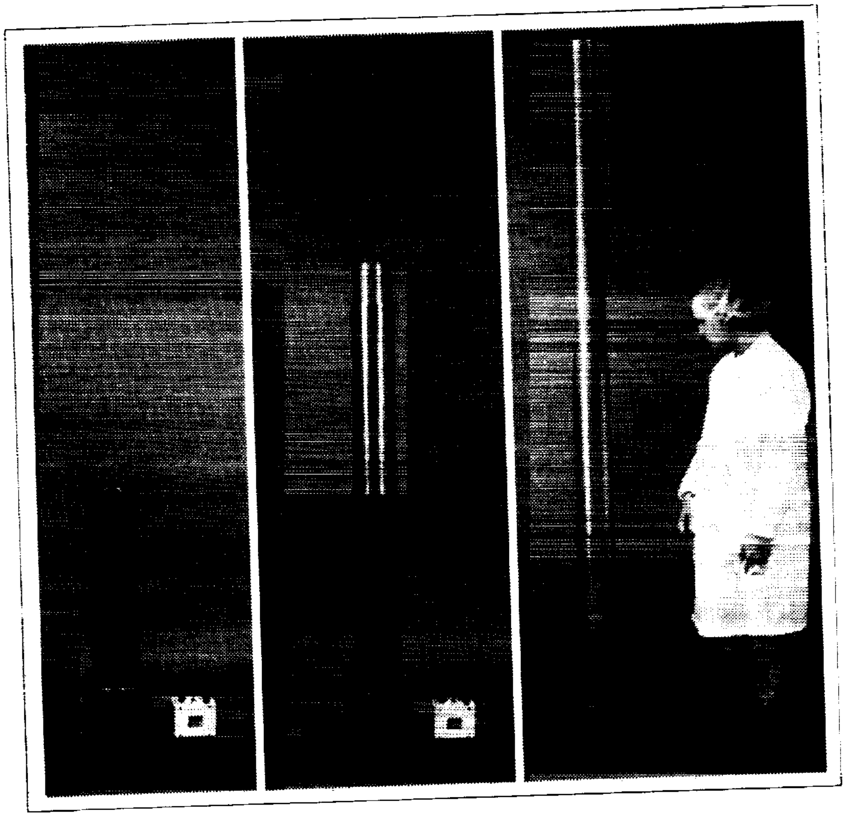


Figure 9. Telescopic Boom Aluminum Prototype.

would have resulted in a relatively bulky latch ring and stowed configuration with the boom diameter selected for the model. The maximum thickness of the latch and stiffening rings is therefore limited to a maximum of 0.61 cm (0.24 inch).

The pins and springs are set in cups, as shown in Figure 10, and the assembly is retained by the conical detent and retraction rim which is threaded into the pin and staked. The pin and cup units can be inexpensively produced in quantity with precisely mated pin and bore diameters. There are 12 identical pin assemblies in each latch ring. The springs used during structural tests provide a preload of approximately 9 N (2 lb). This can be increased to a maximum of about 16 N (3.5 lb) within the envelope available for the springs. The pin assemblies are installed in bores in the latch rings of each tube. Figure 11 shows a sample ring that is detached from the tube. Once the latch pins have been installed, the tube assembly stands alone and requires no additional fabrication.

The axial height of the lower ring along the tube length was set at 1.3 cm (0.5 inch). This height permits a shallow retraction ramp angle and ample tolerances for initial and final engagement with the retraction rims on the latch pins. The ramps have a shallow slope, as shown in the lower right-hand inset of Figure 11, which minimizes the force the BI-STEM must exert to withdraw the pins, thus ensuring smooth retraction.

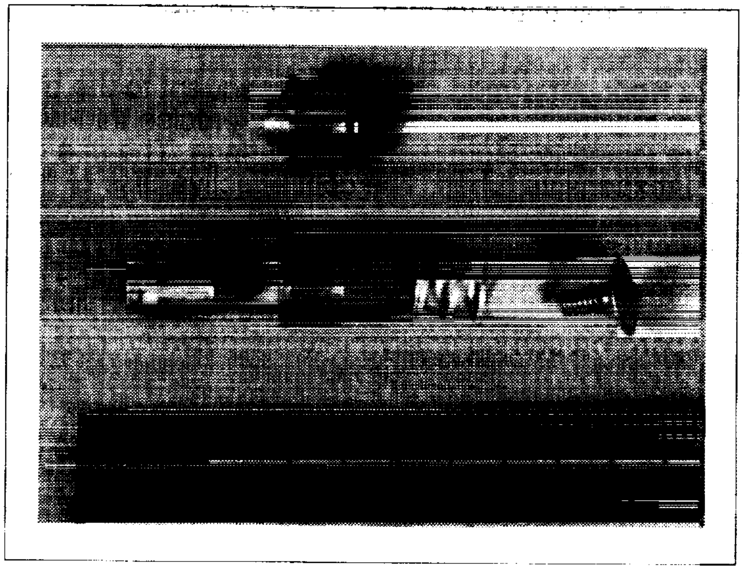


Figure 10. Development Model Latch Pin Assembly.

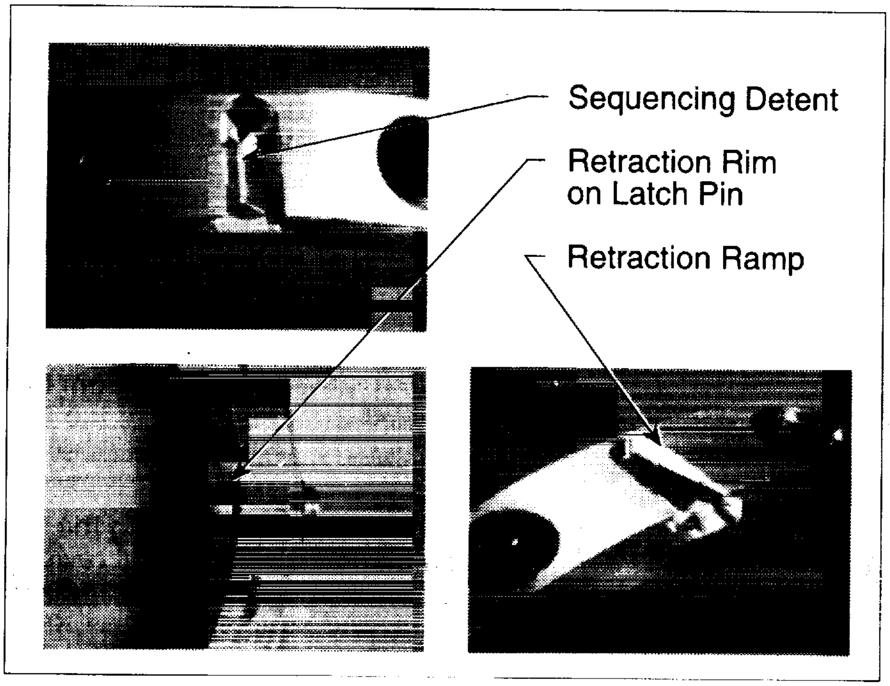


Figure 11. Latch Ring.

The tube manufacturing process is a key technology for the production of low cost telescoping boom systems. The prototype tubes were machined from heavy wall aluminum extrusions. This approach provides tubes with highly consistent dimensions and can be cost effective for smaller diameters.

Development work performed at Astro subsequent to the prototype has resulted in methods for making large and adequately precise thin-wall tubes from sheet metals that are joined to separate stiffening rings. The use of sheet stock results in relatively inexpensive tubes. The cost effectiveness of metallic tubes can be increased if sheet metals that display enhanced material properties from the forming process are utilized. Composite tubes can be bonded to separate metallic rings for further improved boom performance. Because the rings are axially short and the greatest percentage of composite fibers would be axially aligned, the coefficients of thermal expansion can be easily matched between ring and tube.

Depending upon the material, tube wall thicknesses as low as 0.25 mm (0.010 inch) are practical up to diameters of 20 to 25 cm (8 to 10 inches) without sacrificing essential durability or necessary buckling strength. Tubes of around 60 cm (24 inches) diameter in metal or composite would require minimum wall thicknesses of approximately 1 mm (0.040 inch).

The interiors of the prototype tubes are coated with a Teflon-impregnated electroless nickel plating. The plating lowers friction and prevents the aluminum from being galled by the tips of the pins as they slide along the length of the tube during deployment. The pin tips are radiused to provide a significant patch of contact area at their interface with the tube wall. Burnished tracks were left on the interior of the prototype tubes after several hundred deployment and retraction cycles, but wear was low and evidence of galling absent. In the environment of space, the high emissivity of the nickel-Teflon coating would decrease solar-induced thermal gradients across the diameter of the boom, particularly if the tube walls are not perforated.

The diametral clearance between the latch rings and adjacent larger tube walls is 0.8 to 1 mm. This allows the BI-STEM to deflect under moderate loads without binding the moving package of tubes in the deployed segments. The prototype is capable of deploying and retracting with a constant tip moment of 22 Nm (200 in-lb). This tip moment exceeds what is typically induced by the deployment tension of a large flexible solar array blanket that is cantilevered from the boom tip. The clearance between the latch rings and the inside diameter of the adjacent larger tube prevents them from touching when latched.

Detailed tolerance studies were performed while designing the tubes and latch components. The design phase revealed that a very careful review of tolerances is crucial if the latch is to display adequate structural performance, be able to sequence fail-safe deployment and retraction, and be tolerant of a moderate amount of random fabrication errors in the tubes.

PROTOTYPE BOOM PERFORMANCE

Tip load versus deflection for the 2.3-m-long prototype is given in Figure 12. The boom displays linear structural behavior, which confirms that the joints are preloaded. The data was taken after several hundred deployment and retraction cycles. The performance of the boom when new, with a latch pin preload of 9 N (2 lb), was equal to the values reported to within experimental error. Other tests were performed with a latch pin preload of 13 to 16 N (3 to 3.5 lb) which yielded somewhat higher stiffness and lower hysteresis [Ref. 2]. The preload was returned to the lower value to ensure the longevity of the boom for multiple deployment cycles.

The load-deflection curve is characterized by a region of reduced stiffness within approximately ±5 N of zero tip load that is flanked by regions of fully developed stiffness at larger tip loads. Beam theory was used to estimate the stiffness of an idealized conical aluminum boom having the same root diameter, tip diameter and wall thickness as the prototype, but without joints. The idealized boom has a tip stiffness of 9.37 N/mm (53.4 lb/in) which is about 16 percent higher than the fully developed 8 N/mm (46 lb/in) tip stiffness of the prototype.

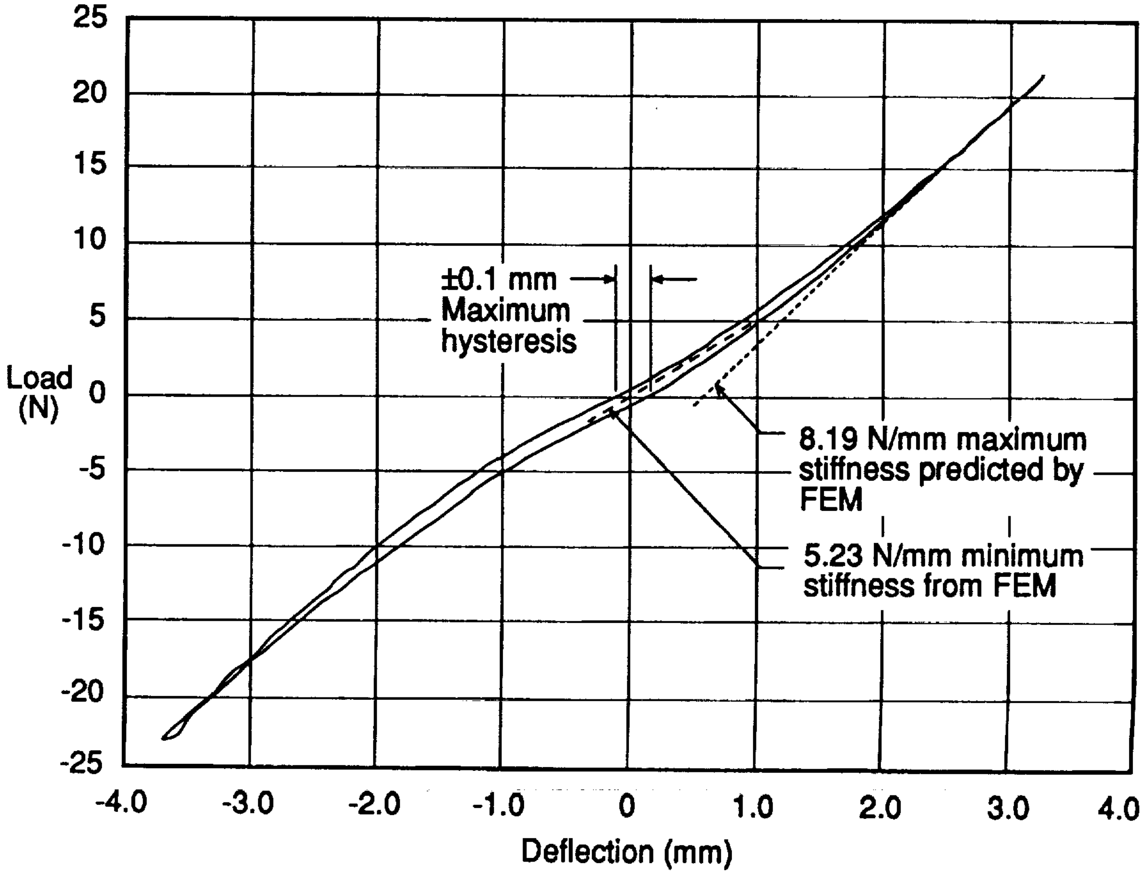


Figure 12. Prototype Boom: Tip Load Vs. Deflection.

A finite element model was constructed using COSMOS/M™ to simulate the actual geometry of the prototype boom. The FEM includes local deformations of the latch ring and tube walls that arise from the discontinuous load path between the stepped tube diameters, as shown in Figure 13. The FEM predicts a tip stiffness of 8.19 N/mm (46.7 lb/in), which correlates well with the fully developed stiffness of the prototype, as shown by the dotted line in Figure 12.

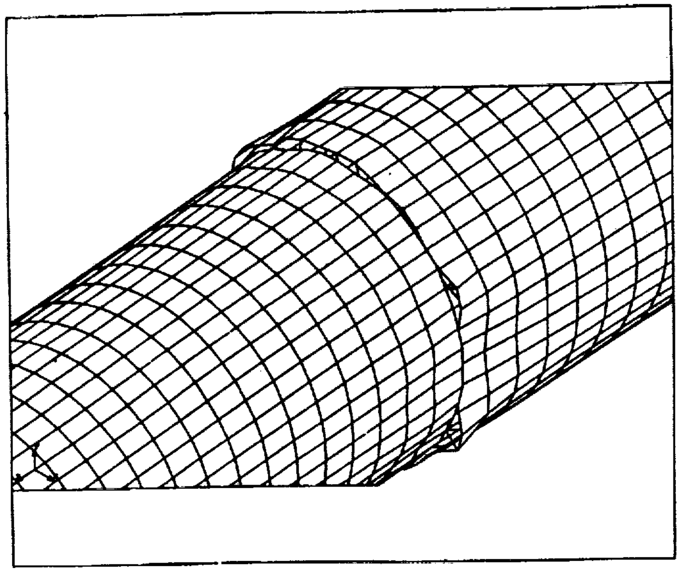


Figure 13. Finite Element Model.

The latch reduces the stiffness of the prototype to 5.1 N/mm (29 lb/inch) for small deflections, a knockdown of 39 percent. It is presumed that the diametral gap between the latch pins and the bores in the cups (Figure 5) prevents most of them from developing high local stiffnesses near zero load. As the beam is progressively loaded, all the latch pins eventually develop fully preloaded contact at the twelve latch points. To model this conjecture it was postulated that only the pins near the bending plane develop full stiffness at zero load. An FEM case was run with four pins engaged, two on each side of the boom. The four-pin case yielded a tip stiffness of 5.23 N/mm (29.8 lb/inch), as noted by the dashed line in Figure 12, which correlates well with the actual stiffness of the boom at zero load.

Hysteresis loops were repeatable to within the resolution of the LVDT used in the test, approximately ±0.02 mm (±0.001 inch). Maximum hysteresis at the boom tip is ±0.1 mm for alternating tip loads of 22 N and higher. For alternating tip loads of up to 4 N, the maximum hysteresis goes down to ±0.05 mm or less.

Dynamic damping was measured between 2 and 5 percent, depending upon amplitude, as shown in Figure 14. The data shown was initiated with a single impulse of 3 mm in the X direction. The fundamental vibration mode in the X direction differs from that in the Y direction by a small amount, probably due to the non-isotropic distribution of latch pins in orthogonal planes. At 17.5 and 17 Hz, the X and Y modes are significantly coupled, as evidenced by the modal cross-talk. For amplitudes over about 0.25 mm (0.010 inch) the damping ratio is 5 percent. Under 0.25 mm amplitude, the damping ratio is reduced to about 2 percent. The reduction of damping correlates well with the relative reduction of hysteresis that was observed at low deflections.

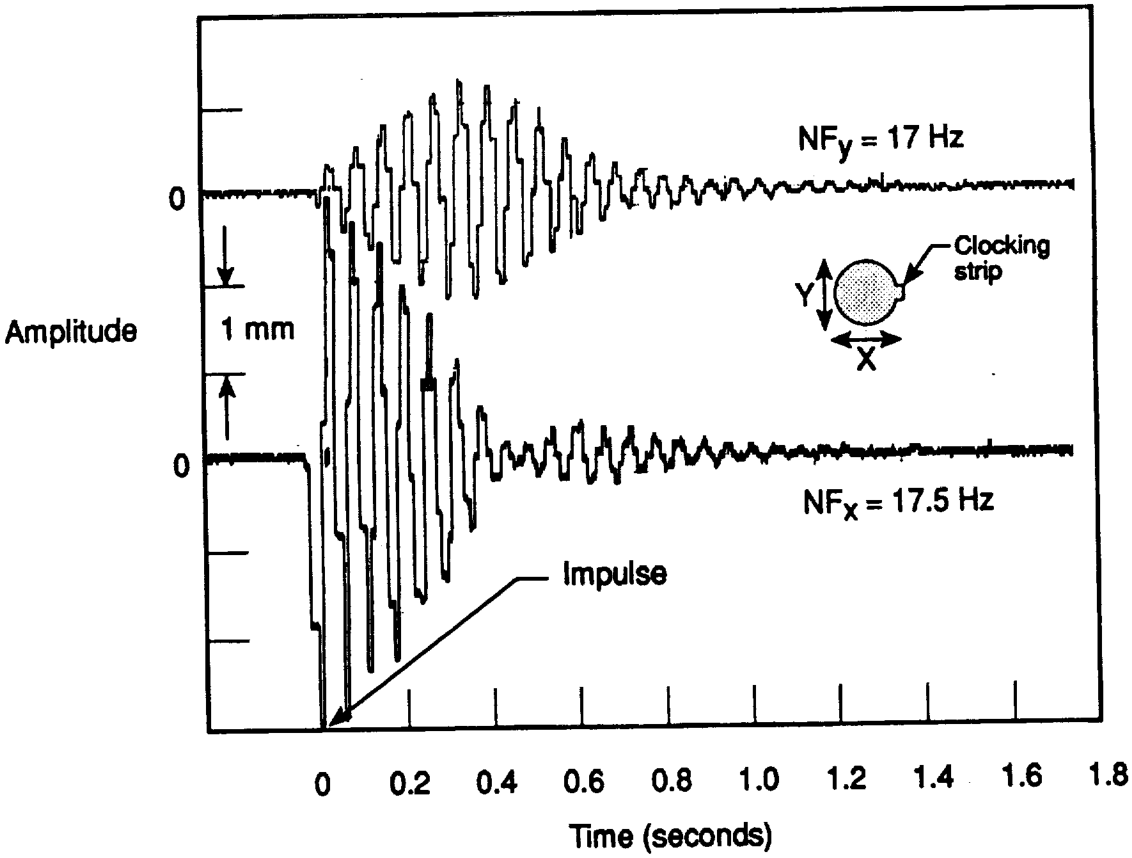


Figure 14. Damping Test Results.

DISCUSSION OF RESULTS

The 39 percent knockdown factor of the prototype latch is higher than desirable, the goal being 25 percent or less. To reduce the knockdown factor for small deflections, several things can be done. The preload can be increased, but the associated gain in stiffness would be difficult to predict. Replacement of the latch springs is very easy to accomplish, so increasing the preload is better left as an optional post-fabrication enhancement if required. Another alternative would be to increase the number of pin latches. This would reduce local deformations and increase the number of pins adjacent to the bending plane. The performance gains can be readily predicted using finite element analysis.

The preferred method of reducing structural knockdown for small deflections, however, is a matter of balancing the tube and latch ring stiffnesses. The prototype latches actually produced much greater stiffness than expected, so the thought of "improving" them leads us to review the relative stiffness of the tubes. The 0.64 mm (0.025 inch) wall thickness of the tubes in the prototype provide more stiffness than would probably be required of a boom that size for a flight program. The knockdown factor using the prototype joint as-is would be in the vicinity of 25 percent if the tubes had a 0.4 mm (0.016 inch) wall thickness, or if 40 percent of the wall material was removed by perforations for high solar thermal stability.

SUMMARY AND CONCLUSION

The new telescoping boom achieves a unique level of performance, reliability and cost effectiveness as a high performance deployable and retractable boom structure. The design of the latch, in concert with the use of the BI-STEM as an actuator, has made this stride in deployable structure design possible.

The performance of the prototype validates the potential of the boom design to position payloads with high accuracy and without structural deadband. The high stiffness and dynamic damping of the boom are advantageous for spacecraft control purposes. Finally, the strength and efficiency of tapered tubular section properties are useful for deploying large payloads and for resisting high on-orbit loads while minimizing mass and stowed volume.

Future designs will benefit from the effort expended to understand the performance of the prototype boom. The design of the latch and the tubes can be balanced to achieve the goal of 25 percent joint knockdown by utilizing the analytical techniques described herein.

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