Practical Considerations for using Constant Force Springs in Space-Based Mechanisms

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Mechanical springs are a common element in mechanism from all walks of life: cars, watches, appliances, and many others. These springs generally exhibit a linear relationship between force and deflection. In small mechanisms, deflections are small so the variation in spring force between one position and another are generally small and do not influence the design or functionality of the device. However, as the spacecraft industry drives towards larger, deployable satellites, the distances a spring or springs must function over can become considerable so much so that the structural integrity of the device may be impacted. As such, an increasingly common mechanism element is the constant force spring – one that provides a constant force regardless of deflection. These elements are commonly suggested in the conceptual design phase to deal with system-level large deflections, but in the detailed design or integration and test phase they can pose significant implementation issues. This article addresses some of the detailed issues in order for these constant force springs to be properly designed into space systems.

I. Introduction

Historically, mechanical springs have exhibited a proportional linear relationship between force and displacement represented by the well known equation F = k x, where F is the force in the spring, x is the displacement of the spring, and k is the linear spring constant. This hardware and relationship is shown in Figure 1.

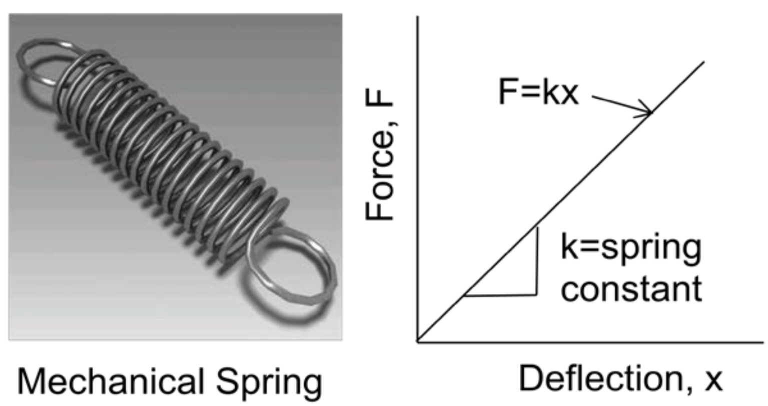

Figure 1. Linear Mechanical Spring.

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In this case, the more a spring is stretched, the larger the force in the spring. However, in the fields of robotics, deployable/separating spacecraft, and large range of motion mechanisms, a relatively new type of spring has become common: the constant force spring. These springs nominally behave as their name implies – the force in the spring is a constant value regardless of how far the spring is stretched. As shown in Figure 2 for example, these springs typically consist of a wound strip of tool steel.

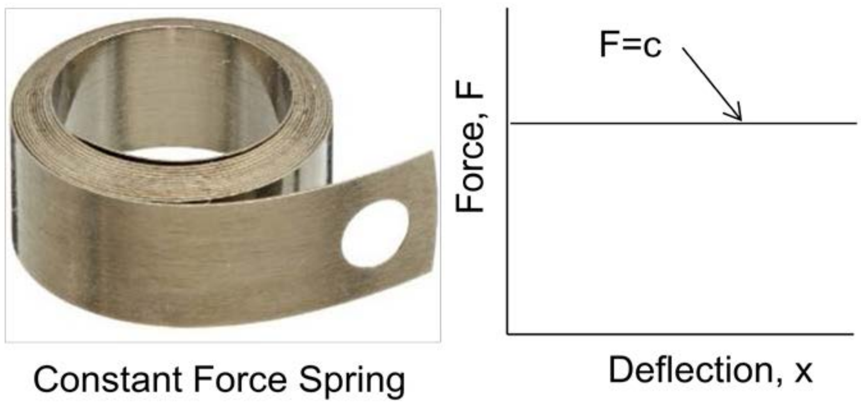
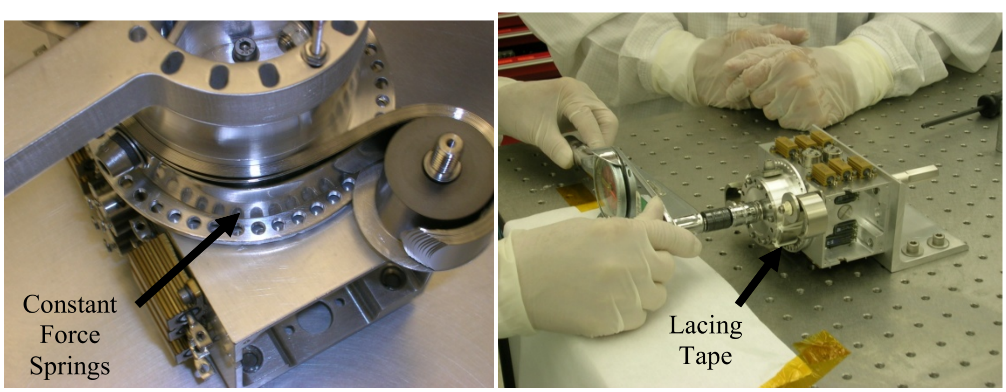


Figure 2. Constant Force Spring.

While such a device is quite useful at the conceptual design level, many practical issues arise during the implementation of constant force springs into the design of a mechanism. This article documents the practical lessons-learned for implementation of these constant force springs on various aspects of two space flight missions led by NASA's Jet Propulsion Laboratory (JPL): the Aquarius/SAC-D Observatory and the Mars Science Laboratory (MSL).

II. Use of Constant Force Springs on the Aquarius/SAC-D Mission

The Aquarius/SAC-D Observatory is an earth science satellite built through a collaborative effort between NASA and CONAE, the Argentine Space Agency and launched successfully in June 2011. The Aquarius instrument, built by JPL, measures sea surface salinity from orbit. The SAC-D spacecraft bus was built by the Argentine counterparts. The Aquarius Instrument uses a 10ft diameter deployable Reflector at the end of a deployable Boom as part of the aperture to collect the desired scientific data. The Reflector and Boom are deployed on orbit using constant force spring-loaded hinges. The stack of constant force springs used in the deployable hinges is shown in Figure 3.



(a) (b)

Figure 3. Aquarius Deployment Hinge Mechanism (a) showing unwanted gaps between spring layers (b) shows the lacing tape used to clamp the spring layers together. (Photos courtesy of NASA JPL/Caltech)

The Observatory is shown in Figure 4, along with the Gravity Offload Fixture (GOLF) during a deployment test in the LIT Test Facility in Brazil. The GOLF is a piece of Mechanical Ground Support Equipment (MGSE) designed using constant force springs to offload the weight of the Aquarius deployable Reflector and Boom during deployment testing on the ground. As shown in Figure 4, the Boom and the Reflector were each attached to constant force spring mechanisms which were sized to provide a vertical force equal to the weight of the hardware along the respective CG. Such offloading enables the deployment to be tested in more on-orbit-like conditions. Furthermore, the GOLF prevented the hinges and primary structure from being required to support the weight of the Boom and Reflector in the deployed state in 1-g, thus greatly reducing hinge/structure mass.

Figure 4. Aquarius/SAC-D Observatory and Gravity Offload Fixture (photo courtesy of NASA JPL/Caltech).

III. Use of Constant Force Springs on Mars Science Laboratory

Mars Science Laboratory is NASA's next generation Mars rover that launched in November 2011 and landed on the Martian surface in August 2012. When the spacecraft reached the Martian atmosphere, it went through a series of sub-system separations as expended or unnecessary portions were jettisoned during the Entry, Descent and Landing phase. When the Cruise Stage separated from the Entry Vehicle, electrical cables were severed by a pyro-fired cable-cutter, and the free ends of the cable were retracted into the Cruise Stage by a constant force spring-driven mechanism. Figure 5 shows the original cable retraction mechanism with two constant force springs and the clamped interface between the spring tips and the cable bundle inside the Cruise Stage. Issues with this design are discussed in the Lessons Learned sections below.

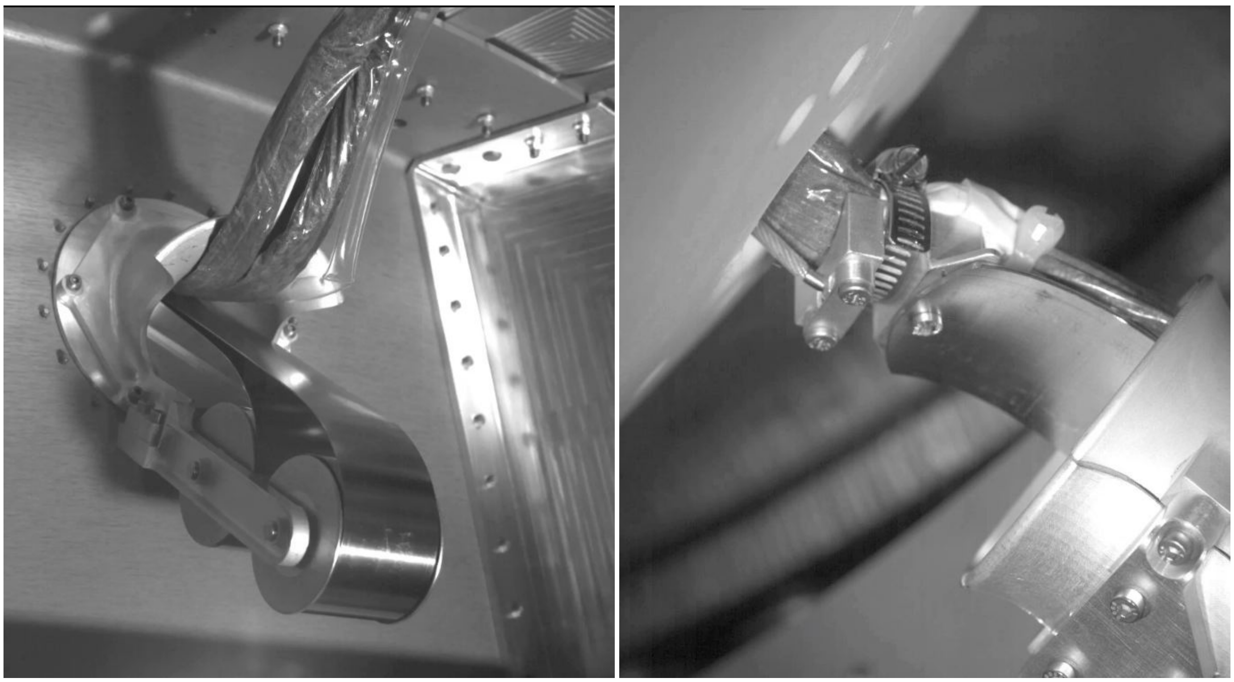


Figure 5. Cable Retractor Mechanism on MSL Cruise Stage (original design). (Photos courtesy of NASA JPL/Caltech)

IV. Lessons Learned for use of Constant Force Springs

In the development of the GOLF, deployment hinges, and cable retractors described above, many challenges and unexpected spring behaviors were observed. The goal of this section is to show quantitative and qualitative data that describes the issues encountered.

A. Issue 1: Non-Constant Force

Despite their name, constant force springs do not really provide a constant force output in several senses. Figure 6 shows two force-deflection curves for pairs of constant force springs mounted back to back in the Aquarius GOLF. First, about 1/3 of the force is obtained with little to no spring extension at all. There is then a clear ramp up in force over about 1.5x the diameter of the spring. Next, both pairs of springs exhibit some force oscillation about their nominal constant force. This oscillation means that more or less force is put into the system than expected which could cause an overload condition or an under-offloaded condition and risk the hardware. This non-constant behavior must be accounted for in the mechanism geometry and structural design. Even within the "constant force" deflection region, the force still varies by some amount, especially near the end of spring travel.

Next, the two families of curves on each plot were measured before and after the springs were removed to proofload their structural housing. After reassembling the offload mechanism, during which the spring diameters are adjusted slightly to fit snugly onto their mounting hubs, the force curve is shifted. Therefore, the spring force must be characterized in-situ and recharacterized after any reassembly.

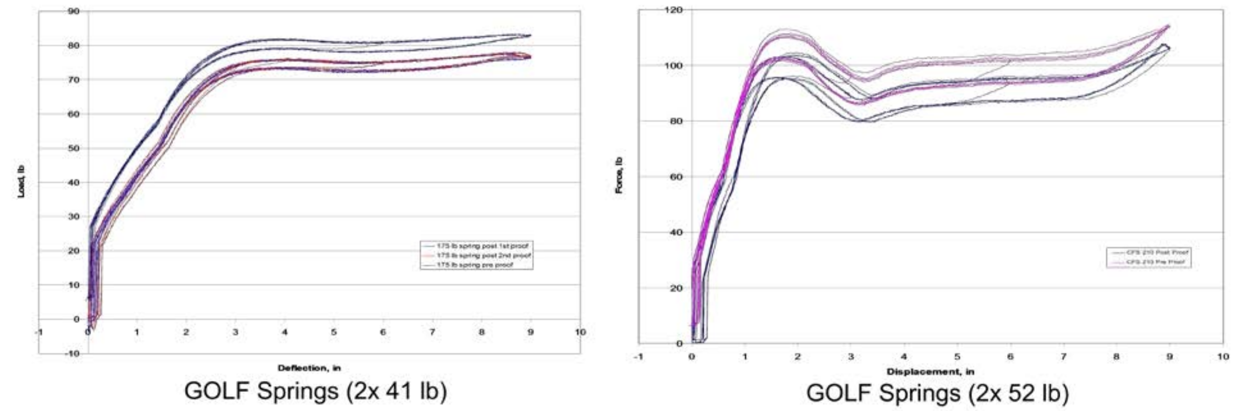


Figure 6. Force vs Deflection Curves for Two Back-to-Back Constant Force Springs.

Next, considering any curve in Figure 6, the first time a spring is extended after mounting provides a slightly higher force profile than every subsequent spring extension. Therefore, it is important to understand and "run-in" a spring at least once before its force is applied to the flight hardware.

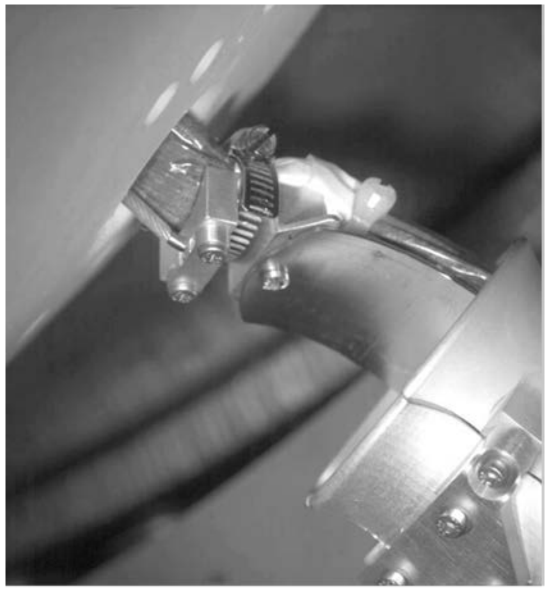
Lastly, all four curves exhibit a great deal of hysteresis. The upper branch of the hysteresis curve is for increasing load. When the peak load is reached and the load/deflection decreased, the springs suddenly lose a potentially significant amount of their force. This behavior is related to the mounting approach as discussed in the next section.

B. Issue 2: Mounting of Constant Force Springs

Another issue with implementing these types of springs arises with their mounting design. Figure 7 shows the housing and large metal hub/axle required to mount the constant force spring so that it can be engaged and supported properly. This hub is typically metal to handle the often large forces developed in these springs and the housing must also be suitably sized. These components can add unexpected mass to the flight system.

Figure 7. Housing and Axle for Aquarius GOLF Constant Force Spring.

The next issue with constant force spring mounting relates to how the free end of the spring interfaces to the hardware. These springs typically come with one or two holes in the end, however, a custom designed interface, as shown in Figure 8, is almost always required that adds mass and complexity to the mechanism design.



MSL Cable Retractor

Figure 8. Custom Clamp design required to interface spring tip to cable bundle.

The next mounting issue stems from the need to use ball bearings to reduce the friction between the hub and the axle used to mount the spring. Bearings, which lower friction, improve the spring performance in several ways that can be seen in Figure 9. The plot on the left shows the hysteresis curve for a spring mounted without bearings, while the plot on the right shows the same springs tested with a bearing mount. First, the data show that the bearings reduce the overall amount of hysteresis from 10-25% down to 3-9%. In addition, the bearings allow for a gradual unloading as opposed to a large, rapid drop in spring force. Based on these results, all constant force spring mounts should use ball bearings to reduce friction if hysteresis and sudden changes in load are to be avoided.

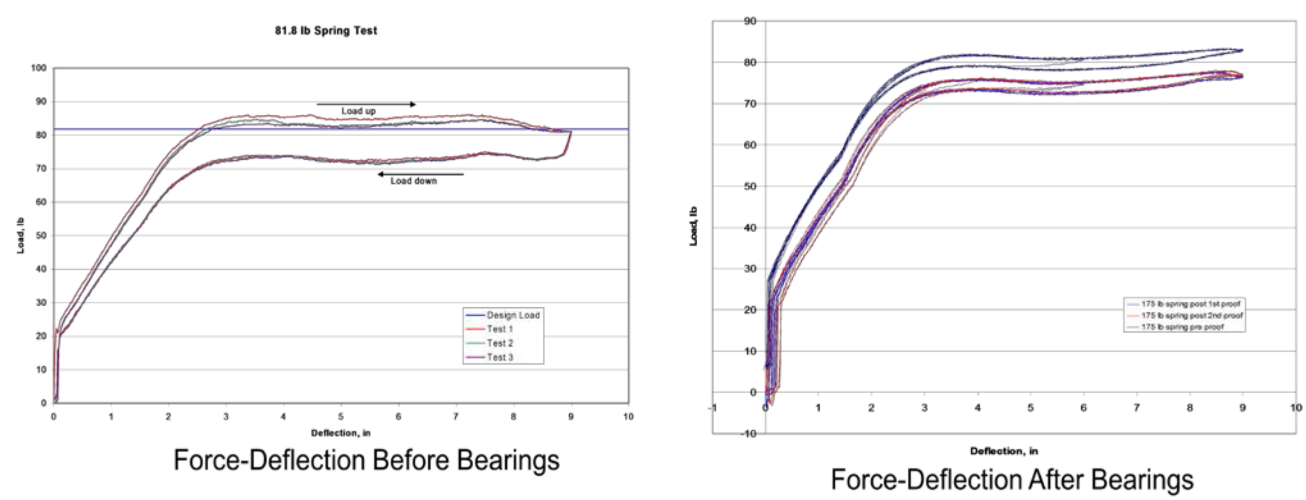


Figure 9. Spring force curves without (left) and with (right) ball bearing mounts.

C. Issue 3: Constant Force Spring Instabilities

As a constant force spring reaches its full range of extension, they have the tendency to become structurally unstable. As shown in Figure 3, the stack of constant force springs tends to separate under full extension. The resulting fix was lacing tape used to secure the spring segments together. Also, as shown in Figure 10, a single constant force spring will tend to twist or buckle when fully extended. While this instability does not necessarily change the force in the spring, it can be an unacceptably risky structural mode.

Figure 10. Twisted, Fully Extended Aquarius GOLF Spring.

D. Issue 4: Nonlinear Retraction

The last main issue with constant force springs is that they do not retract in a linear direction. Figure 11 on the left shows the original MSL cable retractor design on the the Cruise Stage with 2 constant force springs in the so-called "tandem" configuration. The right side of Figure 11 shows the tips of these springs clamped to the cable bundle that passes up from the Entry Vehicle. The white foam is part of the Thermal Protection system.

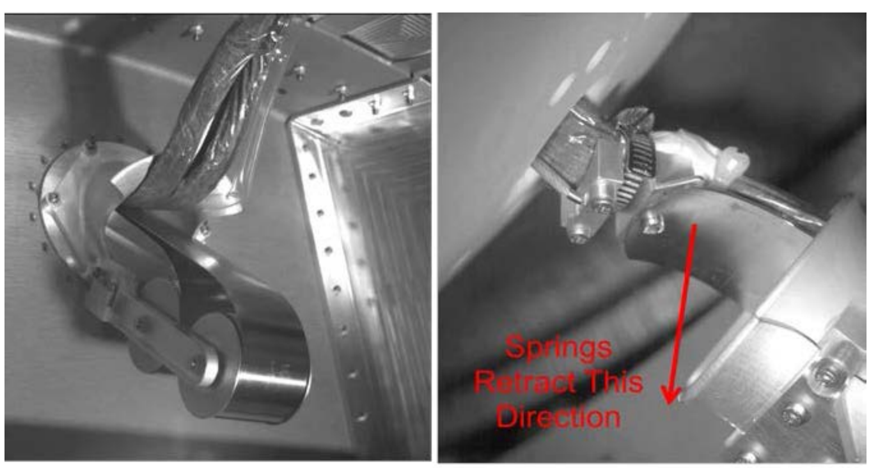


Figure 11. Original MSL Cable Retractor Design with Springs in Tandem Configuration.

As indicated, the wrapped nature of the springs causes them to re-wrap in a circular direction when released. As a result of this nonlinear retraction, the spring tip moved tangentially and damaged the thermal protection foam as shown in Figure 12.

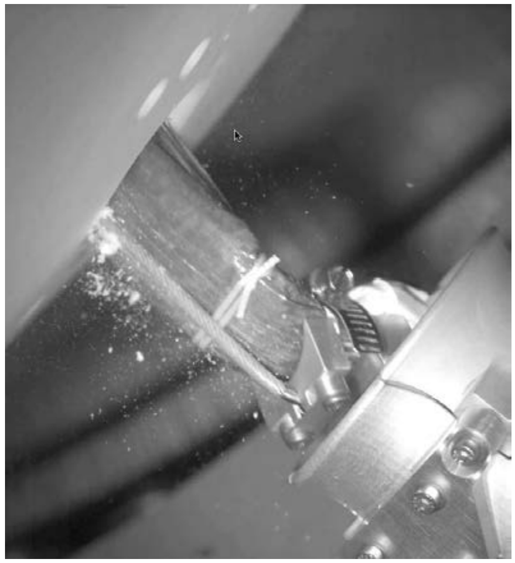


Figure 12. Damage to Thermal Protection System caused by Nonliner Retraction of Constant Force Spring.

As a result of this separation/retraction test, the MSL Cable Retractor had to be redesigned as shown in Figure 13 with the springs in the much more stable "back-to-back" configuration. In this configuration, the springs balance each other out and the result is a linear retraction. This mounting configuration is recommended by the manufacturer to maximize spring stability.

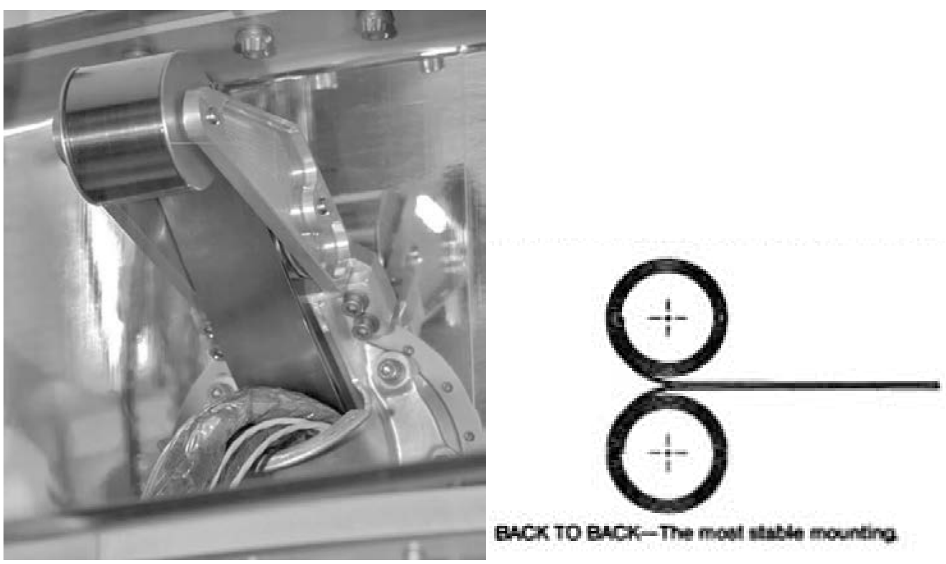


Figure 13. Redesigned MSL Cable Retractor with "Back to Back" Springs.

It should be noted that for this application, the force output of the springs is not necessarily required to be constant because the job of this mechanism is to go from point A to B with a roughly constant force. Therefore, bearing mounts are not necessary, nor is detailed characterization of the force-deflection curve. However, the added mass of the mounting hub and housing are appreciable and should thus be accounted for early in the Systems Engineering effort.

V. Conclusion

This article has provided data that indicate many of the issues that arise during the design and implementation of constant force springs into space-based mechanisms. While this type of spring is suggested often during the conceptual design phase, the challenges of their actual application are not widely known and understood. These devices can work very well, almost as good as their name suggests, but it is important for both systems engineers as well as mechanical designers to be cognizant of the subtle behaviors so that the springs can be mounted and tested properly to ensure proper functionality and not jeopardize mission success.

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