LOW SHOCK NON-EXPLOSIVE ACTUATOR

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ABSTRACT

Launch vehicles are increasing their payload capacity; at the same time these payloads are becoming more sophisticated and susceptible to damage from shock. Sensitive payloads and their components can be damaged by imparted shock from the mechanisms designed to release them. This is true for payloads released from a launch vehicle as well as releasing individual components of a payload after deployment. An increasing need has arisen for release mechanisms capable of restraining higher loads, while reducing emitted shock, yet remaining relatively small and light weight.

To address this need, a non-explosive actuator has been developed that combines new innovative mechanism concepts with heritage proven design elements from G&H Technology products. The new mechanisms provide significant increases in mechanical advantage and space/mass efficiencies that are required to support reduced imparted shock across a wide range of load conditions without compromising release times.

1. GENERAL SPECIFICATIONS

Design goals for this new product included:

- Significantly reduced imparted shock when compared to the G&H Technology Model 9421 at 22,241N (5,000 lb_f) maximum preload and 27,801N (6,250 lb_f) ultimate load ratings.
- Maintain a small compact design envelope.
- Easily field resettable with minimal tooling.
- Provide options for multiple types of payload attachment (bolt, shaft, cable, etc…).

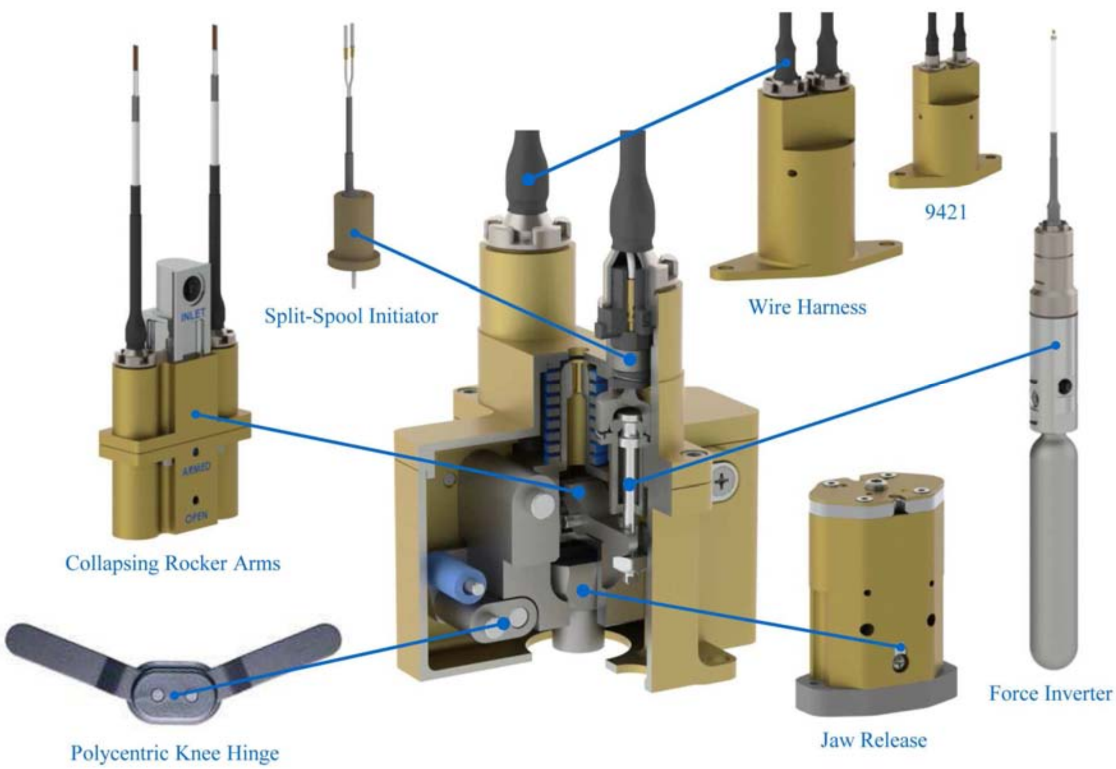

Figure 1: Design Concept Cut View

- Allow for an initial attachment misalignment of at least 4°.
- Reduce cost by using Commercial Off The Shelf (COTS) components and design for manufacturing methodologies.
- Reduction of risk by leveraging heritage-proven platforms and design elements.

2. DESIGN CONCEPT

A combination of heritage proven and new design elements were utilized to produce a reliable and predictable device. Fig. 1 shows a partial cutaway view of the initial conceptual design, surrounded by the heritage products from which existing design elements were utilized.

The G&H Technology Model 9421 separation nut requires a 1,112N (250 lb_f) preload spring to overcome the frictional forces imparted by the locking sleeve during actuation. Upon actuation, the locking sleeve is stopped by a rubber damper. Fig. 2 shows a cross section of the Model 9421 in its armed position. The shock created from this hard stop contributes towards the majority of the source shock and is inherent in the design.

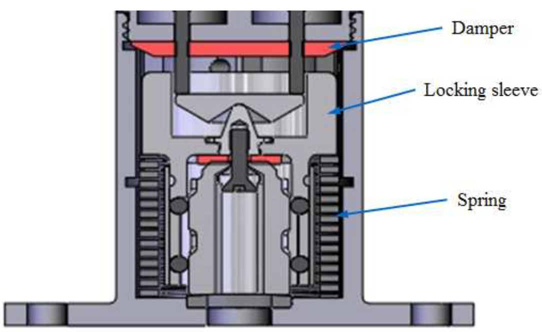

Figure 2: Model 9421 Cross section.

The Low Shock Non-Explosive Actuator eliminates the need of the driving spring by using a portion of the payload preload for separation. In order to achieve this, a system of mechanical advantage is necessary to reduce the preload down to the operational limits of the split spool initiator.

2.1. Patented Split-Spool Initiator

The split-spool initiator assembly is shown in Fig.3. The spool is comprised of two half cylinders with a conical surface on one end. One spool half incorporates a fusible link wire while the other half has features to tie off the restraining wire after wrapping. The two spool halves are placed together and the restraining wire is connected to the spool via a looped end to the fusible link wire. After the spool halves are wrapped spirally, the other end of the restraining wire is tied off to the other spool half to complete assembly. When the spool is placed in the actuator, it is held in compression between the wiring harness insulator and the plunger which is in contact with the conical surface of the spool.

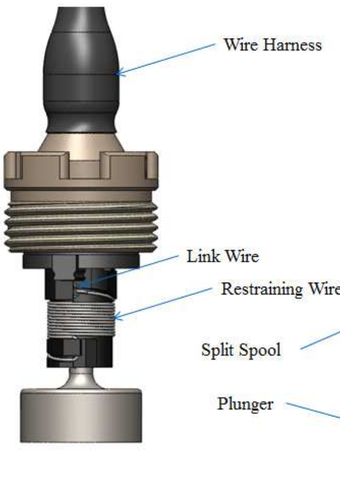

Figure 3: Split Spool Assembly Armed

When an electrical pulse is applied, the fusible link opens and the looped end of the restraining wire is freed. As the restraining wire unravels, the spool halves are free to separate allowing the plunger to drive through as shown in Fig. 4. The Low Shock Non-Explosive Actuator uses two initiator spools working independently allowing the system to actuate normally in the event of firing circuit failure.

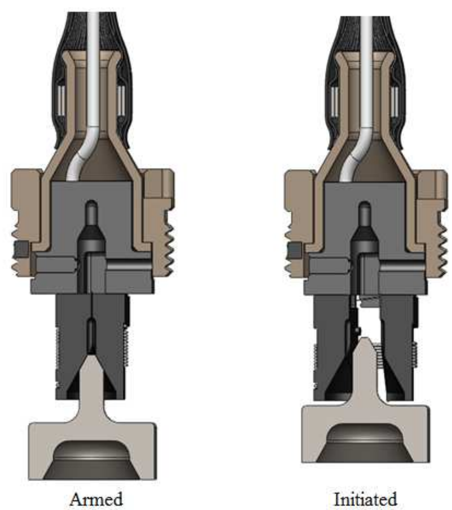

Figure 4: Split Spool Assembly Initiated

2.2. Force Inverter

The force inverting mechanism converts the downward load from the tension shaft to an upward load on the plunger against the spool assembly, as shown in Fig. 5. In addition to changing the direction of the load, the interaction of angled geometry of the components increases the overall mechanical advantage of the system by approximately 2.5:1.

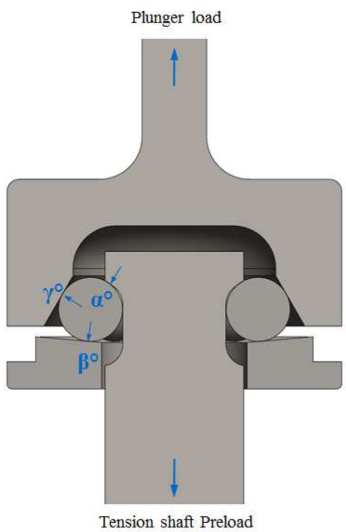

Figure 5: Force Inverter

2.3. Collapsing Rocker Arms

The collapsing rocker arm is a departure from prior rocker assembly designs. The collapsing rocker allows the redundant spool assembly system to function when either or both spool assemblies are initiated. Fig 6 shows the assembly when armed with the load path.

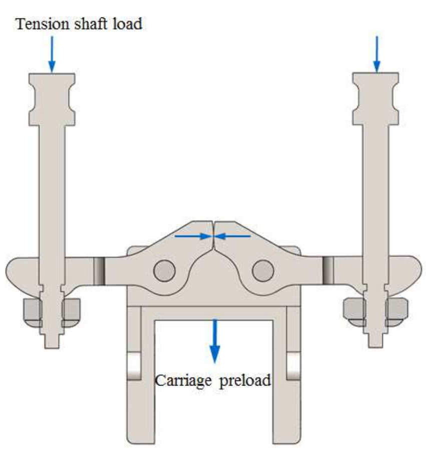

Figure 6: Collapsible Rocker Arms - Armed

When one of the two redundant spools is initiated, the rocker arm rotates with respect to each other and the carriage is free to displace downward as shown in Fig. 7. The mechanism allows the rocker to function independently with respect to the spool assembly.

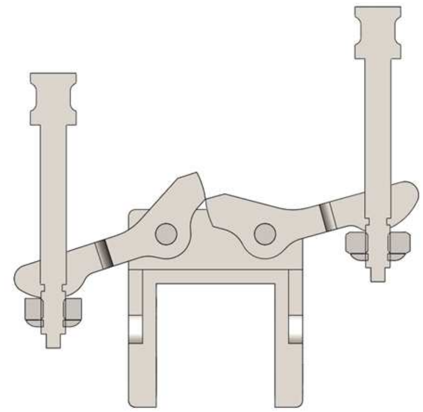

Figure 7: Collapsing Rocker Arm - Initiated

2.4. Polycentric Knee Hinge

The polycentric hinge design is similar to a 4-bar crank-rocker that is typically used in a knee brace design. The difference in the mechanism is that the crank angle is limited to crank and connecting rod angle.

The Low Shock Non-Explosive Actuator uses the concept of an angle limited polycentric knee hinge mechanism in a configuration that the output link is not reciprocating and uses a double sided 4-bar crank slider as shown in Fig. 8. The linkage length and angle was varied in order to increase overall mechanical advantage in the system.

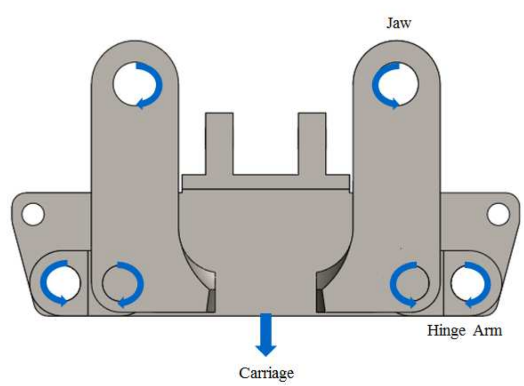

Figure 8: Polycentric Hinge Design

2.5. Jaw Release

The jaw release mechanism is a derivation of the G&H Technology's jaw release mechanism. The mechanism releases a threaded shaft with a ball end, allowing for initial attachment misalignment. The Low Shock Non-Explosive Actuator uses this concept and has a segment that can swivel at angles up to 5° conically from vertical. Fig. 9 shows the threaded segment payload attachment configuration which may be substituted for other types of attachments such as a threaded shaft.

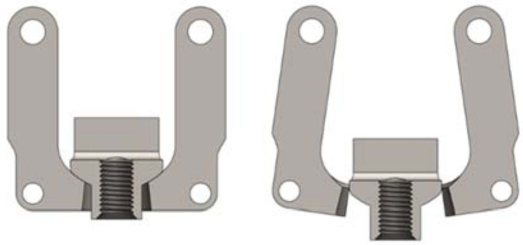

Figure 9: Jaw Release

2.6. Cost and Risk

The assembly consists of 38 different parts and 4 sub-assemblies. Of the 38 parts;

- 17 are military specification or COTS components.
- 11 are existing heritage-proven designs.
- 10 are new unique components.

By using COTS parts and heritage parts, cost and risk is minimized.

3. OPERATION AND RESETTING

3.1. Operation

Once the separation device is mounted using 4X #6-32 screws and washers, the payload can be attached with a proof preload of 22,241N (5,000 lb_f). The separation device can be wired to a typical pyrotechnic circuit. Fig. 10 through Fig. 12 shows the operation sequence based on a single circuit actuation.

1. Armed - Fig.10
   a. A current pulse is applied to one of the initiator spools.
2. Spool – Initiation - Fig. 11
   a. Plunger displaces upward as the spool halves separate.
   b. Tension shaft moves downward as the bearings move outward.
   c. Collapsing rockers rotate clear of each other.
   d. Carriage moves downward.
   e. Hinge arms rotate from the carriage displacement.
   f. Jaws rotate from the hinge arm movement around housing joint.
   g. Segment moves downward from the rotation of the jaws.
3. Actuated - Fig. 12
   a. The jaws open to a point which allows the sacrificial segment to clear the actuator.
   b. The bumper tubes prevent metal to metal contact of the internal components at the end of travel.

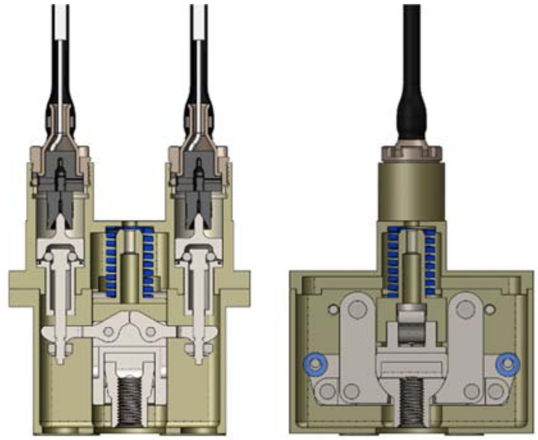

Figure 10: Armed

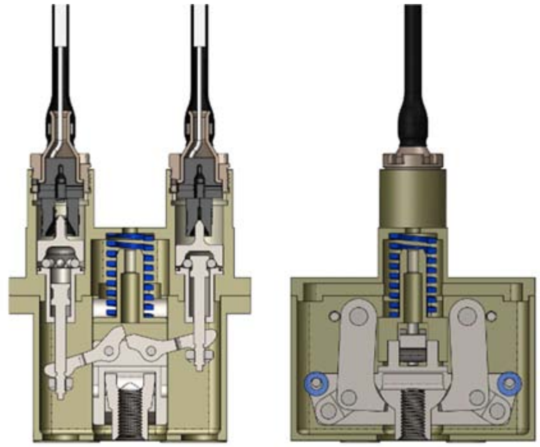

Figure 11: Spool Initiated

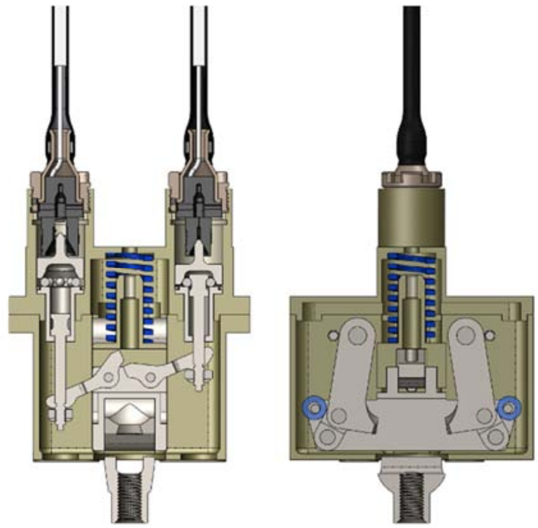

Figure 12: Actuated

3.2. Resetting

From lessons learned from heritage products and customer feedback, resetting of the Low Shock Non-Explosive Actuator is accomplished within a couple of minutes. The only tools needed for resetting are a simple resetting stand, spanner wrench, #6-32 screw and driver. The user will be able to reset on the spot with minimal downtime during any testing.

4. INITIAL PROTOTYPE

4.1. Initial Evaluation

Preliminary testing identified opportunities for several design refinements. Modifications were made to the initial prototype in order to perform further evaluation on the unit. These changes were implemented to prove out the viability of the design concept. In addition, sections of the housing were cut away, in order to visually evaluate the motion of the internal components during additional testing.

4.1.1. Hinge Arm

The hinge arm of the mechanism was altered as well. The initial design had the arm joints horizontal to each other. This results in a purely horizontal load. Due to tolerances, the arm may rotate in a clockwise or counter clockwise direction, depending on the angle between the two joints. This was alleviated by creating an initial angle between the joints to ensure that the mechanism could only rotate in one direction as shown in Fig. 13. A mechanical stop was also added to prevent rotation of the arm in the opposite direction.

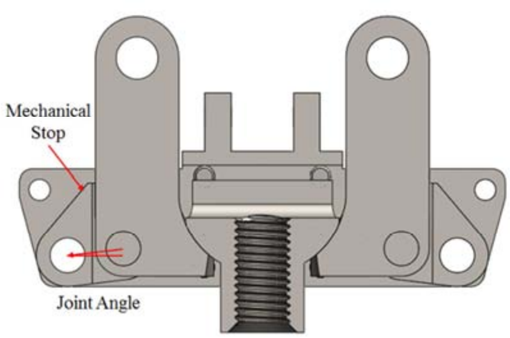

Figure 13: Arm modifications

4.1.2. Carriage stability

Secondary testing revealed a lateral instability in the motion of the carriage that prevented preloading to the maximum designed capacity of the actuator. This was found to be caused by altering the initial angle of the hinge arms. In a classical 4 bar crank-slider mechanism, the slider (carriage) is guided on a rail in order to provide a purely linear translation.

The carriage in the initial design would rotate when preloaded due to the instability created from the initial angle of the hinge arm. This was alleviated by drilling and press fitting 4 pins on each side of the carriage. The pins would press up against the aluminium housing to prevent any rotation when preloading the device as shown in Fig. 14.

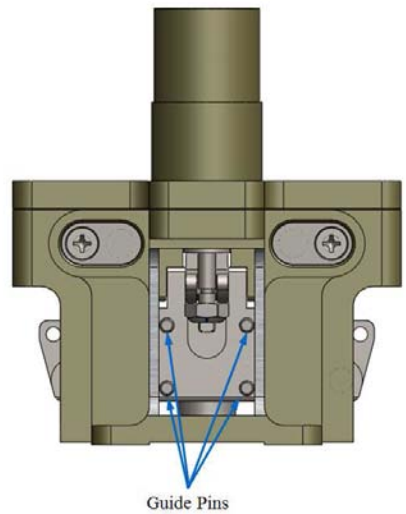

Figure 14: Carriage modification

4.2. Mechanical Advantage Test

In order to achieve the ultimate load of 27,801N (6,250 lb_f) of preload without damaging the spool assembly, a mechanical advantage of 25:1 was necessary.

The prototype was loaded into a fixture as shown in Fig 15. The fixture allowed for a load cell to be attached in replacement of the spool and a compression load cell to measure the bolt preload.

Fig. 16 shows the plot of bolt preload vs. time on the primary axis and spool load and mechanical advantage vs. time on the secondary axis. The plot shows that an average of 20:1 mechanical advantage was achieved. The load was limited to approximately 13,344N (3,000 lb_f).

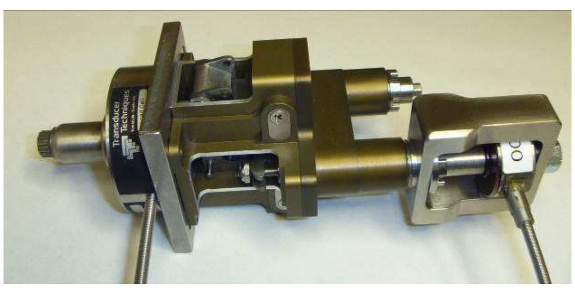

Figure 15: Spool load test set up

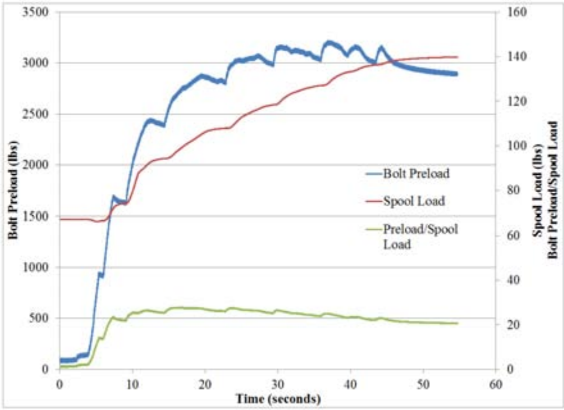

Figure 16: Mechanical Advantage

4.3. Source Shock Test

One of the primary reasons for the new design was to reduce the shock imparted from the separation device. A model 9421 series separation nut was used as a comparison to the new Low Shock Non-Explosive Actuator.

4.3.1. Test Setup

The test setup used a 61 cm X 61 cm X 1.9 cm thick (2 ft. X 2 ft. X 0.75 in.) aluminium plate. The plate was suspended using a bungee cord on each corner. Two tri-axial accelerometers were mounted approximately 5 and 10 inches away from the center of the plate as shown in Fig 17.

The test performed was to electrically actuate each separation device; with zero preload and with various preloads.

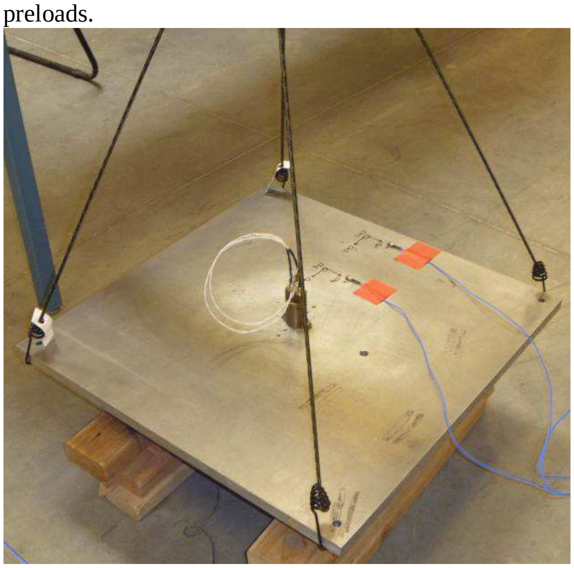

Figure 17: Example Test Set up

4.3.2. Test Results

Initial results shows shock is reduced in comparison to the Model 9421. Fig. 18 is a summary of the shock response spectrum (SRS) results. It has a plot of both devices that is separated at preloads of zero and 6,672N (1,500 lb_f). In frequencies below 100 Hz, the 9421 generates a shock more than 100 times greater than the Low Shock Non-Explosive Actuator.

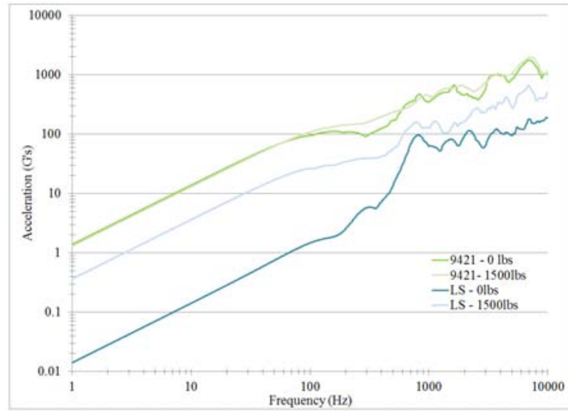

Figure 18: SRS at various loads

Fig. 19 shows the Low Shock Non-Explosive Actuator SRS with loads of zero, 4,448N (1,000 lb_f), and 6,672N (1,500 lb_f). The dark blue line represents zero load with the SRS curves increasing with preload. This shows that the payload preload is the dominant source of shock. The source shock due to payload release is inherent in the concept of a quick releasing actuator (< 25 milliseconds release time).

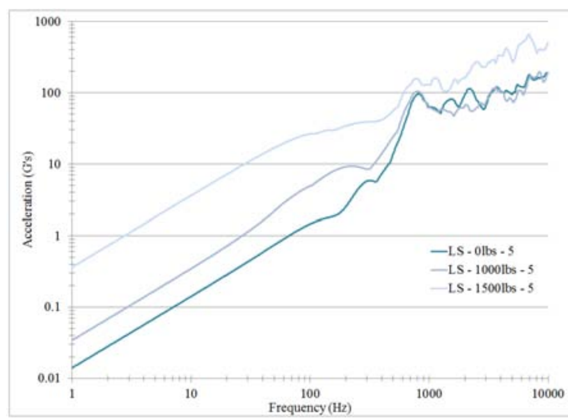

Figure 19: SRS of Low Shock Non-Explosive Actuator at various loads

Fig. 20 shows the Model 9421, with the same preloads. The curves are all approximately the same. This shows that the preload spring, internal to the unit, is the dominant source of shock up to 6,672N (1,500 lbf).

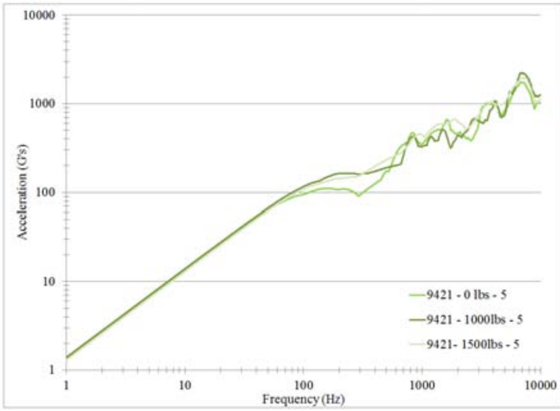

Figure 20: SRS of 9421 Actuator at various loads

5. VERSION 2.0 DESIGN IMPROVEMENTS

5.1. Force reduction

From the initial testing, there was not enough margin in the mechanical advantage to safely reach 27,801N (6,250 lb_f) ultimate preload. Since most of the mechanism incorporates heritage proven designs, the focus was modifying the polycentric hinge design.

Hand calculations were initially performed in order to determine the length of the jaw (crank) and the arm (connecting rod). Finite element analysis was performed in order to determine the reaction force at each pin joint. Fig 21 and 20 shows the 2 planar views of the Finite Element Model (FEM), with joints of the polycentric hinge defined for a preload of 27,801N (6,250 lb_f). Table 1 shows the reaction force at each joint. The load shown in the table is only for ½ the model (13,900N per side). All pin joints were sized in accordance with the expected loads.

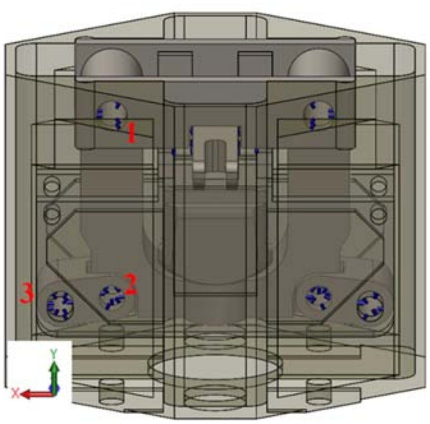

Figure 21: Pin joints definition in X-Y plane

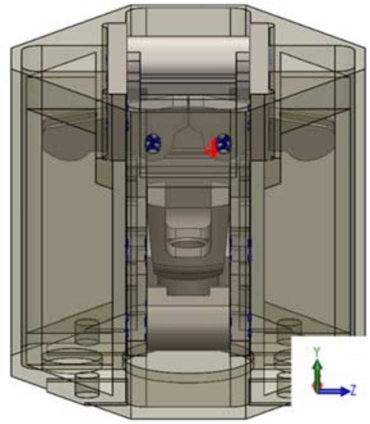

Figure 22: Pin joints definition in Y-Z plane

Table 1: Joint Force

		Force Newtons (lbs)		
Joint	**Description**	**X-dir**	**Y-dir**	**Z-dir**
1	Jaw to Load Plate	-3,336 (-750)	12,455 (2,800)	0
2	Jaw to Arm	12,010 (2700)	1,334 (300)	0
3	Arm to Carriage	-12,010 (-2700)	1,334 (300)	0
4	Carriage to Rocker Arm	0	1,334 (300)	4,448 (1,000)

The reaction loads were found at the base of the housing and the interface between the collapsing rocker and tension shaft, as shown in Fig. 23.

The load that is applied to one of the tension shafts is approximately 1,334N (300 lb_f). With the mechanical advantage of the force inverter of 2.5:1, the total load on the spool is expected to be 445N (100 lb_f), well below the limit of the spool. The base of the housing had a reaction force of 25,132N (5,650 lb_f), distributed between the four mounting pads.

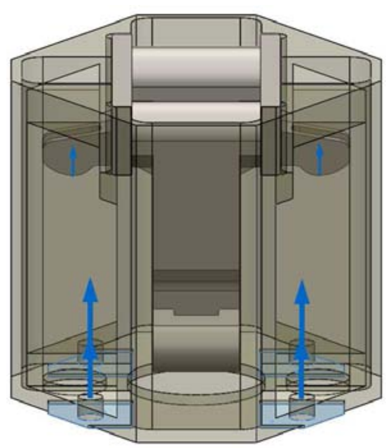

Figure 23: Load on Housing and Tension Shaft

5.2. Components Redesign

In addition to optimize the geometry of the linkages, several other components were redesigned to improve the actuator's performance.

1. Changed engagement angle between the segment to jaw.
2. Changed geometry of the jaw joint location to increase horizontal load and minimize vertical load. Weight was reduced by removing material from low stress areas.
3. Hinge arm assembled at a slight angle in order to have a vertical force component on the carriage.
4. Carriage redesigned for provision of a guide to facilitate a linear displacement. Other geometry changes in order to reduce stress on pin joint and reduction in weight through webbing.
5. Rocker redesigned for greater strength.
6. Load plate added to distribute load on jaw pins and add a carriage guide feature.
7. Cover to base interface was redesigned for structural strength and reduction of weight, where possible.
8. Base completely redesigned to package mechanism.
9. Anti-rattle spring changed from die spring to compression spring.
10. Tension shaft has a slot cut where it interfaces with the rocker to improve the ease of assembly and adjustment.

5.3. Stress Analysis

The stress was verified with the version 2.0 design through finite element analysis. The analysis was performed on the entire assembly with the exception of the force inverter, split spool assembly and the top cover.

The loading scenario was used from the force analysis to determine the maximum stresses for each component. Then the entire assembly was loaded with an ultimate load of 27,801N (6,250 lb_f). A stress distribution image is shown in Fig 24 and Fig 25 in the two planes. The maximum stress occurs in compression between the segment and the jaws, shown in red. All other stresses are below 689 mega Pascal (MPa).

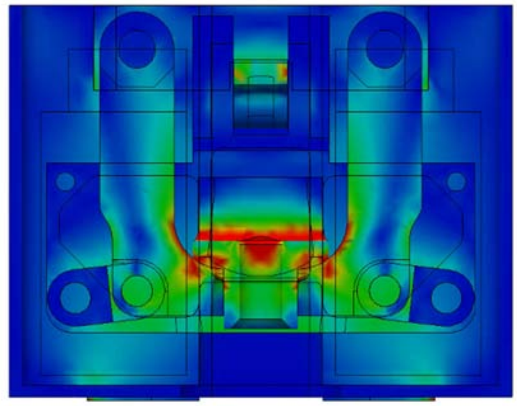

Figure 24: FEA results in plane 1

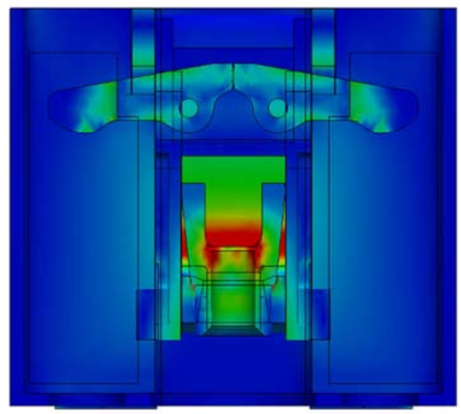

Figure 25 FEA results in plane 2

6. CONCLUSION

This paper has described the evolution of an initial prototype to a version 2.0 product that combined heritage-proven technologies with new innovative design elements. The resultant product offers significant feature and performance improvements when compared to the prior generation of non-explosive actuators:

- Imparted shock is less than 1/100th of the Model 9421 separation nut without compromising response times.
- Faster field-reset capabilities.
- A design platform that is scalable across an extended range of load conditions.

This new product has met or exceeded all initial design goals and has resulted in the filing of U.S. Patent Application No. 13/968,168.