

DESIGN AND DEMONSTRATION OF BOLT RETRACTOR SEPARATION SYSTEM FOR X-38 DEORBIT PROPULSION STAGE

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Abstract

A separation system was designed for the X-38 experimental crew return vehicle program to allow the Deorbit Propulsion Stage (DPS) to separate from the X-38 lifting body during reentry operations. The configuration chosen was a spring-loaded plunger, known as the Bolt Retractor Subsystem (BRS), that retracts each of the six DPS-to-lifting body attachment bolts across the interface plane after being triggered by a separation nut mechanism. The system was designed to function on the ground in an atmospheric environment as well as in space.

The BRS provides the same functionality as that of a completely pyrotechnic shear separation system that would normally be considered ideal for this application, but at a much lower cost. This system also could potentially be applied to future space station crew return vehicles.

The design goal of 40 ms retraction time was successfully met in a series of demonstrations performed at the NASA Marshall Space Flight Center's Pyrotechnic Shock Facility (PSF) and Flight Robotics Laboratory (FRL). It must be emphasized that a full-scale test series was not performed on the BRS due to program schedule and cost constraints.

Introduction

In the late 1990's, NASA conceived the X-38 lifting body and Deorbit Propulsion Stage (DPS) as a prototype for a full size Crew Return Vehicle for the International Space Station. The lifting body was to act as a "lifeboat" for seven crewmembers in the event of a catastrophic emergency that required immediate evacuation from the Space Station. The DPS was designed to conduct the deorbit burn required for the lifting body to reenter the earth's atmosphere and safely return the crew to earth. After the deorbit burn was completed, the lifting body was to jettison the DPS prior to reentry. While the lifting body proceeded to a safe landing, the DPS would burn up in the earth's

atmosphere. A view of the combined lifting body/DPS assembly is shown in Figure 1.

One of the major design challenges was creating a system that would reliably separate the DPS from the lifting body at minimum cost without posing danger to the crew and to anyone on the ground. The system that was chosen for the X-38 program used six separation bolts strategically placed at the interface between the lifting body and the DPS. Each of these bolts was to be held in place by a separation nut, which was previously used for parachute release in the Space Shuttle Solid Rocket Booster (SRB) program. The joint design is shown in Figure 2. The X-38 project office determined that a sequence of two separation commands, each firing three separation nuts, provided the best probability of successful separation of the DPS from the lifting body. In this case, successful separation was defined as a complete disconnect of the two bodies with no recontact between them or catastrophic failure of the lifting body. After careful analysis of the separation event and preliminary testing of the separation nut/bolt configuration in the Pyrotechnic Shock Facility (PSF), X-38 engineers decided to develop a bolt retractor subsystem (BRS) that would forcefully retract each separation bolt across the interface plane between the lifting body and the DPS. The objective of this system was to prevent snagging or pinching of the bolts as they crossed the interface plane during the separation events. Any snagging or pinching of the bolts might prevent proper separation of the two bodies and thus cause mission failure. A separation test was proposed to demonstrate this capability, but was canceled as the X38 program (along with affiliated hardware) was transferred from Marshall Space Flight Center (MSFC) to Johnson Space Center.

Before the BRS was shipped away, Flight Robotics Laboratory (FRL) personnel at MSFC requested the use of it to demonstrate that the laboratory could test pyrotechnic spacecraft separation. Additionally, the BRS design could be demonstrated to work as

designed. Specifically a bolt retraction time could be determined as well as the force impact to the spacecraft from the device. Initial spacecraft acceleration could also be determined. Neither time nor budget would allow a formal test so a demonstration was planned. In this paper ‘demonstration’ is used instead of ‘test’ as a deliberate reminder that a rigorous test was not run; in particular some of the data acquisition equipment planned for the original tests was not used. The use of ‘test’ in this paper in the remaining paragraphs refers to the means used to validate the FRL as a pyrotechnic separation facility and not prove the BRS as flight hardware.

The FRL is functionally a test facility that operates on a flat concrete floor with an epoxy coating. It provides three dimensions (two translation directions and yaw) of almost frictionless movement for testing of a vehicle that floats on a cushion of air. For this demonstration we used the Large Mobility Base (LMB). The BRS (described in detail below) was mounted on the LMB and a static stand. The LMB was maneuvered to the stand and the BRS bolt torqued to the required specifications. The nut separation pyrotechnics were fired and the vehicle movement was measured. However, before any pyrotechnic firing occurred in the FRL the BRS was safely tested in the PSF.

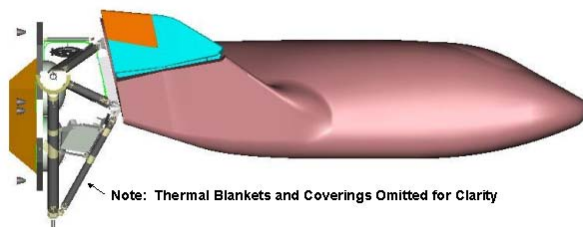


Figure 1: X-38 Lifting Body and DPS

X-38 DPS Bolt Retractor System Design

The BRS design, shown in Figure 2, is a spring / plunger system. The plunger, which is attached to the head of the separation bolt, is loaded by a compression spring. The cylinder in which the plunger rides is slotted to allow air to escape during ground testing and to allow viewing of the plunger motion. Upon activation of the separation bolt, the compressed spring will drive the plunger and the attached separation bolt forcefully across the separation plane. The plunger / separation bolt / spring assembly then impacts the honeycomb-covered endpiece. This serves to absorb the kinetic energy of this mass and to prevent the separation bolt from rebounding across the interface. Several factors influenced the design of this system:

- 1.) Structural margin of safety requirements

- 2.) Bolt retraction time as a function of DPS / lifting body post separation dynamics
- 3.) Expected alignment and tolerances of the lifting body / DPS interface
- 4.) Ease of assembly and installation in the DPS
- 5.) Existing design of DPS and lifting body

Some of these factors were not initially defined during the design process. For instance, the required bolt retraction time was unknown because a full separation analysis of the lifting body and DPS had not been performed; due to program schedule, an educated guess had to be made as to what an acceptable retraction time might be and then base the design on that.

The basic design parameters of the Bolt Retractor Subsystem turned out to be as follows:

- 1.) Structural safety factors of 1.5 on ultimate and 1.0 on yield
- 2.) Required bolt retraction time of 40 milliseconds
- 3.) No interference during mating process of DPS and lifting body
- 4.) No interference with any DPS components during installation
- 5.) Interface with previously designed DPS and lifting body components, such as threads, longerons, etc.

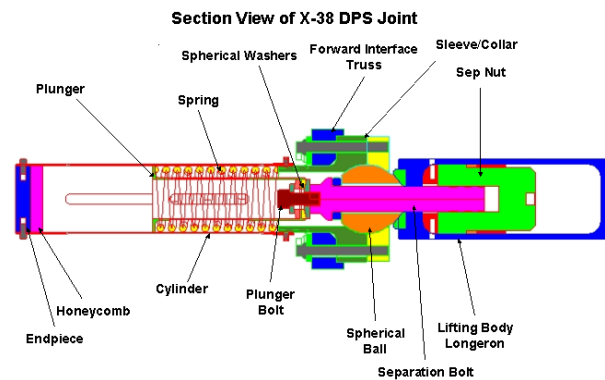


Figure 2: X-38 Joint and BRS Design

Pyrotechnic Shock Facility

The PSF is used to perform pyrotechnic tests, shock tests, and pyrotechnic shock tests of both pyrotechnic and non-pyrotechnic systems and components. High-speed data acquisition is available to record up to 1 mega sample per second per channel. A 21'x 31'x 18' reinforced concrete explosives test chamber is used to test the systems and components.

For the PSF BRS demonstration, the BRS hardware and test fixtures were bolted on a reaction mass in the test chamber. The configuration of the BRS hardware is shown in Figure 2 with the Forward Interface Truss and Lifting Body Longeron being held in place by test fixtures. The demonstration setup is shown in Figure 3. The test fixtures did not allow joint separation but the BRS was able to fully function by releasing the separation nut for full separation bolt retraction. The PSF demonstrations did not simulate the X-38 vehicle/DPS separation event. A functional demonstration of the BRS was performed in the PSF to demonstrate that the BRS would function properly without damaging its components and causing a safety hazard in other test areas. The demonstrations also gave a good estimate of the bolt separation timing.

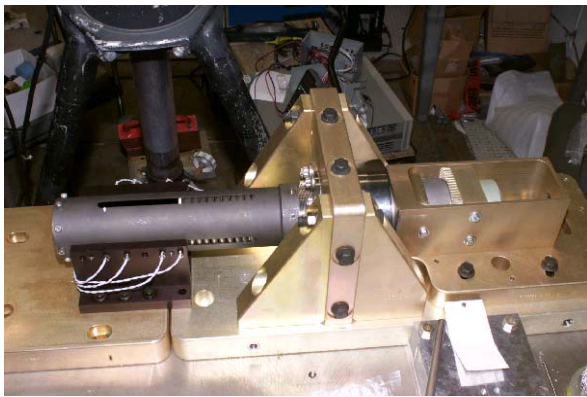


Figure 3 PSF BRS Setup

Large Mobility Base

The Large Mobility Base (LMB), located in the FRL, provided a means of simulating the mass of the DPS and the DPS relative motion from the lifting body after the separation event.

The LMB is a large air-bearing mobility simulator that acts as an air sled and is “flown” across the air-bearing floor, supported by air bearings. The LMB is shown in Figure 4.

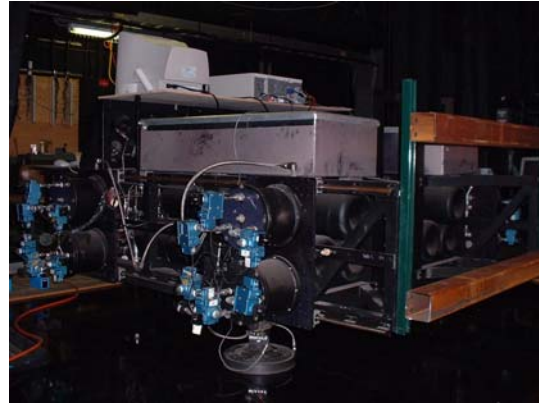


Figure 4 Large Mobility Base

Three air bearings allow the vehicle to float across an epoxy resin floor that has a very close flatness tolerance. The floor is 43 ft by 86 ft. A computer is used to communicate with all sensors and control the thrusters. Two accelerometers and a gyroscope are mounted in the center of mass to sense both the X and Y accelerations along with yaw rate. Three laser range finders are also mounted to provide X and Y location along with the yaw of the vehicle.

Six air tanks rated at 4000 psi provide the air for floating and movement. Two banks of batteries each rated at 24 volts provide power. For the Bolt Retraction Subsystem (BRS), two 4” x 4” steel beams were mounted to give the vehicle some rigidity for attaching the BRS apparatus and for reacting to the separation forces.

LMB misalignment relative to the stationary base could impact proper assembly or performance of the BRS. In addition, misalignment could cause a moment about the center vertical axis of the LMB. Therefore, two threaded rods with crush nuts were used to control the distance between the LMB and stationary base and make them parallel. This hardware is shown in Figure 5.

The center of mass of the LMB needed to be centered on the vehicle as well as the long axis of the BRS so as to not cause a moment about the center vertical axis of the LMB. The LMB is equipped with a mass scale above each air bearing allowing accurate centering of mass by placing lead weights at different points along the substructure.

Proper recording of the precise moment the bolt separation device activated was needed for subsequent data analysis. Since the data acquisition system was on the LMB and the pyrotechnic device was stationary, a way was needed for the firing signal to cross the

interface without impacting the LMB's ability to free-float. The solution was to use an LED and phototransistor. The LMB mount contained the phototransistor while the LED was in the base. Alignment pins were used in a set of match-drilled holes providing positive alignment for the light beam.

A pin-pull test was used to verify the ability of the LMB and flat floor facility to run the pyrotechnic demonstration. The pin-pull system used the identical BRS interface except for a hole in the BRS bolt perpendicular to its main axis that allowed a pin to "lock" the bolt in place for preloading. Once the BRS was installed, the pin was pulled from the hole allowing the bolt to release. This setup is shown in Figure 6.

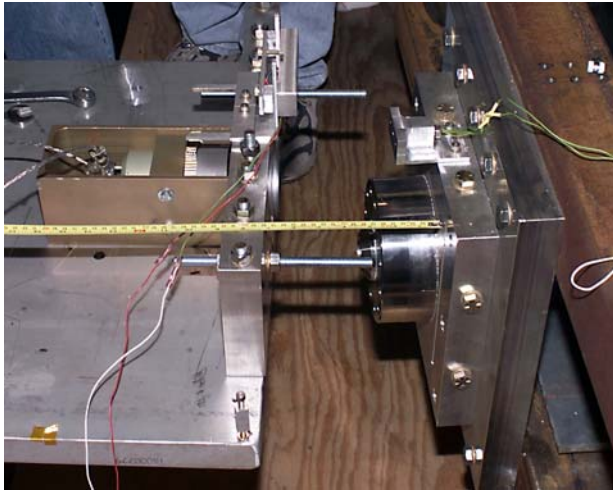


Figure 5 Interface Hardware

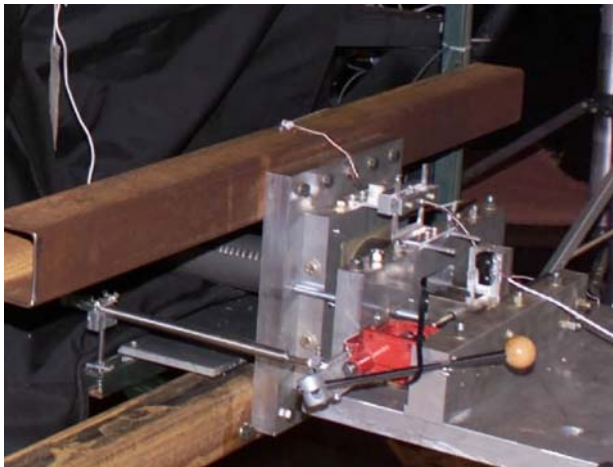


Figure 6 Interface Hardware: Pin Pull Setup

Camera Test Data

High-speed film cameras recorded the separation events in both the PSF and FRL demonstrations with a rate of 400 frames per second (fps). The first camera recorded the plunger/separation bolt retraction as viewed through the slots in the cylinder of the BRS. A painted white stripe on the plunger gave contrast between components. The second camera recorded the movement of the separation nut. One 400 fps camera recorded the separation event in the FRL. The camera recorded the plunger/separation bolt retraction as viewed through the slots in the cylinder of the BRS and showed the separation of the LMB.

The camera data showed that the retraction time from separation to interface crossing was identical (approximately 20 ms) for both the PSF and the FRL demonstrations. Figures 7, 8 and 9 show the plunger motion recorded by the high-speed camera as a function of time for the FRL demonstration. Figure 7 shows the plunger at rest in the FRL, one frame before plunger movement. Figure 8 shows the plunger at the white mark that represents the end of the bolt clearing the joint interface. In figure 9, the cylinder and surrounding fixtures are shown as they moved through the camera's field of view.

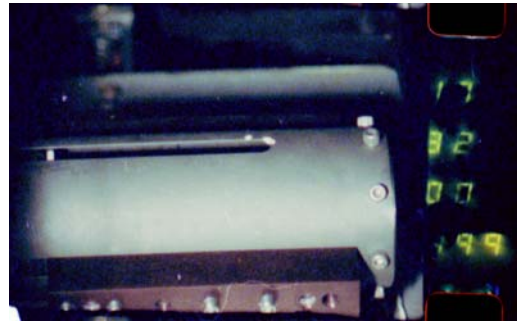


Figure 7 Time = 99 msec (Pyrotechnic fired)

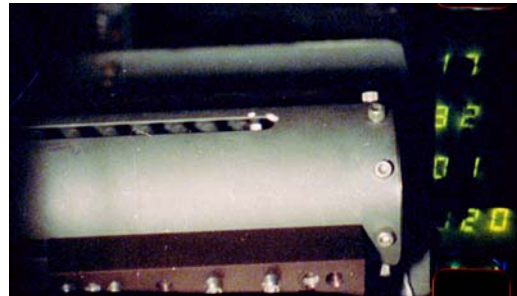


Figure 8 Time = 120 msec (Bolt has cleared)

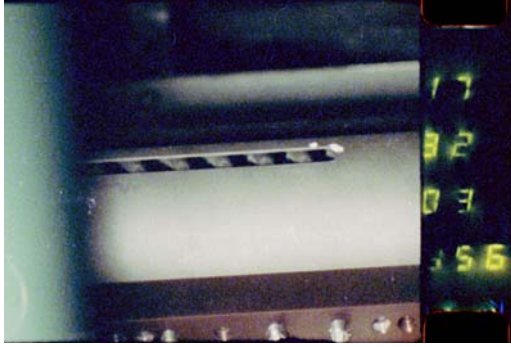


Figure 9 Time = 3 seconds, 156 msec (Shows movement of canister and LMB)

Bolt Timing System Data

To further verify the bolt retraction time, a timing system was designed and built to measure the timing of the plunger in the BRS without physical contact. The system uses four infrared LED light sources and sensors mounted in an aluminum frame. The frame held the LED and sensor firmly in place with the distance from the first to the last sensor being the same as from the installed end of the bolt to the interface plane. Each of these light source/sensor combinations was assigned a channel number corresponding to its relative position. For instance, channel 1 corresponded to the position of the bolt just at release and channel 4 corresponded to the bolt position when it crossed the interface. The LED output is reduced through a small hole in the frame to reduce cross talk to the next sensor. The input to the sensor also passed through a small hole to improve accuracy and to reduce cross talk. The LED and sensor types were a cost efficient and quick solution that would also have met thermal vacuum environment requirements.

The timing system is mounted under the BRS cylinder and the LED light passes through two slots in the cylinder and in front of the plunger. The frame is adjusted so that the output is slightly reduced at the first sensor output. This is done so that the first initial movement can be detected. Upon separation, the first sensor output triggers a data acquisition system that records the output of the four sensors. Time constraints and a recorder failure limited the use of the uncalibrated timing system to the PSF. The timing system results show the same approximate 20 ms separation time that the camera results show. Figure 10 shows the data obtained during the pin-pull demonstration in the PSF.

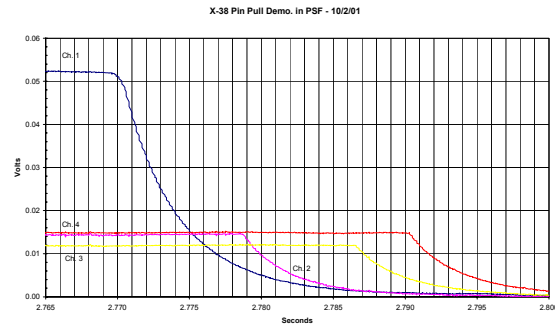


Figure 10 Separation Bolt Position vs. Time

Analysis of Force Impact

Since these demonstrations were performed quickly due to program cost and schedule constraints, the force distribution between the joint components could not be precisely determined. However, visual inspection of video taken during the demonstrations showed that motion occurred several picture frames after the plunger/bolt mass impacted the honeycomb at the end of the bolt retractor cylinder. In other words, the authors deduced that the stored spring energy was the single largest contributor to the motion experienced by the mobility base and not joint energy.

Analysis of Spring Dynamics and Bolt Retraction Time

The bolt retractor spring was designed to retract the separation bolt across the lifting body/DPS interface plane in a time of 0.020 seconds after activation of the pyrotechnic release nut. The spring, with a nominal diameter of 3.355-inch, was designed at the Marshall Space Flight Center and built by Leeco Spring International in Houston, Texas.

Neglecting friction, the idealized equation for a spring-mass system such as that used in the BRS is:

$$m \frac{d^2 x}{dt^2} + kx = 0 \quad (1)$$

where m is the mass of the bolt, plunger, and washer assembly, k is the spring stiffness, and x is the displacement of the bolt/plunger/washer assembly from the spring's free length. The solution of this differential equation is well known and is:

$$x = x_0 \cos \omega t \quad (2)$$

$$\omega = \sqrt{\frac{k}{m}} \quad (3)$$

where t is the time, ω is the natural frequency. Since x is defined from the free length position of the spring and the spring is initially compressed before bolt retractor activation, the initial displacement is x_0 . In the BRS that was demonstrated, x_0 was 5 inches.

The distance that the plunger/washers/bolt assembly needed to travel to clear the interface plane was 4.189 inches. This means that

$$x_{ic} = x_0 - 4.189 = 0.811 \text{ inches} \quad (4)$$

where x_{ic} is the displacement of the spring from its free length at the point of interface crossing. The time of interface crossing, τ_{ic} , is calculated by substituting x_{ic} for x in equation (2):

$$x_{ic} = x_0 \cos \omega \tau_{ic} \quad (5)$$

The equation for calculating τ_{ic} thus becomes:

$$\tau_{ic} = \frac{1}{\omega} \cos^{-1} \left(\frac{x_{ic}}{x_0} \right) \quad (6)$$

The BRS spring had the following values:

$$k = 85.05 \text{ lbf/in}$$

$$m = 5.152 \text{ lbf/386.4 in/s}^2$$

Substituting these values into equations (3) and (6), the time to cross the interface becomes:

$$\tau_{ic} = 0.018 \text{ sec}$$

BRS Results

The X-38 BRS demonstrations tentatively proved that the BRS design was viable for its intended use as part of the X-38 separation system. The design goal bolt retraction time of 40 milliseconds was exceeded by a factor of two (average of 20 msec.) for all the demonstrations. Project engineers were concerned that friction, tolerances and other factors unaccounted for in the analysis would add considerably to the theoretical retraction time. As it turned out, the retraction times were within 2 msec. of the theoretical values. The final honeycomb crush depth after impact of the moving mass for each demonstration was

approximately 0.52-in, which was about half of the original honeycomb depth prior to impact. All of this data significantly increased confidence in the design and that it would perform as intended in the space environment.

It must be emphasized once again that these demonstrations did not qualify the BRS hardware for flight. To do so would require more stringent data acquisition and data collection than occurred during the demonstration.

FRL Results

The X38 BRS demonstration proves the FRL is suitable for doing these kinds of tests. Possibly a second air bearing vehicle, such as the Small Mobility Base (SMB) currently used in the FRL, could be used instead of a static stand. Then an actual two-body separation could be tested. Either the SMB or the LMB can be weighted differently to simulate actual weight differences in the spacecraft.

Any separation mechanism needs to be safe for the FRL personnel and facilities. The BRS, both pyrotechnic and pin puller, was tested in the Pyrotechnic Shock Facility. Once a device has been proven safe, then the FRL facility can be used.

Peak accelerometer data along with differentiating position data from the LMB gave an average acceleration of .01 G's.

Conclusions

Summary of FRL Pyrotechnic Firing Results

| | |
|---------------------------|----------------------|
| Time For Bolt To Clear | 20 msec |
| Bolt Torque | 1100 ft. lbs. |
| Honeycomb Crush Depth | .52 inches |
| LMB Weight | 3795 lbs. |
| LMB Peak Acceleration | .1 m/s ² |
| LMB Peak Velocity | .02 m/s |
| Primary Force Contributor | Stored Spring Energy |

The demonstration was definitely a success. The BRS worked as anticipated. Obviously the time and budget limitations did not allow a complete set of data to be acquired. In an actual test using displacement transducers may have shown a slight displacement from initial release of joint energy that could not be seen with the cameras and a different speed for each of displacements (joint versus the bolt impact). In a rigorous test schedule multiple runs with different bolt tensions would have been recorded and compared. Some of the 'lessons learned' include the following:

1) Soft mounting the accelerometers would have filtered out the higher frequency vibrations from both pyrotechnic shock and tank air flow and reduce the post-test data processing.

2) While the Bolt Timing System provided the bolt retraction time, a fiber optic laser/sensor arrangement would have provided more accurate and reliable timing data (i.e., a sharper 'roll-off' would have been visible in Figure 10).

Acronyms and Abbreviations

BRS – Bolt Retractor Subsystem

DPS – Deorbit Propulsion Stage

fps – frame per second

FRL – Flight Robotics Laboratory

LED – Light Emitting Diode

LMB – Large Mobility Base

m - meter

msec – millisecond

MHz - megahertz

MSFC – Marshall Space Flight Center

PSF – Pyrotechnic Shock Facility

SMB – Small Mobility Base

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