Payload Separation System

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Engineering Analysis

Document

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Background

Launch vehicles that place payloads into orbit require mechanisms to release the payload into orbit. The payloads are typically fragile and are composed of various optical components that can be harmed when transported. Due to this problem, companies have designed various payload separation systems that have become too expensive and complicated. Mary Rogers, the Electronic Packaging and Actuators Manager from Orbital Sciences Corporation, has requested for a new design of the payload separation system. This new design of the system must be reduced in cost, impart minimal shock to the payload, and be less complicated by reducing the number of parts. The team will design, analyze, and build a sub-scale model of the payload separation system for testing for ME 476 Capstone Senior Design by May of 2014.

Problem Statement

Orbital Sciences Corporation, located in Phoenix Arizona, is interested in designing a Payload Separation System (PSS) that is lighter, less expensive, less complicated, and imparts minimal vibrational shock levels onto the payload. The primary interest of this senior design project is to deliver a payload into polar orbit around the Earth. Generally, the design is a ring that must be strong enough to secure a payload to the front of the Pegasus space launch vehicle, separate on command, and release the payload into orbit. The goal is to improve the current payload separation system today while making sure the design is simple so that it can be manufactured at Orbital.

Introduction

Current payload separation systems are generally composed of some cylindrical ring that is mounted on the tip of a launch vehicle just before the payload. The ring needs to be able to withstand the weight of the payload, and the forces and properties at Mach speeds when launched into orbit. Some of the forces that need to be considered are extreme temperatures, accelerations, vibrations, and various other material stresses caused by the environment. The purpose of this report is to explain the analysis process that was performed on the final design. The keys were determined to be the weakest part of the final design and will be the main focus of this analysis. An analysis will also be performed on the thrusters used to separate the payload from the launch vehicle once orbit is reached. The overall project will eventually entail trade studies, design, analysis, and possible sub-scale models and testing. Some payloads that might be used in industry today include: satellites, telecommunication systems, optical systems, and experimental projects. These payloads can be delicate due to the nature of the mechanisms they carry. The payload and the launch vehicle are extremely expensive, although by reducing the number of parts the cost will be reduced as well.

Final Design

The final design consists of two rings, one ring attached to the payload and another attached to the rocket or launch vehicle. The rocket ring (RR) has four keys that secure the payload ring to the rocket when engaged. See figure 1 for an isometric view of the final design in SolidWorks. See appendix A, B, and C for various views of the final design. A servo motor will rotate, pulling each key inward simultaneously by 1 cm. Once the keys reach their final resting position the payload will be released from the rocket and the kick off jets will engage. The kick off jets will use thrust to accelerate the payload away from the rocket. An analysis was performed on the keys and kick off jets to make sure the keys would not fail due to shear and confirm that the kick off jets will successfully separate the payload from the rocket.

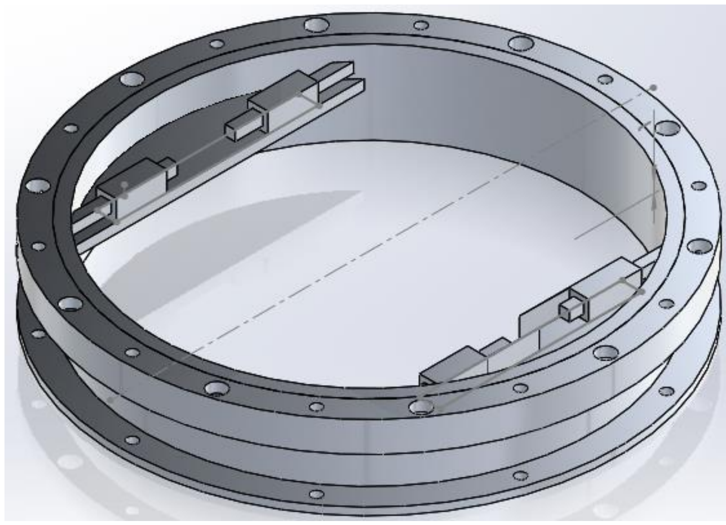

Figure 1: Final design in SolidWorks

Analysis Dimensions

Preliminary dimensions used for analysis (See appendix for dimensional drawings):

***Subject to change*

Rocket Ring (RR)

- RR OD = 98.58 cm
- RR ID = 83.5 cm
- RR wall thickness = 2.5 cm
- RR contact height = 7.5 cm

Payload Ring (PR)

- PR OD =98.6 cm
- PR ID = 83.5 cm
- PR lip thickness = 1.0 cm
- PR wall thickness = 1.25 cm
- PR height = 3.0 cm

Key

- Width = 1.0 cm

- Height = 1.0 cm
- Length = 15 cm
- Key contact surface length = 1.0 cm

Key Housing

- Width = 1.5 cm
- Height = 1.5 cm
- Length = 7.0 cm

Key calculations, based on 1cm X 1cm:

Variables:		**Units:**
A_{s-c}	Key contact surface area	m^2
A_c	Cross sectional area of key	m^2
q_{max}	Maximum dynamic pressure	Pa
q_{key}	Dynamic pressure on each key	Pa
P	Pressure	Pa
ρ	Density	kg/m^3
F_g	Force due to gravity	N
F_{g-key}	Force due to gravity on key	N
F_t	Total force acting on keys	N
W	Weight of payload	kg
I	Key moment of inertia	m^4
t	Key thickness	m
V	Velocity	m/s
g_{local}	Local gravitational constant	m/s^2
τ_{max}	Maximum allowable shear	Pa
F.S.	Factor of safety	N/A
a	Acceleration	m/s^2
$M_{payload}$	Mass of payload	kg
$\dot{m}$	Mass flow rate of CO_2 leaving tank	kg/s
T	Thrust	N
m_t	Mass of total system	kg

m_{CO_2}	Mass of CO_2 in tank	kg
t	Time	s

Equations:

$$A_{s-c} = lw \quad (1)$$

$$A_c = wh \quad (2)$$

$$q_{max} = \frac{1}{2}\rho V^2 \quad (3)$$

$$q_{key} = \frac{q_{max}}{4\ keys} \quad (4)$$

$$F_g = Wg \quad (5)$$

$$F_{g-key} = \frac{F_g}{4\ keys} \quad (6)$$

$$F_t = q_{key}A_{s-c} + M_{payload}a \quad (7)$$

$$\tau = \frac{3F_t}{2A_c} \quad (8)$$

$$F.S. = \frac{\tau}{\tau_{max}} \quad (9)$$

Solved Values:

τ = 59342121.54 Pa

F.S. = 5.58

Shear Force on Keys

The shear force is the dominate force that will cause the keys to fail from the time the Pegasus launch vehicle begins ignition stage 1 to the final stage of payload separation. During analysis and visualization, the keys ended up being the failure point without any question. The keys are by far the most exposed piece to the PSS and the forces upon lift off or stage 1 will be the only force that would have the strength to break the keys and cause a catastrophic failure throughout the whole system. The shear force that would cause the keys to fail is calculated by summing the force of the payload due to gravity acting on the key and the force due to the max dynamic pressure caused by the first stage of ignition. To illustrate, forces caused by the max dynamic pressure were calculated by multiplying q_{key} by A_{s-c}. The A_{s-c}, key contact surface area, was calculated using simple geometry and came to be 0.000134 m^2. See figure 2 for the angles and dimensions that were found to calculate an accurate surface area. The values of each variable can be seen in table 1.

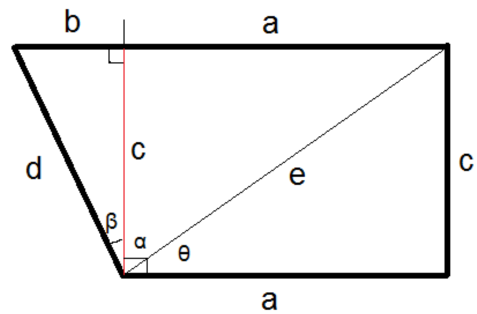

Figure 2: Geometry of calculated contact surface area of key on payload ring

Table 1: Values of each variable in figure 2

a [m]	**b [m]**	**c [m] (thickness)**
0.0075	0.0119	0.01
d [m] (diagonal length)	**e [m] (diagonal)**	**f [m] (width)**
0.0156	0.0125	0.0156
θ [Degrees]	**β [Degrees]**	**α [Degrees]**
53.13	50.13	36.87

The forces due to gravity and weight of the payload are calculated by multiplying the mass of the payload by the acceleration where the max dynamic pressure was calculated. See variables and equations for clarification of definitions. Using equation 7 and 8, the shear force due to these two forces resulted in a value of 5.93×10^7 Pa. 7075 Aluminum has been tested to shear at 3.31×10^8 Pa, therefore concluding with a factor of safety of 5.58. This confirms that the keys will not fail due to shear force given that the keys are made out of 7075 Aluminum. The design is safe and reliable.

Rack and Pinion

The rack and pinion will be one of the more primary pieces to the completion and success of the payload separation system. This system is the most efficient way to move the keys due to the fact that this is the best way to connect the keys to the servo motor. As well, when the keys are fully engaged there is a total surface area of one square centimeter that needs to be pulled out of the payload ring. Because of this fact, the system needs to pull out a total of 1 cm in length, so the pinion will have a total diameter of 2 cm which would make the total circumference of the pinion 6.28 cm. Seeing that the diameter is 6.28 cm, it would only take the pinion a total of 0.32 rotations (115.2°) to remove the key from the fully engaged position, allowing the PR to be fully disengaged and separated in orbit. The position of the rack will be located directly on the keys themselves which will make them the most efficient. While the rack will be located on the keys, the pinion will be located on servos that will be attached to the RR separately. When the servos rotate it will grab the rack located on each key and move them to their fully unengaged position so the PR can fully detach and move itself into orbit. There will be four full systems just like the one described regarding the rack and pinion, which means each one of the four keys will be powered separately with its own servo/rack and pinion system. This is the most efficient and reliable way to separate the payload in orbit.

Servo Motor Assembly

The servos will contribute two main functions:

1. The servos will maintain a position for the key by holding torque within the payload ring (PR) until the desired elevation/separation height is reached.
2. The servos will provide the required torque to disengage the keys from the payload ring.

While in a loaded state the rocket is under acceleration and the keys will naturally maintain their position in the payload ring due to friction from gravity on the contact surface of the interface between the keys and the PR. While under acceleration the servos will give assurance by providing the force to ensure that keys do not separate premature from vibration. Once separation elevation is reached (400 nmi) and the velocity becomes constant, the signal is given and the servos activate by retracting the keys into the housing.

Data at separation:

- height (h) = 400 nmi
- time (t) = 663 sec
- velocity (v) = 24,500 f/s
- acceleration (a) = 0 f/s^2

- pitch (γ) = 0.0°

  ***Pitch is in relation to the tangent plane of Earth's orbit field at some spatial location*.

Using the above zero acceleration before separation, the force in the y-axis is also zero. At separation the frictional force at the interface between the PR and key is zero. The servo will be required to have enough power to move the mass of the key only, at ~47 g. Many off-the-shelf servos exist to move this mass. Future testing will confirm the above assumptions.

Kick Off Jets (KOJ)

To limit a jarring unloading factor from separation, the team has moved from kick off springs to impinging jets. Four compressed air jets will be located on the perimeter of the RR, with targets on the PR respectfully. KOJ allow for a less abrupt separation, where the stream velocity (SV) contributing to the impact force will linearly increase. SV near zero initially has a near zero impact force, and a small acceleration. The team found a desired separation acceleration by using the spring constant for the current Marmon Clamp system. As a reference point to determine force to due to acceleration needed to separate, the team used an initial zero acceleration. With no relative acceleration immediately after the keys retract into the housing, any force imposed between the RR and the PR will force separation. Here the jets will implode an impact force on the interface between the PR and the RR. Current acceleration due to spring force is 0.33 m/s^2, one that needs to be minimized. Here the team chose to split this acceleration in half, thus half the unloading force will be experienced by the payload. To accomplish this, the team developed nozzles with the following dimensions.

KOJ's dimensions and criteria:

- Carbon Dioxide (CO_2)
- Pressure (p) = 1000 psi = 6894.8 KPa
- Nozzle Diameter = 4 mm = .004 m

With these given parameters the following equations calculate the mass flow rate of CO_2 leaving the tanks and the acceleration of the payload and rocket in opposite directions due to thrust.

KOJ's Equations:

$$P = \frac{1}{2}\rho V^2 \tag{10}$$

$$\dot{m} = \rho V A \tag{11}$$

$$T = \dot{m} V \tag{12}$$

$$a = \frac{T}{m_t} \tag{13}$$

$$t = \frac{m_{CO_2}}{\dot{m}} \tag{14}$$

The above equations yield **Acceleration=0.159m/s²**. This acceleration is ~½ acceleration from kick off springs.

If the tank can hold 20 oz (0.57 kg) of CO_2, and the mass flow rate of CO_2 leaving the tank is 0.0657 kg/s, then the release time of CO_2 is the mass of CO_2 divided by the mass flow rate. Using equation 14, the time it takes for all of the CO_2 to be released from the tank is 8.63 s. See figure 3 for a graph of the mass of CO_2 leaving versus time.

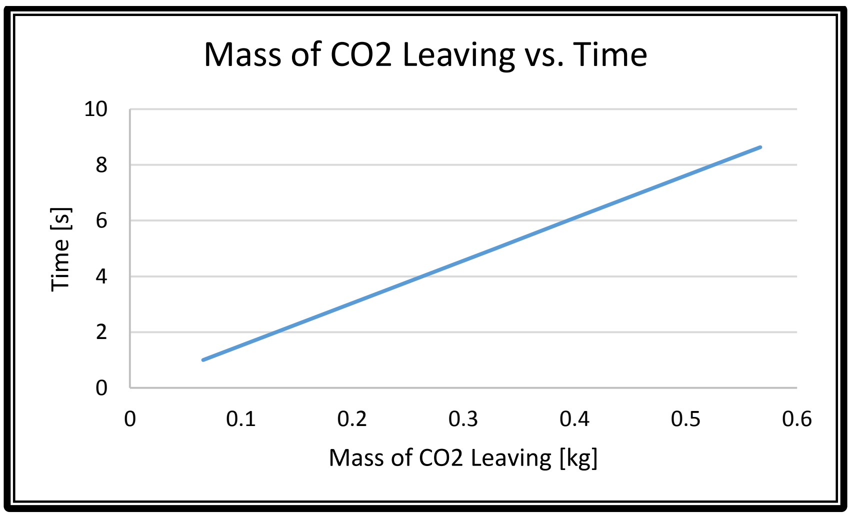

Figure 3: Separation velocity verses time

The velocity of the system is a constant 24,000 m/s at the time of separation. With this constant acceleration a separation velocity can be calculated and seen in figure 4. Figure 5 shows the separation distance caused by the acceleration of 0.159 m/s^2.

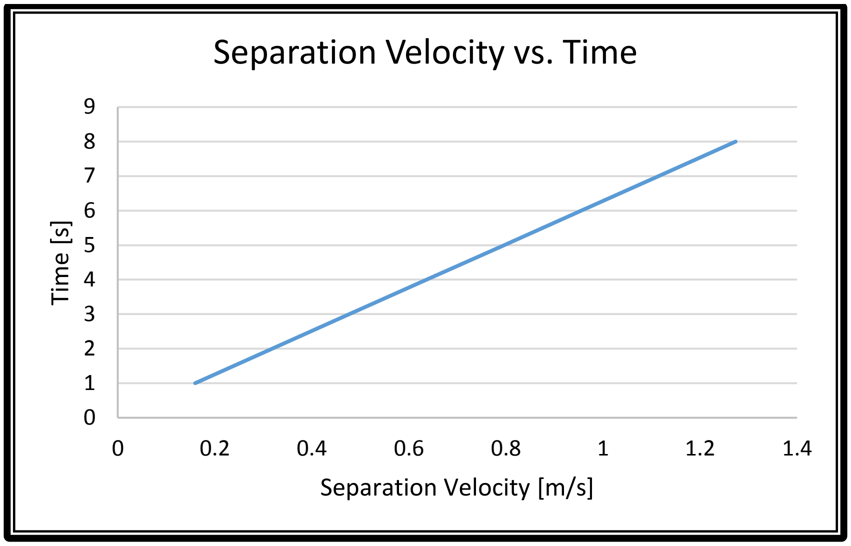

Figure 4: Separation velocity verses time

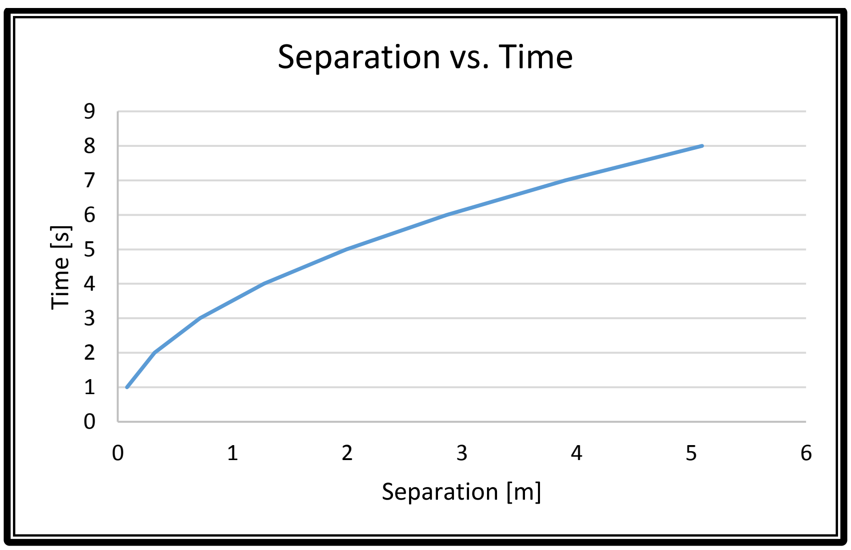

Figure 5: Distance of separation versus time

Future Improvements

This analysis has brought design weaknesses to the teams' attention. Improvements of the final design will include making the payload ring flush with the rocket ring. See figure 6 and 7 for a series of SolidWorks models that gives a better picture of what the design will look like.

Figure 6: Final design in SolidWorks, side view

Figure 7: Altered final design in SolidWorks, with the PR flush with the RR

The purpose of making the rings flush will not only reduce the weight by removing the excess 7075 Aluminum, but the shear forces acting on the keys will be drastically reduced and the keys will not be the weakest part of the whole system. This will also decrease the friction between the key contact with the rocket ring and payload ring. Another improvement will be to design a backup separation system if the current system may fail. This back up system will be an existing payload separation system, such as the Marmon Clamp or Exploding bolt, placed in series with the final design concept. Or the final design can be manufactured twice and be put in series, although this idea is not favorable because having two separation systems will increase the mass of the entire system and take away from the allowable mass of the payload. A second analysis will be performed once final decisions are made.

Project Plan

The Gantt chart, shown in appendix D, illustrates what the upcoming months will be like for the team. No major changes were made to the Gantt chart. CAD drawings are finished and the engineering analysis has now been complete. The final design deadline in December is approaching fast along with the bill of materials. In order to be on schedule some of the tasks will run jointly. There will also be subtasks that go along with the main tasks as soon as those points are reached in this project. There will only be one more report and presentation until design finalization. The date in which our team will have a completed and final design will ideally be on December 2nd, although the final design is tentative and will change as further analysis confirms.

Conclusion

Orbital Sciences Corporation has asked the team to design, build, test, and analyze a less expensive payload separation system that causes minimal shock to the payload. There has now been a further analyzed final design concept. In addition, the final design is drawn in SolidWorks to accurately represent the dimensions of the design. The 3D model helps the team communicate the final product for analysis and show to the client the current progress.

One major design change to the project is the use of a compressed fluid (CO_2) to boost the payload away after separation occurs. As well, the team has moved the rack and pinion assembly to the outer edges of the rocket adaptor. This conforms to the other professional designs available by keeping the release mechanism on the outer edges of the ring. The base plate has been moved to the outer edges of the system which reduces weight and makes a sleeker profile. In addition, the shear forces present on the keys will not cause the keys to fail. This is essential to the analysis because the keys are the only thing holding the payload onto the rocket besides friction caused by surface area. All in all, the design has proven to be successful through many calculations and future improvements will be made as further analysis proceeds. This design will continually be engineered and altered until the final design is presented and fabricated.

References

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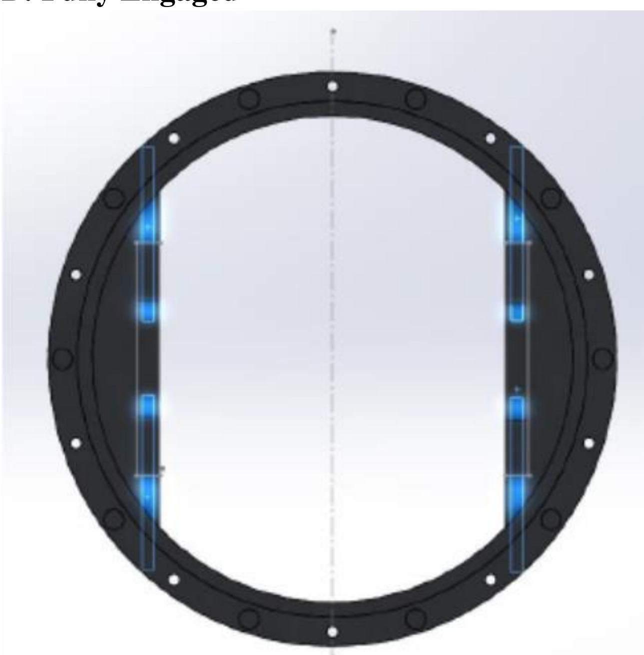
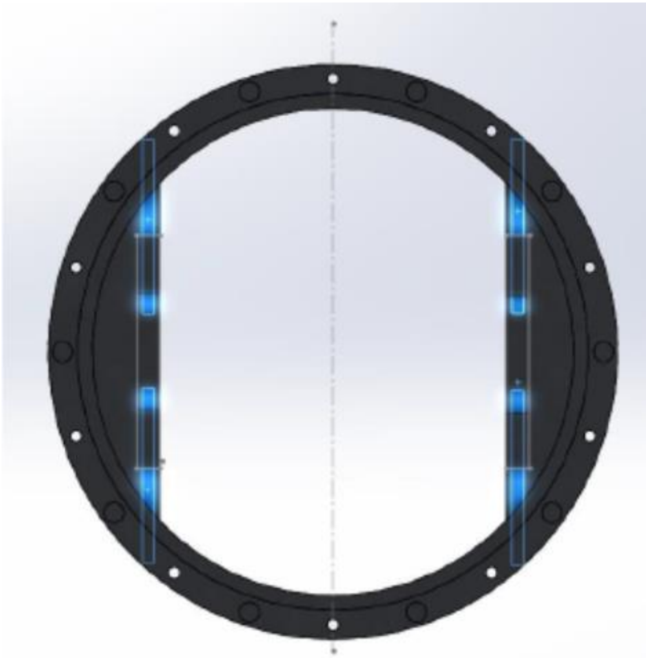
Appendix

A: Side View

B: Fully Engaged



C: After Separation



D: Gantt Chart