

SPINOFF 14B

Force Versus Displacement

Background

Space vehicles are expensive to launch. The rockets, which are used to lift a vehicle into space, are only able to lift a certain maximum weight. Since both the vehicle's structure and payload contribute to the total weight, any decrease in structural weight would increase the payload weight that could be launched. As a result, it is important to design a vehicle and launch system so that the vehicle's structural weight is kept to a minimum. It is also important, where possible, to keep external forces on the vehicle to a minimum. External forces include the force of winds in the atmosphere and the jerking motion encountered when the bolts, which hold the rocket in place before launch, are blown loose. If the external forces can be reduced, then the vehicle's structure will not need to be as strong. This in turn will allow the structural weight to be reduced. In summary, to maximize the payload weight which is typically less than 10 percent of the total vehicle weight at liftoff, it is necessary to minimize the external forces encountered during launch and flight.

Just before liftoff, the rocket engines are ignited and they build up thrust to full power in about 4.5 seconds. During the buildup, the engines ignite at different times, so the thrust is uneven. If the vehicle were just resting on the launch pad, it would tilt and fall over while the engines were building up thrust. Therefore, the vehicle must be held down until all of the engines are balanced, working properly, and up to full power. When all the conditions are go, the vehicle is released.

Release Mechanisms

There are two general types of release mechanisms: soft and hard. A hard release is an instant release at full power. Typically, the hold down bolts of the restraining mechanism are secured by explosive nuts that are blown away to release the vehicle. A hold down bolt with an explosive nut is referred to as a pyrobolt. There is then a sudden jerk as the vehicle accelerates off the launch pad. This is analogous to what would happen at a tractor-pull contest if the cable attaching the tractor to the load suddenly broke. If the cable broke, the tractor would lurch ahead and the driver would be slammed against the back of the seat. Much more force is involved in launching a space vehicle. This sudden acceleration, or jerk, is hard on both payload and passengers. In order to mitigate the jerk, a controlled (soft) release mechanism, CRM, is added to the hard release structure. The diagram in Figure 1 on the next page shows the general components of a release mechanism and their relative positions. If a soft release mechanism is used in a launch, there would be little or no jerk. Then, it is possible that the structural weight of the vehicle could be reduced and its payload capacity increased.

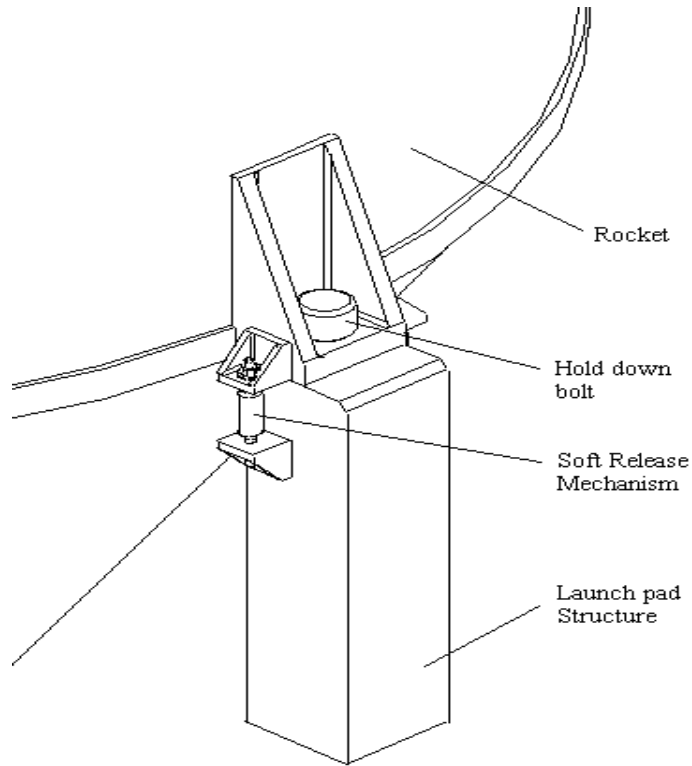


Figure 1: Controlled Release Mechanism

Section I

Restraining Force vs. Displacement Graphs

The general property required of a soft or controlled release mechanism is that it should have a high initial restraining force which will gradually decrease to a small value when the rocket is completely released. The high initial restraining force serves to steady the rocket on the launchpad after the pyrobolts have been exploded. Then, as the restraining force of the controlled release mechanism (CRM) decreases, the rocket will begin to lift off the launchpad. With current requirements, the launch vehicle is under restraint only during its first few inches of liftoff and is then released. If the vehicle were restrained for too long, the rocket exhaust would severely burn the launchpad. Note that after the pyrobolts are blown away, the rocket remains attached to the launchpad by the controlled release mechanism until the rocket is a few inches above the pad. At that point the CRM has separated, and the vehicle is completely released from the launchpad.

The new Evolved Expendable Launch Vehicle (EELV) is now on NASA's drawing boards. NASA scientists are presently evaluating several release mechanisms. To maximize the payload, the EELV will use eight controlled release mechanisms (CRMs), not just a simple hard release system. Figure 2 shows a simplified diagram of the launch forces acting on each CRM. The divisions by 8 shown in the diagram assume that the launch forces are distributed equally to each of the eight CRMs.

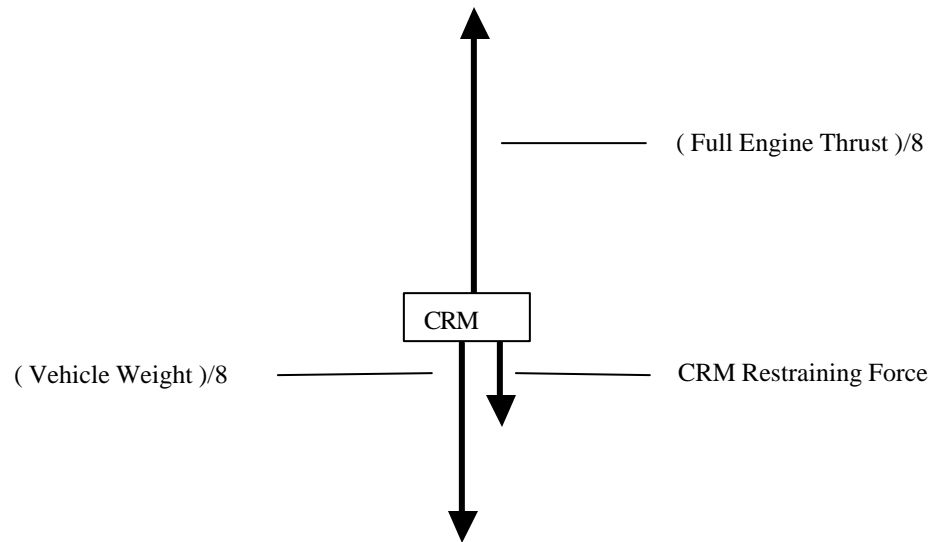


Figure 2: Launch Force Diagram

At the moment when the pyrobolts are blown away, the CRM restraining force together with one-eighth of the vehicle weight should equal one-eighth of the upward thrust of the rocket. The restraining forces of each CRM will diminish to zero, the **net** upward force will increase, and the vehicle will ascend.

Exercise

- 1) Sketch a possible graph which represents the restraining force, F , as a function of the displacement, d , that the launch vehicle is above the launchpad. Assume $d = 0$ when the pyrobolts are blown away. Remember to label your axes appropriately. Your instructor may ask you to work on this Exercise in groups. If so, compare your sketch with the sketches of several other groups. Critique the sketches of the other groups. Do you think the graphs of the other groups satisfy the conditions for a reasonable soft release mechanism? Why or why not? Explain. Remember to label your axes appropriately.

Section II

Characteristics of a CRM Restraining Force vs. Displacement Graph

The graphs of the force versus displacement functions in Figure 3 below represent the same three forces that are shown on the previous page in Figure 2. These graphs pertain to any one of the eight CRMs and assume that the forces are equally distributed to each CRM. Notice that at 0 displacement, one-eighth of the vehicle's weight added to the restraining force equals one-eighth of the full thrust. The graph of the Restraining Force vs. Displacement function is typical of a good soft release mechanism.

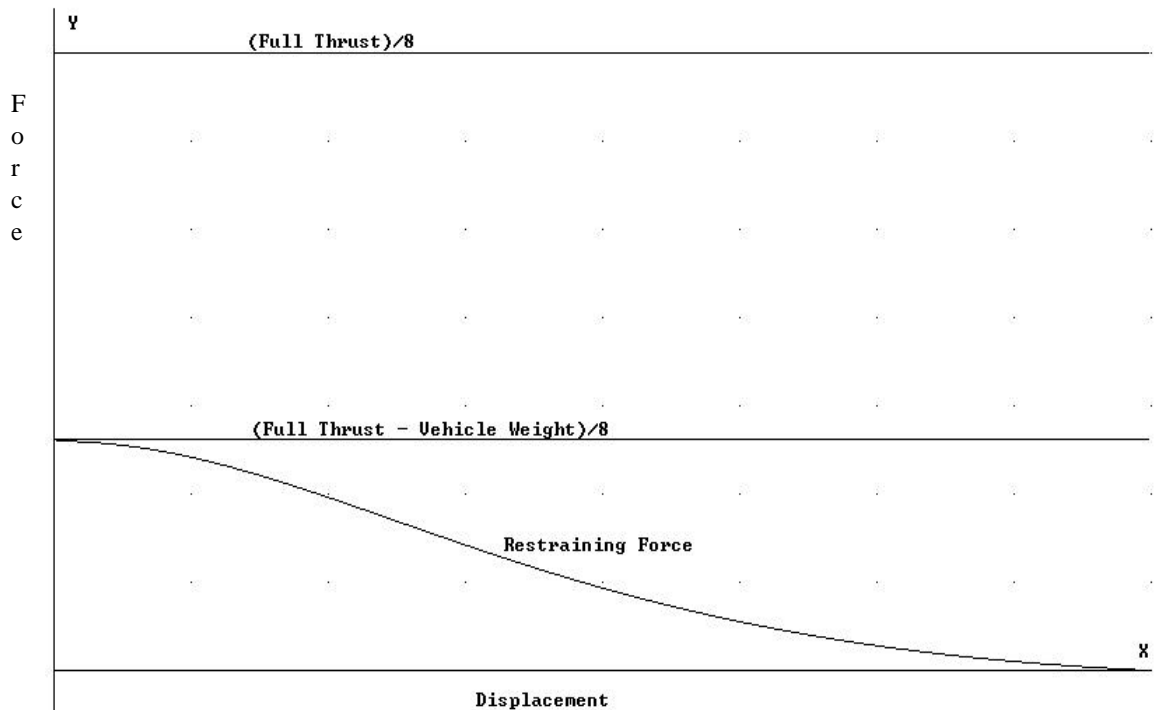


Figure 3: Launch Forces on Rocket

Important characteristics of a CRM restraining force vs. displacement graph:

- **Flat or nearly flat at the initial and final displacements:** This is significant because there will be little or no change in acceleration at these displacements. So, when the pyrobolts are blown away and the vehicle finally lifts clear, there will be a smooth transition. In general, sharp drops in the force curve are undesirable since these cause sudden jerks on the launch vehicle.
- **Decreasing restraining force:** According to Newton's Third Law, $F = ma$, the acceleration of the launch vehicle is directly proportional to the difference between the thrust of the rockets and the sum of the vehicle's weight and the combined restraining forces of the release mechanisms. The objective of the soft release mechanisms is to provide a smooth, yet swift, liftoff. If the force curve were to increase with displacement, then the acceleration of the vehicle would be impeded, slowing

the launch of the vehicle and wasting energy. In fact, if the restraining force kept increasing indefinitely the vehicle would never leave the launch pad. Hence, the CRM restraining force should decrease throughout the entire displacement interval.

- **Low restraining force at release:** Upon release, if the restraining force is nonzero, there will be a jerk.
- **No sharp corners:** Sharp corners in the restraining force curve would also cause jerk.
- **Energy absorption:** Another general property of the restraining force vs. displacement curve is that the area between the curve and the horizontal (displacement) axis represents the energy absorbed by the soft release mechanism during the launch. If too little energy is absorbed, the area under the force vs. displacement curve would be relatively small. If this were the case, the restraining force would diminish too rapidly and the vehicle would experience a jerk during launch. That is, if the energy absorbed by the restraining mechanism is insignificant compared to the energy generated by the thrust, it will not smooth out the motion very much.

On the other hand, the CRM must be designed so that it does not absorb too much energy. The CRM must absorb only enough energy to perform its function of smoothing out the motion. Any energy absorbed above this minimum requirement would take away energy needed to launch the payload. Also, any excess energy absorbed by the CRM would keep the rockets near the launchpad for a longer period of time, a result that could seriously damage the launch platform. In order to balance the need to keep jerk to a minimum against the need to get off the launchpad in a short time, NASA scientists require that the maximum displacement be approximately seven (7) inches when the vehicle is fully released. The requirement of a seven (7) inch maximum displacement allows for the design of a CRM that absorbs enough energy to perform its task without producing adverse side effects.

Section III

Controlled Release Mechanism for the Evolved Expendable Launch Vehicle (EELV)

The general requirements for the controlled release mechanism that will be used on the EELV are:

- 13.5 kip (kilopounds) load capacity
- 7 inch stroke (maximum displacement at release)
- Tension in the mechanism should decrease as the stroke increases.

An example of one type of CRM is shown at the right. The drawing is not to scale. The flight side of the mechanism is attached to the rocket, and the ground side is attached to the launchpad and remains on the ground.

Mandrel Mechanism

Description:

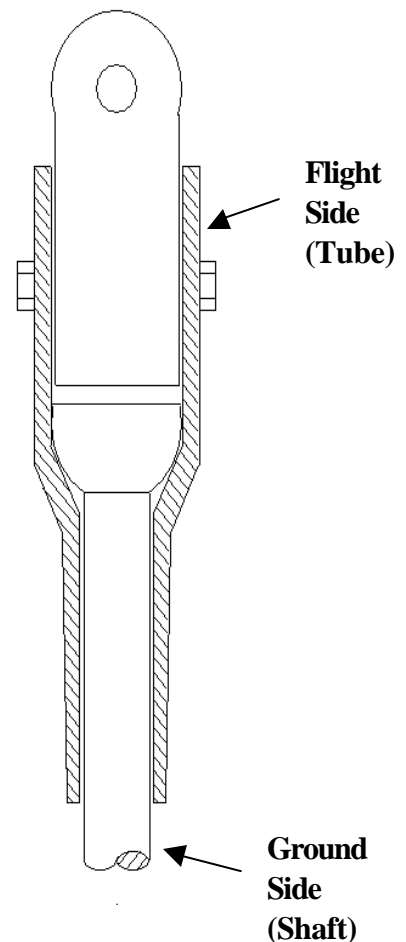
The flight side is a tapered 300 Series stainless steel tube. The ground side is a hardened steel shaft with a hemispherical end. At liftoff the shaft is pulled through the tube. The tube then becomes plastically deformed. The wall thickness of the tube can be designed to “tune” the Force-Displacement diagram. Narrower walls provide less restraint, thicker walls provide more restraint. The taper (decreasing wall thickness) of the steel tube creates a restraining force that decreases with displacement (shaft movement).

Advantages of the Mandrel Mechanism:

- Can be modeled with relative accuracy
- Tolerant of machining errors
- Moderate manufacturing difficulty
- Predictable stroke length
- Tunable Force-Displacement curve means that the jerk can be made small upon release and allows the curve to be smooth during all phases of the liftoff. In particular, the curve can be made relatively flat just before release.

Disadvantages of the Mandrel Mechanism:

- Expensive to build
- Extensive testing required
- Requires pre-loading



Exercises (2 - 5)

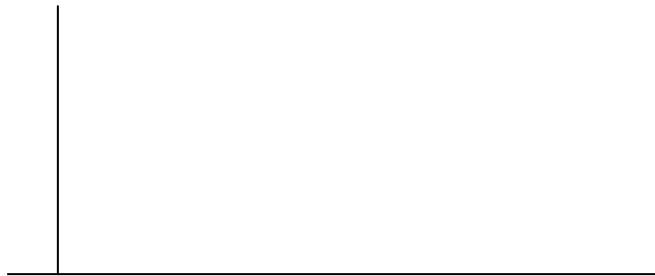
These exercises involve working with the restraining force functions of four (4) controlled release mechanisms. Each of the Exercises 2 through 6 consists of four Parts, a - d.

- Sketch the graph of the restraining force function given in each exercise on the interval $[0,7]$. The restraining force, F_r , is in pounds, and the displacement, x , is in inches.
- For each curve, use Simpson's Rule with $n = 6$ to estimate $\int_0^7 F_r dx$. Show your work, and include appropriate units with your answer.
- Calculate an error bound for your estimates.
- Find the exact areas by evaluating the definite integral on $[0,7]$, and compare your answers to the estimates obtained from Simpson's Rule.

Note: When Simpson's Rule gives the exact value of the definite integral, rounding errors may produce slightly different answers for parts b and d.

2) $F_r(x) = 50000 - 7143x$

a)



b) Simpson's rule calculation: area estimate _____

c) Error Bound = _____

d) Exact value of area = _____

3) $F_r(x) = 50000 - 145.8x^3$

a)



b) Simpson's rule calculation:

area estimate _____

c) Error Bound = _____

d) Exact value of area = _____

4) $F_r(x) = 25000(1 + \cos(\frac{px}{7}))$

a)



b) Simpson's rule calculation:

area estimate _____

c) Error Bound = _____

d) Exact value of area = _____

5) $F_r(x) = 50,000 \cdot e^{-0.3x} - 874.69x$

a)



b) Simpson's rule calculation:

area estimate _____

c) Error Bound = _____

d) Exact value of area = _____

6) Suppose the mechanism fails at $x = 5.8$ inches. How much "kick" would be imparted to the rocket in each of the four cases?

Function from Exercise 2 _____

Function from Exercise 3 _____

Function from Exercise 4 _____

Function from Exercise 5 _____