INFLUENCE OF INTERSTAGE DAMPING ON SATELLITE-LAUNCH VEHICLE LONGITUDINAL VIBRATIONS

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Abstract
While attached to a launch vehicle, satellites are subjected to intense dynamic loads throughout the flight, mainly at lift-off. Part of the vibrations is due to the propulsion system and is transmitted along the launch vehicle to the satellite by the payload adaptor fitting (PAF). This paper analyzes the influence of interstage sections and PAF damping on the acceleration response of the payload to launcher longitudinal vibrations. Simple mass-spring-damper models were used, considering the satellite and the stages as rigid bodies connected by springs and dampers. The satellite response to an oscillating force applied on the first stage was evaluated. The results show that when the damping in the inter-stage is high, the launch vehicle moves as a single mass, exciting the satellite as a moving base. If the damping is low, the stages move separately and the satellite will be excited by higher frequency modes. Moreover, lower PAF damping lead to higher accelerations at the second mode frequency and lower accelerations at higher frequencies, while the interstages damping showed little influence on the response around the second mode frequency but a direct effect on higher frequencies. The study was performed by implementing the models in a MATLAB routine.

Key Words - Launch vehicle, Satellite, Longitudinal Vibrations, Damping, Payload Adaptor Fitting.

1. Introduction
Satellites are submitted to intense loads during the launch vehicle flight. As pointed out in [1], some of these loads vary slightly over time (the quasi-static drag force and quasi-static thrust force) and some present a strong dynamic behavior (the aeroacoustic loads and thrust oscillations). All these loads must be taken into account during satellite design and qualification phases to ensure it will not affect the spacecraft performance during its operational lifetime. In order to reduce the acoustic loads on the payload, passive devices like acoustic blankets and resonators are usually added to the fairing [2].

The propulsion system generated vibration effect on the satellite can be reduced with proper design of the Payload Adaptor Fitting (PAF) a structure that connects the satellite to the launcher. This has been studied by several researchers [1], [3], [4], [5], [6], [7].

When designing a PAF, the transmission of longitudinal vibrations from the rocket must be evaluated. For a preliminary analysis focused on the moments close to lift-off, one can consider the launch vehicle a single rigid body connected to a smaller mass (the satellite) by a spring (the PAF). A slightly more complex but still quite simple model consists of considering the launch vehicle stages as rigid bodies connected by flexible elements (interstage sections).

The aim of this paper is to analyze the influence of the damping in PAF and interstages on the acceleration response in the satellite due to propulsion system generated vibration of the first stage in instants close to the lift-off. The 3-stage launch vehicle studied in [6] is analyzed. The frequency response function that relates the acceleration response in satellite to a force applied on the launcher first stage is evaluated for different damping values of interstages and the PAF. The results obtained show that when the inter-stage damping is very low, other peaks appear in the satellite's response. This shows that the launch vehicle no longer behaves as a rigid body, but as a multi-mass system.

2. Theory
The simplest mathematical model to analyze the longitudinal vibrations of a spacecraft - launch vehicle set is a system of two degrees of freedom (DOF), shown in Fig. 1, in which the launch vehicle is considered a rigid body.

![Figure 1 – Spacecraft and launch vehicle modeled as a two DOF mechanical system](image)

With current technologies, satellite rocket launchers necessarily have two or more stages. With respect to longitudinal vibrations, if the structural connections between the stages are not sufficiently rigid, the launcher may not behave dynamically as a rigid body. In this case, the launch vehicle can be modeled considering each stage...
as a rigid body connected to the neighboring stages by springs and dampers, as shown in Fig. 2.

The equation of motion of a discrete mechanical system is:

$$\{M\}{\ddot{x}} + \{C\}{\dot{x}} + \{K\}x = \{F\} \quad (1)$$

The matrices and vectors for the 4 DOF system displayed in Fig. 2 are:

$$[M] = \begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_3 & 0 \\ 0 & 0 & 0 & m_4 \end{bmatrix}; \quad (2)$$

$$[C] = \begin{bmatrix} c_1 & -c_1 & 0 & 0 \\ -c_1 & c_1 + c_2 & -c_2 & 0 \\ 0 & -c_2 & c_2 + c_3 & -c_3 \\ 0 & 0 & -c_3 & c_3 \end{bmatrix};$$

$$[K] = \begin{bmatrix} k_1 & -k_1 & 0 & 0 \\ -k_1 & k_1 + k_2 & -k_2 & 0 \\ 0 & -k_2 & k_2 + k_3 & -k_3 \\ 0 & 0 & -k_3 & k_3 \end{bmatrix};$$

$$[x] = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}; \quad [F] = \begin{bmatrix} f_1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Where $c_i = 2\zeta_i \sqrt{m_i k_i}$, $\zeta_i$ is the damping ratio and $i = 1, 2, 3$.

If the 2 DOF system is considered, the matrices and vectors for the Equation 1 are:

$$[M] = \begin{bmatrix} m_1 + m_2 + m_3 & 0 \\ 0 & m_4 \end{bmatrix}; \quad (3)$$

$$[C] = \begin{bmatrix} c_1 & -c_1 \\ -c_1 & c_1 + c_2 \end{bmatrix}; \quad [K] = \begin{bmatrix} k_1 & -k_3 \\ -k_3 & k_3 \end{bmatrix};$$

$$[x] = \begin{bmatrix} x_{LV} \\ x_S \end{bmatrix}; \quad [F] = \begin{bmatrix} f_L \\ 0 \end{bmatrix}$$

Where $LV$ stands for the whole launch vehicle and $S$ for the spacecraft.

The dynamic response to a force applied on the first stage (thrust) can be evaluated by solving Equation 1. The frequency response function that relates the acceleration response in the spacecraft to a force applied on the launcher first stage can be evaluated by calculating the response on the degree of freedom $x_1$ (mass $m_1$), which equation can be seen as following:

$$\{a\} = -\omega^2(-\omega^2[M] + j\omega[C] + [K])^{-1}[F]$$

$$\{a\} = \begin{bmatrix} \ddot{x}_{LV} \\ \ddot{x}_S \end{bmatrix} \text{ or } \begin{bmatrix} \dot{x}_{LV} \\ \dot{x}_S \end{bmatrix}; \quad [F] = \begin{bmatrix} f_L \\ 0 \end{bmatrix} \text{ or } \begin{bmatrix} f_S \\ 0 \end{bmatrix}$$

$$f_L = 1$$

The properties of the satellite and the launch vehicle used in the analysis are shown in Table 1.

In order to evaluate the influence of the characteristics of the interstages damping on the dynamic response of the satellite, analyses were performed for various values of damping ratio for these structures (considered the same for both interstages). In addition, the influence of the PAF damping was also analyzed.

### Table 1 - Satellite and launcher – vehicle properties

| Property | Value | Unity |
|----------|-------|-------|
| $m_1$    | 96243 | Kg    |
| $m_2$    | 26300 | Kg    |
| $m_3$    | 12000 | Kg    |
| $m_4$    | 1228  | Kg    |
| $k_1$    | $1 \times 10^8$ | N/m |
| $k_2$    | $1 \times 10^8$ | N/m |
| $k_3$    | 19953 | N/m |

### 3. Results

A MATLAB routine was written to perform the calculations and plot the results for the 2 and 4 DOF systems. The natural frequencies calculated for both models are displayed in Table 2.
| ζ₁ | 0.32 | - |
| ζ₂ | 0.32 | - |
| ζ₃ | 0.015 | - |

| Mode | 2 DOF system | 4 DOF system |
|------|--------------|--------------|
| 1    | 0.0000       | 0.0000       |
| 2    | 0.6445       | 0.6444       |
| 3    | -            | 9.0319       |
| 4    | -            | 18.6680      |

Table 2–Natural frequencies of 2 and 4 DOF models

In both models, the first mode presents no relative displacements (rigid body mode). In the 2nd mode, the satellite and the launcher vehicle move in opposite directions in both models, and in the 4 DOF model, the three stages move together in this mode.

In order to assess the influence of damping of interstage structures and PAF on the satellite dynamic response, the analysis were performed for various values of ζ₁, ζ₂ and ζ₃ obtained as follows:

\[ \tilde{\zeta}_i = \alpha \zeta_{i \text{original}} \]  \hspace{1cm} (5)

Where \(0.01 < \alpha < 1\) and \(i = 1,2,3\).

4. Discussion

To analyze the results, the acceleration response will be divided in three regions: the region A is defined as the region around the second mode from Table 2, B is defined as the region around the third and fourth modes and C is defined as the region with frequencies higher than B. The zone before region A shows practically coincident responses in all studied cases.

By observing the Fig. 3, it can be seen that there's no visible variation in region A, and higher values of damping (ζ/ζ_original close to 1) resulted in lower accelerations in B but higher in C. Compared to the evaluated cases, the 2 DOF model has the lower response in B and the higher in C, which proves that this assumption can lead to underestimation of the actual loads. It is also noticeable that low interstage damping can lead to high load peaks in B, so care must be taken when designing the interface between stages. The observation of Fig. 4 shows no influence of ζ₃ in region B, while higher values of damping lead to lower accelerations in A and higher in C. Finally, Fig. 5 demonstrates the combination of the effects aforementioned.

5. Conclusions

The results show that from certain values of interstage damping ratio, the assumption of a rigid multi-staged launch vehicle when simulating payload longitudinal vibrations can lead to an underestimation of loads near
the natural frequencies of the launch vehicle. When varying the damping between stages, no differences can be noticed around the payload natural frequency (second mode), and lower damping ratios resulted in higher accelerations around the stages natural frequencies but lower accelerations at higher frequencies. Furthermore, when varying the PAF’s damping, a higher damping ratio resulted in lower accelerations around the payload natural frequency, but higher accelerations at higher frequencies. Which configuration is best depends on the project, thus these parameters shall be studied for each case.

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