Launch Vehicle Payload Interface Response

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A method has been developed by which an estimate of the launch vehicle/payload interface response is derived from the interface responses obtained from missions with the identical launch vehicle but different payloads. This method requires the knowledge of the launch vehicle eigenvalues, interface modal displacements, and the dynamic characteristics of the payloads. No other launch vehicle information is required. The organization responsible for the payload is able to perform loads and responses analysis resulting from a payload change without interfacing with the launch vehicle organization.

Introduction

A SPACE mission often utilizes an existing launch vehicle for a new payload designed for a specific mission; such will be the case for future Shuttle missions. The dynamic design loads for the payload are obtained by performing a transient analysis of the analytical dynamic model of the coupled payload and launch vehicle. Each analysis iteration for a specific payload configuration is expensive and time consuming. The combined dynamic model of the payload/launch vehicle is not only large and complex, but the time duration of one iteration is extensive because of the number of different organizations involved. The proposed methodology allows the payload organization to estimate the dynamic loads for a design iteration independent of other organizations. It should be noted that the proposed method can also be applied to the general class of subsystems coupled to relatively large vehicles such as the guidance system on a missile and the auxiliary power unit on an aircraft. This method will make a significant contribution to the time-critical development of subsystems constrained by complex technical and project interfaces.

The procedure assumes that the acceleration time history at the payload/launch vehicle is available from past flight measurements or analyses, the dynamic characteristics of the launch vehicle do not change, the forcing function on the launch vehicle can be approximated by a delta function, and the mass of the payload is small compared to the mass of the launch vehicle. These assumptions are realistic for most projects for design/analysis iterations.

Historically, during the payload design phase, the payload/launch vehicle interface accelerations have been defined as a sine wave input or a shock spectrum.[1,2] Both methods essentially eliminate the time dependency of the interface response.

In the past 10 years, estimates of spacecraft interface accelerations measured from flight data have been used as an input forcing function to the payload to obtain more realistic estimates of the dynamic loads. At the Jet Propulsion Laboratory similar procedures were used on the Ranger, Surveyor, Mariner, and Viking Projects. In 1971, Caughey[3] investigated the potential error in this procedure by assuming that the interface acceleration is invariant as the payload is modified. The study indicates that the error can be very large and is dependent on the dynamic characteristics of the system.

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Recently, methods[4,5] to estimate the change in structural response due to small payload design changes without a complete reanalysis of the new system have been published. However, these methods require the eigenvalues and eigenvectors of the entire original system.

Approach

In the present investigation, a method to obtain a better estimate of a new launch vehicle/payload interface response from previous flights or analysis for a system with an identical launch vehicle but a different payload is developed. The governing equation for a launch vehicle/payload composite model can be written in the finite-element formulation as:

$$\begin{bmatrix} m_1 & 0 \\ 0 & \epsilon^2 m_2 \end{bmatrix} \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \left(\begin{bmatrix} k_1 & 0 \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} \epsilon^2 k_{11} & \epsilon^2 k_{21} \\ \epsilon^2 k_{12} & \epsilon^2 k_{22} \end{bmatrix} \right) \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{Bmatrix} f(t) \\ 0 \end{Bmatrix} \tag{1}$$

where

$\{x_1\}$	$=N$ degree-of-freedom vector representing launch vehicle displacements
$\{x_2\}$	= corresponding M degree-of-freedom vector for the spacecraft displacements
ϵ	= arbitrary small parameter, commonly used in the perturbation theory[4,6]
$[k_1]$	$=N\times N$ launch vehicle stiffness matrix
$[m_1]$	$=N\times N$ launch vehicle mass matrix
$[\epsilon^2 m_2]$	$=M\times M$ spacecraft mass matrix
$[\epsilon^2 k_{11}]$, $[\epsilon^2 k_{22}]$ $[\epsilon^2 k_{21}]$, $[\epsilon^2 k_{22}]$	= submatrices of the total spacecraft stiffness matrix which is partitioned into launch vehicle/spacecraft interface degrees-of-freedom and the remaining spacecraft degrees-of-freedom
$\{f(t)\}$	= vector representing the external forces acting on the launch vehicle

For the purpose of emphasizing the fact that the composite model consists of a "small" payload mated with a "large" launch vehicle, the mass and stiffness of the payload are multiplied by the small parameter ϵ^2. Since both the payload and the launch vehicle are distributed systems whose mass and stiffness are represented by matrices, their magnitudes, whether large or small, may be indicated by the norms of these matrices. For a square matrix $[m_1]$ whose elements are real numbers, the norm of $[m_1]$ is defined as the square root of the trace of the product of $[m_I]$ and its transpose, $[m_I]^T$:

$$\text{norm}[m_I]2 = (\text{trace}([m_I][m_I]^T))^{1/2} \tag{2}$$

Since $[m_I]$ is a symmetric matrix, $[m_I] = [m_I]^T$; by direct multiplication it can be seen that the trace of the product is the sum of the squares of the elements of $[m_I]$. Therefore, the norm of $[m_I]$ can be written as

$$\text{norm}[m_I] = \left[\sum_{i=1}^{N}\sum_{j=1}^{N}(m_I)_{ij}^2\right]^{1/2} \tag{3}$$

Similarly, the norm of the payload mass matrix, $[\epsilon^2 m_2]$, can be written as

$$\text{norm}[\epsilon^2 m_2] = \left[\sum_{i=1}^{M}\sum_{j=1}^{M}(\epsilon^2 m_2)_{ij}^2\right]^{1/2} \tag{4}$$

The meaning of a "large" launch vehicle and a "small" payload can be expressed by the following inequality;

$$\text{norm}[m_I] >> \text{norm}[\epsilon^2 m_2] \tag{5}$$

and the order of the small parameter ϵ^2 is defined as equal to the order of the ratios of these two norms:

$$O(\epsilon^2) = O\left(\frac{\text{norm}\ [\epsilon^2 m_2]}{\text{norm}[m_I]}\right) \tag{6}$$

It becomes clear that the order of the small parameter ϵ^2 is indeed small as long as the norms of the mass matrices of the launch vehicle and the payload satisfy the inequality as expressed by Eq. (5). The important point is that ϵ^2 by itself only represents the order of magnitude not the physical values. But when ϵ^2 appears as a coefficient such as in the term $[\epsilon^2 m_2]$, the product $[\epsilon^2 m_2]$ possesses the physical values and its order of magnitude can readily be identified by ϵ^2. Similarly, the orders of the magnitude of stiffness matrices can be treated in the same manner. For simplicity, the damping has been excluded in the formulation, although it can later be incorporated into the system in the form of modal damping. A subset of the launch vehicle degrees-of-freedom which connect the launch vehicle to the payload will be defined as the interface degrees-of-freedom $\{x_I\}$. For a given forcing function $\{f(t)\}$, the response of the composite system can be calculated. Since only the payload responses are of interest to the payload designer, they will be obtained from the interface acceleration $\{x_I\}$. For simplicity, it will be assumed for the present case that the payload is supported in a statically determinate manner such that

$$[\epsilon^2 k_{II}] = [\phi_R]^T[\epsilon^2 k_{22}][\phi_R] \tag{7a}$$

$$[\epsilon^2 k_{2I}] = -[\phi_R]^T[\epsilon^2 k_{22}] = [\epsilon^2 k_{I2}]^T \tag{7b}$$

where $[\phi_R]$ is the rigid-body transformation matrix which is defined as the payload displacements due to unit displacements of the launch vehicle interface degrees-of-freedom $\{x_I\}$. It must be noted that Eq. (7) is not a general constraint, but an assumption for the present case. Upon substitution of Eq. (7) into Eq. (1), the governing equation can be written as

$$\begin{bmatrix} m_I & 0 \\ 0 & \epsilon^2 m_2 \end{bmatrix}\begin{Bmatrix} \ddot{x}_I \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} k_I + \epsilon^2\phi_R^T k_{22}\phi_R & -\epsilon^2\phi_R^T k_{22} \\ -\epsilon^2 k_{22}\phi_R & \epsilon^2 k_{22} \end{bmatrix}\begin{Bmatrix} x_I \\ x_2 \end{Bmatrix} = \begin{Bmatrix} f(t) \\ 0 \end{Bmatrix} \tag{8}$$

The payload response will be divided into two parts, the rigid-body motion and the elastic deformation as

$$\{x_2\} = [\phi_R]\{x_I\} + \{y\} \tag{9}$$

Upon substitution of Eq. (9) into (8), one obtains

$$[\epsilon^2 m_2]\{\ddot{y}\} + [\epsilon^2 k_{22}]\{y\} = -[\epsilon^2 m_2][\phi_R]\{\ddot{x}_I\} \tag{10}$$

Equation (10) indicates that the elastic response of the payload can be calculated by applying the interface acceleration to the payload.

Consider another composite system which consists of an identical launch vehicle and a new payload structure with an identical forcing function applied to the launch vehicle. The governing equation can be written as

$$\begin{bmatrix} m_I & 0 \\ 0 & \epsilon^2 \bar{m}_2 \end{bmatrix}\begin{Bmatrix} \ddot{\bar{x}}_I \\ \ddot{\bar{x}}_2 \end{Bmatrix} + \begin{bmatrix} k_I + \epsilon^2\bar{\phi}_R^T \bar{k}_{22}\bar{\phi}_R & -\epsilon^2\bar{\phi}_R^T \bar{k}_{22} \\ -\epsilon^2 \bar{k}_{22}\bar{\phi}_R & \epsilon^2 \bar{k}_{22} \end{bmatrix}\begin{Bmatrix} \bar{x}_I \\ \bar{x}_2 \end{Bmatrix} = \begin{Bmatrix} f(t) \\ 0 \end{Bmatrix} \tag{11}$$

where $[\epsilon^2 \bar{m}_2]$, $[\epsilon^2 \bar{k}_{22}]$, and $[\bar{\phi}_R]$ are the mass matrix, stiffness matrix, and the rigid-body transformation matrix of the new payload, respectively. The number of degrees-of-freedom of the new payload may be different from the previous one.

The response of the new payload can be calculated from the interface acceleration as

$$[\epsilon^2 \bar{m}_2)\{\ddot{\bar{y}}\} + [\epsilon^2 \bar{k}_{22}]\{\bar{y}\} = -[\epsilon^2 \bar{m}_2][\bar{\phi}_R]\{\ddot{\bar{x}}_I\} \tag{12}$$

where

$$\{\bar{x}_2\} = [\bar{\phi}_R]\{\bar{x}_I\} \mid + \{\bar{y}\} \tag{13}$$

The objective is to obtain the new interface acceleration $\{\ddot{\bar{x}}_I\}$ without re-solving the governing equation of the new composite system as expressed by Eq. (11). The payload response will be calculated by Eqs. (12) and (13). The degrees-of-freedom of Eq. (12) are much smaller than Eq. (11), and, more importantly, Eq. (12) can be solved within the organization responsible for the payload, thus eliminating the interface between the payload organization and the launch vehicle organization.

Next, the solutions of Eqs. (8) and (11) will be examined and the relationship between the two interface responses $\{x_I\}$ and $\{\bar{x}_I\}$ will be derived. For a composite system consisting of a small structure mated with a large structure such as represented by Eqs. (8) and (11), the eigenvectors are of the form[6]

$$[\phi] \approx \left[\begin{array}{c|c} \phi_{II} & \epsilon\phi_{2I} \\ \hline \phi_{I2} & (1/\epsilon)\phi_{22} \end{array}\right] \begin{array}{l} \}\ \text{launch vehicle DOF} \\ \}\ \text{payload DOF} \end{array} \tag{14}$$

 N modes $\quad$ M modes

where $[\phi_{II}]$ is the eigenvector matrix for the launch vehicle alone, and $[(1/\epsilon)\phi_{22}]$ is the eigenvector matrix for the cantilevered payload. As shown in Eq. (14), the eigenvector for the composite system consists of two parts. Namely, the first N modes are the "global modes," which are extensions of the launch vehicle modes into the payload structure. The next M modes are referred to as "local modes" since the motion of the payload is $O(1/\epsilon)$ or $O(1/\epsilon^2)$ times the launch vehicle motion. With this in mind, the following transformation will be applied to Eq. (8).

$$\begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{bmatrix} \phi_{11} & 0 \\ \phi_R\phi_{11} & (1/\epsilon)\phi_{22} \end{bmatrix} \{u\} \tag{15}$$

Since $[\phi_{11}]$ and $[1/\epsilon)\phi_{22}]$ are the eigenvectors for the launch vehicle and the payload respectively, they satisfy the following orthogonality conditions:

$$[\phi_{11}]^T[m_1][\phi_{11}] = [I] \text{ unity matrix} \tag{16a}$$

$$[\phi_{11}]^T[k_1][\phi_{11}] = [\omega_1^2] \text{ eigenvalues for launch vehicle} \tag{16b}$$

$$[(1/\epsilon)\phi_{22}]^T[\epsilon^2 m_2][(1/\epsilon)\phi_{22}] = [I] \text{ unity matrix} \tag{16c}$$

$$[(1/\epsilon)\phi_{22}]^T[\epsilon^2 k_{22}][(1/\epsilon)\phi_{22}] = [\omega_2^2] \text{ eigenvalues for payload} \tag{16d}$$

Physically, the transformation implies that the normal mode of the composite system consists of two parts, namely the global modes and local modes. For the global modes, the launch vehicle motion is identical to the modes of the launch vehicle alone and the payload motion is rigid-body. For the local modes, the launch vehicle remains stationary and the payload motion is identical to its cantilevered modes. Upon substitution of Eq. (15) into Eq. (8) and premultiplying Eq. (8) by the transpose of the transformation matrix of Eq. (15) and by using the orthogonality conditions in Eq. (16), the following equation is obtained:

$$[M]\{\ddot{u}\} + [K]\{u\} = \{G(t)\} \tag{17}$$

where

$$[M] = [I] + \epsilon[M_1] + \epsilon^2[M_2] \tag{18a}$$

$$[M_1] = \begin{bmatrix} 0 & \phi_{11}^T\phi_R^T m_2\phi_{22} \\ \phi_{22}^T m_2\phi_R\phi_{11} & 0 \end{bmatrix}$$

$$[M_2] = \begin{bmatrix} \phi_{11}^T\phi_R^T m_2\phi_R\phi_{11} & 0 \\ 0 & 0 \end{bmatrix} \tag{18b}$$

$$[K] = \begin{bmatrix} \omega_1^2 & \\ & \omega_2^2 \end{bmatrix} \qquad \{G(t)\} = \begin{Bmatrix} \phi_{11}^T f(t) \\ 0 \end{Bmatrix} \tag{18c}$$

Now the governing equation for the launch vehicle/payload composite system is reduced from Eq. (8) to Eq. (17) in which the coefficients are a power series of small parameter ϵ. The solution of Eq. (17) may be obtained by the perturbation method.[4] Let the eigenvectors and the eigenvalues of the composite system, Eq. (17), be $[\Phi]$ and $[\Omega]$, respectively. They can be expressed by the following power series:

$$[\Phi] = [\Phi_0] + \epsilon[\Phi_1] + \epsilon^2[\Phi_2] + \ldots \tag{19a}$$

$$[\Omega] = [\Omega_0] + \epsilon[\Omega_1] + \epsilon^2[\Omega_2] + \ldots \tag{19b}$$

Following the procedure developed in Ref. 4, the eigenvectors and eigenvalues can be determined as follows:

$$[\Phi_0] = [I], \quad [\epsilon\Phi_1] = \begin{bmatrix} 0 & \epsilon\gamma_1 \\ \epsilon\sigma_1 & 0 \end{bmatrix} \tag{20}$$

and

$$[\Omega_0^2] = \begin{bmatrix} \omega_1^2 & \\ & \omega_2^2 \end{bmatrix}, \quad [\epsilon\Omega_1] = 0 \tag{21}$$

where

$$[\epsilon\gamma_1] + [\epsilon\sigma_1]^T = -[\phi_{11}]^T[\phi_R]^T[\epsilon^2 m_2][(1/\epsilon)\phi_{22}] \tag{22a}$$

$$[\omega_1^2][\epsilon\gamma_1] + [\epsilon\sigma_1]^T[\omega_2^2] = 0 \tag{22b}$$

Substituting Eqs. (20) and (21) into Eq. (19), the eigenvectors and eigenvalues of the composite system can be obtained with the accuracy of the order of ϵ. Equation (21) indicates that the composite system eigenvalues consist of the launch vehicle natural frequencies ω_1 and the payload frequencies ω_2. On the other hand, the composite eigenvectors $[\Phi]$ involve the order of ϵ terms, $[\epsilon\sigma_1]$ and $[\epsilon\gamma_1]$, which are functions of $[\phi_{11}]$, the launch vehicle eigenvectors, and the payload properties such as $[\phi_R]$, $[\epsilon^2 m_2]$, and $[(1/\epsilon)\phi_{22}]$. However, the rigid-body transformation $[\phi_R]$ involves only the interface degrees-of-freedom which connect the payload to the launch vehicle. Therefore the matrix multiplication $[\phi_{11}]^T[\phi_R]^T$ in Eq. (22) can be expressed as $[\phi_1]^T$ $[\phi_R]$ where $[\phi_1]$ is a subset of $[\phi_{11}]$ and defined as the interface modal displacements. From Eqs. (19-22), the composite system eigenvalues and eigenvectors can be determined by the payload organization once the payload characteristics and the launch vehicle natural frequencies and interface eigenvectors are available.

The response of the composite system as expressed by Eq. (8) will be calculated by the following generalized coordinate transformation:

$$\begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{bmatrix} \phi_{11} & 0 \\ \phi_R\phi_1 & (1/\epsilon)\phi_{22} \end{bmatrix} [\Phi] \begin{Bmatrix} q_1 \\ q_2 \end{Bmatrix} \tag{23}$$

The decoupled equation is as follows:

$$\begin{Bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{Bmatrix} + \begin{bmatrix} \omega_1^2 & \\ & \omega_2^2 \end{bmatrix} \begin{Bmatrix} q_1 \\ q_2 \end{Bmatrix} = \begin{Bmatrix} \phi_{11}^T f(t) \\ \epsilon\gamma_1^T\phi_{11}^T f(t) \end{Bmatrix} \tag{24}$$

Critical dynamic environments are typically a result of various staging transients which can be represented by a Delta function.

$$[\phi_{11}]^T\{f(t)\} = \{g\}\delta(t=0) \tag{25}$$

the solution of Eq. (24) is

$$\{q_1\} = [\omega_1]^{-1}[\sin\omega_1 t]\{g\} \tag{26a}$$

$$\{q_2\} = [\omega_2]^{-1}[\sin\omega_2 t][\epsilon\gamma_1]^T\{g\} \tag{26b}$$

The interface acceleration is

$$\{\ddot{x}_1\} = -[\phi_1]\left([\omega_1\sin\omega_1 t] + [\epsilon\gamma_1][\omega_2\sin\omega_2 t][\epsilon\gamma_1]^T\right)\{g\} \tag{27}$$

The interface acceleration of the new composite system with the identical launch vehicle but different payload, Eq. (11), is obtained in a similar manner:

$$\{\ddot{\bar{x}}_1\} = -[\phi_1]\left([\omega_1\sin\omega_1 t] + [\epsilon\bar{\gamma}_1][\bar{\omega}_2\sin\bar{\omega}_2 t][\epsilon\bar{\gamma}_1]^T\right)\{g\} \tag{28}$$

where $\bar{\omega}_2$'s are the new payload natural frequencies, and

$$[\epsilon\bar{\gamma}_1] + [\epsilon\bar{\sigma}_1]^T = -[\phi_1]^T[\bar{\phi}_R]^T[\epsilon^2\bar{m}_2][(1/\epsilon)\bar{\phi}_{22}] \tag{29a}$$

$$[\omega_1^2][\epsilon\bar{\gamma}_1] + [\epsilon\bar{\sigma}_1]^T[\bar{\omega}_2^2] = 0 \tag{29b}$$

where $(1/\epsilon)\bar{\phi}_{22}]$ are the new payload eigenvectors.

For consistency it appears that the ϵ^2 terms in both Eqs. (27) and (28) should be neglected, since only the terms of order ϵ or greater are retained. However, the ϵ^2 term represents the effects to the interface acceleration due to the payload. This is evident since the interface accelerations $\{\ddot{x}_1\}$ and $\{\ddot{\bar{x}}_1\}$ become identical when ϵ^2 terms are neglected. The significance of these ϵ^2 terms is further demonstrated by examining Eqs. (10) and (12), from which the payload responses are calculated. The interface accelerations become the periodic forcing functions whose frequencies are identical to the natural frequencies of the payloads. Therefore, the payload responses due to these ϵ^2 terms are very large. In fact, without considering the damping, as in Eqs. (10) and (12), the response will be infinite despite the small magnitude of the forcing function.

As mentioned before, our objective is to construct the interface acceleration of the new composite system $\{\ddot{x}_I\}$ without a resolution of the new governing equation, Eq. (11). This is accomplished if the values of the generalized forcing function $\{g\}$ can be obtained. Let $(\ddot{x}_I)_j$ be the jth interface degree-of-freedom of the original composite system. From Eq. (27),

$$(\ddot{x}_I)_j = \sum_{i=1}^{N} a_{ji}\sin(\omega_I)_i t + \epsilon^2 \sum_{k=1}^{M} b_{kj}\sin(\omega_2)_k t \tag{30}$$

where

$$a_{ji} = (\phi_I)_{ij}(\omega_I)_i g_i \tag{31}$$

The magnitude of a_{ji} can be determined by using narrow bandpass filters centered at $(\omega_I)_i$'s. Since $(\phi_I)_{ij}$ and ω_I's, the modal displacements of the interface degree-of-freedom and the launch vehicle natural frequencies, respectively, are available from the solution to the original composite system, the g_i's can be calculated from Eq. (31). The interface acceleration of the new composite system can then be constructed according to Eq. (28), where $[\epsilon\bar{\gamma}_I]$ and $[\bar{\omega}_2]$ are functions of the new payload characteristics.

The payload response can be obtained from Eq. (12) as follows:

$$\{\ddot{x}_2\} = [\bar{\phi}_R]\{\ddot{x}_I\} + [(1/\epsilon)\bar{\phi}_{22}]\{\ddot{u}_2\} \tag{32}$$

where

$$\{\ddot{u}_2\} + 2[\rho][\bar{\omega}_2]\{\dot{u}_2\} + [\bar{\omega}_2^2]\{\bar{u}_2\}$$
$$= -[1/\epsilon)\bar{\phi}_{22}]^T[\epsilon^2\bar{m}_2][\bar{\phi}_R]\{\ddot{x}_I\} \tag{33}$$

In Eq. (33), modal damping terms are added to represent the actual system more realistically.

In summary, the new payload responses are calculated from the interface accelerations, which are constructed based on the interface accelerations of a previous composite system with a different payload. The information required to construct the new interface accelerations includes the modal displacements of interface degree-of-freedom $[\phi_I]$, mode shape $[(1/\epsilon)\bar{\phi}_{22}]$, rigid-body transformation matrix $[\bar{\phi}_R]$, natural frequencies $[\bar{\omega}_2]$, mass matrix $[\epsilon^2\bar{m}_2]$ of the payload, and, of course, the interface accelerations of the previous composite system. The advantages of this approach are, as mentioned before, not only to deal with a smaller problem, Eq. (12) as compared to Eq. (11), but to confine the entire analysis within the payload orgainzation. In the following, the methodology will be applied to the Viking spacecraft load analysis by calculating the payload response using constructed interface acceleration from a previous composite system.

Sample Problem

The Viking spacecraft in its launch configuration is shown in Fig. 1. The launch vehicle for the Viking mission is the Titan IIIE/Centaur; Fig. 2 shows the Viking space vehicle configuration and the organizations responsible for the various components. The transient loading events such as stage-zero ignition, stage-one shutdown, and the Centaur second-stage engine cutoff are significant loading events for

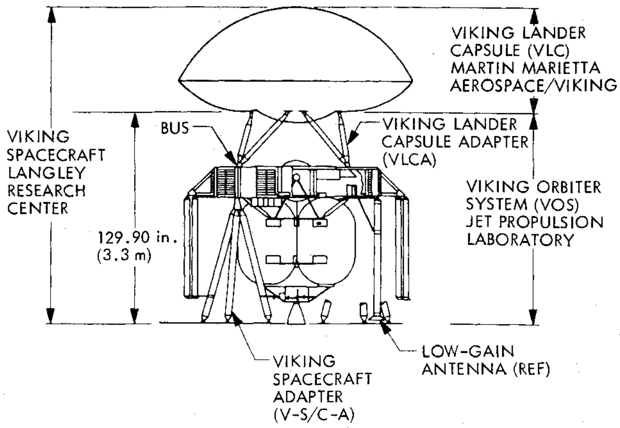

Fig. 1 Viking spacecraft configuration.

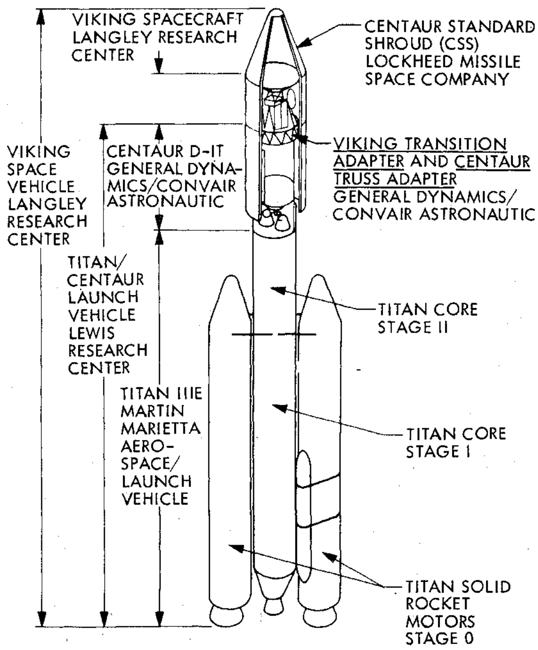

Fig. 2 Viking space vehicle configuration.

the spacecraft which affect its design. Each cognizant organization is responsible for the development of a mathematical model of the structure. These separate models are coupled modally to form the appropriate space vehicle configuration. The loads generated from the transient analysis of the space vehicle are used to design the payload. The design/load process, which can be time consuming because of the interorganization, is iterative because the loads are dependent on the dynamic characteristic of the payload, which is directly related to its design. For example, approximately 10 iterations of loads analyses were performed between July 1969 and Dec. 1973 on the Viking. For the sample problem, the response of the final Viking model (model 8) is calculated from the launch vehicle/payload interface accelerations constructed from the results of a previous model (model 7). The differences of the two models are significant (Table 1), and the load analyses were approximately 1½ years apart. The transient event chosen for the sample problem is the stage-I shutdown. During this event the launch vehicle weight was approximately 129,000 lb and the payload weight was approximately 7800 lb. The interface accelerations in the longitudinal direction from model 7 and model 8 loads analyses are shown in Fig. 3. As expected from Eqs. (27) and (28), the two interface accelerations are similar; the differences are of the order of ϵ^2. As described by Eqs. (27) and (28), the interface accelerations are approximately

Table 1 Vibration modes of the payload structures for the loads analyses, models 7 and 8

Payload for model 7		Payload for model 8	
Frequency, Hz	Description	Frequency, Hz	Description
4.0742	Bending, $+X$, $-Y$	4.3249	Bending, $-X$
4.2378	Bending, $+X$, $+Y$	4.4058	Bending, $+Y$
6.6138	Roll, $-\theta_z$	6.9315	Bending, $+Y$
6.8403	Bending, $+X$, $+Y$	7.0348	Bending, $+X$
7.7841	Axial, $+Z$	9.0466	Bending, $-X$
9.1764	Bending, $+Y$	9.6722	Roll, $+\theta_z$
9.4586	Axial, $+Z$	10.344	Bending, X, $-Y$
9.6729	Roll, $+\theta_z$	10.708	Roll, $+\theta_z$
9.7188	Axial, $-Z$	12.053	Axial, $-Z$
10.467	Axial, $-Z$	13.046	Axial, $-Z$

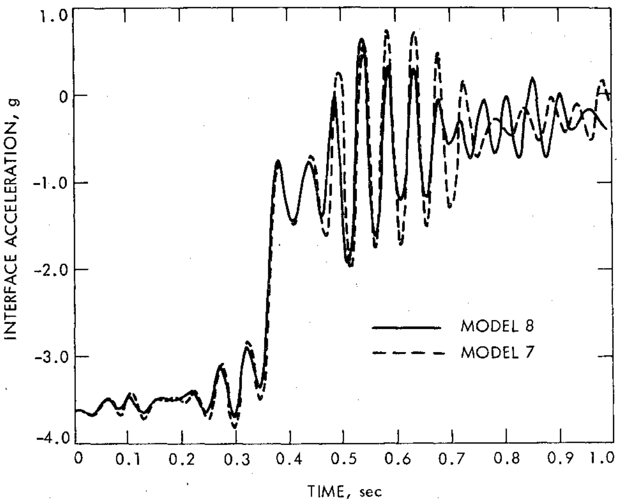

Fig. 3 Longitudinal interface acceleration of Viking model 7 and model 8 loads analysis.

divided into two parts, the larger oscillatory amplitude represents the response of the launch vehicle frequencies and the smaller oscillatory amplitude represents the response of its payload frequencies.

Based on the interface acceleration obtained from model 7 loads analyses, a new interface acceleration is constructed as described herein to excite the model 8 payload. Using Eqs. (32) and (33), the response of the payload is calculated. The results are compared with the "exact" solution, which is the response calculated from model 8 interface accelerations. For comparison purposes, the model 8 payload responses are calculated directly from model 7 interface acceleration without any modification. Figure 4 shows this comparison for a point below the Viking Lander in the longitudinal direction. The response calculated by the present method is very close to the exact solution; especially for $t>0.5$ s, the two solutions are almost identical. It should be noted that the response calculated from the model 7 interface acceleration is also close to the exact solution in amplitude but shows certain deviation in time (phase lag). In calculation of structural loads, the phase of the displacement is as important as the corresponding amplitude.

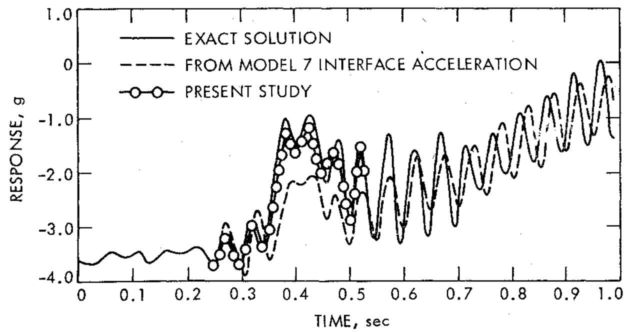

Fig. 4 Comparison of Lander response for stage-I shutdown.

Conclusion

A method is developed by which an estimate of the launch vehicle/payload interface response can be obtained from similar data from a similar mission with the identical launch vehicle but different payloads. The information required includes the launch vehicle eigenvalues, modal displacements of the interface degree of freedom, and the dynamic characteristics of the payload. This method enables the cognizant organization for the payload to perform loads and response analyses resulting from a payload change without interfacing with the launch vehicle organization. The cost savings and improvement of schedules can be significant. The interface accelerations can be obtained from the previous flight measured data as well as from the analyses. A restriction on this method is that the forcing function must have the form of a Delta function.

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