Coupling between Structure and Liquid Propellants in a Parallel-Stage Space Shuttle Design

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Theme

THE purpose of this paper is to study the coupled liquid-structural dynamics of a typical space shuttle configuration—a parallel-stage design. For this, a model was designed and tested to determine the influence of liquid propellants on coupled natural modes. In order to predict these modes, an analytical model was developed in which currently-available mechanical models for liquid sloshing were used. Applicability of this analytical model was examined.

Contents

The shuttle vehicle model design, which is capable of experiencing at least the most fundamental structural dynamics of a prototype system, consists of a parallel-stage booster and orbiter, each consisting of two propellant tanks and appropriate intermediate skirts and rigid masses. Figure 1 shows a schematic of this model. Coupling between the booster and orbiter was achieved by the strongback assembly. The strongback spans the full length of the booster and is attached to it at four locations. A short backstrap was attached to the orbiter spanning between the two flanges of the skirt. Through two guides on the strongback, the relative vertical position between the booster and the orbiter can be adjusted.

In determining natural frequencies of the shuttle vehicle model, the system was suspended in such a manner so that the driving force introduced to the model by the electrodynamic shaker always acted through the gravitational center of the model. Four piezoelectric accelerometers, located on the bottom flanges and the top of the models, were monitored measuring acceleration along the axes of the models, while two others were located at the tops recording acceleration in the lateral direction. In addition, four pressure transducers, one located in each bulkhead, were monitored. All tests were performed with the orbiter tanks full. The liquid level in the booster tanks was varied from empty to full with intermediate conditions. Thus, a normal operational sequence was simulated. Throughout the entire test program, distilled water was used as a modeling liquid propellant. Ullage pressure was provided in all tanks to raise the natural frequencies of nonsymmetric shell modes above the frequency range used during the tests.

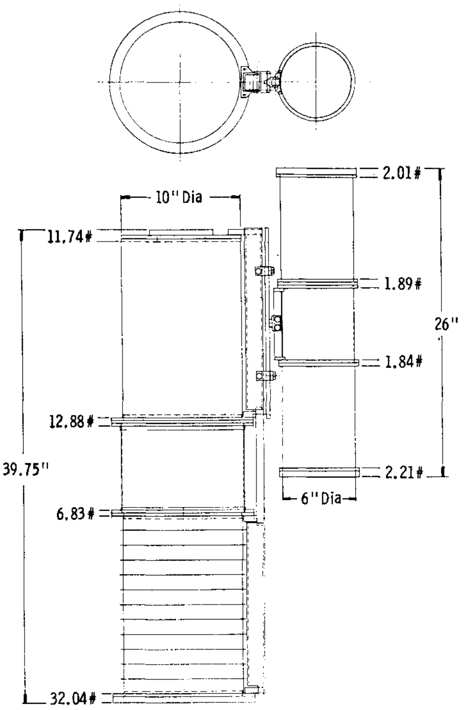

Fig. 1 Schematic of space shuttle vehicle model.

As a conclusion to the experimental program, the modeling liquid was replaced in the tanks by a granular substance with bulk density very closely equal to the modeling liquid and the model was tested at full and half-full levels in the booster tanks, and similar levels in the orbiter tanks. This substitution was implemented to facilitate identification of liquid and structural modes in the data obtained from tests completed on the coupled system, as well as to show more vividly the effects of liquid propellants.

In the modal analysis of free vibration of the shuttle vehicle model, the system was represented by an analytical model of spring-mass system. The motion of the system was limited to translations in vertical and horizontal directions (see Fig. 1) and pitching about an axis perpendicular to the vertical plane (plane of Fig. 1). Thus, there were forty equations of motion (hence, forty degrees of freedom) and twenty-two constraint conditions for this analytical model.[1]

The vertical and lateral sloshing motions of the liquid in a propellant tank are represented independently by two sloshing models. The vertical sloshing model[2] consists of one vertical sloshing mass connected to the neighboring mass elements through two springs. The lateral sloshing model [3–5] consists of one rigid mass rigidly attached to the propellant tank, and one lateral sloshing mass connected to the tank through two springs.

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Index categories: Spacecraft Configurational and Structural Design (Including Loads); Structural Dynamic Analysis.

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For free harmonic oscillation of the above mechanical system, the equations of motion may be expressed in terms of the constraint coordinates **x**:

$$(q_{ij} - \Omega^2 p_{ij})(X_j) = -a_{in}x_n \quad i, j = 1, 2, \ldots 40; n = 1, 2, \ldots 22 \tag{1}$$

where **p** and **q** are, respectively, mass and stiffness matrices of the dynamic equations, Ω is the eigenvalue of a vibration mode, **X** is mass element coordinates and **a** is a nonsquare coefficient matrix. The constraint conditions which relate **x** and **X** may be expressed as

$$c_{lm}x_{lm} = d_{lj}X_j; \quad l, m = 1, 2, \ldots 22 \tag{2}$$

where **c** and **d** are nonsquare coefficient matrices. After eliminating **x** from Eq. (1) by the aid of Eq. (2) there results

$$\{(\mathbf{p}^{-1})_{ki}[q_{ij} - a_{in}(\mathbf{c}^{-1})_{ln}(\mathbf{a}^T)_{lj}] - \Omega^2\delta_{kj}\}X_j = 0 \tag{3}$$

This is the form of a standard eigenvalue problem. Nontrivial solutions for the eigenvector **X** exist if, and only if, the determinant of the coefficient matrix vanishes

$$|(\mathbf{p}^{-1})_{ki}[q_{ij} - a_{in}(\mathbf{c}^{-1})_{ln}(\mathbf{a}^T)_{lj}] - \Omega^2\delta_{kj}| = 0 \tag{4}$$

Thus, the problem reduces to find the eigenvalue of the 40×40 matrix $\mathbf{p}^{-1}(\mathbf{q} - \mathbf{ac}^{-1}\mathbf{a}^T)$. The eigenvalues found by this process are the natural frequencies of the booster/orbiter system expressed in radians per second, including zero frequencies identified with translation and rotation of the system as a rigid body.

Figure 2 compares the theoretical and experimental frequencies for the coupled booster/orbiter system for full orbiter and various booster propellant levels. The two lowest modes, approximately constant at 15 Hz and 70 Hz, represent modes in which the booster and orbiter act essentially as rigid bodies, but vibrate to each other through the torsional coupling spring and the lateral coupling spring, respectively. The third mode is dominantly booster bending, while the fourth mode is the remaining rigid body mode, with relative booster/orbiter motion resisted through the longitudinal coupling spring. The fifth and sixth modes exchange motions of dominantly orbiter bending and booster longitudinal motion. Above this, the discrepancies become quite large.

It appears reasonable to conclude that the liquid propellant models, as derived, provide fair over-all prediction for the couple booster/orbiter system. However, possibilities for refinement of the models can immediately be considered. For example, the use of additional modes for the longitudinal liquid model could very likely improve the results at the higher frequencies. The results of this study indicate that a very effective, yet rather simple model of a typical shuttle system has been developed, whereby many potential problems in parallel stage shuttle vehicles can be studied.

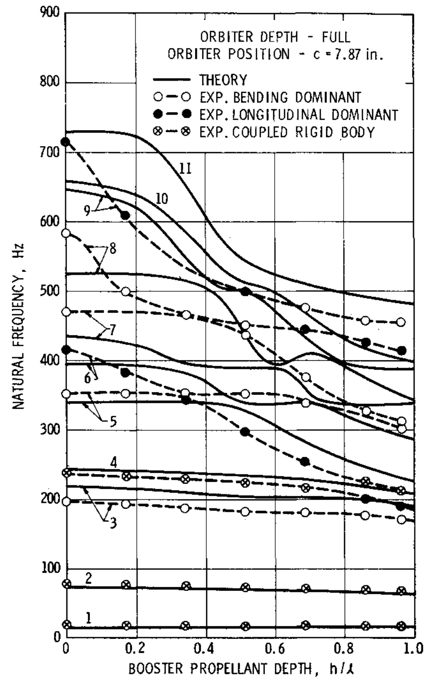

Fig. 2 Natural frequencies for space shuttle vehicle model.

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