A UNIQUE MODEL, SUSPENSION, AND EXCITATION SYSTEM FOR LAUNCH VEHICLE DYNAMICS STUDIES

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A description is given of a flexible model, feedback-controlled suspension, and modified electromagnetic shaker for use in launch vehicle dynamics studies. Test results indicate the effectiveness of the system in simulating the launch phase of liquid-fuel vehicles. Tests are now under way to develop a large vehicle system, using an Atlas and a Titan I with an 89,000 Newton (20,000 lb) force thruster.

INTRODUCTION

A program is under way at the Ames Research Center for studying the interaction of structure and control system in large launch vehicles by simulating the control system and thrust vector and using actual vehicles. The results of the simulation could then be applied to the design of the vehicle structure and control system as an integral unit.

In order to proof test the design of the thrust vector simulation and to explore structural problems, a small-scale idealized model was needed of the vehicle, the suspension system, and the thrust vector. In producing this idealized model, three major problems were confronted: (1) the development of a small (about 30 cm, or 1-ft diameter) launch vehicle model which would duplicate the bending/sloshing frequency ratio of a typical liquid-fuel vehicle; (2) the development of a low-frequency suspension system uncoupled from the vehicle bending modes; and (3) a correct simulation of the engine side thrust used for attitude control.

The purpose of this paper is to describe a novel solution to these problems: the combination of a flexible launch vehicle model with variable bending frequency, a servo-controlled cable suspension system, and a modified electromagnetic shaker with response to zero frequency.

FLEXIBLE MODEL

The requirements of the flexible model were that it should simulate a variety of launch vehicles, it should duplicate the bending frequency of the prototype, and it should maintain the correct bending/slosh frequency ratio.

Unfortunately, these are opposing requirements. In a dynamically similar model, the lateral bending frequency is inversely proportional to the scale factor λ; a one-tenth scale model has a bending frequency 10 times that of the prototype [1] . On the other hand, the fuel slosh frequency of a scale model is inversely proportional to $\sqrt{\lambda}$; a one-tenth scale model has a slosh frequency which is $\sqrt{10}$, or about 3.16 times that of the prototype. As a result of these different factors, it is impossible to reproduce the correct bending/slosh frequency ratio in a dynamically similar model constructed of identical materials.

The model described in this paper abandons dynamic similarity in favor of a segmented tank construction, which allows variation in the bending frequency. The model, shown in Fig. 1, consists of five cylindrical shells connected by their end plates through interchangeable flexures. The model, one-tenth the size of an Atlas, is 30.5 cm in diameter. The tanks may be filled with water to various levels in order to simulate different flight times, and the slosh frequency is fixed by the diameter of the tanks. The choice of five tanks was a compromise between a large number to accurately simulate the bending modes and a small number to simulate fuel slosh at any flight time. Five tanks allow testing only at discrete fluid levels, due to the fact that a minimum depth of fluid is needed in each tank to produce the calculated slosh frequency for the diameter [2] . The flexure stiffness is determined by the required bending frequency, and the diameter needed is calculated from a digital computer solution to the equations of motion of the five coupled masses.

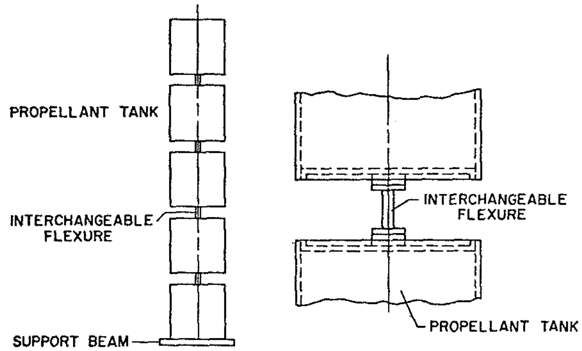

Fig. 1 - Model of flexible launch vehicle

Fig. 2 shows how the lateral bending frequencies of the segmented model compare to those of a theoretical uniform beam with the same first mode frequency. The first two modes are the important ones, and they are reproduced fairly well. As expected, the higher mode frequencies of the uniform beam are more nearly duplicated by the full model than by the empty model.

In practice, since the slosh frequency of the model is fixed, the flexure diameter is chosen to duplicate a given bending/slosh frequency ratio.

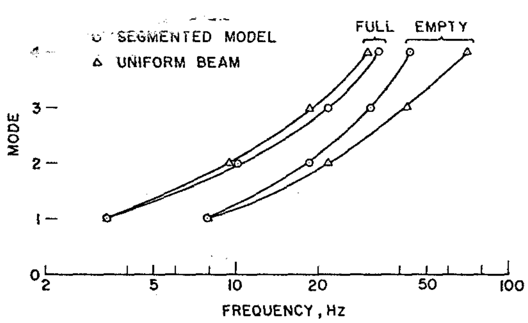

Fig. 2 - Flexible model bending frequencies

SUSPENSION SYSTEM

To simulate as closely as possible the flight conditions of a launch vehicle, a suspension system is necessary which supports the model in the vertical position with a minimum of lateral restraint. The ideal suspension would allow the vehicle to rotate about the c.g. with free-end conditions.

Various suspensions have been used to approach these ideals, including fluid bearings and cable systems [3]. Our study required minimum restraint and large excursions at the vehicle base; our approach was a two-cable suspension, with a top restraining spring which could later be replaced by the control system.

The flexible model is shown mounted in the suspension system in Fig. 3. The two main support cables have a movable pivot point which can be located at the vehicles c.g. or as high as the nose of the vehicle. These cables impart a pendulum frequency to the vehicle which is 0.37 Hz at maximum cable length. Two small nose restraint cables provide lateral stability and introduce a pitching frequency, which can be made as low as 0.2 Hz by lowering the cable tension [4]. To minimize torsional restraint, the support cables are vertical and the restraint cables have a point attachment. The vehicle rests on a support beam which serves as a cable and a shaker attachment.

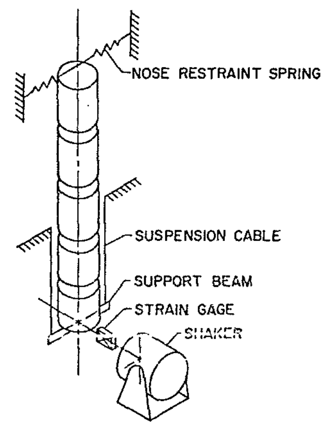

Fig. 3 - Model, suspension system, and shaker

SHAKER SYSTEM

For our study, a shaker system was necessary which would provide an accurate simulation of the control force and would also be well suited for resonance testing at low force levels. An existing electromagnetic shaker was used, which has a 550 N (about 125 lb) force and ± 3.8 cm (± 1.5 in.) motion capability; these values are ample to simulate the Atlas 267,000 N (60,000 lb) force engine and gimbal angle of ± 5°.

This shaker was AC coupled in the input stage, and it was necessary to modify the amplifier in order to achieve the DC response needed by the control system. The modification required a push-pull, balanced drive signal, which is provided by an analog computer.

A particular characteristic of the original shaker amplifier circuit is that an unbalanced drive can cause large internal circulating currents within the amplifier. Such a condition can result in excessive power dissipation in the output transistors, and an output power limitation. Since the shaker had ample power and imbalance was a possible problem, a further modification was made. The original "Class B" amplifier was changed to a push-pull "Class A" amplifier with parameters so chosen that the output signal is proportional to the difference of the two input signals, and careful balance is no longer required.

A much smaller force output than 550 N is desired in resonance testing of models with low damping. For this purpose, the amplifier output of the shaker was further modified to produce lower forces. A series of shunt resistors were installed which allowed the force output to be varied in eight steps from full force down to about 0.2 N (0.05 lb). This modification has been indispensable in resonance testing.

CONTROL SYSTEM

The cable suspension slightly restrains the model in bending. If the shaker could apply a balancing force at the base of the vehicle to keep it vertical, the upper spring could be removed, reducing the bending restraint. The model would then be kept in the proper attitude by precisely the same method used in flight, and this would result in a more accurate simulation of the launch phase.

To control the vehicle attitude by the shaker force, it is necessary to sense the vehicle attitude and to design a control system which would use the attitude signal to provide the proper feedback to the shaker amplifier. The following is a description of such an attitude control system [5].

Analysis

Fig. 4 shows a simplified coordinate system for the model, assumed rigid, and suspension system.

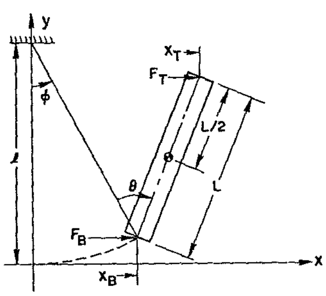

Fig. 4 - Coordinate system for mathematical model

If we assume small amplitudes and set $\ell = L$, the equations of motion may be written:

$$\left.\begin{aligned} \ddot{\phi} &= -\frac{g}{\ell}\phi - \frac{3g}{\ell}\theta + \frac{4}{m\ell}F_B - \frac{2}{m\ell}F_T \\ \ddot{\theta} &= -\frac{g}{\ell}\phi + \frac{3g}{\ell}\theta - \frac{2}{m\ell}F_B + \frac{4}{m\ell}F_T \end{aligned}\right\} \quad (1)$$

where g is the acceleration due to gravity, m is the vehicle mass, F_T is the force applied to the vehicle nose, and F_B is the force applied to the base.

These equations can be scaled by setting $t = \tau/\omega$ and $\omega = \sqrt{g/\ell}$, so that $\dot{\theta} = \theta'\omega$, $\ddot{\theta} = \theta''\omega^2$, which gives

$$\left.\begin{aligned} \phi'' &= -\phi - 3\theta + 2f_1 - f_2 \\ \theta'' &= -\phi + 3\theta - f_1 + 2f_2 \end{aligned}\right\} \quad (2)$$

where

$$f_1 = \frac{2}{mg}F_B \text{ and } f_2 = \frac{2}{mg}F_T$$

For the system to operate with only one shaker at the base, (2) must be controllable with $f_2 = 0$.

For a linear system, the matrix equation $\dot{x} = Ax + bu$ is controllable if the determinant $|b, Ab, A^2b, A^3b|$ does not equal zero [6]. Putting Eqs. (2) in matrix form with $f_2 = 0$, we obtain

$$\begin{pmatrix} \phi' \\ \theta' \\ \phi'' \\ \theta'' \end{pmatrix} = \dot{x} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & -3 & 0 & 0 \\ -1 & 3 & 0 & 0 \end{pmatrix} \begin{pmatrix} \phi \\ \theta \\ \phi' \\ \theta' \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 2 \\ -1 \end{pmatrix} f_1$$

which is of the form $\dot{x} = Ax + bu$. The criterion for controllability then becomes

$$\left|b,\ Ab,\ A^2b,\ A^3b\right| = \begin{vmatrix} 0 & 2 & 0 & 1 \\ 0 & -1 & 0 & -5 \\ 2 & 0 & 1 & 0 \\ -1 & 0 & -5 & 0 \end{vmatrix} \neq 0$$

Evaluating the determinant gives

$$-2\begin{vmatrix} 0 & 0 & -5 \\ 2 & 1 & 0 \\ -1 & -5 & 0 \end{vmatrix} - \begin{vmatrix} 0 & -1 & 0 \\ 2 & 0 & 1 \\ -1 & 0 & -5 \end{vmatrix}$$

$$= 10(1-10)-(1-10) = -81 \neq 0$$

The criterion is met and the system is controllable with $f_2 = 0$.

If we assume a general control force of the form $2f_1 = \alpha\phi + \beta\theta + \gamma\phi' + \delta\theta'$, and set $f_2 = 0$, Eqs. (2) become

$$\left.\begin{aligned} \phi'' &= (\alpha - 1)\phi + (\beta - 3)\theta + \gamma\phi' + \delta\theta' \\ \theta'' &= \left(-\frac{\alpha}{2} - 1\right)\phi + \left(-\frac{\beta}{2} + 3\right)\theta - \frac{\gamma}{2}\phi' - \frac{\delta}{2}\theta' \end{aligned}\right\} \quad (3)$$

These equations can be placed in matrix form $\dot{x} = bx$:

$$\begin{pmatrix} \phi' \\ \theta' \\ \phi'' \\ \theta'' \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \alpha - 1 & \beta - 3 & \gamma & \delta \\ -\frac{\alpha}{2} - 1 & -\frac{\beta}{2} + 3 & -\frac{\gamma}{2} & -\frac{\delta}{2} \end{pmatrix} \begin{pmatrix} \phi \\ \theta \\ \phi' \\ \theta' \end{pmatrix}$$

To find the characteristic equation, set the determinant $|B - \lambda I| = 0$:

$$\begin{vmatrix} -\lambda & 0 & 1 & 0 \\ 0 & -\lambda & 0 & 1 \\ \alpha - 1 & \beta - 3 & \gamma - \lambda & \delta \\ -\frac{\alpha}{2} - 1 & -\frac{\beta}{2} + 3 & -\frac{\gamma}{2} & -\frac{\delta}{2} - \lambda \end{vmatrix} = 0$$

Evaluating the determinant gives the characteristic equation

$$g(\lambda) = \lambda^4 + a_1\lambda^3 + a_2\lambda^2 + a_3\lambda + a_4 = 0$$

where

$$a_1 = \frac{\delta}{2} - \gamma$$
$$a_2 = \frac{\beta}{2} - \alpha - 2$$
$$a_3 = \frac{3}{2}(\gamma + \delta)$$
$$a_4 = \frac{3}{2}(\alpha + \beta - 4)$$

Noting that a_1, a_3 are functions of γ and δ only, and a_2, a_4 are functions of α and β only, we can write

$$\begin{pmatrix} a_1 \\ a_3 \end{pmatrix} = \begin{pmatrix} -1 & \frac{1}{2} \\ \frac{3}{2} & \frac{3}{2} \end{pmatrix} \begin{pmatrix} \gamma \\ \delta \end{pmatrix}; \quad \begin{pmatrix} a_2 + 2 \\ a_4 + 6 \end{pmatrix} = \begin{pmatrix} -1 & \frac{1}{2} \\ \frac{3}{2} & \frac{3}{2} \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

We obtain α, β, γ, and δ as functions of the a's by matrix inversion, giving

$$\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = -\frac{4}{9} \begin{pmatrix} \frac{3}{2} & -\frac{1}{2} \\ -\frac{3}{2} & -1 \end{pmatrix} \begin{pmatrix} a_2 + 2 \\ a_4 + 6 \end{pmatrix};$$

$$\begin{pmatrix} \gamma \\ \delta \end{pmatrix} = -\frac{4}{9} \begin{pmatrix} \frac{3}{2} & -\frac{1}{2} \\ -\frac{3}{2} & -1 \end{pmatrix} \begin{pmatrix} a_1 \\ a_3 \end{pmatrix} \tag{4}$$

Since the system is controllable, we may choose the desired closed-loop poles and use these values of λ to find the necessary a's; in turn these values of the a's determine α, β, γ, and δ. We selected the response of our system by choosing closed-loop poles at the pendulum frequency of $\sqrt{\ell/g}$ (normalized to 1), so that

$$g(\lambda) = (\lambda^2 + \lambda + 1)^2 = \lambda^4 + 2\lambda^3 + 3\lambda^2 + 2\lambda + 1$$

The necessary values of the a's are $a_1 = 2$, $a_2 = 3$, $a_3 = 2$, and $a_4 = 1$. Eqs. (4) then give $\alpha = -16/9$, $\beta = 58/9$, $\gamma = -8/9$, $\delta = 20/9$. From Eqs. (2) and (3),

$$F_B = \frac{mg}{4}[\alpha\phi + \beta\theta + \gamma\phi' + \delta\theta']$$

From Fig. 4, $x_B = \ell\phi$, $x_T = L\theta$. Use of the scaling relation $\dot\phi = \sqrt{g/\ell}\,\phi'$, $\dot\theta = \sqrt{g/\ell}\,\theta'$ and the simplification that $\ell = L$ gives the form of the required control force in real time:

$$F_B = \frac{mg}{4\ell}\left[\alpha x_B + \beta x_T + \gamma\sqrt{\frac{\ell}{g}}\,\dot x_B + \delta\sqrt{\frac{\ell}{g}}\,\dot x_T\right] \tag{5}$$

This simple result shows that the only data necessary to produce the control force are the model top and bottom positions and velocities.

The block diagram of the model and control system is developed in Fig. 5. Two optical trackers are used to detect the model end positions, and an analog computer is used to provide approximate differentiation of these signals for the velocities [7]. The computer also provides the summation and gains necessary to produce the control signal to the shaker amplifier.

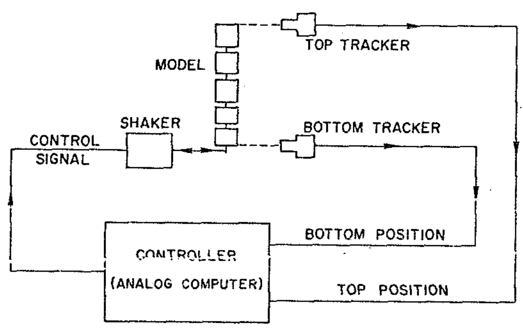

Fig. 5 - Block diagram of model and control system

SIMULATION

An analog computer simulation of the entire system of model, suspension, and controller was made before testing the components. The initial simulation encompassed a rigid vehicle and used computer components for the shaker and amplifier. As the simulation progressed, the shaker was incorporated into the feedback loop; then the model, with tanks rigidly fixed, was added. Finally, the flexibility of the model was used, with a notch filter included in order to attenuate the bending response of the vehicle.

Fig. 6 shows a typical response of the vehicle to a step input force with the controller operating. The command signal is a DC voltage from the analog computer, and above it are the shaker force output and the vehicle end positions. The apparently noisy force signal is due to a 100 Hz "jitter" which was added to the shaker input in order to smooth the shaker output by eliminating the Coulomb friction effects of the bearings. The vehicle position signals show some first bending vibration which is excited by the step input. It should be noted that the response of the suspended vehicle is not perfectly analogous to the launch condition. A steady shaker force will produce a fixed displacement at which the shaker force is just balanced by gravity. A steady force in the launch condition, however, will produce a fixed sideways acceleration which causes an unbounded displacement. If we observe the net force on the vehicle, however, the two cases are identical.

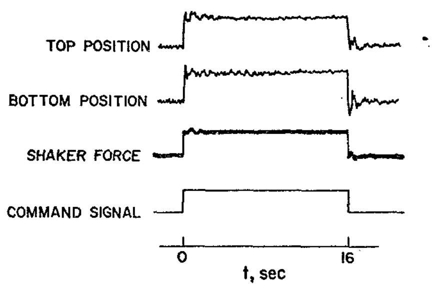

Fig. 6 - Model and control stystem step response

CONCLUDING REMARKS

The results of this model study indicate that the use of a cable support and a feedback control system for maintaining vehicle attitude is an effective system for vibration testing and control system studies of launch vehicles.

The next phase of this program is now under way at Ames Research Center. Two large models representative of real vehicle structures will be mounted in the vacuum tower of the Structural Dynamics Branch. The first of these is the propellant tank section of an Atlas vehicle which is now being installed in the tower on a scaled-up version of the two-cable suspension system, as shown schematically in Fig. 7. This model is representative of monocoque construction. A specially designed 89,000 N (20,000 lb) force thruster of about ±11.4 cm (± 4.5 in.) stroke is being used to simulate the engine control force. The second large model is a complete two-stage Titan I vehicle, which is representative of semimonocoque construction. In addition to the control system studies, it is anticipated that the 3-mb low-pressure capability of the vacuum tower will be used to measure structural damping at reduced pressures.

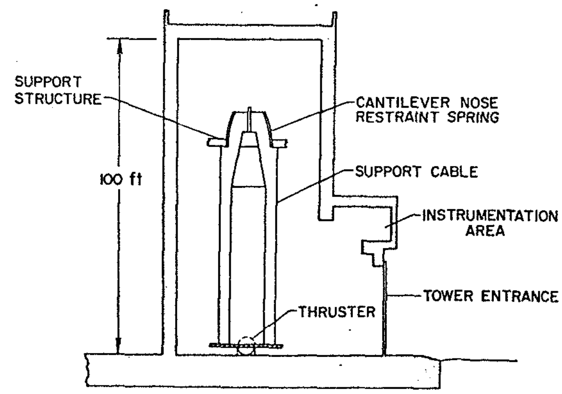

Fig. 7 - Atlas vehicle mounted in vacuum tower

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