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TECHNICAL MEMORANDUM

A METHOD FOR INCORPORATING CHANGING STRUCTURAL CHARACTERISTICS DUE TO PROPELLANT MASS USAGE IN A LAUNCH VEHICLE ASCENT SIMULATION

1. INTRODUCTION

Launch vehicles consume large quantities of propellants and oxidizers quickly, causing the mass properties and structural dynamics of the vehicle to change dramatically. The current method of handling this change for structural load assessments is to simply have a large collection of structural models representing various propellant fill levels. This creates a large database of models and compounds the problem of having easily derivable reduced models. The offline processing required to generate numerous models to populate the database can be large and would have to be repeated for model changes.

2. PROPELLANT MASS METHODOLOGY

Section 2 presents a method for handling these mass changes in a more efficient manner. The method essentially allows for the subtraction of propellant mass as the propellant is used in the simulation. This subtraction is done in the modal domain of a launch vehicle generalized model. The additional computation involved is primarily in terms of constructing the used propellant mass matrix from an initial propellant model and further matrix multiplications and subtractions. There is an additional eigenvalue solution required to uncouple the new equations of motion; however, this is a much simpler calculation since it starts from a system that is already substantially uncoupled.

Assume a vehicle model empty of propellants:

$$\left[M_v\right]\left\{\ddot{x}_v\right\} + \left[K_v\right]\left\{x_v\right\} = \left\{F_v\right\} \ , \tag{1}$$

where

$\left[M_v\right]$ = mass matrix of empty vehicle

$\left[K_v\right]$ = stiffness matrix of empty vehicle

$\left\{\ddot{x}_v\right\}$ = acceleration of empty vehicle degrees of freedom (dofs)

$\left\{x_v\right\}$ = displacement of empty vehicle dofs

$\left\{F_v\right\}$ = applied forces acting on the empty vehicle,

reduced modally:

$$\left\{x_v\right\} = \left[\Phi_v\right]\left\{q_v\right\} \tag{2a}$$

$$\left\{\ddot{x}_v\right\} = \left[\Phi_v\right]\left\{\ddot{q}_v\right\} \tag{2b}$$

$$\left[I\right]\left\{\ddot{q}_v\right\} + \left[\omega_v^2\right]\left\{q_v\right\} = \left[\Phi_v\right]\left\{F_v\right\} \ , \tag{3}$$

where

$\left[\Phi_v\right]$ = eigenvectors or modeshapes of unconstrained empty vehicle

$\left\{q_v\right\}$ = generalized displacement of empty vehicle generalized dofs

$\left\{\ddot{q}_v\right\}$ = generalized acceleration of empty vehicle generalized dofs

$[I]$ = identity matrix resulting from mass normalized modeshapes

$\left[\omega_v^2\right]$ = eigenvalues of unconstrained empty vehicle.

Now, assume a propellant load on a subset of the original vehicle dofs:

$$\left[M_P\right]\left\{\ddot{x}_{vP}\right\} , \tag{4}$$

where

$\left[M_P\right]$ = mass matrix of propellant model

$\left\{\ddot{x}_{vP}\right\}$ = accelerations of propellant model dofs selected from $\left\{\ddot{x}_v\right\}$.

Using the same modal transformation, $\left[\boldsymbol{\Phi}_v\right]$, and selecting the appropriate rows for the propellant dofs, $\left[\boldsymbol{\Phi}_{vP}\right]$, the propellant mass can be reduced:

$$\left[\boldsymbol{\Phi}_{vP}\right]\left[M_P\right]\left[\boldsymbol{\Phi}_{vP}\right]\left\{\ddot{q}_v\right\} = \left[\overline{M}_P\right]\left\{\ddot{q}_v\right\} , \tag{5}$$

where

$\left[\boldsymbol{\Phi}_{vP}\right]$ = propellant model selected rows from $\left[\boldsymbol{\Phi}_v\right]$

$\left[\overline{M}_P\right]$ = propellant model mass matrix converted to empty vehicle generalized dofs.

$\left[\overline{M}_P\right]$ is not necessarily diagonal because the modes are no longer orthogonal; however, this propellant model can now be coupled to the vehicle:

$$\left([I] + \left[\overline{M}_P\right]\right)\left\{\ddot{q}_v\right\} + \left[\omega_v^2\right]\left\{q_v\right\} = \left[\boldsymbol{\Phi}_v\right]\left\{F_v\right\} . \tag{6}$$

This model can then be reduced modally once again. This time the reduction is at a much reduced cost because of the reduced number of dofs and the uncoupled nature of the nonpropellant portions of the equation:

$$\left\{q_v\right\} = \left[\boldsymbol{\Phi}_2\right]\left\{q_{v2}\right\} \tag{7a}$$

$$\left\{\ddot{q}_v\right\} = \left[\boldsymbol{\Phi}_2\right]\left\{\ddot{q}_{v2}\right\} \tag{7b}$$

$$[I]\left\{\ddot{q}_{v2}\right\} + \left[\omega_2^2\right]\left\{q_{v2}\right\} = \left[\boldsymbol{\Phi}_2\right]\left[\boldsymbol{\Phi}_v\right]\left\{F_v\right\} , \tag{8}$$

where

$\left[\boldsymbol{\Phi}_2\right]$ = eigenvectors of modally modified unconstrained empty vehicle

$\left\{q_{v2}\right\}$ = generalized displacement of modally modified empty vehicle generalized dofs

$\{\ddot{q}_{v2}\}$ = generalized acceleration of modally modified empty vehicle generalized dofs

$[I]$ = identity matrix resulting from mass normalized modeshapes

$[\omega_2^2]$ = eigenvalues of modally modified unconstrained empty vehicle.

This would once again make the modes orthogonal and uncouple the equations of motion for easy solution.

If all modes are kept during this process, it is easy to see that the solutions would be the same. However, if modes are truncated, a good deal of information could be lost. This is because the empty vehicle structure would have higher frequency modes that could be truncated. In reality, some of these modes would be lowered in frequency by the presence of the propellant mass and should be retained.

This truncation problem can be compensated for in the following way. The first vehicle model is constructed for a fully loaded vehicle with propellant model. This would assure that all the lower frequencies of interest are retained. The subset propellant model is then actually a model of the propellant used or removed. Equation (6) would then become

$$\left([I] - \left[\overline{M}_P\right]\right)\{\ddot{q}_v\} + \left[\omega_v^2\right]\{q_v\} = \left[\Phi_v\right]\{F_v\} \ . \tag{9}$$

Note the change in sign in the first term. This is to reflect that mass is being removed from the vehicle.

Equation (9) can then be reduced further as in equation (8). This uncoupled set of equations of motion could then be solved to provide the response of the complete system. Since the equations are uncoupled, they could be solved using a closed-form solution of a second-order dynamic equation with initial conditions. This solution still assumes the mass and the dynamics of the system remain constant during the time of solution. However, there is now an approach that would allow a much greater frequency of updating the mass characteristics of the system so the approximation has less of an effect.

Load transformation matrices (LTMs) used for data recovery are most easily defined in terms of the initial model governed by equations (1) and (3). For the displacement method of data recovery, generating the correct response is simply a matter of including the additional transformation of equation (7):

$$\{\text{Resp}\} = [\text{LTM}]\left[\Phi_v\right]\{q_v\} = [\text{LTM}]\left[\Phi_v\right]\{\Phi 2\}\{q_{v2}\} \ , \tag{10}$$

where

{Resp}= desired system response
[LTM] = displacement method LTM.

For acceleration method LTMs, some additional work is required because of the inclusion of an applied force term. Equation (9) can be rewritten by moving the propellant mass term to the right-hand side and treating it as an applied load:

$$[I]\{\ddot{q}_v\} + \left[\omega_v^2\right]\{q_v\} = \left[\Phi_v\right]\{F_v\} + \left[\overline{M}_P\right]\{\ddot{q}_v\} \ . \tag{11}$$

In this case, the acceleration term simply includes the equation (7) transformation. The applied force term must include the propellant inertial load term:

$$\begin{aligned}\{\text{Resp}\} = [\text{LTM}A]\left[\Phi_v\right][\Phi 2]\{\ddot{q}_{v2}\} + [\text{LTM}D]\left[\Phi_v\right][\Phi 2]\{q_{v2}\} \\ +[\text{LTM}F]\left(\left[\Phi_v\right]\{F_v\} + \left[\overline{M}_P\right][\Phi 2]\{\ddot{q}_{v2}\}\right) \ ,\end{aligned} \tag{12}$$

where

{Resp} = desired system response
[LTMA] = acceleration term of acceleration method LTM
[LTMD] = displacement term of acceleration method LTM
[LTMF] = applied force term of acceleration method LTM.

3. EARLY PROTOTYPE

In 2001, the Space Launch Initiative program requested the Marshall Space Flight Center engineering groups to study what would be required to perform integrated system-level technical assessments of candidate launch systems. From this, the Vehicle Integrated Performance Analysis team was formed as a prototype answer and culminated in an assessment of the Saturn V ascent vehicle. This vehicle was chosen to validate the process because of the availability of data and the lack of proprietary or political issues.

Figure 1 shows a comparison of first-stage bending moments for a given flight loading condition with varied propellant mass. The solid lines indicate results with the propellant masses modeled seperately for each propellant fill level. The point marker curves indicate results using the full propellant mass modified by the mass reduction method described in this Technical Memorandum. Further investigation needs to take place regarding modal truncation effects; however, the results are excellent. The full propellant mass vehicle model was reduced carrying modes up to ≈25 Hz.

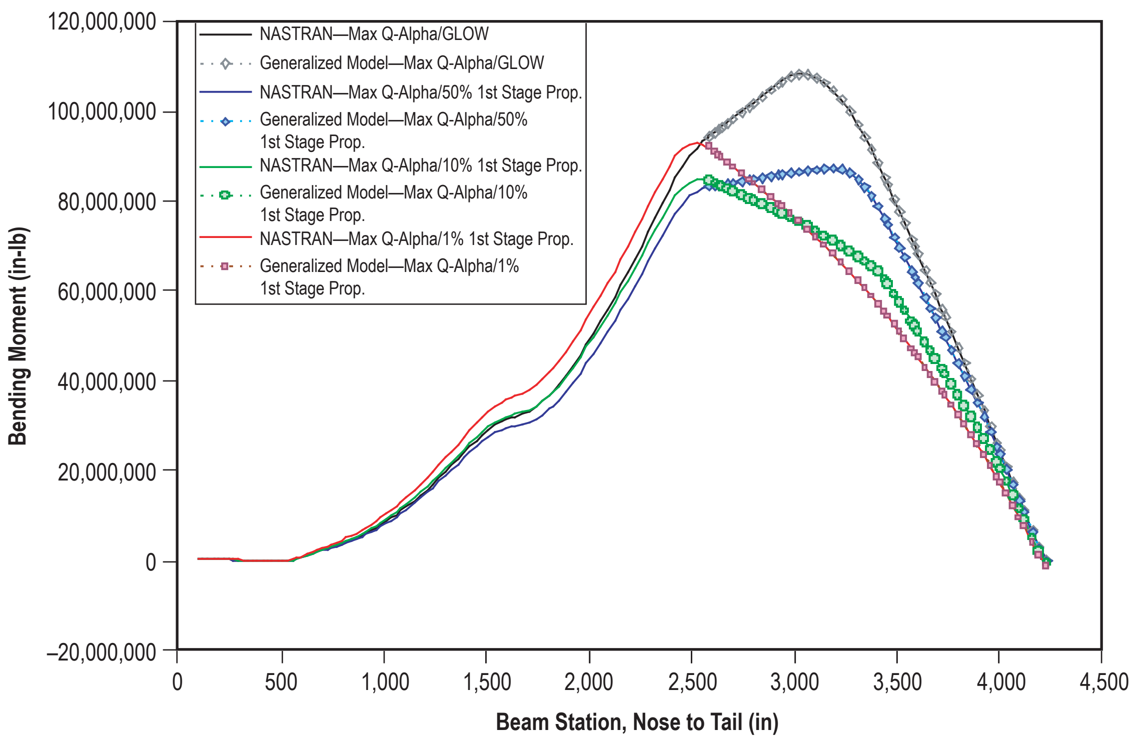

Figure 1. Mass model results comparison; VAC–02 bending moment—max Q-alpha loads.

4. CONCLUSION

Launch vehicles consume large quantities of propellants and oxidizers quickly. A method has been presented for handling these mass changes more efficiently for a structural load analysis simulation. The method allows for the subtraction of propellant mass as the propellant is used. The subtraction is done in the modal domain of a launch vehicle generalized model. The method has been successfully tested in a simulation of Saturn V loads. Results from the use of the method have been compared to results from separate structural models for several propellant levels. This comparison shows excellent agreement. Effects of modal truncation should be assessed when using the method. The method could also be further developed to encompass more complicated propellant models, including slosh dynamics.

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13. ABSTRACT *(Maximum 200 words)* Launch vehicles consume large quantities of propellant quickly, causing the mass properties and structural dynamics of the vehicle to change dramatically. Currently, structural load assessments account for this change with a large collection of structural models representing various propellant fill levels. This creates a large database of models complicating the delivery of reduced models and requiring extensive work for model changes. Presented here is a method to account for these mass changes in a more effiicient manner. The method allows for the subtraction of propellant mass as the propellant is used in the simulation. This subtraction is done in the modal domain of the vehicle generalized model. Additional computation required is primarily for constructing the used propellant mass matrix from an initial propellant model and further matrix multiplications and subtractions. An additional eigenvalue solution is required to uncouple the new equations of motion; however, this is a much simplier calculation starting from a system that is already substantially uncoupled. The method was successfully tested in a simulation of Saturn V loads. Results from the method are compared to results from separate structural models for several propellant levels, showing excellent agreement. Further development to encompass more complicated propellant models, including slosh dynamics, is possible.			
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