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NUMERICAL RESULTS FOR A COUPLED LAUNCHER-SATELLITE SYSTEM ANALYSIS

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Abstract. *This paper presents some preliminary numerical results obtained for the analysis of a coupled launcher-satellite system, namely the first Brazilian launcher, the VLS, and its satellite. The finite element method is used to obtain the response of the system. The launcher is modeled as a 3-D beam-like structure, where beam elements, lumped masses and spring elements were used. Experimental modal analysis results were used to adjust the finite element model of the vehicle. The satellite is represented by a full 3-D model. A curve of thrust as function of time is used to input the dynamic load onto the system. Responses at specific locations are given in both time and frequency domains. In the actual vehicle, accelerometers are used to take measurements during flight. Future flights of the vehicle will generate data that will allow the evaluation of the realibity of the model.*

Keywords: Launcher-Satellite System, Structural Dynamics, Coupled Analysis.

1. INTRODUCTION

This work presents some preliminary results obtained for the structural dynamic analysis of the coupled launcher-satellite system of the first Brazilian satellite launcher, the VLS. The VLS is a four-stage vehicle in which the first stage is composed of four strap-on boosters around a central core. A schematic representation of the VLS system is presented in Fig. (1). The mission of the vehicle is to launch small satellites, of the order of 150 to 200 kg, into low Earth orbit (LEO). The VLS is an integral part of a larger program which has the goal of launching a Brazilian satellite, using a Brazilian-built rocket, from a Brazilian launching site. The satellite development is the responsibility of Instituto Nacional de Pesquisas Espaciais (INPE). The launching site is the Alcântara Launching Complex (CLA) in the Brazilian northern state of Maranhão. Instituto de Aeronáutica e Espaço (IAE), together with its industrial partners, has the responsability of designing and building the launcher itself.

During the development of a launcher system, several important studies in different areas must be undertaken. One such a study is the definition of the level of structural dynamic loads that the system will impose upon the satellite structure. The present paper describes such a study. The widely known commercial code NASTRAN^{TM} (Blakely, 1993) is used to model the launcher and the satellite, as well as to calculate the transient response of the system during liftoff, i.e., the first instants of flight of the 1st stage of the vehicle. The results of the analysis can then be used by the team responsible for the satellite

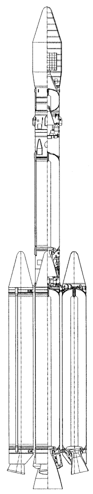


Figure 1: The VLS launcher-satellite system.

development to evaluate the satellite structural integrity under such loads.

The work herein described uses a modal superposition approach (Meirovitch, 1977) to calculate the response of the system. The rigid body part of the response is eliminated from the solution, and modes ranging up to 250 Hz, for this analysis, are included in the calculations.

2. THE FINITE ELEMENT MODEL

A 3-D beam-like finite element model of the VLS vehicle was idealized. Basicaly, beam elements, lumped mass elements, and torsional and linear spring elements were used. A total of 70 elements (Duarte & Mendonça, 1992) were used to model the launcher. Natural frequencies and mode shapes were calculated. Later on, experimental modal analyses were performed. The tests generated data that allowed the adjustment of the finite element model to the actual launcher-satellite system, resulting the fact that the model was then able to predict frequencies and mode shapes which matched the ones experimentally obtained.

Instituto Nacional de Pesquisas Espaciais (INPE) developed a complete 3-D model of their satellite. The model comprises several elements from NASTRAN^{TM}'s library of elements, such as beams, plates, lumped masses, and spring elements. The model has about 2500 elements.

Since nonlinearities are not accounted for in the model, the motion of the complete system is represented by

$$M\ddot{U} + C\dot{U} + KU = F(t)\,, \tag{1}$$

where, M, C and K are, respectively, mass, damping and stiffness matrices. Displacements, velocities and accelerations are represented by U, $\dot{U}$ and $\ddot{U}$, respectively. On the right-hand side, $F(t)$ represents the forces acting on the system. In order to perform a modal analysis of the structural system represented by Eq. (1), the free vibration equilibrium equations with damping and the externally applied forces neglected are written as

$$M\,\ddot{U} + K\,U \;=\; 0\,. \tag{2}$$

Thus, if one writes the displacements in the form

$$U(x,t) \;=\; \phi(x)\,\sin\omega(t-t_0)\,, \tag{3}$$

where ϕ is a vector of order n, t the time variable, t_0 a time constant, and ω a constant identified to represent the frequency of vibration of the vector ϕ, substituting Eq. (3) into Eq. (2) results the generalized eigenproblem

$$(K-\omega^2 M)\phi \;=\; 0\,, \tag{4}$$

from which ϕ and ω must be determined (Bathe, 1996). The calculated matrix of eigenfunctions Φ, whose columns are the M-orthonormalized eigenvectors ϕ_i, allows a change of basis from the finite element displacement basis to a generalized displacement basis, with $U(x,t)$ written as

$$U(x,t) \;=\; \Phi(x)\,Q(t)\,, \tag{5}$$

where $Q(t)$ is the matrix of generalized coordinates $q_i(t)$ (Meirovitch,1977) and (Bathe, 1996).

Assuming proportional damping, it is possible to write

$$\phi_i^T C\phi_j \;=\; 2\omega_i\xi_i\delta_{ij}\,, \tag{6}$$

where ξ_i is a modal damping parameter and δ_{ij} is the Kronecker delta ($\delta_{ij}=1$ for $i=j$, $\delta_{ij}=0$ for $i\neq j$). Thus, it is thereafter assumed that the eigenvectors are also C-orthogonal and the uncoupled modal equilibrium equations are written as

$$\ddot{q}_i(t) + 2\omega_i\xi_i\dot{q}_i(t) + \omega^2 q_i(t) \;=\; r_i(t)\,. \tag{7}$$

As usual, Eq. (7) is time integrated and, once $q_i(t)$, $\dot{q}_i(t)$ and $\ddot{q}_i(t)$ are known, the system's actual displacements, velocities and accelerations, respectively, $U(x,t)$, $\dot{U}(x,t)$ and $\ddot{U}(x,t)$, are calculated using Eq. (5).

3. NUMERICAL RESULTS

Once the finite element model of the structural system was ready, adjusted with the experimental results, and updated, the definition of the load acting on the launcher-satellite system was necessary. The Laboratory of Propulsion of the Institute, through tests on the rocket engines, made available curves of thrust as function of time, which were then used as the liftoff loading applied onto the system. Two sampling frequencies were used for the data acquisition.

3.1 Analysis with a sampling frequency of 100 Hz

The experimental data initially obtained for the thrust curve, shown in Fig. (2), used the sampling frequency of 100 Hz. This curve represents the total thrust available from one of the four boosters, in a direction coincident with the longitudinal axis of the booster. It is important to observe, however, that these forces, in the actual vehicle configuration, act on the boosters with a small deviation with respect to their longitudinal axes, due to the nozzle direction. Thus, the thrust vector on each booster is represented, in the finite

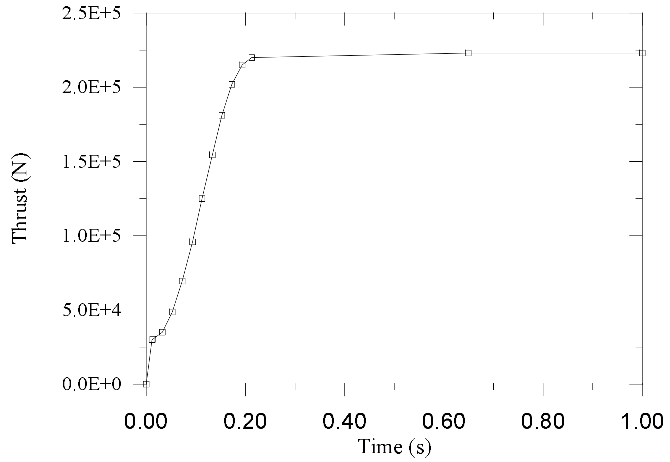
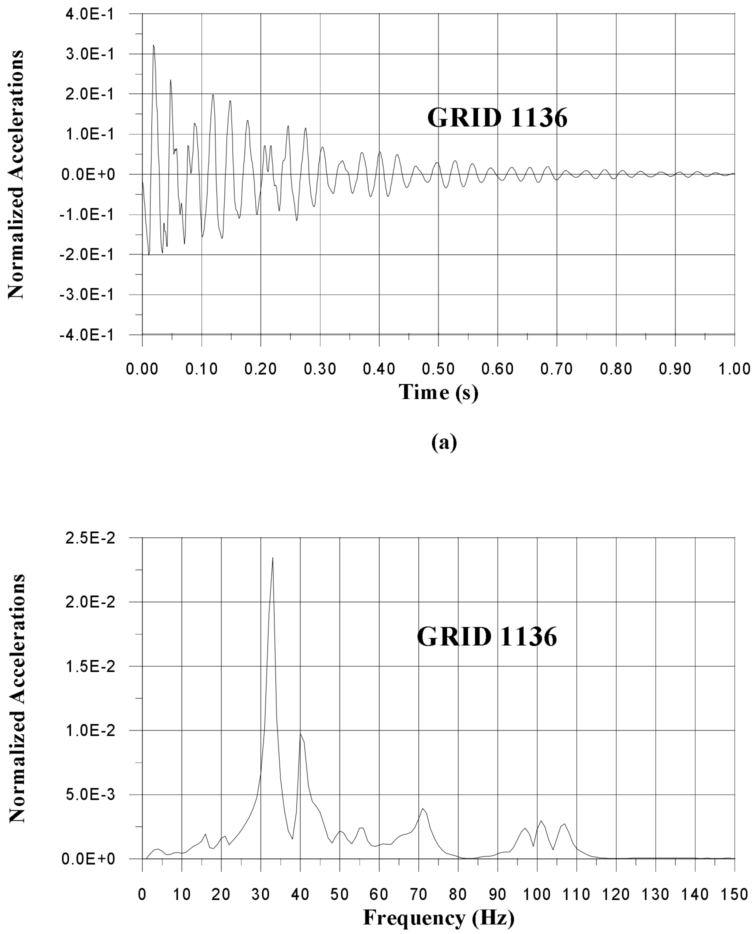


Figure 2: Total thrust for one booster of the 1st stage; sampling frequency of 100 Hz.

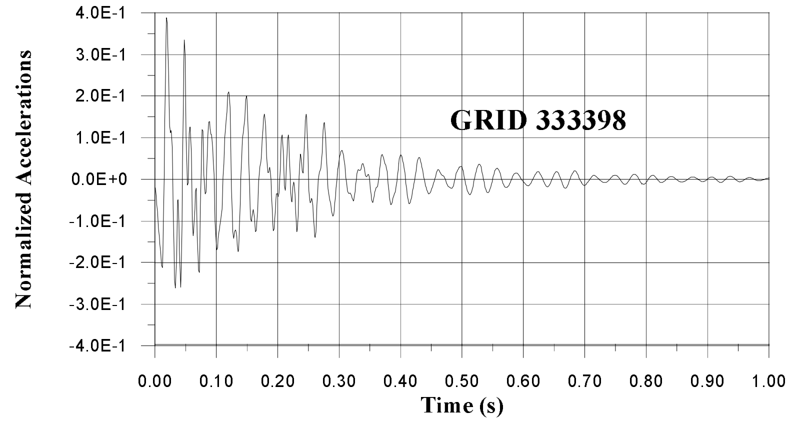


(b)

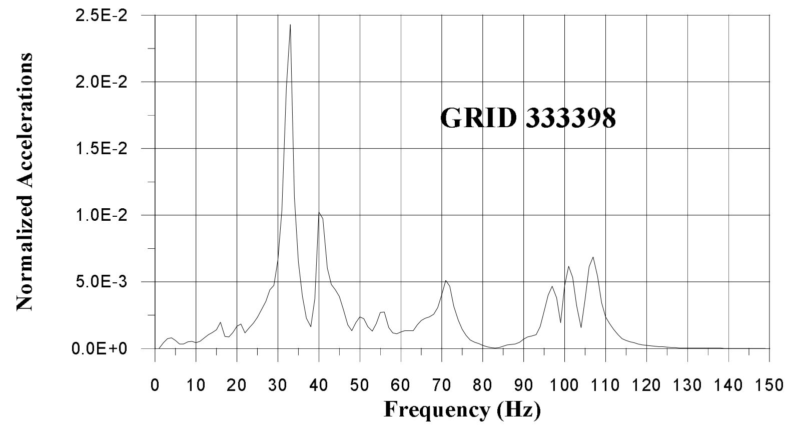
Figure 3: Normalized accelerations at GRID 1136 (sampling frequency of 100 Hz): (a) time history; (b) spectrum of the response.

element input file, by its components. The maximum experimental value of the thrust force is 2.23x10^{05} N. For the simulation it is also assumed that the four booster's engines ignite exactly at the same instant. Obviously, that may not be the case, in general, i.e., a certain delay in ignition might be expected, from one booster with respect to the others. Actually, analyses with ignition's time delay varying from 0 to 30 ms have been performed, but are not reported in this work.

Based on data available for vehicles similar to the VLS system , the damping used on the calculations were $C/C_{crit} = 4\%$ for the longitudinal modes, and $C/C_{crit} = 2\%$ for the lateral modes. It was observed that values up to 5% for C/C_{crit} did not sensitively affect the peaks in accelerations.



(a)



(b)

Figure 4: Normalized accelerations at GRID 3398 (sampling frequency of 100 Hz): (a) time history; (b) spectrum of the response.

Two points on the satellite structure were chosen, namely the points numbered as GRID 1136 and GRID 3398. Accelerations responses, normalized by the acceleration of gravity $g = 9.81$ m/s^2, for these points are pictured in Fig. (3) and Fig. (4), respectively. It is observed, from the responses in the frequency domain, that the thrust load excites actual frequencies of the structural system, with a major contribution from a frequency aproximately equal to 33 Hz. Nevertheless, it may also be observed that the level of the responses are very low, i.e., of the order of 30% of the gravity acceleration g. Although such was excellent a result, at least from the point of view of the team responsible for the launcher design, it enduced a re-study of the whole analysis in development.

3.2 Analysis with a frequency sampling of 1000 Hz

Experimental thrust data, shown in Fig. (5), were taken with a sampling frequency of 1000 Hz. These data showed details of the thrust variation with respect to time that were missed in the thrust curve previously used. Indeed, right at the first hundredths

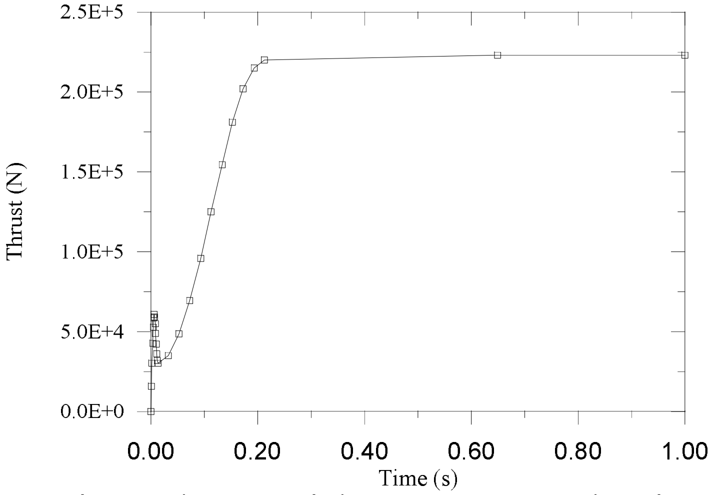


Figure 5: Total thrust for one booster of the 1st stage; sampling frequency of 1000 Hz.

of a second a sharp difference in the value of thrust, with respect to the previous curve, is observed, which can better be seen in Fig. (6). For the remaining period of data acquisition the values are exactly the same as the ones previously obtained. In the same way, as commented above, the new data were input into the finite element code and new results were calculated for the transient response of the system.

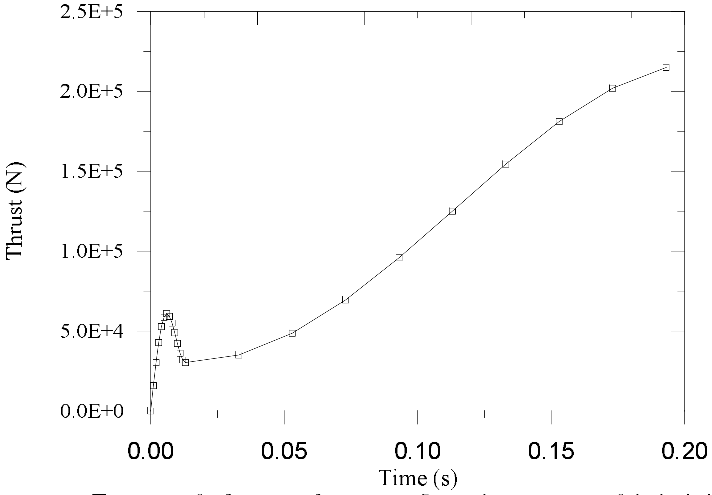
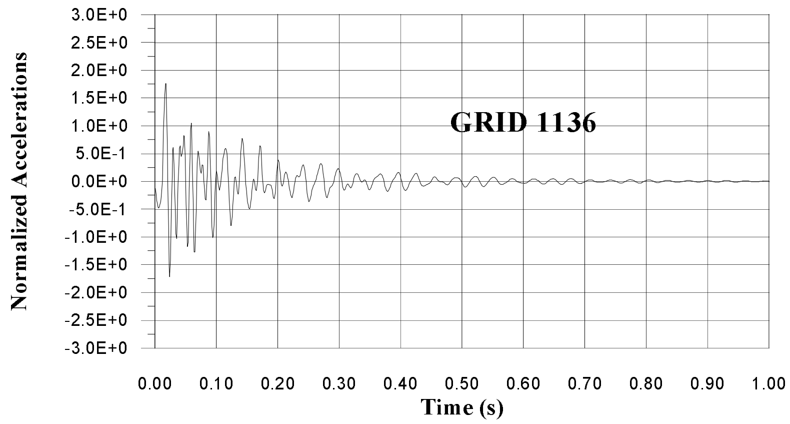
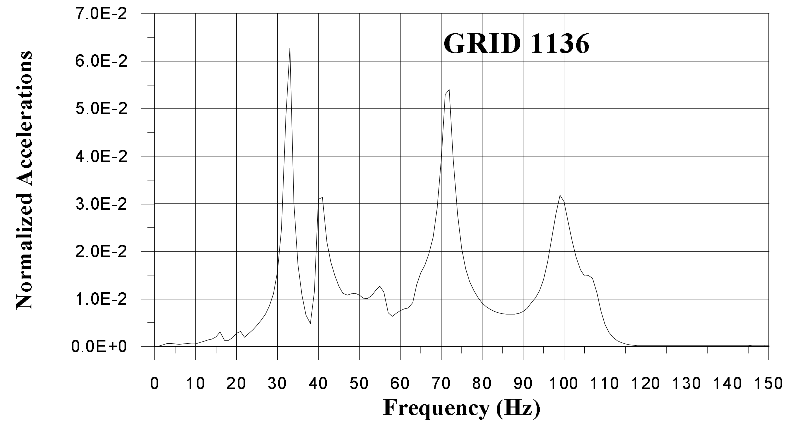


Figure 6: Zoom of thrust data at first instants of iginition.

It is obvious, from Fig. (7) and Fig. (8), the large difference in magnitude of the responses. The sudden blast that occurs when the propellant is ignited, is responsible for the peak accelerations responses 5 times larger than the ones described in Sec. (**3.1**). It is also observed that spectral responses componentes, larger than obtained previously, are present, mainly, on frequencies of 70 Hz and 100 Hz. The interested reader is referred to Duarte & Damilano (1999) for details.



(a)

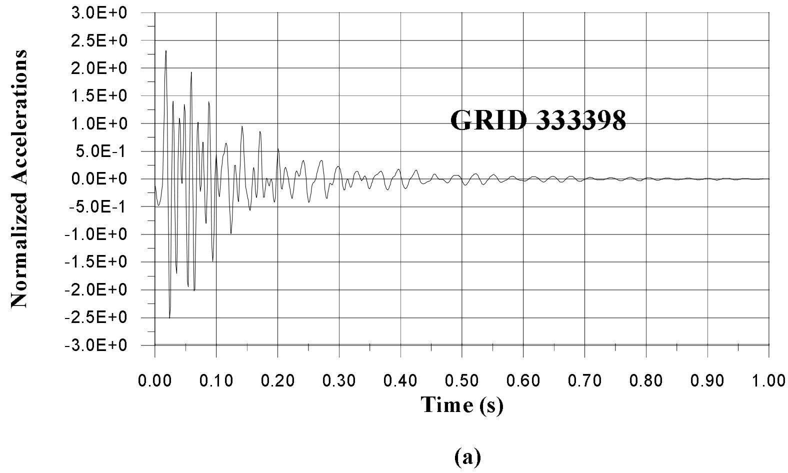


(b)

Figure 7: Normalized accelerations at GRID 1136 (sampling frequency of 1000 Hz): (a) time history; (b) spectrum of the response.

5. CONCLUSIONS

A coupled launcher-satellite analysis has been performed to obtain the transient response of the system during liftoff, through a modal superposition approach. The finite element method is used on modeling the launcher-satellite system. A simplified 3-D beam-like model is used to represent the launcher. A full 3-D detailed model represents the satellite and all its equipments. Rigid body modes are eliminated from the solution. Natural mode shapes of frequencies up to 250 Hz are included in the responses calculations. The results presented herein emphasize the importance of accurately acquiring the thrust data that will be used as input load onto the finite element model. Discrepancies of orders of magnitude can occur. Only flight data obtained in future flights of the vehicle will allow a correlation study between the calculated transient responses and the actual ones.



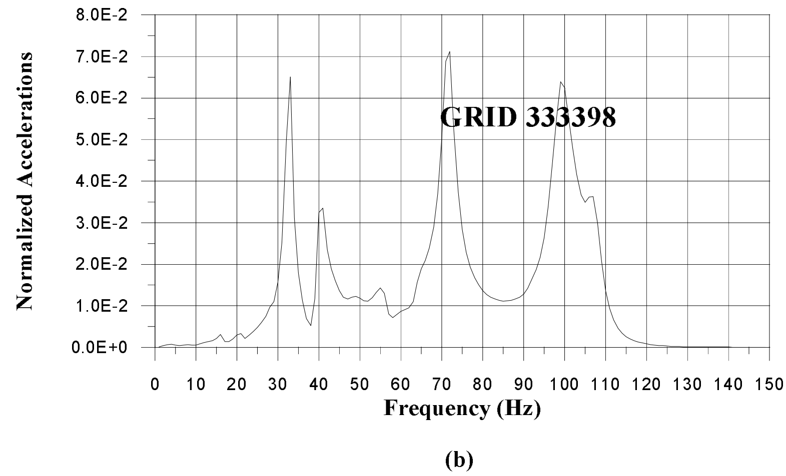


Figure 8: Normalized accelerations at GRID 3398 (sampling frequency of 1000 Hz): (a) time history; (b) spectrum of the response.

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