Dynamic Characterization of Large Structures and Its Application to Solid Rocket Motor Testing and Launch

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Abstract Launch vehicle stages and sub-assemblies experience severe dynamic loads due to extreme launch vibration environment, thrust oscillations from solid motors, etc. Launch vehicle/spacecraft structural members and ground support structures suffer higher dynamic stress levels when the excitation frequency of vibration environment matches with its natural frequency. In addition to this, pressure oscillations inherent of large solid rocket motors tends to generate thrust oscillations with magnitude up to 1% of mean thrust. True thrust oscillation component is essential in coupled load analysis (CLA) and also in deciding the control plant requirements of launch vehicle. However, during the static test, the measured thrust suffers the structural dynamics' interactions of the test stand. To understand the behavior of structural members under a dynamic environment, its modal parameters, viz., natural frequency, modal damping and mode shapes need to be estimated. In the present paper, dynamic characterization of large structures is discussed which has applications to launch vehicles and solid motor testing. In the first part, the dynamic characterization of a large solid rocket motor ground static test stand is studied for estimating the actual thrust oscillations generated during the ground test. The force transfer function was obtained between the motor interface to load cells using experimental modal analysis with modal shaker-based excitation. From the force transfer function, actual thrust oscillations generated by the motor are determined. In the subsequent part of the paper, dynamic characterization of the entire launch vehicle (mass of 500 tons), using the transport vibration measurements was discussed. Vibration responses of the launch vehicle at different locations were measured using servo accelerometers

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and its modal parameters were derived from operational modal analysis. The mode shapes are compared with that of predicted natural frequency, which match quite well. The damping ratios obtained are essential for finite element model updating to estimate the dynamic loads on the launch vehicle.

Keywords Force transfer ratio · Thrust oscillations · Operational modal analysis · Modal Shaker

1 Introduction

Dynamic characterization is the process of determining the modal parameters, viz., natural frequencies, damping factors and mode shapes of a linear, time-invariant system. Dynamic characterization of large structures is specifically complicated due to several reasons like difficulty in the excitation of the structure, measurement of vibration responses from very low frequency and proper cabling along the structure. Often, extraction of modal parameters of large structures is very difficult due to the limitations of the excitation source. The best way for such cases is by using multiple modal shakers for excitation. However, it will be difficult in certain cases to deploy multiple exciters due to the operating conditions. The modal parameters for such structures are obtained by measuring responses only. The deflection shapes plotted using responses alone either at a moment of time or at a given frequency are called operating deflection shapes (ODS) [8]. Modal parameters for a response only measurements are obtained by selecting a reference location and computing a special frequency response function (FRF) called ODS FRF. Using ODS FRF, the nonstationary signals can be analyzed for estimating the modal parameters [10]. This analysis is especially useful in the case of launch vehicles, whose modal parameters need to be estimated from the response only measurements. A similar technique had been implemented in the case of a space shuttle using the roll-out vibration responses for plotting the operating deflection shapes [6] and for estimating the loading functions [1]. Identification of modal parameters is very useful in predicting the behavior of the launch vehicle in the global sense and also at a sub-assembly level for the induced flight environment. Modal identification tests for launch vehicle requires huge test set-up and accurate instrumentation to capture the very low frequency and amplitude responses. Test set-up for such modal tests typically include multiple modal shakers distributed along the structure, simulation of required boundary condition, measurement channels spanning along the structure to identify/capture modes of interest, etc. Various modal tests performed on an upper stage of the Ariane-5 launch vehicle [7] and Ares 1-X [9] are illustrating these details.

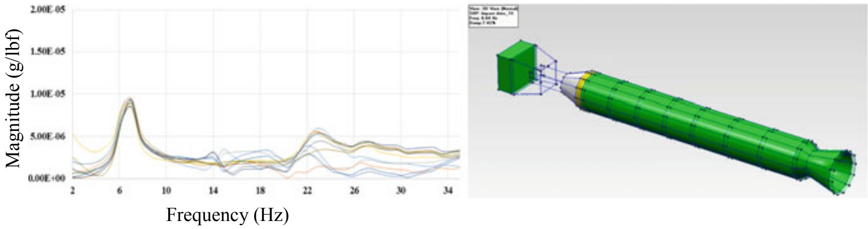
During the firing of large solid rocket motors, due to pressure perturbations in the motor chamber, thrust oscillations will be generated [2]. The occurrence of thrust oscillations due to pressure oscillations inside solid rocket motor chamber was reported during the static firing of shuttle SRM motors [4] and are believed to have occurred at the fundamental duct acoustic mode. The complex interactions between internal pressure oscillations resulting from vortex shedding, motor internal acoustic modes and motor structural vibration modes were assessed for the shuttle SRM and ETM-3 motors through numerical solving of solid rocket motor's acoustic equations of motion and computational fluid dynamics simulations [5]. Over the years, several studies have come up with mitigating mechanisms for thrust oscillations by changing the internal geometry of a solid motor or introducing a flexible element in the transfer path of thrust in the rocket. However, accurate estimation of thrust oscillations is essential to ensure its dynamic coupling effect on full launch vehicle, accurate coupled load analysis and deciding the control plant requirements [3]. In a launch vehicle mission, direct thrust measurement is not possible and thrust oscillation amplitude is derived from acceleration measurement, compared to that static test of SRM offers direct thrust measurement. However, due to the dynamic coupling of a static test stand of solid rocket motors, most of the time it is very difficult to measure the accurate thrust oscillations. Hence, the dynamic characterization of the solid rocket motor test stand is highly essential in this context. In the present paper, two specific cases of dynamic characterization of large structures are discussed with application to a solid rocket motor testing and rocket launch.

2 Dynamic Characterization of Large Structures

To bring forth the applications of dynamic characterization of large structures, two specific cases are discussed which have direct application to the characterization of pressure oscillation to thrust oscillation transfer function and full structural dynamics of launch vehicle.

2.1 Experimental Setup for Dynamic Characterization of Large Solid Rocket Motor Static Test Stand

The test stand for ground static testing of a large solid rocket motor weighing up to 230 tons consists of several structural members for providing a suitable interface to the motor and the thrust measurement system. Due to internal flow disturbance in the large SRM, pressure perturbances generated causes pressure oscillation in the combustion chamber, which produces thrust oscillations. Accurate estimation of the magnitude of the thrust oscillation component is essential for understanding its effect during the actual flight of the rocket. The presence of structural members in the test stand induces dynamic interference into the thrust oscillation component measured by the load cell during ground static testing of the motors. Hence, the dynamic characterization of the test stand structural elements needs to be performed for estimating its effect on transferring oscillatory thrust components to the load cell. Accurate estimation of the natural frequencies and force transfer ratios of the test



(a). FRF traces from impact test *(b). First axial mode of test stand at 6.5 Hz*

Fig. 1 Experimental modal analysis of a solid rocket motor static test stand

stand are essential for determining the correct thrust oscillations generated due to motor firing.

A modal survey of the test stand with the motor has been performed using the impact hammer method for estimating the natural frequencies and damping ratios. Since the test setup is huge, the sledge hammer impact excitation can only induce very small response levels. To acquire such low vibration responses from the test stand, high sensitivity accelerometers (500 mV/g) are used. Frequency response functions (FRF) shown in Fig. 1 are derived from the measured response and excitation. By curve fitting the FRFs using the global polynomial technique, natural frequencies of the test stand are determined.

For determining the force transfer ratio (FTR) of the test stand across the frequency band of interest, modal shaker-based excitation is performed on the thrust measurement system. Two numbers of 100 kgf modal shakers are connected to the test stand where the motor is assembled and a sine sweep excitation was performed from 10 to 150 Hz. Force applied on the test stand is measured through the force sensor mounted at the modal shaker stinger to the test stand. The actual force measured by the load cell is recorded during the sine sweep. The responses are measured along the test stand using 11 numbers of accelerometers positioned in axial and lateral directions. By computing the force transfer ratio, the dynamic characteristic of the test stand force transfer is obtained from the setup shown in Fig. 2.

2.2 Vibration Measurements During Movement of Launch Vehicle from Assembly Bay to Launch Pad

Launch vehicles during final preparations on the launch pad and during the ascent phase are subjected to several dynamic loads due to external excitations. The modal model of the launch vehicle will complement the finite element model in assessing the structural loads on the launch vehicle and its adequacy. Usually, the launch vehicle modal model is generated from the Ground Resonance Test (GRT). Usually, GRT is performed during the development phase of a launch vehicle, which is before the first flight. Due to several improvements in the launch vehicle structures especially

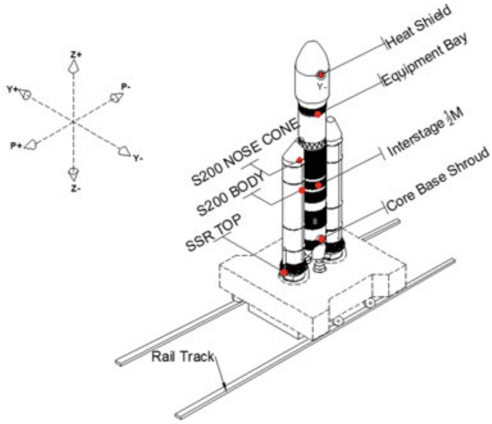
(a). Modal shaker excitation test set-up *(b). Force sensor and stinger attachment*

Fig. 2 Modal shaker excitation of the thrust measurement system of a solid rocket motor static test stand

after the initial one or two experimental flights, the dynamic characteristics may get altered. However, performing GRT again to verify the dynamic characteristics is highly time consuming and costly. An alternative approach for measuring the dynamic characteristics, mainly natural frequencies and modal damping of the launch vehicle, is from the movement vibration data.

Launch vehicle after completion of assembly activities is moved to the launch pad on a rail track for a distance of approximately 900 m. During the movement of the launch vehicle on the rail track, several excitations will be induced on it due to track joints, wind loads, etc. These disturbances are broadband in nature and invoke the natural modes of the launch vehicle. Capturing the vibration response along the launch vehicle gives useful insight into the natural frequencies and corresponding modal damping ratio. Figure 3 shows the movement of a GSLV Mk-III launch vehicle from the assembly building to the launch pad and vibration measurement accelerometer locations. Since the mass of the launch vehicle is huge (~500 tons), vibrations induced are very low. Also, the natural frequencies of a typical launch vehicle will be starting from a very low frequency (~1 Hz), which most of the piezoelectric accelerometers cannot measure. Total 20 numbers of accelerometers with 1 V/g sensitivity and frequency range from DC to 20 Hz are used for measuring the vibration responses. Since the excitation cannot be measured, by performing the operational modal analysis of the measured vibration data, the natural frequencies and damping ratios are obtained.

(a). GSLV Mk-III rocket movement to launch pad



(b). Accelerometer locations

Fig. 3 Vibration measurements during movement of a launch vehicle

3 Results and Discussion

3.1 Application of Dynamic Characterization of Static Test Stand for Large Solid Rocket Motor Testing

From the impact hammer-based experimental modal analysis of a full test stand with a large solid rocket motor (weighing 230 tons), the fundamental axial mode is found to be at 6.5 Hz. During the static firing of the motor, thrust oscillations are identified predominantly in a 22–25 Hz frequency band. Since the fundamental axial mode of the test stand is approximately three times less than the thrust oscillation component generated from the motor, the measured thrust oscillation magnitude might be attenuated unless there is another mode near the thrust oscillation frequency.

From the modal shaker-based excitation of the test stand alone (without motor), FTR of the test stand is determined. Since the total mass of the system has reduced, the axial fundamental frequency has increased by a factor of the square root of the ratio of the initial and actual mass of the test stand. Initial mass (m_{initial}) of the test stand with motor is ~310 tons whereas, the actual mass of the test stand during modal shaker excitation (m_{actual}) is ~14 tons. As the least stiff element in the test stand, i.e., load cell flexure present in both the cases, the frequencies will be shifted corresponding to the square root of the mass ratio approximately. From the experimental modal analysis, the fundamental axial mode is found to be at 27 Hz, which is closely matches with the shifted frequency (30 Hz) as per the mass ratio. Hence, the frequencies corresponding to thrust oscillations (22–25 Hz) are assumed to be shifted from 103 to 117 Hz frequency band as per the mass ratio. Since the load cell responds only to axial load, the force transfer characteristics are assumed to follow that of a full

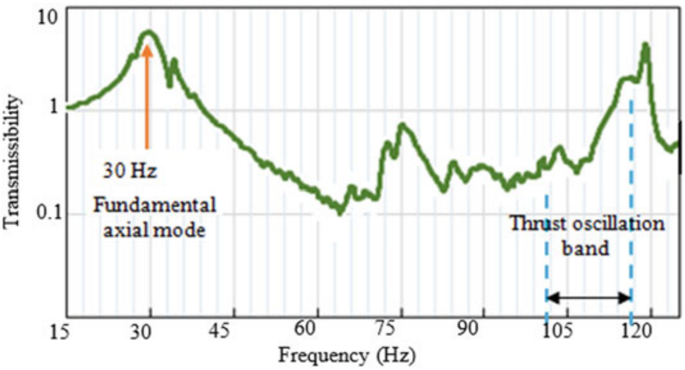


Fig. 4 Force transfer characteristics of solid rocket motor static test stand

test stand with the motor except for the shift of frequencies corresponding to the square of mass ratio as mentioned earlier. From Fig. 4, it is clear that the magnitude of the thrust oscillation component will be attenuated in the frequency band of 103–112 Hz and will magnify from 113 to 117 Hz. The corresponding thrust oscillation frequency band in the attenuation zone is 22–24.3 Hz and in the amplifying zone is 24.3–25 Hz. Hence, to arrive at the correct thrust oscillation magnitude, the measured thrust oscillation magnitude needs to be corrected by identifying the thrust oscillation frequency component and applying the corresponding correction factor from the FTR plot shown in Fig. 4.

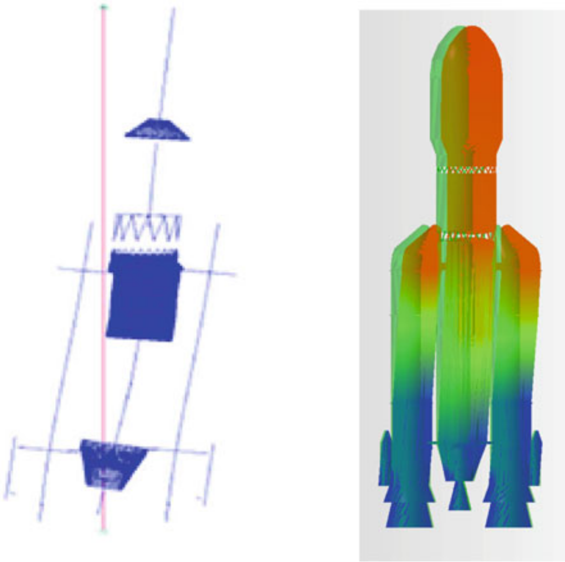
3.2 Operational Modal Analysis of Launch Vehicle

Launch vehicles while moving from the assembly bay to the launch pad is subjected to several excitations, viz., wind loads, track disturbances, etc., which are broadband in nature. The response of the launch vehicle to such broadband excitations consists of natural modes of vibration. Since the excitation cannot be measured in this case, operational modal analysis (OMA) is performed from the responses only. The reference accelerometer selected is at the tip of the launch vehicle (on heat shield). Natural frequencies and modal damping of the launch vehicle are obtained from the OMA. The natural frequencies obtained from OMA match closely with that of the finite element (FE) predictions. Further, the damping ratios estimated from OMA are used for finite element model updating to predict the response of the launch vehicle to wind loads when it is standing on the launch pad. Also, the full launch vehicle response in the atmospheric regime and control plant requirements depends mainly on the full launch vehicle dynamic characteristics such as its fundamental modes and damping factors. Table 1 shows the natural frequencies and modal damping obtained from measurements and predicted natural frequencies from FE. Figures 5 and 6 show the mode shapes obtained from OMA and comparison with FE.

Table 1 Comparison of predicted and measured natural frequencies of GSLV Mk-III launch vehicle

SI. No.	Axis	Measured from OMA		Predicted natural frequency
		Natural frequency (Hz)	Damping ratio (%)	
1	Yaw	1	2.5	1.23
		2.75	2.9	2.55
2	Pitch	1.64	2.1	1.65
		3.45	3.3	2.8

Fig. 5 First mode shape in the pitch axis

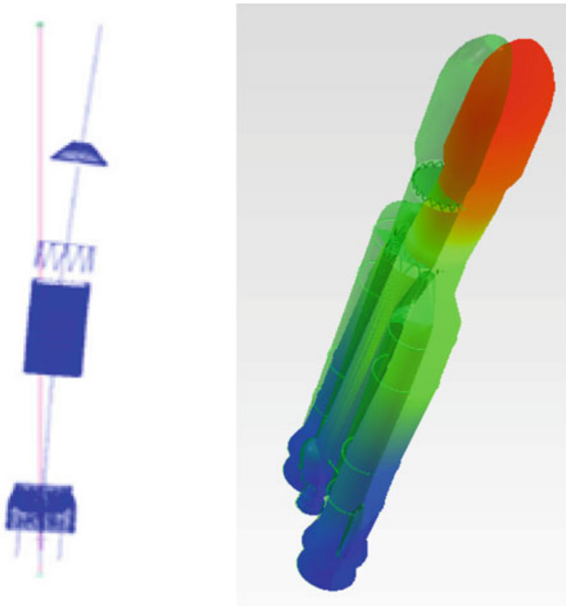


(a). FE prediction-1.6 Hz (b). OMA-1.6 Hz

4 Conclusions

In the present paper, two specific cases of dynamic characterization of large structures are discussed with applications in rocketry. Ground-based test stand structures used for static testing of large solid rocket motors are huge and will impose dynamic interference in the measured thrust oscillation data from the static testing of the motor. Dynamic characterization of the test stand system helps to identify the natural frequencies of the test stand and force transfer characteristics, which in turn are used to correct the measured thrust oscillations. In the present paper, the dynamic characterization of a large solid rocket motor static test stand is discussed. The test stand has a fundamental axial natural frequency at 6.5 Hz; thrust oscillation components generated by the motor are in a 22–25 Hz frequency band. From the dynamic force transfer characteristics, the test stand is found to be attenuating the measured thrust oscillation component in the 22–24.3 Hz frequency band and slightly

Fig. 6 First mode shape in the yaw axis



(a). FE prediction-1.2 Hz (b). OMA-1 Hz

amplifying from 24.3 to 25 Hz. In the second case, operational modal analysis of GSLV Mk-III launch vehicle movement vibration data is discussed. From OMA, the natural frequencies and respective modal damping ratios are measured. The measured natural frequencies closely match with that of the finite element predictions. The measured damping ratios help in estimating the dynamic loads on the launch vehicle by finite element model updating.

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