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A Review on Vibro-Acoustic Analysis of a Launch Vehicle Structure

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Abstract: Space vehicles are subjected to significant dynamic pressure loads when their rocket propulsion systems are in use during flying missions. During the aerodynamic and launch phases, launch vehicles, payloads, and their parts are subjected to extremely high random acoustic loads. The noise from the engine exhaust gas, aerodynamic boundary layer noise, transonic buffering, structure-borne vibration, engine thrust fluctuation, etc. is the source of these loads, which also result in a secondary acoustic load. When the vehicle is lifting off and traveling at a speed greater than Mach number, acoustic stresses to the spacecraft and payload are very harsh and significant. This loading causes the structure to vibrate randomly, which could be dangerous for some vehicle parts, avionics, propulsion systems, and payloads like satellites. This paper discusses the vibration of the structure subjected to acoustic excitation on a diffuse acoustic field and the software used for the analysis.
Keywords: Dynamic Pressure, Acoustic Excitation, Vibration, Acoustic Loads, Diffuse Acoustic Field

I. INTRODUCTION

The science of acoustics is concerned with the measurable measurement of sound production, control, transmission, and reception. A longitudinal wave or disturbance known as the sound propagates through a physical medium (such as metal, water, or air) from a source. Acoustic pressure, often known as sound pressure, is the variation between the average local medium pressure and the pressure experienced by a sound wave at the same location and instant. A vibrating object generates a traveling wave that spreads through a medium (gas, liquid, or solid) as a result of particle interactions.

Lift-off acoustics and aerodynamic noise produced during the transonic regime are of primary concern in the design and development of launch vehicle structures. A launch vehicle consists of one or more rocket engines, guidance, navigation, and control systems, a payload, and a structure housing all of these elements. The high amounts of noise produced during various flight phases, such as takeoff and atmospheric flight, are referred to as acoustics in launch vehicles. One of the unwelcome by-products of launch vehicle lift-off and atmospheric flight regime is the high acoustic level. The structural vibrations caused by these acoustics might permanently damage important components like avionics packages, propulsion modules, and payloads or are detrimental to their proper operation. During launch and the atmospheric domain of flight, launch vehicle structures are vulnerable to acoustic excitations. These excitations are caused by the noise field generated by the propulsion system surrounding the vehicle during takeoff and low subsonic stages of flight, while during transonic and supersonic portions of the flight, the aerodynamically generated acoustic field is dominating. These excitations cause the launch vehicle's structures to vibrate randomly, which results in transmitted acoustic field occurrences on the systems inside. To determine the vibration environment for components and subassemblies, the response to these excitations must be determined. The acoustic test can be used to precisely determine the internal acoustic environment and random vibration response. Research is heavily focused on the analytical prediction of vibroacoustic response. Acoustic tests conducted all over the world serve as a crucial tool for estimating vibroacoustic response. However, efforts are being undertaken to address the issue entirely analytically. The development of mathematical models to represent the structural dynamic behavior valid over a very wide bandwidth from 20Hz to 2000Hz is essential for the accuracy of vibroacoustic forecasts.

II. ACOUSTIC TESTING FACILITY

The objective of India's space program is to launch several remote sensing and communication satellites. To ensure that these space-bound systems and components can resist the intense wire fields encountered throughout the trans-atmospheric flight to their final locations in space, sonic exposure testing is required on the ground. To expose appropriate signature spectra to space-bound packages, an acoustic test facility needs a sizable reverberation chamber as well as an energy source to produce the desired noise. Concrete reinforced with cement has been used to create a reverberation chamber. To determine the reinforcement, the chamber has been designed as an ideal pressure vessel with an internal pressure of 13 kPa. The chamber is separate from the other facility structures and is supported by a raft foundation.

Reverberation, or the persistence of sound, can be heard in any completely enclosed space. Repeated boundary reflections of sound are the source of this. Electro-pneumatic transducers are now the best and most effective way to create massive acoustic noise fields. These devices use air energy and typically convert pneumatic energy to acoustic energy at a conversion efficiency of 6–7%. a typical 2-3 minute acoustic facility operation. A satellite typically uses roughly 1000kg of compressed air for one trans-atmospheric transition.

III. FINITE ELEMENT MODELLING

For numerically resolving differential equations arising in mathematical and engineering modeling, the finite element method (FEM) is a well-liked technique. The conventional topics of structural analysis, heat transfer, fluid flow, mass transport, and electromagnetic potential are typical issue areas of interest. Using two or three spatial variables, the FEM is a general numerical method for solving partial differential equations (i.e., some boundary value problems). The FEM breaks down a complex system into smaller, more manageable pieces known as finite elements to solve an issue. The numerical domain for the solution, which has a finite number of points, is implemented by creating a mesh of the object using a specific space discretization in the space dimensions. In the end, a set of algebraic equations emerges from the formulation of a boundary value problem using the finite element approach. The technique makes domain-wide approximations of the unknown function. The small system of equations that describes these finite elements is then combined with other equations to model the full issue. The calculus of variations is used by the FEM to minimize an associated error function and then approximate a solution. Finite element analysis is a term used to describe the study or analysis of a phenomenon using FEM (FEA). MSC PATRAN/NASTRAN, ABAQUS, ANSYS, SOLIDWORKS, OpenFOAM, etc. are the software that uses FEM. Finite element modeling was done using MSC PATRAN software. QUAD, TRIA, and BAR elements were used in the modeling. The BAR elements are used to connect the deck where components are mounted to the structure. The components are modeled by providing the mass at the center of gravity location and connected using a RIGID BEAM element.

A. About MSC PATRAN/NASTRAN

The most popular FEA pre-and post-processing software in the world, MSC Patran, offers solid modeling, meshing, analysis setup, and post-processing for a variety of solvers, including MSC Nastran, Marc, Abaqus, LS-DYNA, ANSYS, and Pam-Crash. For linear, nonlinear, explicit dynamics, thermal, and other finite element solutions, Patran offers a comprehensive collection of tools that simplify the development of analysis-ready models. Patran makes it simple for anybody to construct FE models, from geometry cleanup tools that help engineers deal with gaps and slivers in CAD to solid modeling tools that enable the production of models from start. Surfaces and solids can both readily be meshed using fully automatic meshing processes, more controllable manual techniques, or a combination of both. The majority of popular FE solvers provide built-in loads, boundary conditions, and analysis setup, reducing the need to adjust input decks. To evaluate product performance against criteria and optimize your ideas, Patran's comprehensive and industry-tested features make sure that your virtual prototyping efforts provide results quickly.

The most used Finite Element Analysis (FEA) solver in the world is MSC Nastran. MSC Nastran is still the greatest and most dependable software in the world when it comes to simulating stress, dynamics, or vibration of real-world, complicated systems. With the aid of high-performance computing, engineers can perform static, dynamic, and thermal analysis in both linear and nonlinear domains using MSC Nastran, a multidisciplinary structural analysis application. It is also complemented by automated structural optimization and award winning embedded fatigue analysis technologies. MSC Nastran is used by engineers to make that structural system have the strength, stiffness, and longevity required to prevent failure (excess loads, resonance, buckling, or harmful deformations) that could jeopardize structural function and safety. The Finite Element Method is the most important numerical technique used in MSC Nastran. Built-in implicit numerical techniques can be used to solve nonlinear FE issues. There are many optimization methods, including IPOPT and MSCADS. The quickest and most reliable fatigue solution on the market today, CAEfatigue, is used by MSC Nastran's fatigue capabilities.

IV. VIBRO-ACOUSTIC MODELLING

Software from ESI called VA One was used to model vibroacoustics. The finite element model and the outcomes of the normal mode analysis were imported to perform vibroacoustic modeling. The creation of structural FE subsystems such as the top cone, bulkheads, deck, dome, isolators, components, and rigid linkages follows. The vibroacoustic model represents structural elements using FE structural subsystems. Separate FE faces are made for the top cone, bottom cone, and dome to provide the model with acoustic stimulation.

For the acoustic test data, the excitation spectrum was simulated and used as the acoustic excitation. Sensors are installed on the deck and bulkheads to record vibration responses before doing the vibroacoustic study. The nodes of structural FE subsystems can be equipped with sensors, which can be compared to virtual accelerometers.

A. About ESI VA One

Vibro-acoustics analysis and design can be done in a single environment called ESI VA One. To achieve product performance goals, it enables engineers to conduct precisely predicted noise and vibration design assessments early in the design cycle. Aggressive design-time restrictions can be met by users, guaranteeing that engineering decisions can be taken at the precise moment when they benefit the most from the requirements of a multidisciplinary development environment. Through a set of flawlessly integrated and tried-and-true modeling techniques, the VA One environment can be accessed through a common user interface and covers the entire frequency spectrum. Users may reach the highest level of design productivity with VA One without having to deploy several solutions that need training for various user interfaces and data transfer between environments.

B. Benefits of VA One

With precise noise prediction models developed early in the design process, VA One meets operational targets (quality, cost) and project milestones. To swiftly evaluate prototype ideas with speedy model building, it combines noise prediction techniques into already-existing design environments.

To cut down on simulation time, it uses an ideal collection of quickly coupled, seamless procedures. To achieve attribute targets, it assesses your design and quickly tests countermeasures. In a single context, it aids in achieving design goals for both interior and outdoor noise. It gets rid of pricey, late-stage changes.

V. VIBRO-ACOUSTIC ANALYSIS

Vibro-acoustic analysis was carried out in the FE regime up to 500Hz. Consequently, modes up to 500Hz were used. A Uniform damping loss factor of 1% is used for analysis. Analysis was initially carried out on a basic model without a cavity. FE analysis was used in the low-frequency regime to analyze the model and these results are compared with the test results. The model was further developed with additional features incorporated to compare the modified model with the basic one. The basic model without cavity was analyzed in the FE regime up to 500Hz and the vibration responses in bulkhead and deck in radial, tangential and axial directions are compared with test responses.

The basic model was incorporated with some additional features incorporated to improve the results and to understand the deficiencies in the model and the reasons for the mismatch between test and prediction. The model was further modified with a single cavity as well as separate cavities. An enclosed cavity is modeled inside the structure which is considered a single cavity and the fluid considered is air. The model is modified with two separate cavities one above the deck and the other below the deck to study the interaction between deck and cavity, which is the separate cavityThe model is again modified by increasing the damping by 2% to study the effect of damping in the vibration response. The modal displacement patterns of local modes are highly dependent on local mass and stiffness distributions. This specifically limits the numerical characterization of closely spaced modes in the system. The reliability of predictions through vibroacoustic analysis explicitly relies on the goodness of modal parameters estimated through analysis.

VI. CONCLUSIONS

Vibroacoustic analysis has been carried out and the simulated response obtained from VA One is compared with the acoustic test measurements. Initially, a basic model without a cavity was analyzed and the overall trend of the responses was captured up to 500Hz. It is seen that the acoustic test gives more accurate results than the vibroacoustic analysis. It is seen that the response shows a better match after each update on the model. The response was improved and become closer to the test response when two separate cavities are modeled. It is understood from the analysis that the modifications in the basic vibroacoustic model caused the peak responses to shift towards a lower frequency regime. It is also confirmed that the peak values of the response can be reduced and a better match with the test response can be obtained by damping the structure. It is also understood from the results that the vibration response on the deck can be reduced by the use of isolators. It is also seen that there are certain modes obtained in the analysis which does not represent the actual scenario. The effect of modeling assumptions, deck-cavity interaction, and the variation in damping on the vibration responses are analyzed through vibroacoustic analysis.

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