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Vibro-acoustic modeling and validation using viscoelastic material

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ABSTRACT

In aerospace industries, on-board electronics are carried during flight, and such equipment must be qualified to withstand the loads to which they are exposed. In this fashion, the knowledge of the different dynamic aspects of excitations and the behavior of structures, components and/or acoustic enclosures are crucial to have controlled and performing space systems. Passive control techniques using viscoelastic materials (VEM) are widely applied and their effects on space systems must be studied aiming to obtain adequate operational environments. The effect of damping insertion on the dynamic behavior of a vibro-acoustic system is assessed in this work. A coupled structural–acoustic system, composed by a VEM coated aluminum panel and an acoustic box, is modeled by Finite Element Method (FEM). On the other side, tests are preformed using the KU Leuven facilities to validate the FEM model. Numerical vs. experimental comparisons were done and acceptable agreement was obtained. On the other side, it was found that sound inside the box reduces due to the smaller sound radiation generated by the treated panel.

1. Introduction

Expendable launch vehicles (ELV) carry payloads and electronics inside fairings and bays and such equipment must withstand the dynamic environment to which they are submitted. During flight, ELV experience loads from acoustic noises at lift-off, transonic and maximum dynamic pressure flights as well as vibration due to motors operation up to mechanical shocks generated during stage separations. Along the many years developing space systems, one could verify that these dynamic loads are characterized as highly intense, random and with large spectral contents. However, it is well known that qualification processes of space systems have high costs if intense dynamic levels are required. As a consequence, such an intense levels to which on-board equipment are exposed must be suppressed or attenuated.

The knowledge of the different dynamic aspects of excitations and the behavior of structures, components and/or acoustic enclosures are crucial to have controlled and performing space systems. Virtual prototyping supported by vibro-acoustic solutions is a significant tool to be used on space system developments, due to the proven cost benefits reflected into projects. Low-frequency deterministic methods such as Finite Element Methods (FEM) [1] and Boundary Element Methods (BEM) [2] have, due to increasing computer speed, been able to run deterministic models to higher and higher frequencies,

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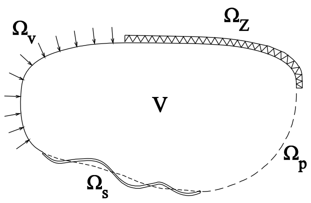

Fig. 1. Vibro-acoustic system.

while Statistical Energy Analysis (SEA) [3] has become an accepted method for both acoustic and vibration high-frequency analysis. One still may highlight mid-frequency methods as Wave Based Method (WBM) [4] and hybrid techniques (e.g., FEM/SEA) [5], among others.

The novelty in structures and materials and the increasing complexity of systems require new and more accurate numerical formulations as well as experimental validation procedures, to study their mechanical characteristics. Although computer models have evolved substantially, there are still many open issues, which impair design engineers to fully exploit virtual design processes. Nowadays, the demand on numerical simulations is high in the field of Noise and Vibration Harshness (NVH), e.g., the numerical modeling of multi-layer trim acoustic material and structural damping, largely used to attenuate air- and structure-borne noise. Structural damping insertion using viscoelastic materials (VEM) is a well-known passive control technique, widely applied in the aerospace industry. On the other side, the use of blankets or poro-elastic materials is spread as air-borne noise control technique. However, accounting vibro-acoustic systems, the structural noise radiation can be considered as an additional portion, when acoustic responses must be attenuated. In this framework, the effect of VEM insertion on the acoustic responses of coupled vibro-acoustic systems seems to be an appropriate assessment.

There is a significant motivation in the space industry to study sandwich structures (e.g., homogeneous panel + constrained VEM), since these systems present good NVH controlling performances as well as cost-effective mounting designs. This work focuses on the vibro-acoustic modeling of the KU Leuven Sound Box and an aluminum homogeneous plate treated with a VEM damper. In order to well characterize the frequency-dependent shear behavior of the VEM compound, measurement procedures using Dynamic Mechanical Analysis (DMA) and Differential Scanning Calorimetry (DSC) tests are applied [6]. Since the DMA tests are limited in frequency range, Time–Temperature Superposition Principle (TTSP) is applied aiming at building the master curve of the rubber up to 10^6 Hz and the four parameters constituting the Fractional Derivative Model (FDM) are identified from the master curve by using a least square method [7] and accounted in the structural part of the FEM vibro-acoustic model.

Two coupled vibro-acoustic FEM models are built: (i) bare panel + sound box and (ii) VEM coated panel + sound box. The responses of the structure and the acoustic cavity to a unitary point excitation are computed at selected points distributed along the structural and acoustic subsystems. Aiming to validate the numerical models, dynamic tests are performed, by reproducing the same configurations as those modeled by FEM. The structural and acoustic responses are measured by accelerometers and microphones at the same geometrical observation points as those generated in the numerical models, being an impact hammer used to excite the system. Numerical vs. experimental comparisons are done and good agreement is obtained, despite a slight under-prediction of the structural damping. It is observed that the sound inside the sound box cavity reduces, due to the smaller sound radiation generated by the treated panel.

2. Vibro-acoustic modeling using FEM

2.1. FEM/FEM coupled model

In a coupled vibro-acoustic system, the fluid is comprised in a bounded acoustic domain V, of which the boundary surface Ω_a contains imposed boundary conditions as pressure Ω_p, impedance Ω_z and velocity Ω_v as well as an elastic structural surface $\Omega_s(\Omega_a = \Omega_s \cup \Omega_p \cup \Omega_v \cup \Omega_Z)$, as shows Fig. 1.

FE based models for vibro-acoustic problems are most commonly described in an Eulerian formulation, in which the fluid is described by a single scalar function, usually the acoustic pressure, while the structural components are described by a displacement vector. The resulting combined FE/FE model in the unknown structural displacements and acoustic pressures at the nodes of, respectively, the structural and the acoustic FE meshes are [8,9],

$$\left(\begin{bmatrix} K_s & K_c \\ 0 & K_a \end{bmatrix} + \mathrm{j}\omega \begin{bmatrix} C_s & 0 \\ 0 & C_a \end{bmatrix} - \omega^2 \begin{bmatrix} M_s & 0 \\ -\rho_0 K_c^{\mathrm{T}} & M_a \end{bmatrix}\right) \cdot \begin{Bmatrix} w_i \\ p_i \end{Bmatrix} = \begin{Bmatrix} F_{si} \\ F_{ai} \end{Bmatrix} \tag{1}$$

where $[\boldsymbol{K}_c]$ is the cross-coupling matrix in the coupled stiffness matrix and $[-\rho_0 \boldsymbol{K}_c^{\mathrm{T}}]$ is the cross-coupling matrix in the coupled mass matrix.

In comparison with a purely structural or purely acoustic FE model, the coupled stiffness and mass matrices are no longer symmetrical due to the fact that the force loading of the fluid on the structure is proportional to the pressure, resulting in a cross-coupling term K_c in the coupled stiffness matrix, while the force loading of the structure on the fluid is proportional to the acceleration, resulting in a cross-coupling term $M_c = -\rho K_c^{\mathrm{T}}$ in the coupled mass matrix [8,9].