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Numerical modelling of structures with thin air layers

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ABSTRACT

During launch, satellites and their equipment are subjected to vibration loads of random nature and within a wide frequency range. Their vibro-acoustic response is an important issue to be analysed, in particular, for structural components such as solar arrays in folded configuration. The modelling of these structures in the low frequency range (low modal density) requires combining models for the air layers, the structural elements and the surrounding air. This work studies different combinations of numerical methodologies (FEM, BEM, SEA) to model the system in order to simulate the modal and the vibro-acoustic responses outlining their advantages and drawbacks. The modal and acoustic simulated responses are determined and analysed to find out the efficiency of the combinations of the numerical methodologies proposed. Two different cases are considered: a simple benchmark case (two structural elements and one air layer) and a real solar wing design (three solar panels and two air layers). For the latter, experimental results on both the modal and vibro-acoustic responses are also presented.

1. Introduction

The objective of this study is to model and analyse the modelling of a kind of structural system that arises commonly in spacecraft structures: the coincidence of structural panels and thin air layers. Solar wings in folded configuration, or close equipment platforms [8] are examples of this configuration. The fluid–structure interaction between the structural elements and the air regions affects the response of the system in several ways. In general, compared to its *in vacuum* response, air surrounding structures add reactive and resistive impedance to the structure, changing its eigenfrequencies and modifying its damping, which, in turn, leads to lower resonant frequencies. Instead, the coupling of structural elements because of air layers can modify greatly the dynamic response. This work lays stress on the influence of the air layers on the system responses and on the use of different methods for its determination. The effect of the air layers is the combination of the non-resonant load transmission and the dynamic coupling. The former modifies the level of the response in the system and the latter affects greatly the dynamic behaviour of the system as the shift of the first eigenfrequencies [5,10]. Although the effect of the coupling described cannot be isolated from other effects as the apparent higher structural damping, the latter contribution is known and is smaller in general [12,18]. For instance, changes in the dynamic behaviour of a given structure as shown in Table 1 can be attributed mainly to the coupling by the air layers.

Table 1
First eigenfrequencies of the ARA Mark 3 solar wing determined numerically (FEM model considering only structural elements) and experimentally (through a modal test).

Eigenfrequency	Structural FEM model (Hz)	Modal testing on specimen (Hz)
1	81	19
2	108	26
3	140	32

In present design the main sizing loads are those derived from the shock loads and from the structure–fluid interaction, which are known as acoustic loads. To simulate the response of the systems to these loads, an issue arises [3]: the need of developing a numerical model which is able to reproduce these low frequency considerations while being compatible with numerical models for higher frequencies.

Then, numerical models developed in the industry have to be extended to include the air layers between those structural elements in which its influence is high. This process has evolved over time: from the use of qualitative and specific models to the need of implementing these elements in a fine-tuned numerical model with commercial codes used by the industry. To model these structures, several numerical techniques can be considered for both structural and fluid domains and for both ranges of frequency and

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[1] Sadly passed away during the preparation of this work.

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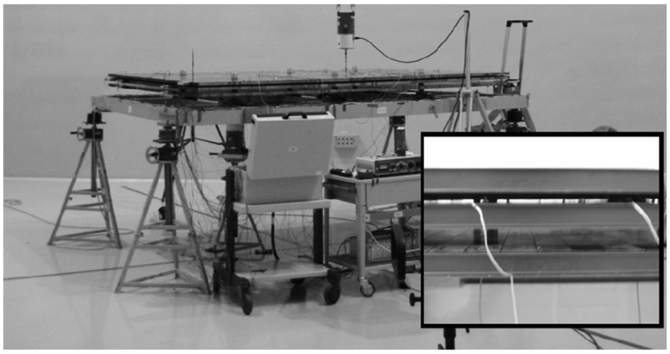

Fig. 1. Dutch Space ARA Mark 3 solar wing in folded configuration. Close up shows the gap thickness between panels (Courtesy of Dutch Space).

modal density (deterministic and stochastic) [16]. The most widely used methods (as they provide an equilibrium between practicality and accuracy) are: Finite Element Method (FEM), Boundary Element Method (BEM) and Statistical Energy Analysis (SEA). The coupling of the models for the different domains (especially for the specific air layer formulations) requires the analysis of the mathematical coupling between formulations [20,21]. Focusing on the development of industrial models the three general formulations (FEM, BEM and SEA) are used to model the response of the elements of the system: structural panels, air layers and the surrounding air [9].

The application of these techniques to this type of structures is studied and their particularities (combination of structural and fluid elements) are taken into account to propose several combinations of the three numerical techniques stated above. A total of five calculus strategies is presented and analysed. Particularly, the capability of strategies based on energetic approaches for the modelling of the surrounding air as alternative to the usual BEM approach will be presented. In order to assess the adequacy of the different configurations, two indicators will be considered: the dynamic behaviour (in terms of the frequency response of the system to structural loads) and the vibro-acoustic behaviour (the structural response under an acoustic load).

Although the kind of structure described is usual in spacecraft structures, solar wings in folded configuration are chosen as the objective of the work for their high interest and for being a critical subsystem of any satellite. This main element will define the cases to analyse: First, a benchmark case consisting in two structural panels and one air layer so that there is no mechanical junction between the panels, thus the behaviour of the coupled system is only affected by the effects of the air layer. The second is an actual solar wing development (ARA Mark 3 by Dutch-Space) made up of three structural elements and two air layers. This case is studied assessing the simulation strategies with experimental results from modal survey and acoustic tests.

The present paper is structured as follows: first, a qualitative study of the phenomenon based in simple inertia and stiffness elements is presented; in addition, a set of modelling strategies based on combinations of the different numerical formulations is proposed; then, the two cases to be considered (the benchmark case and the solar wing) are defined geometrically and structurally; afterwards, the benchmark case is analysed in terms of the frequency and acoustic responses implementing the set of models defined previously; afterwards, the analysis of the solar wing in folded configuration is presented along with experimental results, leading finally to a discussion of the advantages and drawbacks of the strategies.

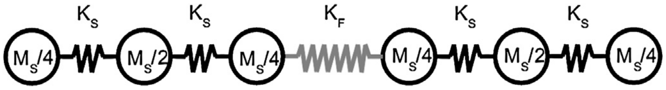

Fig. 2. Model of inertia and stiffness elements for two identical structural panels separated by an air layer considering exclusively the air stiffness.

2. Physical phenomenon

The phenomenon of frequency matching between the structural and fluid elements of a system can be studied with a basic mathematical model based on inertia and stiffness elements. This section presents a qualitative study of the behaviour of such systems depending on their stiffness and mass. The object of the study is a system composed of two identical structural elements separated by an air layer.

This kind of problems is common in structural acoustics where the study of double-leaf partitions are of main interest [4]. The analysis of the acoustic field established by the displacements of one of the structural elements leads to a maximum of the acoustic transmission coefficient that defines the so-called *mass–air–mass* resonance frequency

$$\omega_0 = \left[\left(\frac{\rho_0 c^2}{d}\right)\left(\frac{m_1 + m_2}{m_1 m_2}\right)\right]^{1/2} \tag{1}$$

where ρ_0 and c are the speed of sound and the mean density of the fluid, d is the distance between the structural elements and m_1 and m_2 are the mass per unit area of each element. For identical structural elements, this frequency can be expressed in terms of the ratio of the masses of the structural (M_S) and fluid (M_F) elements as

$$\omega_0 = \left(2\frac{M_F}{M_S}\frac{c^2}{d^2}\right)^{1/2} \tag{2}$$

and therefore defining the stiffness of the air layer as

$$K_F = \omega_0^2 \frac{M_S}{2} \tag{3}$$

This allows analysing the system through a model based on inertia and stiffness elements: A problem of two identical plates with a first eigenfrequency of 500 Hz separated by an air layer is considered. To study the influence of the mass of the structural elements, these are modelled through a three degrees of freedom system and the air layer is included as a stiffness element (Fig. 2). The properties of the structural elements are defined by the total mass of the structure and the stiffness is set accordingly to the first *in vacuum* eigenfrequencies of the panel. The stiffness element for the air layer is the one deduced above.

Fig. 3 depicts the eigenfrequencies of the model in Fig. 2 for different values of the panels mass and the value of the *mass–air–mass* resonance frequency predicted by Eq. (2).

The results show that for heavy and stiff structures the first resonance of the system is equal to the predicted *mass–air–mass* one and the structural elements behave as rigid elements. On the contrary, for lighter and flexible structures the coupling of the fluid and structural elements leads to a lower first eigenfrequency compared to the ideally predicted value.

Traditionally it used to be assumed that the transmission through the air layers was non-resonant, whereas here it can be observed that, due to the physical characteristics of the structures designed nowadays, the resonant coupling because of the air layer takes on importance on the response of the whole structure.

3. Mathematical models

From the numerical formulations stated in Section 1, FE and BE methods are used for the low frequency range and SEA for high