Identification of the dynamic influence of non-structural elements in aerospace structures

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Abstract
Non-Structural Elements (NSEs) in aerospace structures have long been modeled as lumped mass, even though their dynamic behavior plays a crucial role in the damping of the global structure. Better assessment of the influence of Non-Structural Elements requires previous knowledge about their dynamic behavior. The number and diversity of Non-Structural Elements in such structure make it difficult to study each of them individually and therefore, another method is needed. In this paper is presented a strategy to identify the dynamic influence of Non-Structural Elements on a host structure by the combination of experimental data and finite element model. The effects of the Non-Structural Elements will be determined by comparing the frequency response functions of the structure with and without their presence. The example of a simple structure of two degrees of freedom will be taken as a proof of concept.

1 Introduction

Aerospace structures are submitted to high amplitude vibrations during the different phases of their flights. Those structures are always composed of a host structure and of so-called Non-Structural Elements (NSEs) such as cable harnesses, that represent ten to thirty percent of the total mass of the structure [1]. It has been proven that those elements could significantly dampen the global structure [2, 3]. Indeed, the non thorough knowledge of the dynamic effects of the Non-Structural Elements, particularly on the high vibration amplitudes, might explain the observed and noteworthy differences between numerical models and experimental results. In some industrial applications like aerospace structures, the dynamic behavior of those elements has not been considered into the global model.

The study and development of a dynamic coupling model between the NSEs and the main structure could significantly improve the prediction of the global structure. The promising results could lead to a global mass reduction of the aerospace structure and therefore a reduction of the total costs.

Predictive models of NSEs based on geometrical and material aspects would be a too complex task to fully understand their dynamic influence on aerospace structures. A good alternative to face this problem is the extensive experimental characterization of the NSEs by their frequency response functions [1, 4–7]. However, such method is not appropriate for all types of NSEs. Indeed, some NSEs of launch vehicles are not necessarily accessible individually and it might be interesting to identify their models from experimental dynamic analysis of the global structure.

The present work aims at developing a suitable strategy to determine the dynamic model of NSEs based on the vibratory experimental tests available of the aerospace structure. For the identification procedure, the host structure is assumed well-known and modelled through a finite element model, to which the NSEs are coupled. The NSEs model identification is based on the evaluation of the experimental frequency response functions of the host structure with and without their presence. In order to illustrate this proposed method, a two degree of freedom (DoF) host structure is considered and the attached NSE is modeled by a one DoF system.

In section 2 will be presented a general strategy that allows to identify NSEs dynamic influence on a host structure. To illustrate this strategy, a simplified example of a two DoF system is given in section 3. Finally this paper is concluded by section 4.

2 NSEs Identification Strategy

2.1 Mechanical model

In order to identify the dynamic behavior of the NSEs coupled to a host structure, the system is subjected to a base harmonic excitation. During the experiment, several accelerometers are placed on different locations of the host structure and two set of frequency response functions (FRFs) are measured: the response of the host structure with the NSEs, and the one without them. The evaluation of these two set of measured FRFs allows to assess the influence of the NSEs and to identify their dynamic behavior.

For this purpose, let us consider that the host structure is well known and modeled using finite elements method to which the NSEs can be attached. The global system is submitted to a motion base excitation of amplitude $X_0(t)$ and is schematically represented in Figure 1. By assuming two cases where the NSEs are coupled and not coupled to the host structure, the equations of motions are readily written in the Fourier space as:

$$\left\{ \begin{array}{c} -\omega^2 \left(\mathbf{M} + \mathbf{M_{app}}\right) \left(\underline{X_0} + \underline{X_{w/}}\right) + j\omega\mathbf{C}\underline{X_{w/}} + \mathbf{K}\underline{X_{w/}} = \underline{0} \\ -\omega^2\mathbf{M} \left(\underline{X_0} + \underline{X_{w/o}}\right) + j\omega\mathbf{C}\underline{X_{w/o}} + \mathbf{K}\underline{X_{w/o}} = \underline{0} \end{array} \right. \tag{1}$$

with $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ representing the mass, stiffness and damping matrices of the host structure that can be determined using finite elements method. The vectors $\underline{X_{w/}}$ and $\underline{X_{w/o}}$ are, respectively, the relative complex displacement of the structure with and without the influence of the NSEs with respect to the motion base displacement vector of amplitude $\underline{X_0}$ and excitation frequency ω. $\mathbf{M_{app}}$ is the frequency-dependant apparent mass matrix representing the dynamic influence of the NSEs at their fixation points and modeled as a dynamic inertial load. The force applied by the NSEs at the interface point with the host structure can be readily computed as $\underline{F_{NSEs}} = -\omega^2\, \mathbf{M_{app}}\, (\underline{X_0} + \underline{X_{w/}})$.

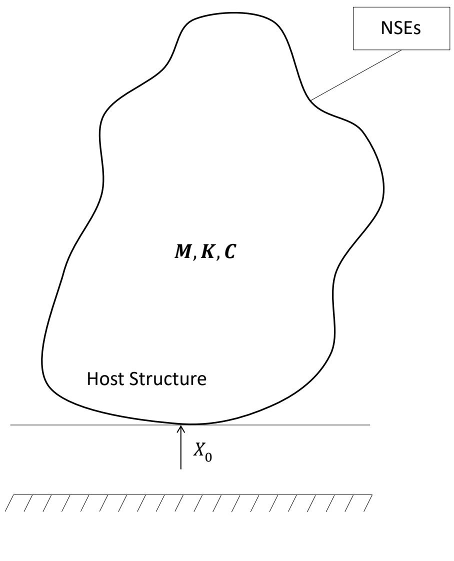

Figure 1: Diagram of a structure coupled to NSEs subjected to a base excitation

2.2 Apparent mass identification

It is important to remark, based on Equation 1, that he presence of NSEs on the host structure affects the way it will respond faced to external excitations. This interference is represented by the apparent mass response function $\mathbf{M_{app}}$. Somehow, the goal of the present paper is to identify the dynamic response of the NSEs based on the evaluation of those of the host structure obtained with and without the NSEs. Therefore, by substituting the second line of Equation 1 back into the first one, one obtains:

$$\left(-\omega^2\mathbf{M} + j\omega\mathbf{C} + \mathbf{K}\right)\frac{\underline{\Delta X}}{x_0} = \omega^2\mathbf{M_{app}}\left(\underline{\Sigma} + \frac{\underline{X_{w/}}}{x_0}\right) \tag{2}$$

with

$$\begin{cases} \underline{X_{w/}} = \underline{X_{w/o}} + \underline{\Delta X} \\ \underline{X_0} = \underline{\Sigma} x_0 \end{cases} \tag{3}$$

where $\underline{\Sigma}$ is the inertia force distribution vector provided by the base motion excitation which is composed of elements of value either 1 or 0. The value 1 is assigned to the degrees of freedom of the host structure which are affected by the motion base excitation. The value 0 is assigned elsewhere.

Thanks to the finite element analysis of the host structure, $\mathbf{M}, \mathbf{C}, \mathbf{K}$ and $\underline{\Sigma}$ are known. Moreover, the measurements of the host structure acceleration with and without the NSEs along with the known base excitation acceleration provided by an electro-dynamic shaker give the frequency response functions of the system. Therefore, the vectors $\frac{\underline{\Delta X}}{x_0}$ and $\frac{\underline{X_{w/}}}{x_0}$ are known at each measured point.

Finally, by combining the experimental data to the finite element analysis, the only unknown term is the apparent mass $\mathbf{M_{app}}$ that has to be identified. For this purpose, the Equation 2 can be written as:

$$\mathbf{A}\underline{X} = \underline{b} \tag{4}$$

where

$$\begin{cases} \mathbf{A} = \left(-\omega^2\mathbf{M} + j\omega\mathbf{C} + \mathbf{K}\right) \\ \underline{X} = \frac{\underline{\Delta X}}{x_0} \\ \underline{b} = \omega^2\mathbf{M_{app}}\left(\underline{\Sigma} + \frac{\underline{X_{w/}}}{x_0}\right) \end{cases} \tag{5}$$

The term $\mathbf{M_{app}}$ is considered identified if the variation of the frequency response function $\frac{\Delta X}{x_0}$ in Equation 4 fits the experimental data within a tolerance ε. The algorithm proposed is schematically represented in Figure 2.

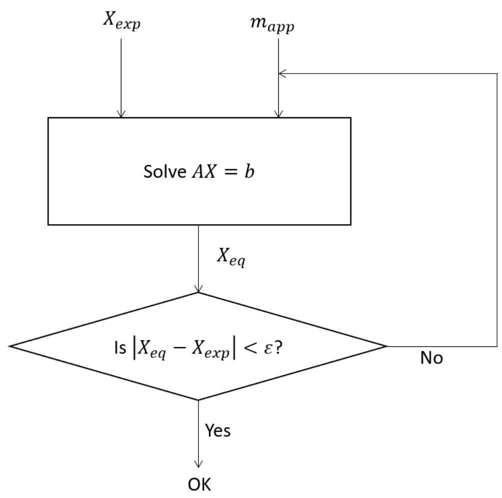

Figure 2: Algorithm for the identification of the apparent mass

3 Application to a two degree of freedom structure

For the present paper, a two degree of freedom host structure model as shown in Figure 3 is considered in which the NSE is supposed to be attached to the second mass M_2. The mass, stiffness and damping matrix $\mathbf{M}, \mathbf{K}$ and $\mathbf{C}$, as well as the mass apparent function matrix $\mathbf{M_{app}}$, can be readily obtained as follows:

$$\begin{array}{ll} \mathbf{M} = \begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix} & \mathbf{M_{app}} = \begin{bmatrix} 0 & 0 \\ 0 & m_{app} \end{bmatrix} \\ \mathbf{C} = \begin{bmatrix} C_1 + C_2 & -C_2 \\ -C_2 & C_2 \end{bmatrix} & \mathbf{K} = \begin{bmatrix} K_1 + K_2 & -K_2 \\ -K_2 & K_2 \end{bmatrix} \end{array} \tag{6}$$

with $\underline{X} = \begin{bmatrix} X_1 \\ X_2 \end{bmatrix}$

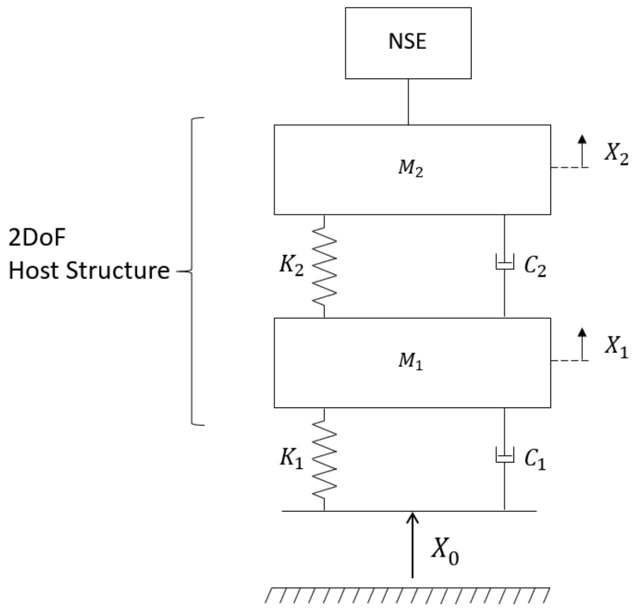

Figure 3: Diagram of a 2 DoF structure coupled to a NSE subjected to a base excitation

In order to simulate experimental data, arbitrary values for the parameters of the host structure will be considered. Among the different strategies to model the NSEs, the fuzzy model one [2, 8] is chosen in which an oscillatory system is considered with its frequency tuned to the host structure. The theoretical apparent mass function for a one DoF system is written as [2]:

$$m_{app}(\omega) = m\frac{k + j\omega c}{-\omega^2 m + j\omega c + k} \tag{7}$$

with m, c and k the mass, damping coefficient and stiffness of the theoretical NSE. The mass m is defined by a ratio of the whole mass of the structure.

3.1 Numerical Application

At this stage, the mechanical characteristics of the NSE are known in order to simulate the measured responses. Those measurements will be used afterwards to identify back the NSE. For the numerical example presented hereunder, the following parameters are taken: $M_1 = M_2 = 1\,\text{kg}$, $K_1 = K_2 = 40\,\text{N/m}$ and $C_1 = C_2 = 0.25\text{Ns/m}$. The mass of the NSE represents ten percent of the total mass, its natural frequency is tuned with the first resonance frequency of the host structure and its damping coefficient is assumed to be ten percent. In order to take into account the very likely presence of noise during a measurement, a proportional artificial noise of ten percent of the simulated response is added.

Figure 4 shows the frequency response functions (FRF) taken at the first and second mass of the host structure obtained with the simulated NSEs. As expected, the presence of the chosen NSE dampen the global response of the structure as it can be seen around the first mode of the host structure.

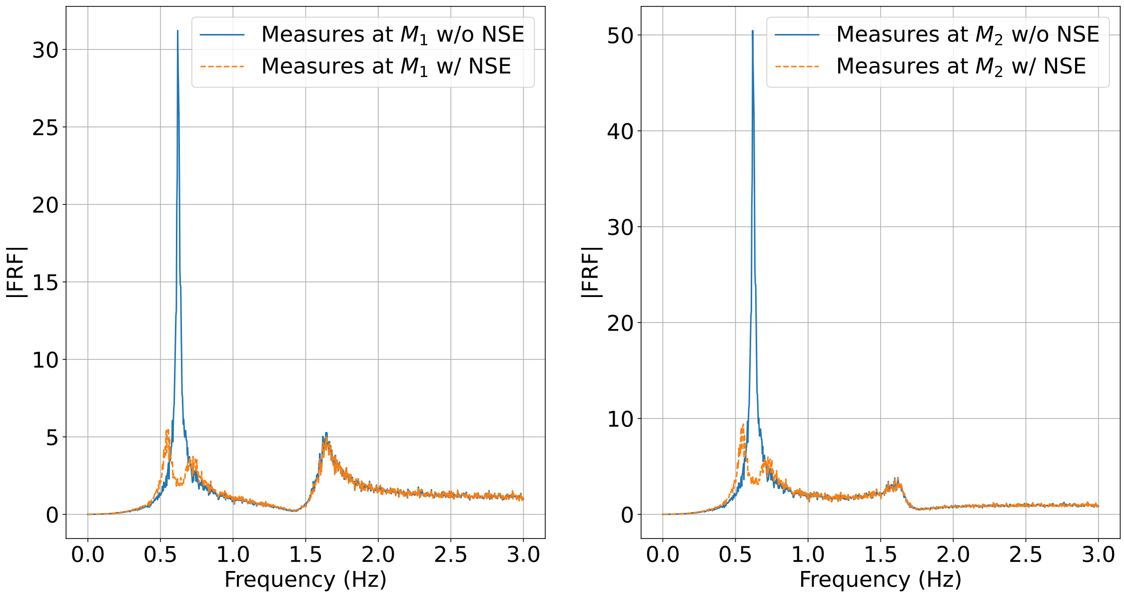

Figure 4: Frequency response functions measured at the mass M_1 and M_2 with and without the influence of the NSEs located on M_2

3.2 NSE Identification

The aim of this section is to determine the apparent mass function m_{app} of the NSEs based on the simulated frequency response functions of the global system, accordingly to algorithm proposed in Figure 2 with the help of Equation 4. This procedure is repeated for each frequency step in the measured frequency response function. It is important to stress that the finite element model of the host structure is assumed known.

The apparent mass of the NSE obtained with the proposed identification strategy is shown in Figure 5 and compared with the simulated function.

Here, it is interesting to note how accurate the prediction of the apparent mass function of the NSE is. Indeed, Figure 5 shows that the prediction and the theoretical function assumed of the apparent mass are very similar.

Putting the identified apparent mass back in Equation 1, one can plot the predicted frequency response function of the system with the NSE. Figure 6 shows the results.

It is interesting to see that this method allows to obtain very good results since the FRFs of the coupled system obtained experimentally and obtained using the above presented method closely fit.

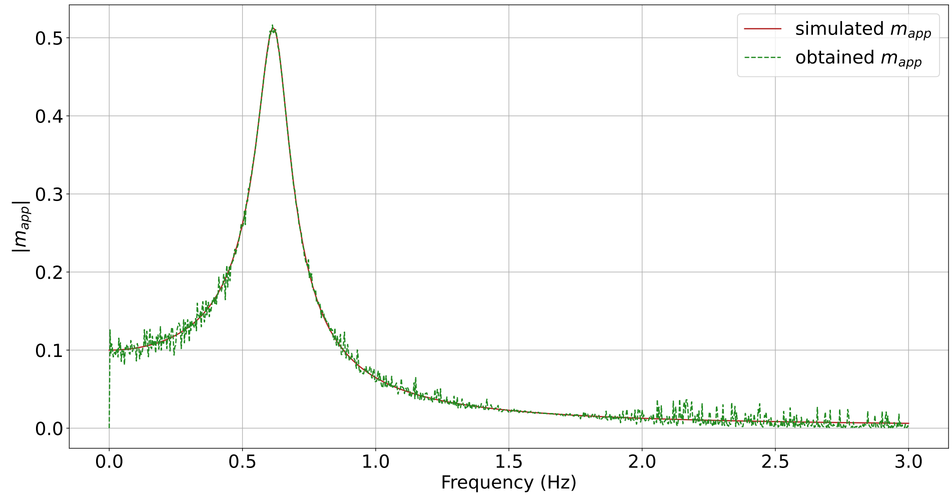

Figure 5: Identified apparent mass function compared to the theoretical function

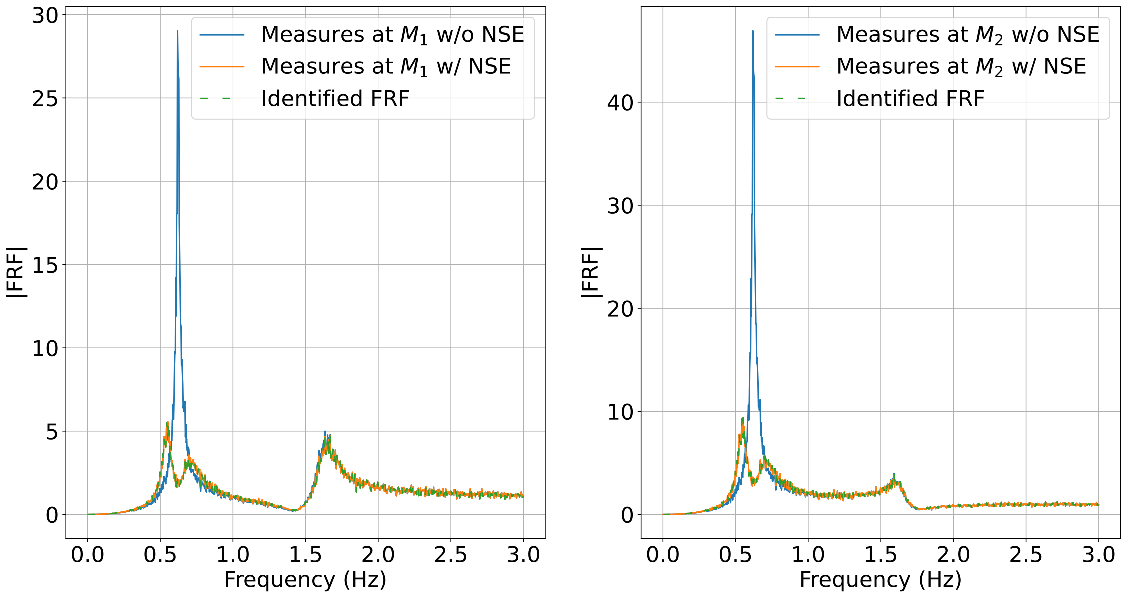

Figure 6: Comparison between the measured FRFs obtained at the mass M_1 and M_2 and the predicted FRF computed using the identified mass apparent function

4 Conclusion and Perspectives

In this paper is developed a strategy to identify the dynamic influence of non-structural elements (NSEs) based on dynamic experimental tests and finite elements analysis. This method was illustrated using a simple two degrees of freedom structure example.

The strategy presented here is capable of accurately predict the influence of unknowns NSEs on the dynamic behavior of the global structure using the comparison between the experimental data of the frequency response functions of the structure with and without their presence.

This work presents the considered methodology for influence identification and an illustration of the method for a simple two DoF host structure. In the future, this strategy should be applied to the results from a set of experiments on a more complex structure with unknown NSEs whose dynamic behavior would have to be determined. Moreover, the experimental study should be done for different base excitation amplitudes in order to highlight potential nonlinear effects.

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Appendix

A Nomenclature

$\mathbf{C}$	stiffness matrix of the host structure
$\mathbf{K}$	damping matrix of the host structure
$\mathbf{M}$	mass matrix of the host structure
$\mathbf{M_{app}}$	apparent mass matrix of the NSE
$\underline{X_0}$	position vector of the base excitation
$\underline{X_{w/}}$	position vector of the host structure with the NSEs
$\underline{X_{w/o}}$	position vector of the host structure without the NSEs
$\underline{\Delta X}$	difference position vector
$\underline{\Sigma}$	inertia force distribution
ω	frequency of excitation

B Abbreviation

DoF	Degree of Freedom
FRF	Frequency Response Function
NSE	Non-Structural Element