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An efficient modeling methodology of structural systems containing viscoelastic dampers based on frequency response function substructuring

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ABSTRACT

In this paper it is suggested a modeling methodology of structural systems supported by translational and rotational viscoelastic mounts or joints based on a frequency response function coupling technique. Such strategy enables to predict the dynamic behaviour of the composite systems given a set of frequency response functions of the main structure and a driving point frequency response function of the viscoelastic support. These frequency response functions can be obtained either experimentally or by finite element modeling. Both cases are considered in the study. After presenting the underlying theoretical aspects, the results of numerical simulations of two-dimensional structures are presented, emphasizing the procedure conceived to compute the frequency response functions of the viscoelastic mounts or joints from a detailed finite element model using commercial packages and material properties provided by manufacturers. The dependency of the viscoelastic behaviour on frequency and temperature is accounted for by using the complex modulus approach and the concepts of reduced frequency and shift factor. An investigation using experimentally acquired frequency response functions of a frame structure with a translational viscoelastic damper is presented. Based on the obtained results, the main features of the modeling methodology are highlighted.

1. Introduction

In the context of passive control of mechanical vibrations of complex engineering systems such as automobiles, airplanes, civil structures and space structures, viscoelastic materials have long been used. Much of the knowledge available to date is compiled in books by Nashif et al. [1] and Mead [2] as well as in review papers [3,4].

As compared to other control strategies, passive techniques based on viscoelastic materials present some important advantages such as inherent stability, effectiveness in broad frequency bands and moderate development and maintenance costs [5]. However, some drawbacks must be dealt with, such as ageing and chemical instability in the presence of some substances. Moreover, the minimization of the mass added by the viscoelastic material is often an engineering concern.

The incorporation of the viscoelastic behaviour into finite element (FE) models and the numerical resolution of the resulting equations of motion are particularly relevant aspects of the modeling procedures since for viscoelastic structures

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the stiffness matrix is frequency dependent. Besides the traditional complex modulus approach and other standard rheological models [1,2], other models intended to represent the dynamic behaviour of viscoelastic materials have been developed, such as the Golla–Hughes–McTavish (GHM) [6], anelastic displacement field (ADF) [7], and models based on fractional derivatives [8]. The three latter are adequate for frequency response, eigenvalue and time response analyses, at the expense of a large increase in the dimension of the FE models.

In this paper, discrete viscoelastic dampers, which are believed to be more adequate for large structural systems, such as civil engineering structures, are considered. Based on the complex modulus approach and a substructuring procedure based on frequency response functions [9–11], it is suggested a method enabling to evaluate the dynamic behaviour of structural systems supported by viscoelastic mounts or joints. According to this approach, the frequency response functions of the combined system (main structure+viscoelastic mount) are computed from the frequency response functions of each component, considered independently. One interesting feature of this technique is that the necessary frequency response functions can be obtained either from experiments or from numerical modeling, which also enables hybrid numerical–experimental modeling. Moreover, since the viscoelastic behaviour is assumed to be confined to the mount or joint, the separate computation of the frequency response functions of the two components makes the method very cost-effective from the computational standpoint.

To illustrate the effectiveness and the main features of the suggested technique, numerical simulations and experimental tests were performed in which viscoelastic mounts were used to reduce the vibration levels of frame like-structures. To enable to apply the modeling strategy to viscoelastic devices of complex geometries, particular emphasis is given to the use of commercial FE software for computing the frequency response functions of those devices.

2. The complex modulus approach. Influence of temperature

According to the linear theory of viscoelasticity, the one-dimensional stress–strain relation can be expressed in frequency domain as follows [12]:

$$\sigma(\omega) = G(\omega)\varepsilon(\omega), \tag{1}$$

where

$$G(\omega) = G'(\omega) + iG''(\omega) = G'(\omega)(1 + i\eta(\omega)), \tag{2}$$

with

$$\eta(\omega) = G''(\omega)/G'(\omega). \tag{3}$$

In the equations above, $G'(\omega)$, $G''(\omega)$ and $\eta(\omega)$ are defined, respectively, as *storage modulus*, *loss modulus* and *loss factor* of the viscoelastic material. Any pair formed from these three parameters completely characterizes the dynamic behaviour of viscoelastic materials in the frequency domain. This model is adopted in the study reported herein since it enables the direct use of the data commonly provided by the manufacturers of viscoelastic materials in terms of storage modulus and loss modulus versus frequency, or storage modulus and loss factor versus frequency.

According to Nashif et al. [1], the influence of temperature can be accounted for by making use of the so-called *Frequency–Temperature Superposition Principle*, also known as *Williams, Landell and Ferry* (*WLF*) *Principle*, which establishes a relation between the effects of the excitation frequency and temperature on the properties of thermorheologically simple viscoelastic materials. This implies that the viscoelastic characteristics at different temperatures can be related to each other by changes (or shifts) in the actual values of the excitation frequency. This leads to the concepts of *shift factor* and *reduced frequency*. Symbolically, the Frequency–Temperature Superposition Principle can be expressed as

$$G'(\omega, T) = G'(\omega_r, T_0) = G'(\alpha_T\omega, T_0), \tag{4a}$$

$$G''(\omega, T) = G''(\omega_r, T_0) = G''(\alpha_T\omega, T_0), \tag{4b}$$

$$\eta(\omega, T) = \eta(\omega_r, T_0) = \eta(\alpha_T\omega, T_0), \tag{4c}$$

where T is an arbitrary value of the temperature, T_0 is a reference value of temperature, $\omega_r = \alpha_T(T)\omega$ is the reduced frequency, ω is the actual frequency, and $\alpha_T(T)$ is the *shift* function. Functions $G(\omega_r)$ and $\alpha_T(T)$ can be obtained from experimental tests for specific viscoelastic materials [1,2]. Drake and Soovere [13] suggest analytical expressions for the complex modulus and shift factor for various commercially available viscoelastic materials. The following equations represent, respectively, the complex modulus and shift factor as functions of temperature and reduced frequency for the 3 M ISD112$^{\text{TM}}$ viscoelastic material [14] (which is considered in the numerical applications that follow), as provided by those authors:

$$G(\omega_r) = 430,700 + \frac{1200 \times 10^6}{1 + 3.241 \times (i\omega_r/154,300)^{-0.18} + (i\omega_r/154,300)^{-0.6847}}, \tag{5}$$