Journal of Sound and Vibration 333 (2014) 4051–4070

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Correlation of finite element models of multi-physics systems

K.K. Sairajan *, G.S. Aglietti, Scott J.I. Walker

Astronautics Research Group, University of Southampton, Southampton SO17 1BJ, United Kingdom

ARTICLE INFO

Article history:
Received 12 September 2013
Received in revised form
31 March 2014
Accepted 3 April 2014
Handling Editor: H. Ouyang
Available online 9 May 2014

ABSTRACT

The modal assurance criterion (MAC) and normalized cross-orthogonality (NCO) check are widely used to assess the correlation between the experimentally determined modes and the finite element model (FEM) predictions of mechanical systems. Here, their effectiveness in the correlation of FEM of two types of multi-physics systems, namely, viscoelastic damped systems and a shunted piezoelectric system are investigated using the dynamic characteristics obtained from a nominal FEM, that are considered as the 'true' or experimental characteristics and those obtained from the inaccurate FEMs. The usefulness of the MAC and NCO check in the prediction of the overall loss factor of the viscoelastic damped system, which is an important design tool for such systems, is assessed and it is observed that these correlation methods fail to properly predict the damping characteristics, along with the responses under base excitation. Hence, base force assurance criterion (BFAC) is applied by comparing the 'true' dynamic force at the base and inaccurate FEM predicted force such that the criterion can indicate the possible error in the acceleration and loss factor. The effect of temperature as an uncertainty on the MAC and NCO check is also studied using two viscoelastic systems. The usefulness of MAC for the correlation of a second multi-physics FEM that consists of a shunted piezoelectric damped system is also analyzed under harmonic excitation. It has been observed that MAC has limited use in the correlation and hence, a new correlation method – current assurance criterion – based on the electric current is introduced and it is demonstrated that this criterion correlates the dynamic characteristics of the piezoelectric system better than the MAC.

1. Introduction

Traditionally in the field of spacecraft structures, we deal with purely mechanical systems/models. However, to control the dynamics of the structure using active/passive methods or to enhance the structural performance of aerospace systems, the analysis of multi-physics models becomes necessary. A method to assess the accuracy of such models is vital to improve the analytical predictions and the widespread use of the modeling techniques. Here, two types of widely employed multi-physics systems, namely, viscoelastic damped system and an electric circuit-fed piezoelectric system under base excitation are considered. Base excitation is generally used to qualify a structure for aerospace applications and the results can be used to verify the design margins and to update the FEMs [1]. Although a number of FEM correlation methods such as the MAC [2], NCO check [3], COMAC [4] and FRAC [5] are available for conventional structures, a specific correlation method for multi-physics system has not been reported. Moreover, these subsystems are developed independently and sometimes

* Corresponding author. Present address: ISRO Satellite Centre, Vimanapura, Bangalore 560017, India. Tel.: +91 80 25083672.
E-mail address: kk_sairaj@yahoo.com (K.K. Sairajan).

http://dx.doi.org/10.1016/j.jsv.2014.04.010
0022-460X/© 2014 Elsevier Ltd. All rights reserved.

supplied by an external organization. A specific correlation method for the subsystems will help to suitably assess the system before it is integrated into the main structure. Here, the correlations of FEMs of viscoelastic and shunted systems are assessed using common and simple configurations. However, the concept can be adapted to more complex systems.

Viscoelastic materials have been effectively used to reduce the vibration response of light weight structures such as spacecraft, reaction wheel assemblies, and airplane fuselages [6]. These materials can also be used to increase the damping in plates and sandwich structure and this passive damping method is easy to implement and more economical than active damping techniques [7]. For example, in spacecraft structure, thin aluminium plates embedded with viscoelastic materials can be used to mount small antennae such as telemetry and tele-command patch antennae or micro strip antennae. Honeycomb sandwich panels have widespread use in aerospace structures to form equipment mounting decks and solar panels. These panels are generally larger in dimension than the thin plates mentioned previously along with higher load bearing capability. The capability of viscoelastic material to exhibit properties of both a viscous fluid and an elastic solid is effectively used to absorb the vibration energy and thereby reduce the structural responses. The amount of viscous or elastic behavior depends primarily on the temperature of the system and the frequency or the rate of loading. The effectiveness of the damping of such systems is generally assessed using the modal loss factor of a specified mode of interest. A modal loss factor is the ratio of the total energy dissipated per cycle to the maximum amount of energy stored during the cycle [8].

The accurate determination of the loss factor is an important step in the design of damped structural systems using viscoelastic material. The pioneering work to determine the loss factor of assemblies consisting of viscoelastic elements using an energy method was performed by Ungar and Kerwin [9]. FEMs have been effectively utilized to analyze the viscoelastic damping in practical systems by many researchers [6,10–12]. Among these methods, the modal strain energy (MSE) [11] method is widely used to determine the loss factor of constrained viscoelastic systems using a commercial finite element program. Here, the MSE method is used to determine the loss factor of two viscoelastic damped systems, namely, a simply supported sandwich plate and a honeycomb sandwich panel constrained at the hold down locations. The first model, Configuration A, simulates a small antenna support structure whereas the second model, Configuration B, simulates the solar panel of a spacecraft along with the hold down locations that are used to assemble the panel to the spacecraft during launch.

The second type of subsystem considered in this study consists of a piezoelectric patch connected with an electric shunt circuit and then bonded to the host structure for vibration damping [13–15]. This system is identified as Configuration C. The relevance of these assemblies is that they are mainly used to control the dynamics of the system in which they are embedded. The electro-elastic systems have been analyzed by different researchers [16–18] and Tzou and Ye [19] used the variational principle to define the piezo-thermoelastic finite elements. The FEM which consists of structural and non-structural dofs (coupled FEM) has been effectively used for the analysis of piezoelectric systems [20–23] and a commercially available software such as ANSYS [24] provides a convenient way to model more complex and practical systems.

The MAC and NCO check are the most commonly employed correlation tools for validating the conventional structural FEMs [25,26]. In this work, the usefulness of these standard methods to correlate the FEMs of the viscoelastic systems is assessed by studying the relationship between the analytical prediction of modal loss factor and these correlation indices. Two different systems are analyzed to consider the various modeling inaccuracies such as boundary conditions, material properties, and hinge stiffness (in the honeycomb sandwich panel). The characteristics of the system determined from the original/nominal FEMs are considered as the experimental or ‘true’ parameters and those obtained by FEMs with modeling inaccuracies are considered as analytical parameters. The effect of damping on the MAC is analyzed using the complex modes of the system. The recently introduced base force assurance criterion (BFAC) [27] is applied to correlate the viscoelastic systems. Also the effect of temperature on the MAC and NCO is studied using the viscoelastic systems. In addition, the usefulness of the MAC for the correlation of a FEM of a piezoelectric system connected with a shunt electric circuit is analyzed whilst it is subjected to harmonic excitation. A new correlation method called the current assurance criterion (CAC) is defined using the frequency-dependent current in the electric circuit to correlate the shunted piezoelectric system.

2. Theoretical background

2.1. Determination of the loss factor for structural system

The modal loss factor for the constrained layer damping system can be calculated using the undamped modes and the material loss factor for each constituent material [11]. In the constrained layer damped system, viscoelastic layers are placed between the stiff face sheets. Generally, the face sheet material will have an exceedingly low loss factor compared with the viscoelastic core. Hence, the modal loss factor η^r for each mode r is approximated as [11]

$$\eta^r = \eta_v \left(\frac{V_v^r}{V_T^r} \right) \tag{1}$$

where η_v denotes the loss factor of the core at the resonance frequency of mode r, V_v^r and V_T^r are the elastic strain energy of the viscoelastic material alone and the strain energy of the total system during the mode r. Generally, the ratio, η^r/η_v, can be directly obtained from the FEM results as the ratio of the modal strain energy of the core to the total elastic strain energy. In this study, 3M viscoelastic materials are considered for the damping layers and η_v is taken as 1.0 at 30 °C for the core in the desired frequency range [28]. Although this modal strain energy method computes the loss factor from the undamped