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Analytically driven experimental characterisation of damping in viscoelastic materials

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ABSTRACT

The damping assessment of highly dissipative materials is a challenging task that has been addressed by several researchers; in particular Oberst defined a standard method to address the issue. Experimental tests are often hindered by the poor mechanical properties of most viscoelastic materials; these characteristics make experimental activities using pure viscoelastic specimens prone to nonlinear phenomena. In this paper, a mixed predictive/experimental methodology is developed to determine the frequency behaviour of the complex modulus of such materials. The loss factor of hybrid sandwich specimens, composed of two aluminium layers separated by the damping material, is determined by experimental modal identification. Finite element models and a reversed application of the modal strain energy technique are then used to recover the searched storage modulus and loss factor curves of rubber. In particular, the experimental setup was studied by comparing the solutions adopted with the guidelines given in ASTM-E756-05. An exhaustive validation of the values obtained is then reported.

1. Introduction

Noise and vibration control is a relevant design requirement in several industries, such as aerospace and automotive, the reduction of these two phenomena being a major criterion for achieving customer satisfaction [9,22,30]. Passive damping technology often uses viscoelastic materials to decrease the vibratory level transmitted and noise field generated. Because of the peculiar properties of these materials, the mechanical energy is transformed into heat and subsequently dissipated. Used since the 1950s, traditional treatments envisage the deposition of a ply of damping material on the interested surface (free layer damping, or FLD). The main concept of this intervention is that the shear strain acting in the viscoelastic layer stores some energy that is drained from vibrations. Improvements in damping have been achieved with the introduction of a conveniently designed constraining lamina at the free surface (constrained layer damping, or CLD). This configuration results in higher performances with relatively small penalties in weight. There is an extensive body of literature on methods suitable for predicting the intrinsic properties of beams and panels treated in these ways, and the results of their use in fundamental studies and actual applications have been published since the end of the 1950s [5,18–20,25,27,36]. An exhaustive survey of these prediction methods is presented in [32]. Several applications of viscoelastic damping for noise control in the automotive and aircraft fields are presented in [26]. More recent papers approach the same problem using the Finite Element (FE) method [1,17,24,35].

In terms of actual applications, the constrained layers are mainly observed as an a posteriori intervention needed to fulfil noise requirements not satisfied by the bare structure. Even if these methodologies can generate suboptimal solutions in terms of vibration-performance-over-weight ratios, the separation between dissipative and structural functions has the advantage of not affecting the standard design process. Either analytical or finite element methods can be used to satisfy structural integrity requirements, and the presence of dissipative treatments can be neglected when discussing such requirements.

The growing use of such dissipation mechanisms has motivated many authors to study a deeper integration of viscoelastic layers (integrated layer damping, or ILD) into the structural panel at the expense of simplicity. The concept of damped structures composed of metal–viscoelastic or composite–viscoelastic sandwiches allows for an improvement in the vibro-acoustic behaviour even if the drawbacks in terms of structural efficiency are still not obvious [2,4,11].

Regardless of the treatment type (free, constrained or interleaved layer damping) and the predictive method employed

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(e.g., Ross–Kerwin–Ungar formulation, modal strain energy, frequency response derived from finite element model), reliable information about the constitutive laws of the viscoelastic material must be acquired. This requirement is typically satisfied by measuring the complex modulus, namely, the frequency behaviour of the shear modulus $G(f)$ and loss factor $\eta(f)$.

This task is often taken for granted in many works, e.g., [13] and [10]. However, this task actually represents a challenge from an operative perspective because of the large number of factors that influence the characteristics of rubbers, e.g., temperature, strain level, speed of load application, and pre-stress state. In [6], the presence of nonlinear effects is outlined and confirmed based on experimental observations. In [3], the Golla–Hughes method is applied to develop a finite element model suitable for identifying a model in the time domain with application to a low-frequency range. In [33], an experimental setup suitable for dynamic tests is presented. However, problems are generally magnified at the high frequencies typically involved in noise applications; the setup and operation of such experimental rigs tend to become more difficult as the upper frequency bound increases.

The properties of a VEM can also be characterised directly in a relatively low frequency range. The temperature-frequency equivalence is then employed to project data into a higher frequency range. However, this approach, based on the classical theory for Dynamic Mechanical Thermal Analysis (DMTA), is not of general validity, e.g., it is not applicable in the case of blended materials [37].

In the present study, the properties of a Styrene Butadiene Rubber were evaluated at relatively high frequencies of up to 2500 Hz, which cover typical helicopter applications.

The cantilever beam method, typically based on the Oberst method [23], was used but linked to other techniques to overcome the previously mentioned theoretical limitations of the DMTA approach; this approach has also been used by other researchers, e.g., [24]. The ASTM E756-05 document [7] describes a number of guidelines for the reliable experimental characterisation of viscoelastic materials. One guideline suggests size ratios of a metal/viscoelastic/metal sandwich specimen: for a typical specimen the length should be approximately 250 mm, the width approximately 10 mm and the metal layer thickness approximately 10 times that of the viscoelastic one, approximately a few millimetres. With these dimensions, the presence of few bending modes suitable for experimental identification below 3000 Hz can be easily verified, as later discussed in Section 3. This fact could make it difficult to obtain a reliable frequency-dependent regressive model in the band of interest. Furthermore, the advised thickness ratio could vary considerably for typical applications, thus possibly introducing discrepancies in the actual strain level acting in the dissipative ply as well as nonlinear effects. In contrast, the use of thinner metallic layers makes the experiment prone to other effects, namely, mode shapes different from bending, the coupling of bending deflection with twists, modes straining the cross section in the transversal direction and modes with longitudinal bending waves. In these cases, the data processing conceived assuming a pure bending deflection cannot be easily applied. The path presented in other studies based on a mixed approach, e.g., [16], was retraced by using correlation techniques to identify the shear modulus but working only with experimentally identified modal data reliably correlated to finite element models. Furthermore, the Modal Strain Energy approach, based on finite element models, is used to determine the material loss factor. A free-specimen geometry was assumed to allow for the use of metal/viscoelastic/metal sandwich size ratios close to the application at hand, and the effects of the eigenvector shapes were accounted for by utilising a finite element model and a correlation procedure widely used in experimental modal analysis. A section of the paper is devoted to the presentation and discussion of results and issues concerning such procedures. Two of the specimens available from a previous study were used to perform the identification procedure. Additional test data related to other layouts were used to confirm the correctness and reliability of the identified data under different conditions.

2. Method for estimating properties of a viscoelastic material

Viscoelastic materials exhibit a combination of viscous and elastic behaviours, with the relative contributions being dependent mainly on the temperature and frequency, or strain rate. This effect introduces a delay between the input strain and output stress at a given frequency. A simplified frequency modellisation is often assumed to account for such a delay: the frequency description of the viscoelastic behaviour is based on the elastic/viscoelastic equivalence principle. It is also possible to formulate viscoelasticity problems in the framework of elasticity theory with complex Young's and shear moduli depending on the frequency [9,22,30]. Because viscoelastic materials are mainly used in shear strain conditions, the relevant stress–strain law suitable to characterise the hysteretic damping can be reduced to the complex shear modulus $G^*(f)$. The storage and shear loss moduli G' and G'', respectively, are introduced in terms of real and imaginary parts as follows:

$$G^*(f) = G'(f) + iG''(f) = G'(f)\big[1 + i\eta(f)\big] \tag{1}$$

The relation between the shear loss factor and modal damping is useful for identifying this modellisation with the modal experimental results:

$$2 \cdot \zeta(f) = \eta(f) = \frac{G''(f)}{G'(f)} \tag{2}$$

However, a fully three-dimensional stress–strain law can be developed by simply assuming Poisson's ratio not frequency dependent [14]. An inverse procedure can be adopted to establish the viscoelastic properties assuming that a suitable set of pairs resonance frequency-loss factors are available from the experimental data for hybrid specimens related to metal/rubber stacking.

2.1. Estimation of the shear modulus

Two methods are available for determining $G'(f)$. The first method, which is purely analytical, is based on the theory of De Saint Venant and is described in [7]. The main advantage of this simplified technique is the short time needed to obtain the curve; however, this technique also has several potential drawbacks, such as the requirement to use only bending modes to define the frequency behaviour or the hypothesis that layers remain straight along the width, a questionable assumption at high frequencies.

The second method is based on the identification of mechanical properties using a classical correlation process; a real eigenvalue analysis of a detailed finite element model linked to an optimisation process to match experimental data: assuming known data for the constraint layer materials, the shear modulus of the dissipative material is modified until the frequency of the desired mode matches the experimental value.

The last technique was deemed more suitable for this work despite its longer time requirement because it guarantees a deeper insight into the dynamic behaviour of the specimen. The elastic property (E) of the viscoelastic material is identified at the modal frequencies by matching the measured frequency with the corresponding finite element frequencies.

The value of G' is updated based on the formula

$$G'(f) = \frac{1}{2(1+\nu)} E'(f) \tag{3}$$