A STUDY OF SELF-HEATING EFFECTS IN VISCOELASTIC DAMPING DEVICES

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Abstract. It is well-known that applying cyclic loading on a structure results in vibrations whose level depends both on the excitation and the structure's mechanical properties. In this context, passive structural damping using viscoelastic polymers and elastomers has lead to various studies and practical applications over the last decades. The energy dissipated by the viscoelastic dampers is converted into a small amount of heat. When subjected to cyclic loading, this heat may cause significant temperature rise. Taking into account the fact that the components of the complex modulus (respectively known as storage and loss moduli) are highly temperature-dependent, the evolution of the temperature field can result in two distinct phenomena, namely: a) the thermal equilibrium, which occurs after a large number of cycles if the influence of the reached temperature field on the mechanical properties is small enough. In this configuration, since the pseudo-equilibrium is reached, the temperature gradually increases at a very small rate until the load is removed b) the "thermal runaway" described by Lesieutre and Govindswamy happens when the heat generation is large enough to cause chemical reactions which makes the material less rigid and may result into irreversible degradation of the structure. The main objective of this paper is to present the results obtained with a finite-element tool based on a commercial software in order to calculate the transient temperature distribution into a tridimensionnal viscoelastic structure subjected to a harmonic loading. This procedure involves a coupling between thermal and structural fields since the heat generation calculations at every time step is based on the strain energy values in the viscoelastic parts, determined by harmonic damped structural analyses. Moreover, since the temperature distribution is non-uniform and time-dependent, it is necessary to update the structural stiffness and damping matrices and thus perform a new harmonic analysis. This step is repeated at various stages of the global analysis.

After giving a general overview of the theoretical aspects, the detailed procedure is discussed in terms of physical and computational aspects. Afterwards, the FE modelling strategy applied to a 3D structure is presented. Finally, the results are discussed and compared to those obtained from previous simulations.

Keywords: dynamics, viscoelastic damping, finite element, thermoviscoelasticity

1. INTRODUCTION

Viscoelastic materials (VEM) have been used in several industrial application related to vibration damping, because of their ability to dissipate a significant part of the mechanical strain energy and thus soften the dynamic response level of the structure in which they are integrated. Viscoelastic behaviour is a consequence of the chemical structure of the VEM. In the case of viscoelastic polymers, friction mechanisms between the chains causes the dissipation of a part of the total mechanical strain energy. A fraction of this dissipated energy is converted into heat, which results in local temperature increases inside the VEM. In most cases, the complex Young’s modulus, which is used to describe the mechanical behaviour of the VEM both in terms of elastic response and damping, is highly temperature and frequency-dependent. As a consequence, self-heating effects caused by viscoelastic dissipation may turn the VEM softer and loosen its damping ability; the fact that such physical phenomena are eager to alterate the damper’s performances turns necessary the use of a predictive model to evaluate the transient self-heating of a viscoelastically damped structure in response to harmonic loading. Since the heat source field values is calculated from the strain energies, the problem must be solved by a two-way coupled-field analysis involving both structural harmonic and thermal transient responses. Gopalakrishna and Lai (1998) presented an iterative methodology to determine the equilibrium temperature field inside a translational joint. More recently, Merlette (2005) developed a simplified, 4 degrees of freedom thermomechanical model whose results were relatively close to those of experiments performed on simple shear translational joints. A previous work was done in which the thermomechanical behaviour of a simplified 2-D torsional damper was simulated with a FE tool based on the commercial software ANSYS (Cazenove, Lima and Rade, 2009). In this paper, the same algorithm is applied to a more
2. THERMOMECHANICAL MODELLING PROCESS

2.1 The complex modulus approach

In the case of dynamic solicitations, the linear viscoelastic behaviour of most VEM can be represented by the complex Young’s modulus, as described by Nashif (1985). The complex modulus is the direct Fourier transform of the relaxation function which describes the viscoelastic response of the VEM in time domain. As a consequence, it depends on the frequency. According to the properties of most VEM, various other factor affect the complex modulus values, in which the temperature is considered to be the most influent.

\[ E^*(\omega, T) = E'(\omega, T) + iE''(\omega, T) = E'(\omega, T) [1 + \eta(\omega, T)] \] (1)

In Eq. (1), \( E'(\omega) \) and \( E''(\omega) \) are known as storage and loss moduli, and represent respectively the elastic response and viscous dissipation of the VEM when submitted to a dynamic load. The storage modulus can be factored out to introduce the loss factor \( \eta(\omega) = \frac{E''(\omega)}{E'(\omega)} \) which represents the ratio between the stored energy and the dissipated energy for each vibration cycle (Merlette, 2005). When introduced into a finite element model, the complex modulus results into a complex, temperature-dependent and frequency-dependent stiffness matrix which can be decomposed into its real and imaginary components, which are assumed to represent respectively the stiffness and hysteretic damping matrices of the system. Therefore, the general equation of dynamics has the following form:

\[ (-\omega^2[M] + [K(\omega, T)] + i[H(\omega, T)]) \{x\} = \{f\} \] (2)

Alternatively, it is possible to express the damping matrix in the equation of motion using conventional viscous damping model. This is done by defining an equivalent viscous damping matrix \([C_{eq}(\omega, T)] \) so that Eq. 2 becomes:

\[ (-\omega^2[M] + i\omega[C_{eq}(\omega, T)] + [K(\omega, T)]) \{x\} = \{f\} \] (3)

2.2 Heat source

The amount of dissipated energy at time \( t \) can be expressed from the damping force vector \( f_d(t) \):

\[ \{f_d(t)\} = [C_{eq}(\omega, T)] \{\dot{x}(t)\} \] (4)

From Eq (4) it can be deduced the mechanical power dissipated by damping effects:

\[ \dot{W}_d = \{\dot{x}\}^T [f_d(t)] = \{\dot{x}\}^T [C_{eq}(\omega, T)] \{\dot{x}(t)\} \] (5)

From this dissipated power, only a part is converted into heat while the other part is asabsorbed by material microstructural changes. As shown by Rittel (2000), it can be assumed that the ratio of generated heat per time unit to the total dissipated power can be represented by the thermal dissipation fraction \( \beta \):

\[ \dot{W}_{th} = \beta \dot{W}_d = \beta \{\dot{x}(t)\}^T [C_{eq}(\omega, T)] \{\dot{x}(t)\} \] (6)

Most \( \beta \) values for VEM are comprised between 0.1 and 1. The \( \beta \) parameter is considered to depend both on the frequency and the deformation amplitudes. In the case of harmonic excitation, the heat source per time unit becomes:

\[ \dot{W}_{th} = -\beta \omega^2 \{x\}^T [C_{eq}(\omega, T)] \{x\} \] (7)

Equation (7) gives the expression of the heat source to be input into the transient thermal calculations. Using element matrices, this quantity can be calculated for each viscoelastic element depending on the angular frequency \( \omega \) of the excitation, on the displacement response to the harmonic loading \( \{x\} \) and on the element temperature. However, when using commercial FE codes it is often difficult to access element matrices. This issue can be solved by substituting the element damping matrix in Eq. (7):

\[ [C_{eq}(\omega, T)] = \frac{1}{\omega} [H(\omega, T)] + \frac{\eta(\omega, T)}{\omega} [K(\omega, T)] \] (8)

This assumption is valid since the VEM is considered to be isotropic and the Poisson ratio is frequency-independent, which enables to factor out the loss factor from the expression of the equivalent damping matrix, which can now be substituted according to Eq.(8). We have for element \( i \):

\[ \dot{W}_{thi} = -\beta \omega \eta(\omega, T) \{x(t)\}^T (\{K(\omega, T)\}_i) \{x(t)\}_i, \] (9)
\{x(t)\}_{i}^{T} (\{K_\omega, T\}_{i}) \{x(t)\}_{i} \text{ is the strain energy multiplied by 2 for element } i \text{ and can easily be obtained from the harmonic structural solution at each step of the analysis. Afterwards, the element heat source per time unit can be calculated according to the loss factor corresponding to the element temperature and the chosen value for the thermal dissipation fraction } \beta \text{, according to the material, the frequency of the analysis and the stress-strain rate.}

### 2.3 Iterative process

The heat source per time unit for each element is calculated from the strain energy resulting of harmonic loading and the loss factor evaluated at the corresponding element temperature. Since the structural hysteretic damping and stiffness matrices depend on the temperature field, they have to be updated according to the transient thermal analysis results. Therefore it is necessary to implement an iterative process in which, for a given } \Delta t \text{ time increment, a structural solution is performed, afterwards strain energies are computed to evaluate the corresponding element heat sources and then obtain the temperature field at } t + \Delta t. \text{ Subsequently the structural matrices are updated. Figure (1) shows the flowchart associated to this iterative solution, which has been implemented using the ANSYS parametric language APDL.}

![Flowchart](image.png)

**Figure 1. Iterative thermomechanical solution flow diagram**

### 3. NUMERICAL SIMULATIONS

#### 3.1 Presentation of the structure

Figure 2 depicts the rotational joint used for the numerical simulations. The inner and outer hollow cylinders are made of steel whereas the intermediate layer is made of the VEM ISD112 manufactured and commercialized by 3M™. The global structure has been modeled in ANSYS using the following 8-node solid elements:
• **SOLID45**: element having 3 degrees of freedom per node (translations in the $X$, $Y$ and $Z$ directions) used for the structural solution).

• **SOLID70**: element having one degree of freedom per node (the temperature $T$), used for the thermal solution).

![Figure 2. Sketch of the rotationnal joint (a) (adapted from Lima et al., 2008) and its FE model (b) (dimensions in millimeters)](image)

Since the complex modulus of the VEM is a function of both the temperature and the frequency, its numerical implementation in the context of finite element simulations is easier when using the *Frequency-Temperature Superposition Principle*, which consists in introducing a temperature-dependent coefficient $\alpha_T$ to link the angular frequency $\omega$ to a reduced angular frequency $\omega_r$ so that $\omega_r = \alpha_T \omega$. The experimental determination of the VEM relaxation coefficients at a reference temperature $T_z$ lead to an expression of the complex modulus as a function of the reduced frequency:

$$E^*(\omega, T) = E^*(\omega_r) = E^*(\alpha_T \omega)$$

A function providing the values of the complex modulus of material 3M™ISD112 for a determined range of frequencies between 1 and $1 \times 10^6$ Hz and for a given temperature $T$ was implemented by Lima, according to the reference given by Drake and Soovere (1984). The ANSYS software allows the definition of temperature-dependent structural material properties. During the pre-processing phase, the modulus of elasticity and damping material ratio are defined by a 2-dimension table where each temperature value matches the corresponding value of $E''(\omega_r, T)$ and $\eta(\omega_r, T)$. Table (1) shows the value of the mechanical and material parameters for the standard steel and the VEM.

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Standard Steel</th>
<th>3M™ISD112</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg.m$^{-3}$)</td>
<td>7850</td>
<td>1100</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.3</td>
<td>0.499</td>
</tr>
<tr>
<td>Specific heat (J.kg$^{-1}$.K$^{-1}$)</td>
<td>476</td>
<td>2000</td>
</tr>
<tr>
<td>Thermal conductivity (W.m$^{-1}$.K$^{-1}$)</td>
<td>35</td>
<td>0.14</td>
</tr>
</tbody>
</table>

(1): from Merlette, 2005

### 3.2 Discussion of the simulation results

A 21 N.mm torque in the vertical $Y$ direction was applied to the damper at a 10 Hz frequency during 1000 seconds. The total simulation time is 1500 seconds, in order to observe the temperature decrease after the removal of the load. A 10 seconds time interval was considered for the iterative process. The evolution of temperature values over time was observed at 4 keypoints, whose localizations are shown by Fig. 3. A value of 0.6 for the $\beta$ parameter was chosen, according to the results of the identification procedure proposed by Merlette (2005) for an numerical-experimental study in similar conditions.
Figure 4 shows the evolution of the temperature at the 4 keypoints over time. It appears that after 400 seconds of loading the temperature values increase at a very low rate, so that it can be considered that a quasi-equilibrium configuration has been reached. As shown by Fig. 4, the maximal temperature value is reached at keypoint 2, which is localized in the middle of the viscoelastic layer, while the lower value observed on the upper boundary of the layer (keypoint 4) can be explained by the influence of external convection.

The lowest temperature values are observed at keypoints 1 and 3, localized on the horizontal symmetry plane of the damper, respectively at the outside and inside limits of the viscoelastic layer. It should be reminded that the steel’s thermal conductivity is about 200 times higher than the MVE’s conductivity, consequently the outside and inside steel cylinders are eager to evacuate the heat generated inside the viscoelastic parts by conduction mechanisms.

4. CONCLUSION

In this paper, an algorithm for modeling transient thermal auto-heating effects in viscoelastic dampers has been described and applied to the case of a complex tridimensional damping structure. The main drawback of this strategy is that the computational time necessary to obtain the transient thermal response remain high, due to the fact that the structures’s mesh has to be refined in the areas of interest, which are, obviously, the viscoelastic layers. However, the results tend to
prove that the same procedure may be applied for various types of damping devices including viscoelastic constrained layers, since it can be used as a predictive model to ensure that the self-heating effect caused by harmonic loadings may not result in material degradations inside the viscoelastic layers. A further work may include a time step control tool based on a convergence criteria. A maximal value can be imposed for a parameter which can be calculated from the relative difference between the displacement field values obtained from the structural harmonic analysis, at each iteration. The transient thermal analysis and, subsequently, the new structural analysis would be repeated for a shorter time step until the relative difference value is inferior to the chosen error value. Finally, it should be reminded that the thermal properties values used to simulate the thermomechanical behaviour of the MVE are generic values used for soft polymers, and that an experimental identification of these parameters for the simulated MVE may lead to more accurate simulation results.

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6. REFERENCES


7. RESPONSIBILITY NOTICE

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