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ABSTRACT
Material damping can be modelled by a complex Young's and shear modulus in which the ratios η_E respectively η_G between the imaginary and real parts are a measure for the damping. In the case a strucure consist of an isotropic homogeneous material with η_E=ηG a frequency independent damping for the structure can be obtained with a finite analysis. However, for inhomogeneous materials (like laminates) of for isotropic materials with $\eta_E \neq \eta_G$ a frequency dependent damping for the structure can be obtained. To quantify the influence of the different damping ratios on the total damping of the structure as a function of frequency different aluminium strips with vixdo-elastic layers were analysed. The analytical results were verified experimentally. The calculations were carried out with a finite element model of the strip in which laminate elements with a complex element stiffness matrix were used. For the damping measurements a special experimental set-up and procedure was developed. The experimental and numerical results are in good agreement with each other.

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A FREQUENCY DEPENDENT STRUCTURAL DAMPING MODEL

by

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A FREQUENCY DEPENDENT STRUCTURAL DAMPING MODEL

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ABSTRACT

Material damping can be modelled by a complex Young's and shear modulus in which the ratios η_E respectively η_G between the imaginary and real parts are a measure for the damping. In the case a structure consists of an isotropic homogeneous material with $\eta_E=\eta_G$ a frequency independent damping will be obtained with a finite element analysis. However, for inhomogeneous materials (like laminates) or for isotropic materials with $\eta_E \neq \eta_G$ a frequency dependent damping for the structure can be obtained.
To quantify the influence of the different damping ratios on the total damping of the structure as a function of frequency different aluminium strips with visco-elastic layers were analysed. The analytical results were verified experimentally. The calculations were carried out with a finite element model of the strip in which laminate elements with a complex element stiffness matrix were used. For the damping measurements a special experimental set-up and procedure was developed. The experimental and numerical results are in good agreement with each other.

NOMENCLATURE

E^*	Complex Young's modulus
E^R	Real part of E^*
E^i	Imaginair part of E^*
G^*	Complex shear modulus
G^R	Real part of G^*
G^i	Imaginair part of G^*
i	$\sqrt{-1}$
λ^*	Complex eigenvalue obtained from FEM analysis
λ^R	Real part of λ^*
λ^I	Imaginair part of λ^*
η_{fem}	Damping ratio equal to λ^I/λ^R
η_E	Damping ratio equal to E^I/E^R
η_G	Damping ratio equal to G^I/G^R

INTRODUCTION

Damping of noise and vibration is one of the means to enhance passenger comfort in transportation vehicles. This can be achieved by applying special materials with high damping properties. However, the manufacturer wants to use as less material as possible due to the vehicle weight costs constraints. Therefore it is important to be able to predict the effect of damping in the design phase and to optimise the amount of damping material to be added to the structure. This means that the damping behaviour of individual parts of the structure has to be modelled.
A common method to account for damping is using a modal base for the response analysis and to add damping per mode. The modal damping value is obtained experimentally or is estimated (based on experience). However, the modal damping is a value averaged for the whole structure. This means that local damping can not taken into account properly. In a finite element model a local damping can be defined as material property for each element separately.

At NLR research on visco-elastic tape material, so called damping tape which is bonded to shell like structures is carried out. The objective of the research is to develop a design tool to optimise damping tape distribution on shell like structures. The damping tape consists of a visco-elastic layer and a constraining layer. Therefore one speaks of constraining layer damping.
Firstly a 3 layered laminate shell element was developed and programmed in the finite element program B2000 [Ref. 1, 2] used by NLR for the development of new methods and theories. Next a damping formulation for this laminate element was introduced. With this element in B2000 dynamic as well as coupled acoustic analyses can be performed. At this moment the module to optimise the damping tape distribution is under development.
This paper is focused on the description of the damping model and the verification of the damping prediction.

THE DAMPING MODEL

In literature different damping models are proposed such as structural damping, viscous damping, complex damping [Ref. 3], Augmented Thermodynamic Field damping [Ref. 4], Augmented Hooke's Law damping [Ref. 5]. The choice of the model depends on the material but also the applicability in large numerical analyses. For instance a frequency dependent damping model increases the computation time needed for a frequency response analysis dramatically which makes it practically impossible to use it. From this point of view structural material damping is a favourite model because the damping is represented as a constant material property.
For structural damping the damping is defined by the ratio between the imaginary and real part of the elastic modulus E^* and the shear modulus G^*.

$$\eta_E = E^I/E^R \qquad (1)$$
$$\eta_G = G^I/G^R \qquad (2)$$

with: $E^* = E^R + iE^I$
$G^* = G^R + iG^I$

When the structure consists of an isotropic homogeneous material the shear modulus is derived from E^* and Poisson's ratio and therefore $\eta_G = \eta_E$. In that case the damping of the structure will be frequency independent. However, in the case a complex shear modulus is defined separately with a damping ratio $\eta_G \neq \eta_E$ a frequency dependent damping of the structure can be obtained (see also [Ref. 6]). Also for a layered structure for example a visco-elastic layer between two constraining layers where $\eta_{Elayer1} \neq \eta_{Elayer2}$ and/or $\eta_{Glayer1} \neq \eta_{Glayer2}$ the damping of the structure is frequency dependent.

The validity of the description of the damping behaviour of a visco-elastic layer and an aluminium constraining layer with a structural damping model in finite element analyses has been verified with experiments on strips.

THE EXPERIMENTAL SET-UP

A special device (see Fig. 1) was developed for measuring damping of strips of material. Special attention was paid to the mounting of the strips in the device to minimise the influence of the damping introduced by the mounting. To this end the strips are mounted in the device at the node lines of the natural bending modes. This means that for each natural mode the strip must be mounted at another position.
The strip is excited with a magnetic transducer (Type MM 0002 of Bruel & Kjaer) at frequencies around one of the strip's eigenfrequencies. The response of the strip is measured with a laser beam sensor (Type LXS of T.P.A. Systems B.V.).
The damping is measured in two ways.

1. For light damped strips the Logarithmic Decrement is measured from the (damped) response signal at a certain eigenfrequency in the time domain
2. For strips with high damping the response signal is Fourier transformed and the damping is obtained from the width of the response peak at an eigenfrequency.

The damping as function of the frequency can be obtained by measuring the damping at frequencies belonging to different modes for strips with different lengths. In this way the influence of the mode shape on the frequency dependent damping ratios can be investigated, too.

THE NUMERICAL MODEL

The strips have been modelled with 8 node 3-layered laminate plate elements. Each node has nine degrees of freedom namely the three translations and two rotations around the in plane axes of the mid-layer and the two in-plane translations of the upper and lower layer. For each layer separately, (elastic and damping) material properties can be defined.
With the finite element model of the strip the complex eigenfrequencies and mode shapes can be calculated. The damping of the whole strip at a certain eigenfrequency can then be obtained from the ratio between the imaginary and real part of the complex eigenvalue λ^*.

$$\eta_{fem} = \lambda^I/\lambda^R \qquad (3)$$

with: $\lambda^* = \lambda^R + i\lambda^I$

The boundary conditions of the finite element model are such that the so-called free-free bending modes are calculated.
Variation of the length of the strips gives just like in the case of the experiments different eigenfrequencies for certain bending modes. In this way the frequency dependent damping can be calculated for a certain bending mode and the influence of the mode shape on the frequency dependent damping ratios can be obtained.

THE VERIFICATION

Verification experiments were carried out with aluminium strips of 10 mm width and a thickness of 0.6 mm. On these strips 3M tape was bonded with a visco-elastic layer of .05 mm thickness and a constraining aluminium layer of .125 mm thickness. To cover the frequency range from 10 to 1000 Hz. strips with a length of 386.5, 247.2, 192.07, 160.5, 137.04, 121.28, 110.24, 99.25 and 90.68 mm were analysed. The measurements were carried out at a temperature of 26 ^{0}C.
The material properties necessary for the finite element analyses are summarised in table 1. The properties of the visco-elastic material were obtained from product data sheets belonging to the 3M damping tape. The damping in the strip is caused by the shear in the visco-elastic layer. In shell like structures shear will occur in bending (modes) especially. From parameter studies was found that in the case the Young's modulus of the visco-elastic layer is smaller than 10^4 times that of the base and constraining layer material the damping of the whole strip is completely determined by η_G of the visco-elastic material. Therefore only a complex shear modulus for the visco-elastic material is used in the finite element model.

The measured and calculated damping ratios of the strips as function of the frequency for the first, second and third bending mode are depicted in figures 2, 3 and 4 respectively. In figure 5 the calculated frequency dependent damping for the three bending modes is plotted.

E-modulus aluminium	7.0e+10 N/m^2
Poisson's ratio aluminium	0.3
E-modulus visco-elastic material	2.98e+6 N/m^2
Poisson's ratio visco-elastic material	0.49
Damping ratio η_G visco-elastic material	0.5
Density aluminium	2700.0 kg/m^3
Density visco-elastic material	1.0 kg/m^3

Table 1. Material properties of strip materials.

DISCUSSION AND CONCLUSIONS

The measurements show that the damping of the strip is frequency dependent. The calculated damping gives a frequency dependent course, too, although "constant" material properties are used. There are differences between the measured and calculated frequency dependent damping ratios however the values have the same order of magnitude and show the same trend.

For the higher frequencies (700-1000 Hz) it was more difficult to measure the damping because no significant response could be obtained due to the limited power of the exciter. Therefore the measured damping ratios in this area are not reliable.

Figure 5 shows a small influence of the mode shape on the damping value. Probably, this is caused by the difference in shear in the visco-elastic layer for the different modes. The higher the mode the smaller the radius of curvature and thus the larger the shear.

The application of a visco-elastic layer on a fuselage wall reduces the sound transmission by reduction of the vibration of the fuselage wall. Especially the bending modes which are most important for the noise transmission will be damped. The damping mechanism is similar to the shear in the visco-elastic layer on the aluminium strips. Therefore it is expected that for noise transmission analyses the modelling of damping with a complex modulus is a good way to take local damping into account.

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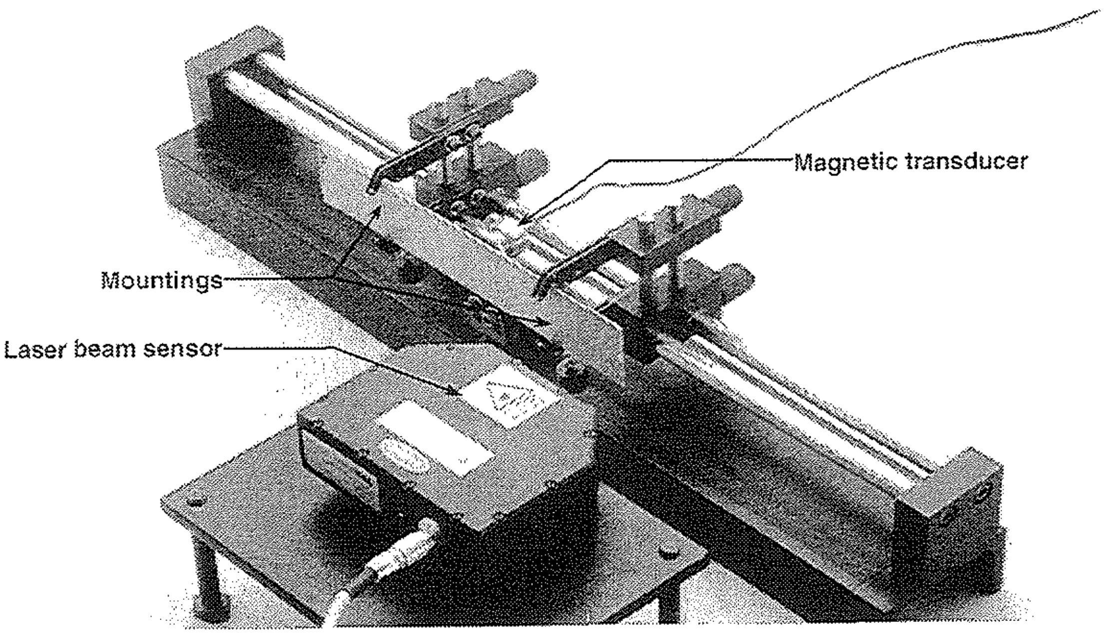

Figure 1. The experimental set-up

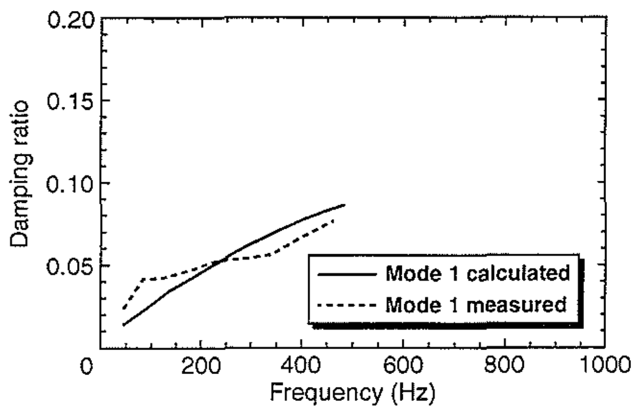

Figure 2. Measured and calculated damping ratio belonging to the first bending mode

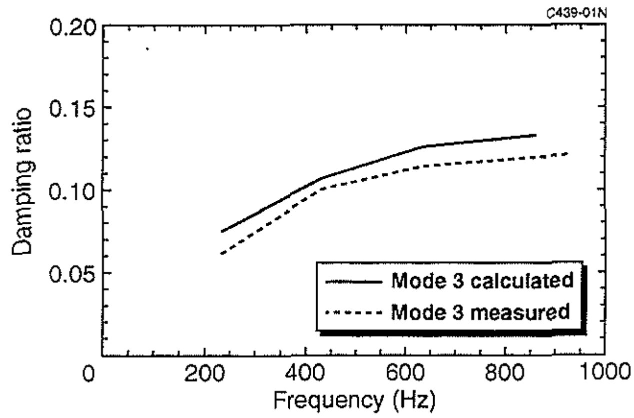

Figure 4. Measured and calculated damping ratio belonging to the third bending mode

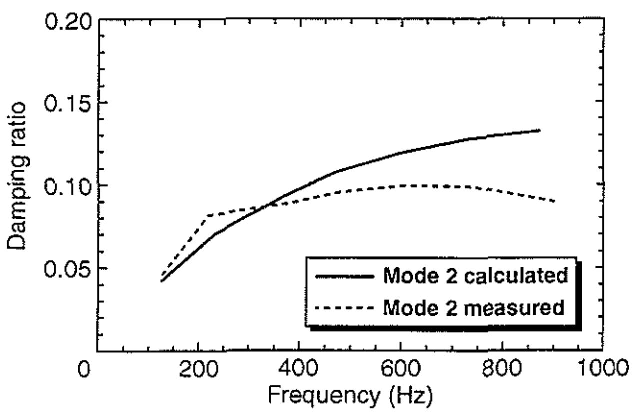

Figure 3. Measured and calculated damping ratio belonging to the second bending mode

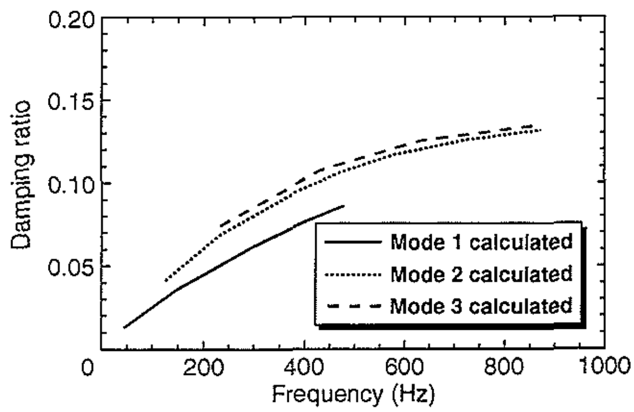

Figure 4. Calculated damping ratio belonging to the first three bending modes