Vibration Dynamics Modeling of Anisotropic Porous Foam Materials

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For an accurate prediction of the low to medium frequency surface vibration and sound radiation behavior of multilayer trim components with polyurethane foam core materials, improved means of estimating the dynamic elastic and damping properties of the foam are necessary. This is due to the fact that in the manufactured porous polyurethane foam materials typically used in acoustic trim components, there is a geometric anisotropy in the foam cell microstructure. The foam cells and struts are elongated in the rise and injection flow directions of the manufacturing process. The density, elastic and damping properties of the foam can then be considered to be highly dependent upon manufacturing process techniques, along with the polyurethane chemical formulations. For a balanced cost and acoustic performance optimization of these materials in the product development cycle, it is important that this inherent anisotropy is correctly represented in the acoustical numerical simulation methodology. Through a hybrid combination of experimental deformation and strain field mapping, and physically based porous material acoustic Finite Element (FE) simulation modeling, the anisotropic dynamic elastic coefficients and damping properties of the foam may be correctly estimated. This new methodology of model-based porous material characterization is demonstrated here for a simplified seismic mass configuration. The improved accuracy of the subsequent low-mid frequency multilayer surface vibration numerical predictions is discussed. This leads to improved NVH analysis during the development lifecycle of the vehicle acoustic sound package, allowing a better balance between acoustic performance and a minimization of material usage to be achieved.

1 Introduction

Foam materials are commonly introduced as lightweight, means to control noise and vibration in many applications. In manufactured porous foam materials acoustic trim components; there exists an inherent geometric anisotropy in the foam cell microstructure. The foam cells and struts are elongated in the rise and injection flow directions of the manufacturing process. The density, elastic and damping properties of the foam can then be considered to be highly dependent upon manufacturing process techniques, along with the polymer chemical formulations. For a balanced cost and acoustic performance optimization of these materials in the product development cycle, it is important that this inherent anisotropy is correctly represented in the acoustical numerical simulation methodology.

Such an enhanced methodology has the potential of leading to improved NVH (Noise, Vibration, and Harshness) analysis during the development lifecycle of an acoustic sound package, allowing a better balance between acoustic performance and a minimization of material usage to be achieved.

2 Modeling

In the case of general NVH aspects, many system properties are as yet difficult to simulate accurately. The reasons for this are many; e.g. scatter in physical/material properties, frequency dependent constitutive material models, etc. Furthermore, the physical modelling of the dynamic behaviour of an anisotropic foam vibration response is as yet an open question. To determine and validate physical foam material models as well as analysis methods requires a combined experimental and numerical approach, as illustrated in Figure 1:

![Combined experimental and numerical approach](image_url)

Figure 1: Combined experimental and numerical approach
The three main steps required to reach a validated material model are:

- **Characterisation**: Static and dynamic experiments as well as finite element models are used to determine the elastic, viscoelastic properties (moduli) and the acoustic properties of the anisotropic material. This is typically performed in a seismic mass setup, involving in vacuo measurements, and in a static flow rig.

- **Material modelling**: A constitutive, frequency dependent model of the anisotropic foam material is established, based on the determined moduli. This model includes the elastic and viscoelastic response of the material.

- **Validation**: The foam material model is used in finite element simulations, typically for a sandwich configuration, conducted using a finite element model and compared to experimental result.

3 **Static Characterisation**

This step involves three parts; first the fully relaxed static moduli are measured using static compression. CCD cameras are then used, enabling the full field mapping of the deformation under static loading. These data are then used to fit a material modulus matrix via finite element simulations using a model of the setup used [1],[2]

3.1 **Fully relaxed elastic moduli estimation**

The stress relaxation of the foam samples under a constant strain is determined through measurements in the setup shown in Figure 3:

![Figure 3: Experimental setup for static modulus determination](image)

The recorded force is found to be highly time dependant due to the materiel relaxation. The pressure is described as a function of time in Figure 4:

![Figure 4: Recorded pressure over time](image)
The static moduli are estimated through a fractional Maxwell model \([3][4]\), in which the stress appears as a non-integer order derivative of the strain. Two non-integer values are used, one for short time that is close to zero (behaviour close to the ideal elastic solid), and one longer (plastic-like), as shown in Figure 5:

![Figure 5: Relaxation fit.](image)

The microstructure of the foam under consideration is shown in Figure 2: As may be inferred from Figure 2: and confirmed by the data shown in Figure 4: the sample tested is found to be anisotropic, but with almost equal moduli in two different directions (15% difference). This proximity suggests that for some properly chosen material system orientation, a transversally isotropic material model might be found. The variation in the modulus for the z-direction was within +/- 10% between different samples.

3.2 Deformation field mapping under static loading

In addition to the measured elastic moduli, also the deformation fields at the free surfaces of the samples were determined through speckle interferometry. The samples under load are recorded by two CCD cameras, see Figure 6: A random structure marking is applied to the object’s surface which deforms along with the object. The deformation of the structure under different loading conditions is recorded by the CCD cameras, one picture frame half hour. The initial image processing defines the macro-image facets.

![Figure 6: Speckle interferometry measurement setup](image)

These facets are tracked in each successive image with sub-pixel accuracy. On the basis of the 3D-coordinates, the 3D-displacements, the strains and shape of the sample are calculated with a high degree of accuracy and resolution in the relevant directions of deformation, see Figure 7:

![Figure 7: Interferometry principle](image)

To illustrate the mapping of the deformation fields, a representative result is shown in Figure 8: together with a hypothetical cell orientation sketch.

![Figure 8: Deformation fields and cell orientation](image)
The time relaxation dependencies as well as the difficulty of reproducing exactly the deformation were a limiting factor in the deformation field measurement. In order to improve the accuracy of the experiments, the specimen was placed on a rotating table, and the four faces were observed one after the other before the compression and after the relaxation, see Figure 9. This improved the exactness of the measurement as well as the time efficiency.

Faces matching on the edge of each face of the tested sample gave us a good estimation of the quality of the measurement and permit to validate the measurement, see Figure 10:

![Constant deformation](Image)

Rotating table

Figure 9: Rotating set-up

4 Material system determination

As discussed briefly above, the measured moduli indicated a possibly transversely isotropic material. To find the material modulus matrix an inverse estimation was performed using a finite element model of the setup shown in Figure 1: to fit predicted deformation fields to the interferometry maps. Five moduli and three orientation angles were used to find a least squares match between the measured and predicted fields at two orthogonal surfaces.

Obviously, this procedure leads to a non-unique modulus matrix, i.e. there are an infinite number of realisations that give a matching deformation pattern on the surface. To fix the range of allowable moduli also the normal stress level in the loading direction was included in the estimation. In Figure 11: the results from the initial estimates of the material modulus are shown in the form of the fitted deformation fields together with the measured speckle interferometry maps at the final step of the measurement sequence.

The modulus matrix thus estimated was viewed as a representative estimates for the tested samples. As such it may be used in a validation of a dynamic model of the same set of samples.

![Illustration of calculated deformation fields, load in y-direction.](Image)
5 Air flow resistivity measurements

In addition to the static modulus estimations, a series of static air flow resistivity measurements were also performed for the studied foam. The test rig consists of the measure pressure differences across both the foam sample and a calibrated element of known flow resistance. It was found, see Figure 12: that the orientation of the cells is also strongly affecting the air flow behaviour and that the values found for the transverse directions were rather similar.

6 Viscoelastic characterisation

To determine the anelastic material moduli a set of in vacuo, dynamic tests have been performed. The sample are fixed to a plate with adhesive tape and linked to a shaker a seismic mass, which statically correspond to a fully relaxed 2.5% deformation of the foam, was fixed on the top of the sample. The shaker is producing a band limited random noise, one laser is use pointing to the surface of the seismic mass and measure the velocity of the four corner points, the other on the bottom plate, see Figure 13:. This set up is mounted in a vacuum chamber and the ratio between the 2 lasers is recorded. Measurements are conducted in all the three Cartesian coordinate directions.

The vibration spectrum in vacuum as well as when the setup was measured in air (observe Figure 14:). From the measurements performed it was clear that the response of the top surface was highly non-uniform. To get a more deep understanding, the in vacuo dynamic responses are shown in Figure 15: at three different time steps over a half period of vibration. The observed motion of the seismic mass is an immediate effect of the anisotropic properties of the tested sample.
7 Validation

At the conference the results from predictions will be validated against measurements. Thus the dynamic and acoustic anisotropic model of the studied foam will be demonstrated for the seismic mass setup tested in air and in vacuum.

8 Conclusion

The research presented in this paper is concerned with the determination of constitutive models for elasticity and dynamic behaviour in polymer foams. The goal is to derive models useful in numerical prediction methods and to demonstrate those in typical applications.

The results from a static and dynamic characterisation performed, suggest that a transversely isotropic material model with proper principal material directions is a valid representation of real foam.

The principal relevant new notions of this article are:

- To apply a coherent and integrated set of experimental and numerical methods to characterize the anisotropic, fully-relaxed static and dynamic foam elastic properties.

- The validation of these materials models applied in numerical analysis methods based on viscoelastic principles for simulating the linear vibration response of flexible foam materials. The current research is a step towards a design methodology for soft foam materials alleviating this lack of proper design tools.

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10 References


