The Development of an Analytical Model for the Acoustics of a Porous Melamine Foam Material

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Abstract

COMSOL Multiphysics® has proven to be an invaluable "virtual laboratory" tool in assisting our development of a new generation of efficient analytical models describing the acoustics of highly porous fibre and open-cell foam materials. From the definition of the physical relations describing the fundamental viscous dissipation and oscillatory heat transfer mechanisms for the underlying microscale cylindrical geometries, we have been able to use validated COMSOL Multiphysics® Thermoviscous Acoustics and Fluid-Solid Heat Transfer models to conceptually scale-up the approach, firstly towards arrays of fibres representative of thermal-insulation materials, and now targeting open porous foam materials having predominately cylindrical struts, like the Melamine foam material considered here.

This analytical approach requires only geometrical microstructure information and constitutive material parameters, thus allowing for a very efficient prediction of the acoustics of these porous materials and also other new material concepts, without the need for the inverse estimation or measurement of transport parameters from actual physical material samples [4].

In this paper, we begin with a representative Kelvin Cell geometry typical of Melamine foam materials, and utilize high resolution COMSOL Multiphysics® creeping flow CFD, Thermoviscous Acoustics, Heat Transfer and Structural Mechanics simulations to validate the extension of our analytical relations for microstructural viscous energy dissipation, oscillatory heat transfer and elasticity towards the three-dimensional foam geometry. This extension provides very promising results for the Melamine foam material, and the subsequent implementation within the Transfer Matrix Method (TMM) allows for an excellent prediction of the acoustics of this open-celled porous foam material.

Introduction

We have recently demonstrated the possibility of using thermoviscous acoustics (TVA), solid-fluid heat transfer and structural mechanics modelling within COMSOL Multiphysics® in order to predict the dynamic viscous drag forces, oscillatory heat transfer and elasticity matrices for generic porous cellular materials [1]. These are then incorporated into the coupled solid-fluid momentum equations, and a non-equilibrium fluid dilatation equation, allowing the prediction of the vibroacoustic performance of the poroelastic material, using only geometric information and constitutive material parameters.

The main drawback of this approach is that the TVA analysis, which is used for the dynamic viscous drag force estimation, may be computationally prohibitive for practical design and development cycles.

For highly porous fibrous materials which have predominantly cylindrical fibres, we have also developed validated analytical expressions [2, 3] for the dynamic viscous drag force and oscillatory heat transfer phenomena, which when used with the acoustic TMM, allows for a very efficient prediction of the acoustic performance of fibrous materials.

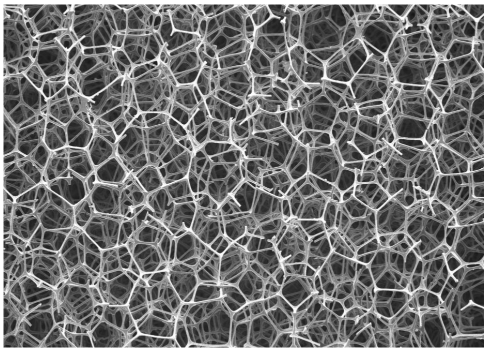


Figure 1. Melamine foam cell micrograph, image courtesy of BASF Basotect®.

Many open-cell foam materials, and 3D-printed lattice materials, also exhibit cylindrical-like struts between their joints. It would then be highly desirable for acoustic models of these poroelastic materials to be able to also utilise the analytical drag force and oscillatory heat transfer expressions developed previously for fibrous materials. This would then allow the rapid estimation of the acoustic potential of open-cell foam and lattice-cell concepts.

Therefore, in this paper, we now use COMSOL Multiphysics® as a "virtual laboratory", to provide a reference case to validate the extension of the cylindrical fibre viscous drag force and oscillatory heat transfer analytical expressions towards the 3D orientation of the interconnected struts of an open-cell porous material. In this case, the application material has properties typical of Melamine foam, as shown in Fig. (1), which is widely used for acoustic purposes in the building and transportation industries.

Melamine Foam Unit Cell

For this development, the cells of the Melamine foam are represented as a simple iso-parametric, Kelvin-Cell like foam structure [5], as shown in Fig. (2). Each cell has a length of 0.283 mm (x, y, z-dir.), with the assumed cylindrical struts having a diameter of 5 microns, and a length of 0.100056 mm (point-to-point between the strut joints). Due to the hexagonal geometry of the cell, the oriented struts are assumed to have an off-axis alignment angle of 60 degrees. These geometric properties have been chosen to be representative of typical Melamine foam materials, but have not been specifically measured.

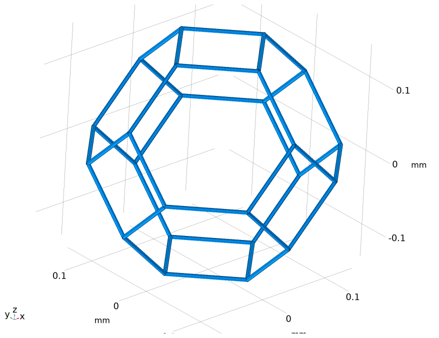


Figure 2. Conceptual 0.283 mm Melamine foam cell, with 5 micrometre diameter and 0.100056 mm length cylindrical struts.

The volume of the foam cell can then be estimated using the relation for an iso-parametric Kelvin cell [5]

$$V_K = 8\sqrt{2}L^3, \tag{1}$$

where L is the nominal strut length. The porosity of the foam cell is also defined as

$$\phi = 1 - V_S / V_K \, . \tag{2}$$

Here, V_S is the solid volume of the inter-connected cylindrical struts and joints comprising the foam cell.

The Melamine foam cell under consideration is assumed to be produced using the standard foaming process for melamine-formaldehyde resin, resulting in a fine, low-density open-celled foam having desirable acoustic absorption and thermal insulation properties. The resin was assumed to have a density of 1574 kg/m^3 and a bulk modulus of 560 MPa, a thermal conductivity of 0.5 W/mK at 20 deg. C. The specific heat was assumed to be 1200 J/kgK. The properties of the thermoviscous fluid surrounding the foam microstructure were that of air at 20 deg. C.

Framework for the Dynamics of Highly Porous Foam and Fibrous Materials

In our recent work [1], a general framework for the dynamics of poroelastic materials was proposed, refer to Fig. (3), consisting of coupled fluid and solid momentum equations, together with a non-equilibrium fluid dilatation equation which includes oscillatory heat transfer effects. In this approach, the elasticity matrix, dynamic viscous drag force and oscillatory heat transfer inputs can be determined experimentally, through finite element simulation, or analytically when the microgeometry is regular, such as for the cylindrical strut geometries considered here.

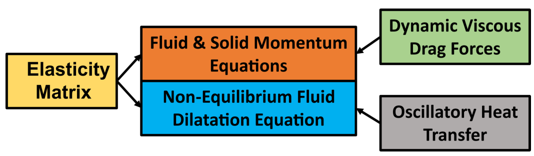


Figure 3. Framework for general dynamic poroelastic relations with elasticity, viscous drag force and oscillatory heat transfer inputs.

Beginning with an overview of the principal governing equations, the steps leading to the development of analytical expressions for elasticity, dynamic viscous drag force and oscillatory heat transfer for the open-cell Melamine foam application are now outlined.

Governing Momentum Equations

As a starting point, we begin with the governing fluid and solid momentum equations [1, 3]

$$\phi \rho_f \ddot{U}_i = \frac{\partial \sigma}{\partial x_i} + F_{D_i}, \tag{3}$$

$$(1-\phi)\rho_s \ddot{u}_i = \left(\frac{\partial \sigma_{ii}}{\partial x_i} + \frac{\partial \sigma_{ij}}{\partial x_j} + \frac{\partial \sigma_{ik}}{\partial x_k} \right) - F_{D_i}, \tag{4}$$

where F_{D_i} are the components of the volume-averaged dynamic viscous drag force vector $\mathbf{F}_D$, existing at the fluid-solid interface of the foam material, and is defined in terms of the dynamic viscous drag force impedance, $\mathbf{Z}_{L,T}$, and the solid frame excitation velocity, v_{exc}, as [2]

$$\mathbf{F}_D = \mathbf{Z}_{L,T} \cdot v_{exc}. \quad (5)$$

We have previously demonstrated that the viscous drag force impedance matrix can be estimated using analytical relations for simplified cylindrical geometries [2, 3], as was the case for our previous work on fibrous poroelastic materials. Under the assumption that the solid struts of open-cell foams are primarily cylindrical, we can now define a dynamic viscous drag force impedance matrix, based on the oriented viscous impedances of each of the 36 struts of the isotropic Melamine foam cell [5]

$$\mathbf{Z}_{\mathbf{cell}} = \frac{(1-\phi)}{V}\sum_{n=1}^{N}\mathbf{R}_{\mathbf{n}}\left[\hat{Z}\right]\mathbf{R}_{\mathbf{n}}^{T}. \quad (6)$$

Here $[\hat{Z}]$ is the dynamic viscous drag force impedance matrix for the longitudinal and transverse cylindrical struts, as defined in [2],

$$Z_L = 2\pi r_s k_\beta \mu_f \frac{H_1^{(2)}\left(k_\beta r_s\right)}{H_0^{(2)}\left(k_\beta r_s\right)}, \quad (7)$$

$$Z_T = i\pi r_s^2 \rho_f \omega\left[1-\frac{4H_1^{(2)}\left(k_\beta r_s\right)}{k_\beta r_s H_0^{(2)}\left(k_\beta r_s\right)}\right], \quad (8)$$

and **R** is the foam cell alignment rotation matrix.

Note that the dynamic viscous drag force impedance matrix may be defined for not only isotropic, but also fully anisotropic materials [7], as well as for statistical distributions of porous cell geometries.

Non-Equilibrium Fluid Dilatation

Stress and strain for any porous material are related by coupled constitutive stress-strain relations of the form

$$\{\sigma\} = [D]\{\varepsilon\}, \quad (9)$$

where [D] is the stiffness matrix of the porous material. For the case when waves propagate through the poroelastic material, one-way oscillatory heat transfer occurs between the solid phase and the surrounding viscous fluid, resulting in a thermal expansion of the fluid [3]. This leads to an extension of the fluid dilatation terms of the stress-strain relations away from equilibrium, which for the isotropic case is

$$\chi\sigma = R\varepsilon + Q\left(e_{xx}+e_{yy}+e_{zz}\right), \quad (10)$$

where R and Q are coefficients of the stiffness matrix. The fluid pressure term then is scaled by the frequency-dependent thermal coefficient χ

$$\chi = \left[1-\frac{\alpha\eta R}{j\omega\rho_f Cp_f \phi}\right], \quad (11)$$

where

$$\alpha = \eta T_f' \left\{\frac{\rho_f Cp_f \phi}{\bar{Y}_e}+\frac{1}{j\omega}\right\}^{-1}, \quad (12)$$

and $\bar{Y}_e$ is the effective thermal impedance function,

$$\bar{Y}_e = \frac{(1-\phi)}{A}\left[\frac{1}{Y_f}+\frac{1}{Y_s}\right]^{-1}. \quad (13)$$

The oscillatory thermal fields of the respective fluid and solid phases, Y_f and Y_s, averaged over all of the struts of the foam cell [5] are also defined as

$$Y_f = 2\pi r_s \kappa_f k_{tf}\frac{H_1^{(2)}\left(k_{tf} r_s\right)}{H_0^{(2)}\left(k_{tf} r_s\right)}, \quad (14)$$

$$Y_s = -2\pi r_s \kappa_s k_{ts}\frac{J_1\left(k_{ts} r_s\right)}{J_0\left(k_{ts} r_s\right)}. \quad (15)$$

A more detailed description of the derivation of the effective thermal impedance function is provided in [3, 5].

Microscopic Cell Elasticity

We have assumed that the Melamine foam cell has isotropic cubic symmetry and cylindrical struts. Using the procedure defined in [6], the respective effective longitudinal Young's modulus and Poisson's ratio can be estimated for input into the stiffness matrix [D] using the following relations

$$E_f = \frac{\left(11N+4M\right)}{2\sqrt{3}L\left(10N^2+31NM+4M^2\right)}, \quad (16)$$

$$\nu_f = \frac{\left(N-M\right)\left(5N+4M\right)}{\left(10N^2+31NM+4M^2\right)}, \quad (17)$$

where $q^2=A/(4\pi)$, $M=L/(EA)$ and $N=L^3/(3EAq^2)$ are coefficients specifically for the case of cylindrical struts. Here, E is the strut modulus, L is the length of the strut and A is the cross-sectional area. This results in an estimated effective isotropic Young's modulus of 471 kPa and a Poisson's ratio of 0.4992 for the foam cell.

These relations assume that deformation in the foam cell occurs for strut bending and stretching only, while neglecting torsional behaviour. To check the consequences of neglecting torsional behaviour, we can use the procedure defined in [1], where the Structural Mechanics module of COMSOL Multiphysics® was used to estimate the elasticity matrix of the foam cell without neglecting any structural deformation modes, as shown in Fig. (6).

A total of 1400000 quadratic tetrahedral finite elements were used for the analysis, yielding an effective foam cell Young's modulus of 720 kPa, and a Poisson's ratio of 0.4978. Note that the Poisson's ratio prediction is comparable to that obtained from the analytical relations, while the finite element estimate of Young's modulus is 35% greater than the result from the analytical expressions. This difference indicates the potential importance of including the torsional mode in the elasticity analysis of this category of foam cells, which we will investigate in future work.

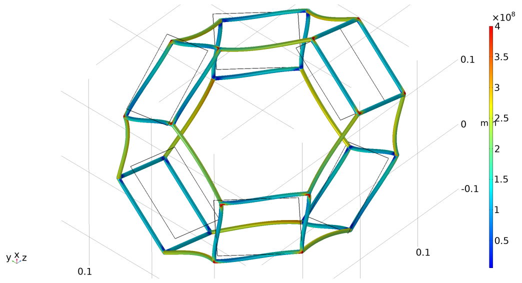


Figure 6. Melamine foam cell von Mises stress, N/m^2, for the first loading case of the elasticity matrix estimation.

Microscopic Dynamic Viscous Drag Forces

In previous work [3], we have developed and validated the methodology to estimate the dynamic viscous drag force impedance of fibrous materials using the thermoviscous acoustics analysis (TVA) feature of COMSOL Multiphysics®. This was also later applied to Kelvin Cell foam type materials [1]. It was possible to achieve high levels of accuracy using this approach, but an important drawback was the extreme computational demands required.

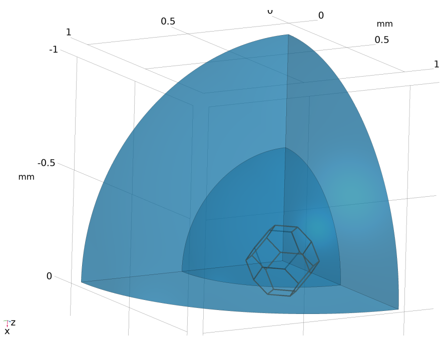


Figure 7. Model geometries for the TVA simulations using 3 symmetry planes: Melamine foam cell, and surrounding thermoviscous fluid and PML layers.

To then continue moving forward with our efforts to develop new physical models for porous materials, we have realized that the most effective use of TVA analysis is in the form of a "virtual laboratory", where high-fidelity finite element solutions provide a reference for the development of efficient analytical models of the important physics at the microstructure level.

For the current case of the Melamine foam cell, we first utilise a TVA finite element model to establish a reference for the dynamic viscous drag forces present on the structural struts and joints of the foam cell, as shown in Fig. (7). In this model, the cell was surrounded by a thermoviscous acoustic fluid layer, which was further encapsulated by a non-reflecting PML layer to allow sufficient decay of the viscous, thermal and acoustics fields, at the excitation frequency of 0.01 Hz. The isotropic nature of the Melamine foam cell allowed 3 symmetry planes to be used in the TVA analysis in COMSOL Multiphysics®, and using quadratic tetrahedral finite elements, approximately 90 million degrees-of-freedom (DOF) were required for sufficient accuracy. The symmetric velocity field in the immediate vicinity of the foam cell structure is shown in Fig. (8).

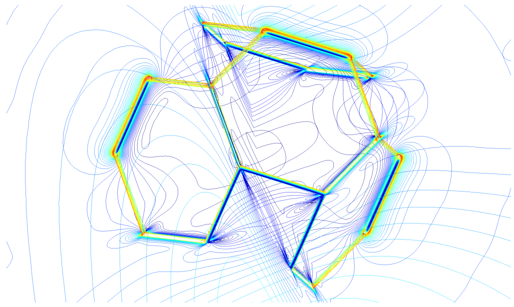


Figure 8. Symmetric velocity field in the vicinity of the Melamine foam cell, 0.01 Hz excitation frequency.

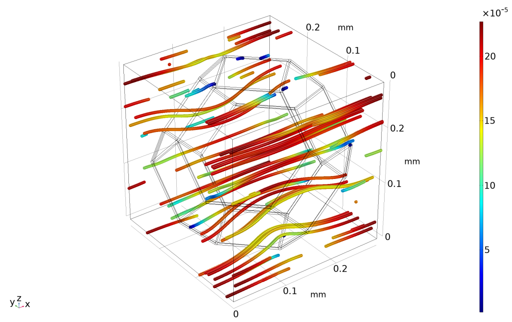


Figure 9. Velocity field streamlines of the Melamine foam cell, m/s.

As the low excitation frequency of 0.01 Hz is almost quasi-static, a creeping-flow CFD simulation in COMSOL Multiphysics® of the Melamine foam cell, see Fig. (9), was also performed to establish an additional viscous drag force reference.

For the analytical representation of the dynamic viscous drag force of the Melamine foam cell as shown in Fig. (2), we now consider the foam cell microstructure to be excited in the x-dir. only, which is sufficient due to the isotropic nature of the cell.

Using Eqns. (6-8), a superposition of the dynamic viscous drag forces of the purely longitudinal struts, purely transverse struts, and those oriented at 60 degrees (due to the hexagonal configuration of the cell) are estimated at 0.01 Hz, and compared to the reference TVA and CFD values, as shown in Table (1).

Table 1: Dynamic drag force estimation comparison

	TVA Model	Analytical Model	% Difference
Porosity	0.9983	0.9938	0.5%
Strut Volume	6.946438E-5 mm^3	7.072514E-5 mm^3	1.8%
Strut Surface Area	0.055385 mm^2	0.056580 mm^2	2.1%
Drag Force Impedance @ 0.01 Hz	**6291 Ns/m^4**	**6081 Ns/m^4**	3.3%

Here, the dynamic viscous drag force estimated from the reference TVA model is 6291 Ns/m^4, which differs by only 0.3% from the creeping-flow CFD drag force estimate of 6275 Ns/m^4. The real part of the analytical estimate provided by Eqns. (6-8), which represents dissipation, yields a value of 6081 Ns/m^4, which differs from the TVA result by 3.3%.

Considering that the very simplified analytical model, which only considers the dynamic viscous drag forces of the cylindrical struts, and not also the strut joints (which are considered in the full three-dimensional TVA model), the estimate from the analytical model should be considered as excellent. This is especially true, since this result is obtained in seconds, as opposed to the multi-hour computation time required for the TVA model. The analytical expressions assume that there is not significant interaction between the viscous fields of neighbouring struts, whereas the fully 3D TVA model does include the complete field interaction effects. These results then indicate that we should not expect a strong influence of field interaction even at low frequencies, which is a requirement for application of the analytical expressions.

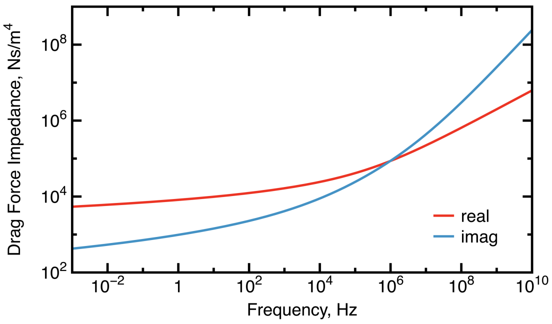
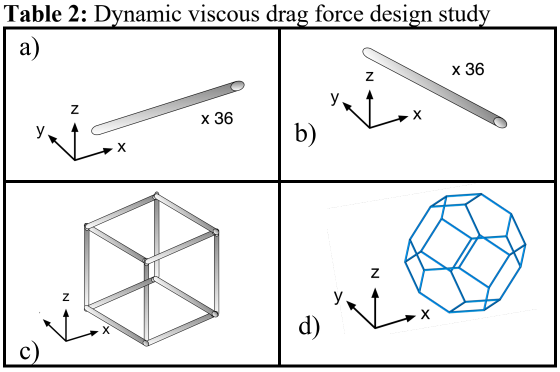


Figure 10. Real and imaginary parts of the estimated dynamic viscous drag force impedance function, Ns/m^4.

The analytical expressions can also be used to estimate the dynamic viscous drag force over a wide frequency range as shown in Fig. (10), which can be useful for assessing the dissipative potential of various foam cell microstructures.

As a further design study, we can then choose a strut diameter, and then explore various microstructure configurations, as shown in Table (2). Using our 5 micrometre diameter cylindrical strut as a starting point, the following configurations have been considered: a) 36 longitudinal struts, b) 36 transverse struts, c) a 12 strut unit cube and d) the reference Melamine foam cell. Each configuration has been chosen to have the Melamine foam cell porosity of 0.9938.

Table 2: Dynamic viscous drag force design study



Using Eqn. (6), the estimated dynamic viscous drag force impedances for each configuration are: a) 4054 Ns/m^4, b) 8108 Ns/m^4, c) 6757 Ns/m^4 and d) 6081 Ns/m^4. Configuration a) has purely longitudinal struts and should be expected to offer the lowest viscous drag forces [2], while b) is purely transverse and is expected to offer the highest viscous drag forces [2]. The unit cube and Melamine foam cell are comprised of combinations of longitudinal and transverse struts, and thus provide intermediate viscous drag force impedance results. Of interest is that the unit cube consists of a higher proportion of transverse struts per unit volume than the Melamine foam cell for the considered x-dir. excitation, leading to a higher viscous drag force impedance value than the Melamine foam cell.

Microscopic Solid - Fluid Oscillatory Heat Transfer

Within our framework for the dynamics of wave propagation through porous materials [1, 3], it is assumed that solid-to-fluid oscillatory heat transfer is responsible for a non-equilibrium scaling of the fluid dilatation, as defined by Eqn. (10). This has the effect of acoustically stiffening the viscous fluid, thus increasing the propagation rate of the fluid dilatation wave through the porous material. The phenomena becomes most pronounced for cellular materials have high thermal conductivities and very fine microstructures [1, 3], where the transition from isothermal to adiabatic thermal conditions may occur with the audible frequency range. As noted in our previous work [1, 3, 5], thermal dissipation effects are negligible as compared to viscous dissipation and are not considered here.

In order to validate the extension of the analytical cylindrical thermal impedance relations given by Eqns. (13-15) towards the Melamine foam cell application, the methodology developed in [1] has been followed. The Heat Transfer in Solids and Fluids module within COMSOL Multiphysics® has been used to simulate the coupled oscillatory thermal fields within both the solid structure of the foam cell and the surrounding air, over a frequency range of 0.001 Hz – 10 kHz. For the analysis, the Melamine foam cell was encapsulated within a thermally insulated spherical air domain, with a harmonic temperature perturbation of 293.15 K applied to the foam cell surface, i.e. the solid-fluid interface region. A symmetric quadratic tetrahedral thermal finite element model was used, having a total of 16.3 million DOF. The thermal fields of a slice through the foam cell and surrounding air, for frequencies of 1 Hz and 10 kHz, are shown in Figs. (11, 12) respectively.

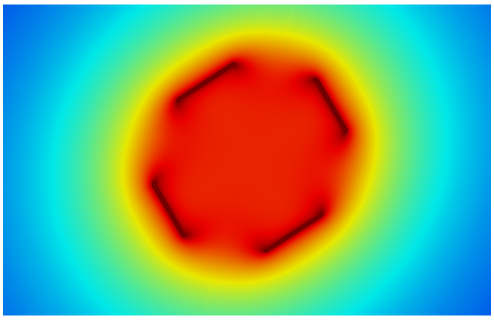


Figure 11. Slice view of the thermal fields within the Melamine foam cell solid struts, and the surrounding air in values of K, for an excitation frequency of 1 Hz.

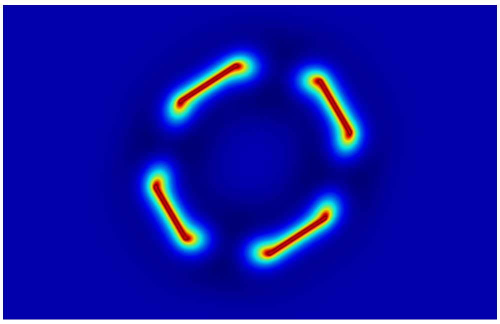


Figure 12. Slice view of the thermal fields within the Melamine foam cell solid struts, and the surrounding air in values of K, for an excitation frequency of 10 kHz.

Net heat rates for both the solid struts of the foam cell, along with the surrounding air, were computed along the solid-fluid interface region of the foam cell. This allows the respective solid and fluid dynamic thermal impedances to be estimated, allowing the effective thermal impedance to be compared to results obtained using the volume-fraction scaled analytical relations defined by Eqns. (13-15). Further details of the scaling procedure are provided in [5]. The comparison of the results from the numerical and analytical models is shown in Fig. (13). The general trend is represented well by the analytical approach, which considers the oscillatory heat transfer effects of isolated struts only. Clearly, thermal field interaction effects [3] are present in the 3D numerical model which cannot captured by the analytical approach.

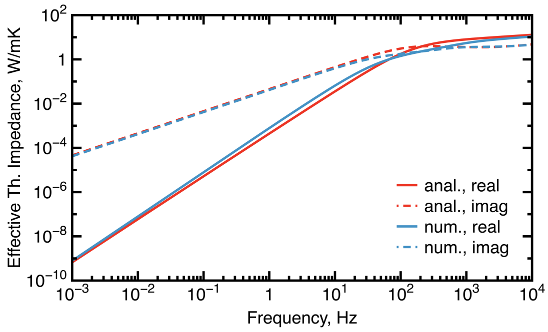


Figure 13. Real and imaginary parts of the air and foam solid thermal impedance, W/mK.

In addition, from the estimated thermal impedances and Eqns. (11, 12), the χ thermal scaling coefficient can also be estimated, refer to Fig. (14), indicating a transition from isothermal to adiabatic thermal behavior within the audible frequency range. Subsequent acoustic performance analysis for the Melamine foam cell should then also consider not only viscous dissipation, but also oscillatory heat transfer effects.

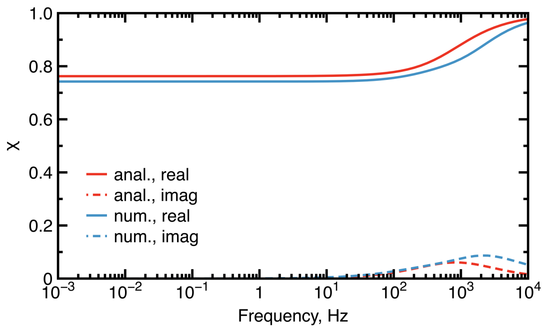


Figure 14. Real and imaginary parts of the χ coefficient, indicating the transition from isothermal to adiabatic thermal behaviour.

Macroscopic Acoustic Performance

Lastly, the analytical dynamic viscous drag force, oscillatory heat transfer and cell elasticity expressions can be implemented in a Transfer Matrix Method (TMM) solution of the governing momentum and fluid dilatation expressions [1, 3], thus allowing acoustic performance prediction.

In the TMM model, only the Melamine foam cell microgeometry, and the Melamine resin and air constitutive properties were used to simulate acoustic and structural wave propagation through a 51 mm thickness of the material. The impedance tube absorption coefficient was predicted and compared to published measurements [8]. Except for the very lowest frequencies, where sample edge effects can influence the measurements, the predicted results correspond to the measurements exceptionally well, as shown in Fig. (15).

Of note is that once the cell geometry and material parameters have been chosen, the resulting acoustic performance is predicted in seconds, making this approach very well suited for design investigation and optimisation. In a later step, final design verifications may then be made using the much more numerically costly 3D finite element procedures if necessary.

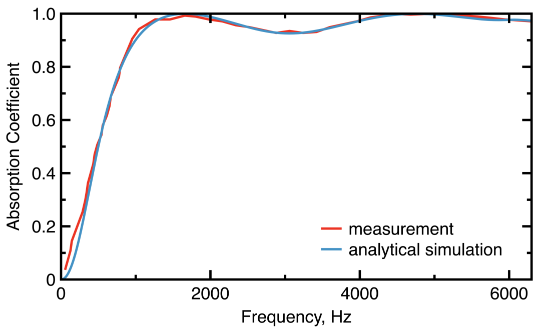


Figure 15. Estimated normal-incidence absorption coefficient for a 51 mm thickness sample of the Melamine foam cell array. Note that the measurements are adopted from [8] with acknowledgement.

Conclusions

In this work, we have demonstrated the successful extension of our analytical-based poroelastic modelling approach for highly porous fibrous materials, towards open-celled foam materials, under the assumption that the struts of the foam are primarily cylindrical.

We have utilized high-fidelity finite element simulations in COMSOL Multiphysics® as a controlled "virtual laboratory", in order to validate the extension of the analytical dynamic viscous drag force, oscillatory heat transfer and analytical foam cell elasticity expressions towards usage for the open-cell Melamine foam application.

At the microscopic level, the approach yields dynamic viscous drag force and oscillatory heat transfer results very similar to the reference 3D finite element simulations. At the macroscopic level, the subsequent prediction of the acoustic behaviour of a finite sample of Melamine foam material yields results which very closely match experiments.

This efficient analytical approach presented here provides a very good representation of the governing physics of porous materials, meaning that new designs for open-cell foams and lattice microstructures can be efficiently investigated virtually, without the need for actual material samples required for the inverse estimation of transport parameters.

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