

Modeling and Characterization of a Novel Porous Metallic Foam Inside Ducts

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ABSTRACT

A novel porous metallic foam has been studied in this work. This composite material is a mixture of resin and hollow spheres. It is lightweight, highly resistive to contamination and heat, and is capable of providing similar or better sound absorption compared to the conventional porous absorbers, but with a robust and less degradable properties. Several configurations of the material have been tested inside an expansion chamber with spatially periodic area changes. Bragg scattering was observed in some configurations with certain lattice constants. The acoustic properties of this material have been characterized from the measurement of the two-port matrix across a cylindrical sample. The complex density and speed of sound can be extracted from the transfer matrix using an optimization technique. Several models were developed to validate the effect of this metallic foam using Finite Elements and the Two-port Theory. There was a good agreement between both models and the measurement results.

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INTRODUCTION

Acoustic absorptive fiber materials from basalt are widely used in automotive silencer systems. Usually, fibers from these materials are set loose and are emitted through the exhaust opening. There is a continuous interest in developing new materials which provide similar acoustic properties to the fiber materials but do not degrade with time. Mechanical and chemical degradation of the fiber material reduces the performance of the silencer system. The performance of the muffler is optimized when the truck or car leaves the factory but decreases during the lifetime of the vehicle.

Since performance, weight and economy constantly are under consideration regarding the choice of material; new materials are always of great interest if they can improve the performance.

To optimize the performance and also to be able to use them in simulation programs their acoustic properties need to be known and therefore they need to be tested. Different materials can exhibit similar acoustic properties by changing their bulk densities. In porous materials the attenuation capabilities are mainly determined by the static airflow resistivity. This is known from the work of Delany and Bazley [1]. This means that if the airflow resistivity of the material is known many acoustical properties, i.e., transmission loss,

characteristic impedance, speed of sound, absorption and reflection coefficient can be predicted with a great accuracy.

If the speed of sound and the characteristic impedance are known, then a complete description of the material can be made using the equivalent fluid model of Mechel, 1976 [2]. This model characterizes the fibrous or porous material as a homogenous fluid but with a complex speed of sound and characteristic impedance.

The material under consideration is a novel robust porous metallic absorber [3] made up of stainless steel and can withstand temperatures up to 900°C, shown in Figure 1. Acoustical properties of the material were studied in this work and were found to be comparable to the conventional porous absorbers.

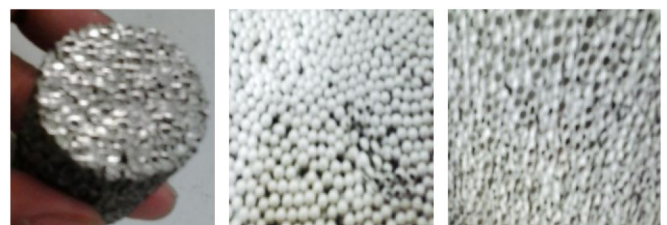


Figure 1. The porous metallic foam.

THEORY

Two Port Theory

Duct systems or networks acting as acoustic wave guides are assuming linear wave propagation suitable for analysis using so called building block or matrix methods. When the low frequency regime is considered, and plane wave propagation can be assumed, this approach leads to the two-port transfer matrix method, as described in [4]. This method splits the system into several smaller duct parts, acoustic elements, in which the sound propagation is well defined. Since plane acoustics waves propagate between different elements the sound field can be characterized by two state variables. One convenient choice is to use acoustic pressure p and volume velocity v . The sound propagation inside each element is analyzed separately and higher order modes can exist inside the element.

There exists a complex frequency dependent 2×2 matrix, T , the so called two port transfer matrix, which describes the sound transmission within a certain two port element. The acoustic pressure and volume velocity on each side of the element can be related with the following expression

$$\begin{bmatrix} p_1 \\ v_1 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} p_2 \\ v_2 \end{bmatrix} \quad (1)$$

where p and v are the acoustic pressure and volume velocity, the subscript 1 refers to the inlet side (or node) and 2 refers to the outlet side (or node), and T_{ii} are the elements of the two-port transfer matrix.

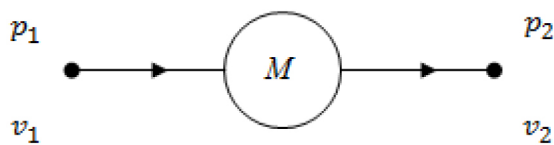


Figure 2. Representation of a two port element relating two pairs of state variables 'p' and 'v'.

Assuming the acoustic state vectors to be Acoustic Pressure ' p ' and Acoustic volume velocity ' v ', as shown in Figure 2. By making use of standing-wave relation Munjal [4] derived the four parameters which resulted in closed form relationship for a pipe element can be written as,

$$\begin{bmatrix} p_2 \\ v_2 \end{bmatrix} = \begin{bmatrix} \cos k_a h & i\zeta_s \sin k_a h \\ (i/\zeta_s) \sin k_a h & \cos k_a h \end{bmatrix} \begin{bmatrix} p_1 \\ v_1 \end{bmatrix} \quad (2)$$

where $k_a = \omega/c_a$, the complex wave number, with c_a =complex speed of sound, h = sample thickness (m), and $\zeta_s = Z_a/Z_0$ is the normalized characteristic impedance.

Calculation of Equivalent Material Properties

If the acoustic impedance $Z = \frac{p}{v}$ can be derived from the sample transfer matrix, a couple of acoustical properties can be calculated.

The transfer matrix equation is,

$$\begin{bmatrix} p_3 \\ Z_0 v_3 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} p_4 \\ Z_0 v_4 \end{bmatrix} \quad (3)$$

For a rigid backed sample, $v_4=0$, and this implies that

$$\begin{bmatrix} p_3 \\ Z_0 v_3 \end{bmatrix} = \begin{bmatrix} T_{11} p_4 \\ T_{21} p_4 \end{bmatrix} \quad (4)$$

The input impedance can now be calculated as:

$$Z_3 = \frac{p_3}{v_3} = \frac{T_{11} Z_0}{T_{21}} \quad (5)$$

If we assume that the equivalent fluid model can describe the sample, and that the sample is homogenous along the centre of the sample, then Transfer matrix must have the form as in equation 2.

One way to determine the complex speed of sound is to form the complex exponential from the elements of T.

$$e^{(ik_a h)} = \frac{(T_{11} + T_{22} + T_{12}/\zeta_s + \zeta_s T_{21})}{2} \quad (6)$$

From this it is possible to derive the complex wave number as,

$$k_a = \frac{\ln(T_{11} + T_{22} + T_{12} + T_{21})}{ih} \quad (7)$$

k_a is a complex wave number; physically, it means the plane wave attenuates as it propagates, the energy lost by the wave is converted to heat energy in the porous material.

The complex density of sound and complex density for the material can also be written as

$$c_a = \omega/k_a \quad (8)$$

$$\rho_a = Z_a k_a / \omega \quad (9)$$

The final property that can be calculated from the normalized transfer matrix is the transmission loss with the expression,

$$TL = 10 \log \left(\frac{1}{4} |T_{11} + T_{22} + T_{12} + T_{21}|^2 \right). \quad (10)$$

Optimization Process

The reason behind the optimization was that other indirect schemes such as by Åbom [5] and others [6, 7, 8, 9] were not able to give correct material properties such as Flow Resistivity. One of the reasons for such a behavior is the complex shape and profile of this metallic foam, which is neither proper porous foam nor a simple

fibrous material. This optimization method was based on a function called “fminsearch” from the Optimization toolbox within MATLAB. This function finds the minimum of a scalar function of several variables, starting at an initial estimate. The optimization approach used by this function is generally referred to as unconstrained nonlinear optimization. The measured Transmission loss, TL for a specimen as in Figure 8 was compared with Transmission loss of a random specimen which was given an initial value for complex speed of sound and complex density, c_a and ρ_a . Simultaneously the elements of the Transfer matrix, T'_s (Eqn. 27) were also compared in the same fashion. Finally the total error (cost function) was calculated as the sum of errors in Transmission loss and Transfer matrix elements and forwarded as the input to the optimization function. The process is repeated by the optimization function till the total error reaches its minima. The output from the optimization function was the complex speed of sound and complex density which can be used for characterizing the porous material. These values were further linearly interpolated as per need and then used in simulations for evaluating the performance of the specimen. This method of optimizing the parameters to match a transfer function (TL and TM in this case) is called “model updating” [10]. The flowchart for the optimization technique is depicted in Figure 3.

Models

The complex speed of sound and complex density which were the output of the optimization function were fed to two different software for a comparative performance analysis of two different modeling methods: Two port theory and Finite elements method.

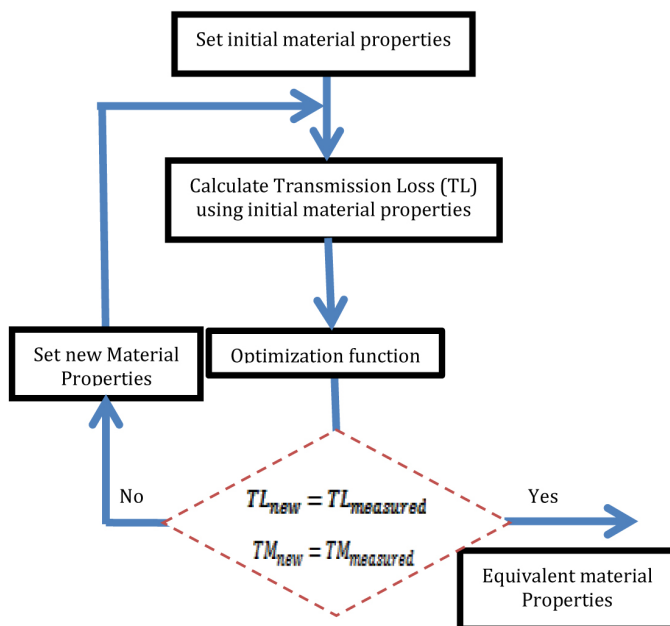


Figure 3. A Flowchart illustrating the optimization scheme. TM symbolizes the Transfer Matrix elements and TL symbolizes Transmission Loss.

Several different cases were modeled using the 1D duct acoustic software SIDLAB [11] implementing the two port theory and COMSOL implementing the Finite element method. The porous material was assumed to follow an equivalent fluid model and

complex speed of sound and complex density was the only input for characterizing this model. Figure 4 shows realization of an expansion chamber in form of 1D SIDLAB circuit. Figure 5 shows the surface response of the sound Pressure level (dB) of three dimensional expansion chamber with one annular ring of the porous material fixed at the centre.

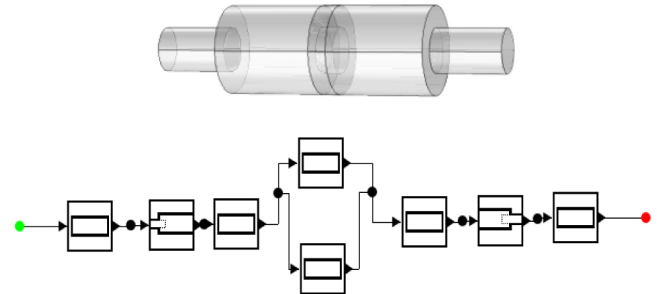


Figure 4. An expansion chamber with the porous material ring at the centre. At bottom, SIDLAB representation of the expansion chamber with the porous material ring.

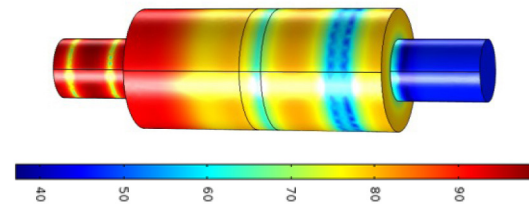


Figure 5. Surface SPL (dB) response of the expansion chamber with a porous material ring at the centre simulated in COMSOL.

Measurement of Transfer Matrix

By measuring the input and the output of a system, a transfer matrix that describes the system can be derived.

$$\hat{y} = T_{tot} \hat{x} \quad (11)$$

In this expression $\hat{x}$ and $\hat{y}$ are acoustic state vectors that describe the input and the output of the system. T_{tot} is the 2×2 matrix that describes the system. Since the matrix contains four unknowns, four equations are needed in order to solve the system of equations. This means that two pairs of state vectors are needed and this can be accomplished either by changing the termination of the duct or by changing the sound source, from upstream speaker (A) to downstream speaker (B). The first method is called “the two-load method” and the second method is called “the two-source method”. Since it has been shown by Åbom, 1990 [12] that better results are obtained with “the two-source method”, this is the method used in this paper. Considering a test set up as in Figure 6, the task is to determine the acoustic two-port across the sample. As discussed earlier, the choice of variables used in this work are pressure (p) and the volume velocity (v).

The test rig has 6 microphone positions. The microphones are numbered (1-6) from right to left in Figure 6. The distance from the sample to the closest microphone is denoted by l . h is the sample thickness.