ACOUSTIC MODEL FOR SHODDY-BASED FIBRE ABSORBERS

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1. INTRODUCTION

As the world becomes more mechanized and increasing populations push people closer together, the need for sustainable noise reduction and control methods become ever more important to maintain individual comfort and quality of life. Post-industrial and post-consumer recycled fibres, otherwise known as 'shoddies' have been used in the manufacture of fibrous noise absorbers for many years. Shoddies as a raw material have historically been a low cost, lower quality alternative but have recently garnered more attention as a sustainable alternative since they are sourced from diverted waste streams and are fully recyclable. The acoustic behaviour of shoddies is not well understood when compared to more ubiquitous porous materials such as fiberglass and certain polymeric foams. Designers must therefore rely on predictive models that are either highly complex or simpler models developed for different materials. Complex models such as the model developed by Biot[1] require several material properties that may be difficult to measure. Simpler models include those developed by Delaney and Bazley[2] for fiberglass and Garai and Pompoli[3] for PET fibres but to the author's knowledge no model exists for shoddy fibres.

This project seeks to investigate the acoustic behaviour of sound absorbers composed primarily of shoddy fibres and to create a simple predictive acoustic model based on the materials bulk density only. The model is semi-empirical, semi-phenomenological based on the equivalent fluid hypothesis.

2. METHOD

The sample set for this study consisted of three shoddy-based fibrous materials manufactured by three different techniques: thermal bonding, resin bonding and mechanical bonding. For each material, three constructions (unique combination of bulk density and thickness) were tested. Materials were tested directly for airflow resistivity and porosity. Static thermal permeability, viscous characteristic length and thermal characteristic length were determined using the indirect methods of Panneton-Olny[4,5]. Characteristic impedance, complex wavenumber and absorption were measured using an impedance tube for frequencies from 300 - 4000Hz. Empirical formulas were then derived that linked each parameter to the material's bulk density. In addition, estimates of the distribution of fibre diameter within each of the three materials were made based on a microscope analysis.

Several popular equivalent fluid models were chosen and populated with one or more of the parameters measured above depending on the complexity of the model. These models include: the model of Delaney and Bazley, two models proposed by Miki[6], the model of Johnson[7] in conjunction with the model of Champoux-Allard[8], and the model of Johnson in conjunction with the model of Lafarge[9]. Each model was evaluated based on its ability to effectively predict the materials characteristic impedance and normal incidence absorption and the most accurate model selected.

3. RESULTS

Estimates on the average fibre diameter for each material are as follows: mechanically bonded - 19.4μm, thermally bonded - 23.8μm, resin bonded - 19.7μm.

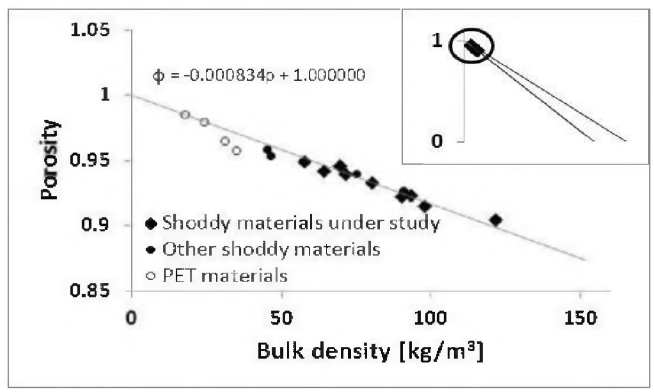

Figure 1. Porosity as a function of bulk density.

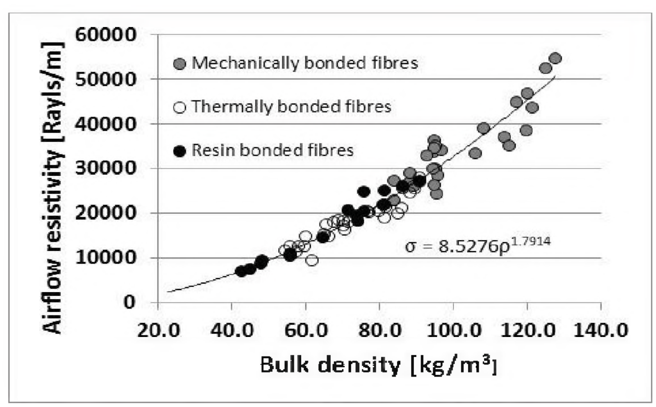

Figure 2. Airflow resistivity as a function of bulk density.

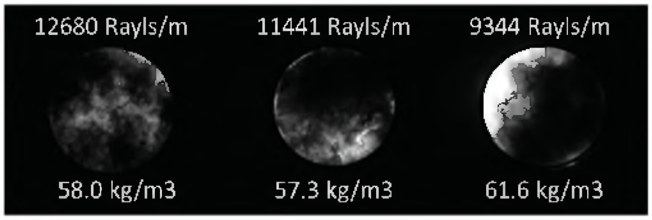

Figure 3. Effect of web inhomogeneity on flow resistivity.

Table 1. Expressions linking model parameters to bulk density

Porosity (ϕ)	$1-\phi = 0.000834\rho$
Flow resistivity (σ)	$\sigma = 8.527\rho^{1.7914}$ [Rayls/m]
Tortuosity (α_∞)	$\alpha_\infty = 1$
Viscous char. length (Λ) Thermal char. length (Λ') [mech. bonded = mb] [thermally bonded = tb] [resin bonded = rb]	$\Lambda_{mb} = 28.1$, $\Lambda'_{mb} = 3.415\rho^{-1.928}$ x10^5 $\Lambda_{tb} = -0.746\rho+104.9$ $\Lambda'_{tb} = -0.755\rho+156.0$ $\Lambda_{rb} = -0.874\rho+115.6$ $\Lambda'_{rb} = -1.416\rho+182.3$ [μm]
Static therm. perm. (k_0')	$k_0' = 44.55\rho^{-1.269}$ [x10^{-8} m^2]

4. DISCUSSION AND CONCLUSIONS

Figure 2 shows the porosity to bulk density relationship with porosity defined as ϕ = 1 - [solid volume/total volume]. For highly porous samples the differences in measured porosity is negligible between similar materials as illustrated in the top right inset chart of figure 2. As most shoddy-absorbers are manufactured with a high porosity, a single expression linking porosity to bulk density was chosen to describe the behaviour of all three material types.

Shoddy fibre absorbers are inherently more variable than homogeneous fibre materials. Poor textile recycling, dense fibre packing, poor fibre blending and adhesives cause localized differences in the web bulk density as shown in figure 3. Unfortunately these inhomogeneities occur on a scale at or near the sample size for measuring flow resistivity and acoustic parameters by standard means. This leads to scatter in the sample measurements. On average, the flow resistivity can be predicted well but individual results may vary widely. The effect can be mitigated by using a larger test sample, however, these tests are more expensive and labour intensive. The second pronounced effect is a microscopic one. Raw shoddy contains a haphazard mix of different fibre types and sizes and characterizing the microstructure for use in predictive models is difficult. Each material will possess a distinct flow resistivity - bulk density relationship that is dependent on fibre diameter. However, due to the uncertainty in the measurement of the average fibre diameter, the scatter in the resistivity vs. density data and in the interest of simplicity, a single power law expression has been chosen to reflect the dependence of airflow resistivity on bulk density for all three material types. The estimates of average fibre diameter may be used with a modified Bies-Hansen formulation[10] to derive individual flow-resistivity to density formulas for each material but the improvement is doubtful considering the variation in individual tests. Average fibre diameters are suggested to provide a reference for validity of the model in terms of fibre size and to enable comparisons with other models where fibre diameter is considered.

Table 1 summarizes the individual parameter's dependence on bulk density. Tortuosity is assumed to be unity as highly-porous fibrous materials regularly display a tortuosity very near to 1. The model exchanges a minor loss in precision for this simplification. Charts of the characteristic lengths and static thermal permeability have been omitted for brevity. The behaviour of the characteristic lengths is such that individual expressions relating the characteristic lengths to bulk density for each material type are chosen in favour of general expressions. The behaviour of thermally bonded and resin bonded materials are similar and adhere remarkably well to the 2:1, $\Lambda':\Lambda$ ratio predicted by the theoretical expression for the characteristic lengths of highly porous fibre materials[11]. The behaviour of the mechanically bonded material begins to differ at high bulk densities, but it should be noted that at these densities, the mechanically bonded samples are approaching porosities for which highly porous assumptions are no longer valid. The method chosen for determining the characteristic lengths relies on acoustic measurements to determine the dynamic density and dynamic bulk modulus. The results of these tests can be affected by the web inhomogeneity problem. By comparing the characteristic lengths, acoustic results, flow resistivity tests and bulk density data, erratic samples were filtered out and were not considered in the derivation of the characteristic length - bulk density relations.

After populating each selected model with the relations outlined in table 1, the most accurate model at predicting acoustic indicators was the model of Johnson-Lafarge. It is suggested that this model be used to predict the acoustic behaviour of shoddy-based sound absorbers. The test samples are a good representation of the range of densities and thicknesses of the material that are commercially produced and the model is considered valid within this range.

REFERENCES

[1]Biot, J. Acoust. Soc. Am., 28, 168 (1956).
[2]M.E. Delany and E.N. Bazley, Applied Acoustics, 3, 105 (1970)
[3]M. Garai and F. Pompoli, Applied Acoustics, 66, 1383 (2005)
[4]R. Panneton and X. Olny, J. Acoust. Soc. Am., 119, 2027 (2006)
[5]R. Panneton and X. Olny, J. Acoust. Soc. Am., 123, 814 (2008)
[6]Y. Miki, J. Acoust. Soc. Japan, 11, 19 (1990)
[7]D.L. Johnson et al, J. Fluid Mech. 176, 379 (1987)
[8]Y. Champoux and J.F. Allard, J. Appl. Phys. 20, 1975 (1991)
[9]D. Lafarge et al. J. Acoust. Soc. Am., 102, 1995 (1997)
[10]D.. Bies and C.H. Hansen, Applied Acoustics, 13, 357 (1980)
[11]J.F. Allard, Propagation of sound in porous media, Elsevier, NY (1993).