NOVEM
10-12 JANUARY • AUCKLAND • NEW ZEALAND 2023

COMPARING ACOUSTIC PREDICTION METHODS FOR ADDITIVELY MANUFACTURED POROUS STRUCTURES

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ABSTRACT

While macroscale methods for predicting the acoustic properties of porous structures have been popular in the past, they often require time-consuming manufacturing and testing workflows. Meanwhile, microscale approaches allow the prediction of transport parameters based exclusively on a periodic structure's unit cell geometry. Here, we compare these methods to predict the characteristic impedance of additively manufactured porous structures. We use the microscale approach to estimate the geometry's transport parameters, then predict the characteristic properties using the Johnson-Champoux-Allard (JCA) model. We measure the acoustic properties of the printed structures using a normal incidence impedance tube and estimate the transport parameters using an inverse characterization approach. We use the two-thickness method as a macroscale approach to predict the characteristic properties from the measured surface impedances of two sample thicknesses. Finally, we compare these characteristic prediction methods. Our results show that the inverse characterization and two-thickness methods offer the closest match to the measured values at low frequencies.

1 INTRODUCTION

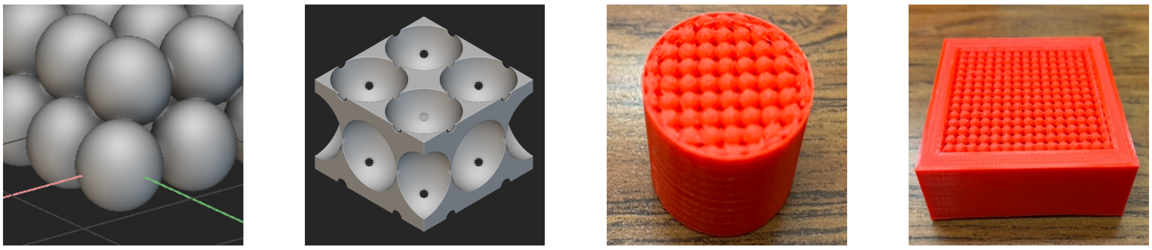
Predicting a porous structure's characteristic acoustical properties, such as its characteristic impedance, Z_c, and propagation constant, Γ, is an important step for designing noise mitigation structures with desired sound absorption characteristics. Traditional macroscale prediction methods often rely on expensive and time-consuming fabrication and testing of multiple samples to educe these thickness-independent characteristic properties. Recently proposed numerical approaches offer an alternative method to predict these properties [1]. These numerical methods rely on the prediction of the periodic porous structure's unit-cell-dependent transport properties [2], such as porosity, φ, tortuosity, α_∞, flow resistivity, σ, viscous characteristic length, Λ_v, and thermal characteristic length, Λ_{th}. These transport properties are then used within semiempirical prediction models, such as the Johnson-Champoux-Allard (JCA) model, to predict the required characteristic impedance and propagation constant—a measure of change in amplitude and phase per unit distance—and their dependence on the porous structure's various geometrical parameters.

In the presented work, our focus is on comparing the prediction accuracy of the microscale modeling method, the inverse characterization approach, and the two-thickness macroscale method. We use a simple 3D printed porous bead pattern as the target absorptive structure. The printed structure is tested using the normal-incidence impedance tube method, and the measured acoustic impedance spectra are used to predict the characteristic impedance using the inverse characterization method and the two-thickness method. Simultaneously, the unit cell microscale modeling approach is used to predict the structure's transport properties, which are then used within the JCA model to predict the characteristic impedance. Below, we outline the workflows used for the three methods and compare their predictions to the experimentally measured characteristic impedance, Z_c, and propagation constant, Γ.

2 METHODS

We use three methods to predict the characteristic properties of the simple porous bead structure: microscale modeling, inverse characterization, and macroscale modeling using the two-thickness method. The characteristic properties predicted by each method are then compared with experimental measurements conducted using the four-microphone normal impedance tube method.

We model the simple bead pattern using the commercially available implicit modeling software nTopology (nTop). Each bead is a 3.4-mm-diameter sphere, and the beads within each layer are placed between the beads of the neighboring layer, as shown in Figure 1(a).



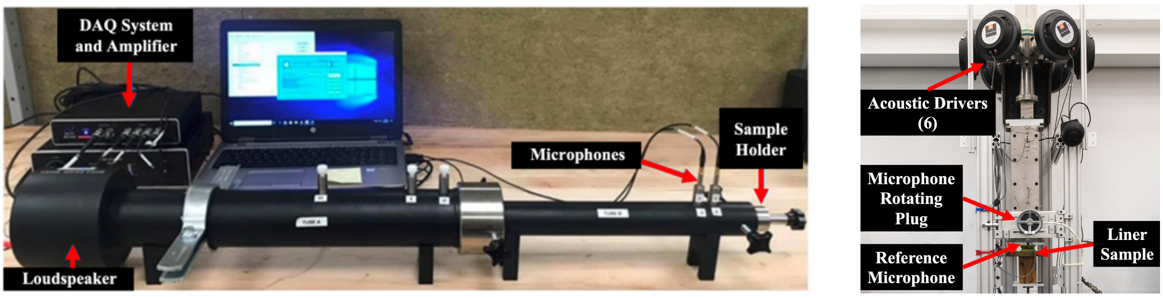
(a) (b) (c) (d)

Figure 1. (a) Bead pattern depiction; (b) the unit cell of the fluid domain; (c) a printed 30-mm diameter sample; (d) a 50.8-mm square sample for use in the two-thickness method.

We create a unit cell of the fluid domain within nTop, as shown in Figure 1(b). In this example, nTop calculated the porosity to be 0.265. Then, three partial differential equations as defined in Ref. [2] to account for the inertial, viscous, and thermal effects. These boundary value problems are solved to predict the transport parameters based on the input unit cell geometry. We use COMSOL Multiphysics to conduct this microscale approach.

We print all samples using an Ender 5 Pro FDM desktop printer with standard polylactic acid (PLA) material and a 0.12-mm layer height, as shown in Figures 1(c-d). We print cylindrical samples to conduct a two-microphone test using a normal-incidence impedance tube with the setup shown in Figure 2(a). Using an inverse characterization approach, the measured absorption curve and sample porosity are used to estimate the remaining transport parameters. For both the microscale and inverse characterization approaches, we use the semiempirical JCA model to predict the required acoustical properties, Z_c and Γ.

For the macroscale modeling approach, additional samples are printed to be compatible with the square-shaped normal incidence tube (NIT) used at the NASA Langley Research Center (Figure 2(b)). A simplified two-thickness method is implemented by the structural acoustics team at NASA Langley as outlined in Ref. [3]. This method assumes the porous samples to be uniform; any inconsistencies in the 3D printing process could affect the accuracy of the results. This macroscale approach provides another method to estimate the characteristic properties.



(a) (b)

Figure 2. Normal-incidence impedance tube setups used: (a) Wichita State, (b) NASA Langley Research Center.

Finally, since all three modeling methods estimate the characteristic properties, we conduct a four-microphone normal-incidence impedance tube test to offer the measured Z_c and Γ as a comparison. For each model, the characteristic impedance is used to predict the absorption coefficient and surface impedance for a porous bead sample with a thickness of 38.1 mm using the process implemented by Ref. [4].

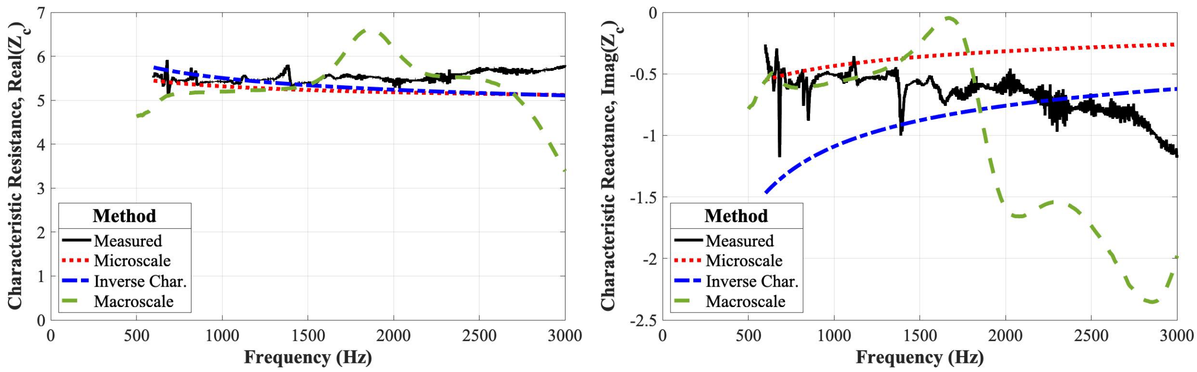
3 RESULTS AND DISCUSSION

As shown in Table 1, the microscale approach correctly matches the modeled porosity within nTop of 0.265. However, this modeled porosity is lower than the measured porosity of the printed structure, 0.301, indicating possible errors in the 3D printing process. These two prediction methods differ greatly on the airflow resistivity, and the microscale method predicts the characteristic lengths to be roughly twice those of the inverse characterization approach.

Table 1. Transport parameters obtained using microscale modeling and inverse characterization. Measured values are denoted by an asterisk.

Prediction Method	Porosity, φ	Tortuosity, α_∞	Resistivity, σ (Pa s/m^2)	Visc. Length, Λ_v (μm)	Therm. Length, Λ_{th} (μm)
Microscale	0.265	1.651	3,647	251.6	419.6
Inverse Characterization	0.301*	1.801	19,034	104.9	236.9

Figure 3 compares the characteristic impedance, Z_c (normalized by ρc), from the three prediction models with that measured using the four-microphone method (solid line). While all three models offer reasonable matches to the characteristic resistance at frequencies less than 1500 Hz, they differ at higher frequencies. Microscale and inverse characterization methods offer the closest match to the measured data; inaccuracies in the two-thickness method may be due to a lack of uniformity in the 3D printed samples. Similar trends were observed while predicting the propagation constant, Γ, inverse characterization offers the closest match to the measured values. Therefore, results for Γ are excluded for brevity.



(a) (b)

Figure 3. Normalized characteristic (a) resistance and (b) reactance.

As shown in Figure 4, the microscale method incorrectly predicts both resistance and reactance. Meanwhile, the inverse characterization and two-thickness approaches correctly identify the frequency location of the relative extrema throughout the frequency range, but they incorrectly predict the magnitude, especially for the surface resistance.

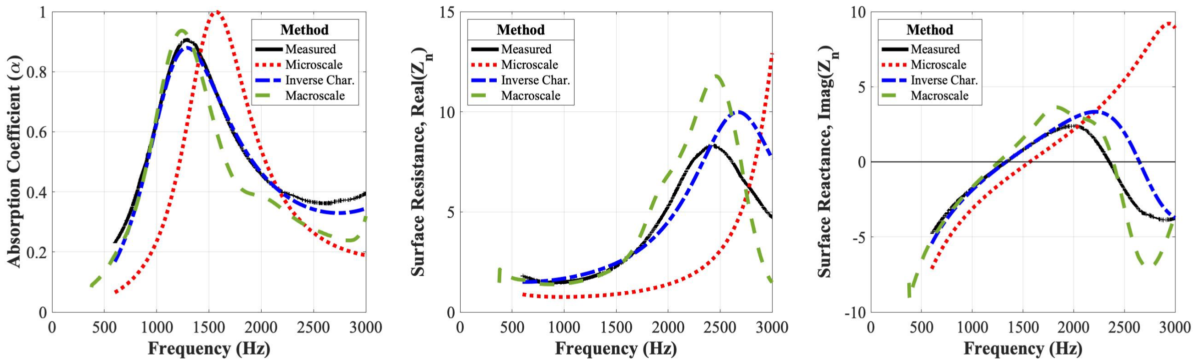


Figure 4. (a) Absorption coefficient, (b) normalized surface resistance and (c) reactance predictions for a 38.1 mm sample.

4 CONCLUSIONS

While none of the prediction models offer a precise match to the experimental data, the inverse characterization and two-thickness approaches offer reasonable predictions for the characteristic impedance at frequencies less than 1500 Hz. Dimensional differences between the modeled bead structure in nTop and the printed structures are identified as one possible cause of the microscale approach to be the least accurate. As a result, future work will include analyzing the dimensional errors in the 3D printing process and modeling a unit cell with enhanced accuracy. Eventually, this work will progress to more complex classes of porous structures.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Amulya Lomte of Wichita State University for her assistance in this project. William Johnston would also like to acknowledge the support of the Kansas Space Grant Consortium, which is supported by the National Aeronautics and Space Administration under Cooperative Agreement No. 80NSSC20M0109.

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