Acoustic Characterisation of Thin Layer Nanofibers

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The acoustic absorption of porous media can be significantly improved by adding a nanofiber layer on the incident surface. Through acoustic characterisation of the nanofiber layer, a predictive model for nanofiber-porous systems was established. Subsequently, relating the nanofiber morphology to it's acoustic parameters allows the design of nanofiber-porous systems directly from fabrication parameters.

1 Introduction

The impact of nanofiber layers on acoustic absorption of a porous substrate has been demonstrated in [1, 2] and shown to be influenced by areal density [3]. Statistical optimisation of different configurations using multi-criteria decision analysis was investigated in [4]. Nanofibers as a bulk material were shown to be more absorptive than conventional porous media of equal thickness [5, 6] and acoustically characterised using the limp-frame model by [7] for predicting absorption coefficient. Artificial neural networks were also used to carry out similar predictions [8].

This work focuses on the acoustic characterisation of nanofibers as a thin layer to enable transfer matrix modelling of nanofibers over porous substrates, henceforth referred to as nanofiber-porous systems. Building on prior work on nanofibers [9] and resistive layers [10], the characterisation methodology for resistive screens in [11] was applied to nanofibers to inversely derive JCA [12] parameters and a lumped acoustic impedance. A relationship with nanofiber physical properties was then obtained using regression.

2 Sample Fabrication and Measurement

The electrospinning precursor was PA6 polymer solution at 5%, 10% and 15% concentration, giving nanofibers of different diameters measured using SEM imaging and DiameterJ [13]. Varying the electrospinning duration gave samples of different areal densities and layer thickness together with a standard PP non-woven fabric backing was measured using a Hanatek FT3 Precision Thickness Gauge as per ISO 9073-2:1995 with foot pressure of 0.5kPa. Static flow resistance was measured using a TexTest F3300 at the lowest possible flow velocity for each sample. Static flow resistivity σ, porosity ϕ and areal density ρ_A were computed from these measurements for comparison with acoustically-characterised values.

3 Characterisation Methods

The nanofiber samples were framed using sheet Mylar for consistency of mounting in the impedance tube over an air cavity. Based on simplifying assumptions of identical, parallel cylindrical perforations from [14], the nanofiber dynamic mass density $\tilde{\rho}_{\text{c,nf}}$ was computed from surface impedance measurements using Eqn 13 from [11], which also details the derivation of JCA parameters to give characteristic acoustic impedance Z_c and wave number k_c. A lumped acoustic impedance Z_L was also computed by subtracting the analytical solution for surface impedance of the air gap from the same measurements. The melamine foam substrate was characterised using the two thickness method [15].

4 Results and Discussion

The characterised JCA and lumped element parameters were used in transfer matrices to model nanofiber-porous systems and predict absorption coefficient for comparison with measurement. Higher polymer concentration gave larger fiber diameters and pore sizes, resulting in lower flow resistance for the same areal density. The reduction in absorption coefficient was not proportional with change in flow resistance and this is still being studied. Nevertheless, within each batch of the same concentration, increasing areal density via longer electrospinning duration gave proportionately higher flow resistance and absorption coefficient. Results for the best performing batch are shown in Figure 1.

4.1 Prediction vs Measurement

Strong agreement in absorption coefficient was observed using both the JCA and lumped element models for samples A1-A5 in nanofiber-porous systems while in sample A6 the peak frequency was slightly over-predicted. Hypothesised causes were vibrational waves in the nanofiber layer or flow distortion at the nanofiber-porous interface. Biot theory [16] was used to account for the former and for the latter, dynamic tortuosity correction [14] was applied to the JCA parameters and an empirical offset added to $\mathrm{Im}(Z_L)$. This offset was based on the $(1 + \delta/\Lambda)$ factor observed in the high frequency expression of mass density in Equation 4 of [14] comprising the boundary layer thickness δ and viscous characteristic length Λ. Predictions with these 3 approaches are shown together with measurement in Figure 1; the $(1 + \delta/\Lambda)$ offset gave the best agreement and will be the subject of further study.

4.2 Physical vs Acoustic Characterisation

Directly-measured σ and ϕ exhibited some correlation with acoustically-characterised values within each batch of nanofibers, but differed by several orders of magnitude as similarly observed in [17]. In this context, the JCA parameters derived via [11] serve as effective values for modelling purposes. This disparity is another area of investigation, possibly via other methods of obtaining JCA parameters such as in [18].

To establish the feasibility of predicting nanofiber acoustic performance directly from physical parameters, Z_L was simplified into the constants $\mathrm{Re}(Z_L)$ and $\Delta\mathrm{Im}(Z_L)$ for regression model outputs. Applying iterative forward selection to physical parameters as regression model inputs, ρ_A was identified as the primary predictor for $\mathrm{Re}(Z_L)$ and $\Delta\mathrm{Im}(Z_L)$ while the latter output also had fiber diameter as a secondary predictor, giving R^2 of 0.8 to 0.9 at 95% confidence interval.

This regression model is the first step towards a design tool for specifying acoustic performance directly from electrospinning parameters. The application of the $(1 + \delta/\Lambda)$ offset to Z_L predicted from this regression without *a priori* characterisation of Λ will also be further investigated, alongside more detailed regression modelling using JCA parameters as outputs.

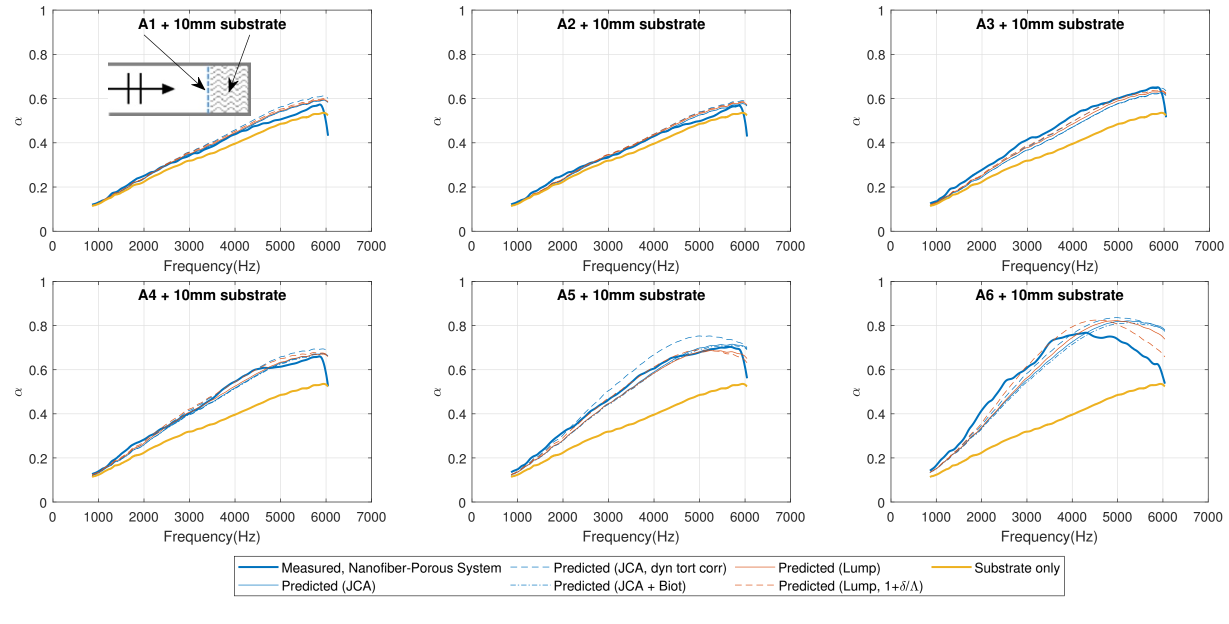

Figure 1: Predicted and measured absorption coefficients for nanofiber-porous systems (5% conc, 10mm thick substrate) with corrections applied. A1 to A6 are in increasing order of areal density.

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