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Sound Absorption Characteristics of Membrane-Based Sound Absorbers

J Stuart Bolton
Purdue University, bolton@purdue.edu

Jinho Song

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http://docs.lib.purdue.edu/herrick/25

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Sound Absorption Characteristics of Membrane-Based Sound Absorbers

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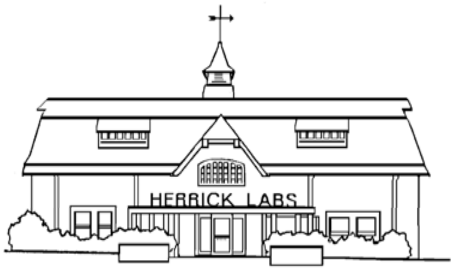
Jinho Song and J. Stuart Bolton

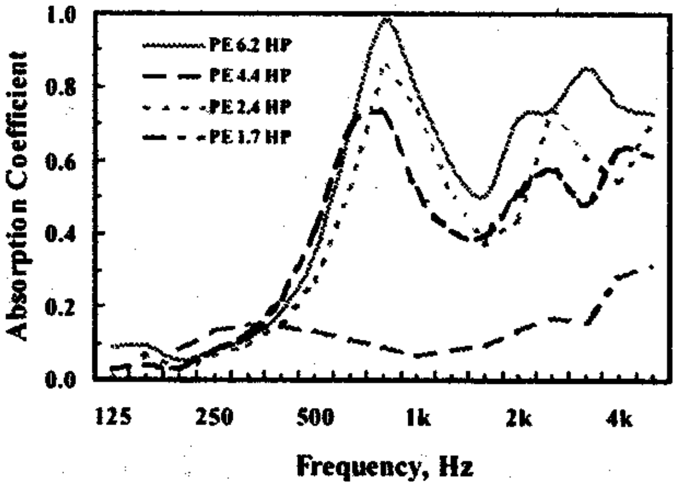
Ray W. Herrick Laboratories

Purdue University



Motivation

- Recently, it has been observed that
  - ◆ *Macro-cellular polyolefin foams (e.g.,Quash-like) absorb sound energy even though the foams are mostly closed-celled and the average cell size is very large.*



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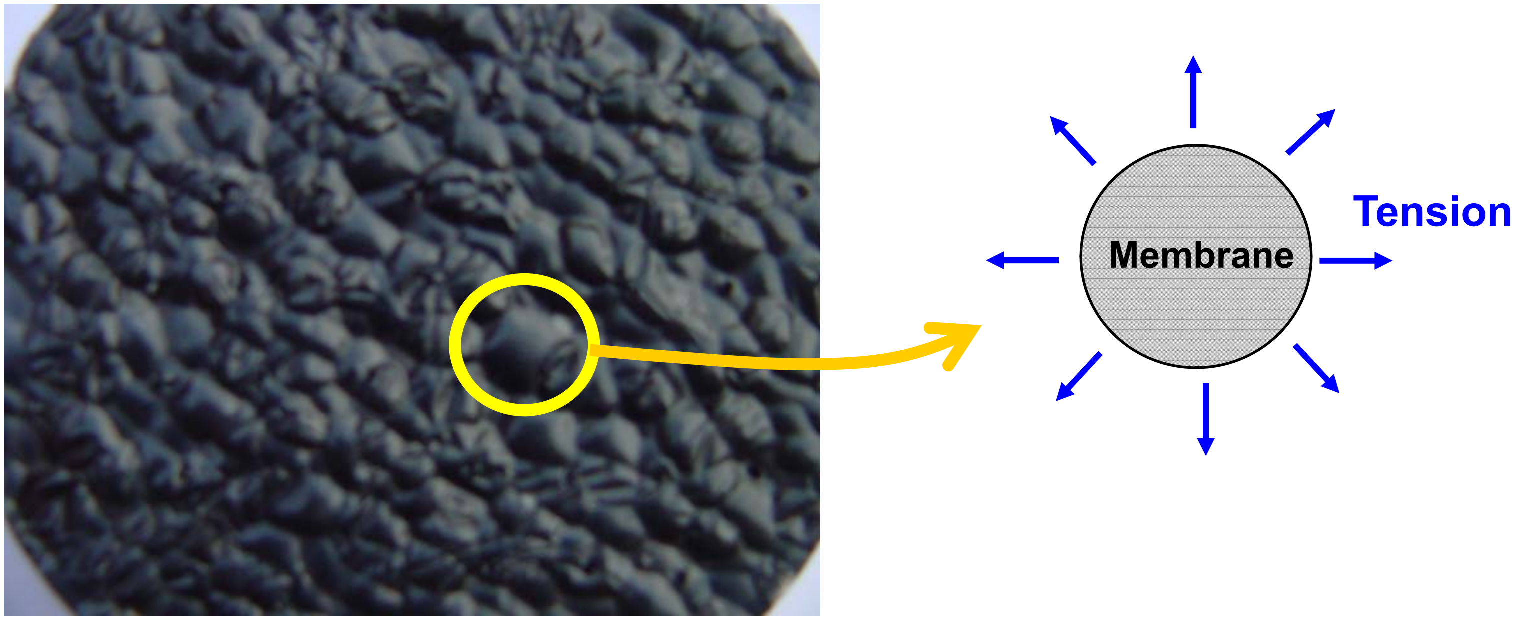
- How does this sound absorption arise?
- How do you model this effect?

* C. Park *et al.*, New Sound-Absorbing Foams from Polyolefin Resins, *Proc. of Inter-Noise 2000*, pp 583-586, 2000

Quash Membrane Model

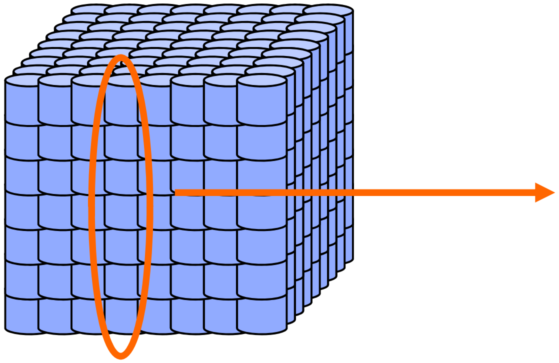
- To this point, model is based on tensioned membranes
- Stiffness of this model is provided by tension of membrane

Top View of Quash

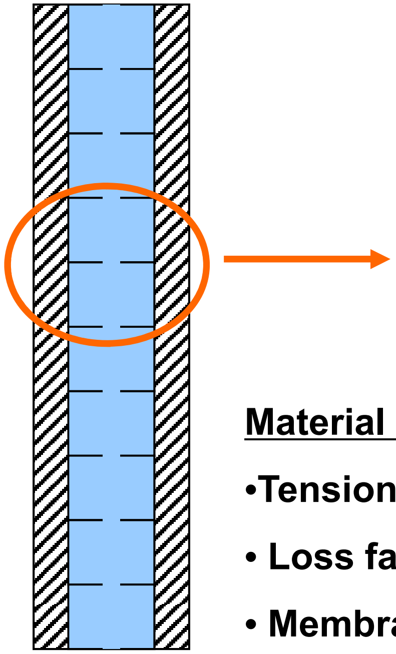


Foam Modeling Procedure

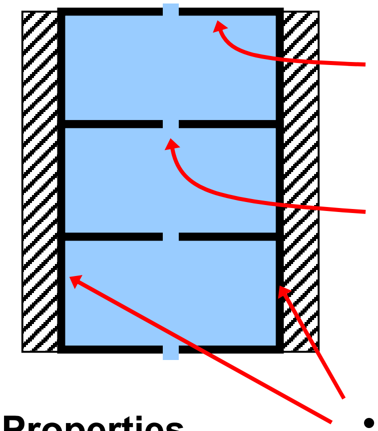
3-D Model



2-D Model



Sound Energy Loss Mechanisms

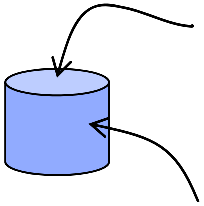


- Energy dissipation by membrane flexure
- Viscous loss through perforation
- Thermo-viscous boundary layer effect

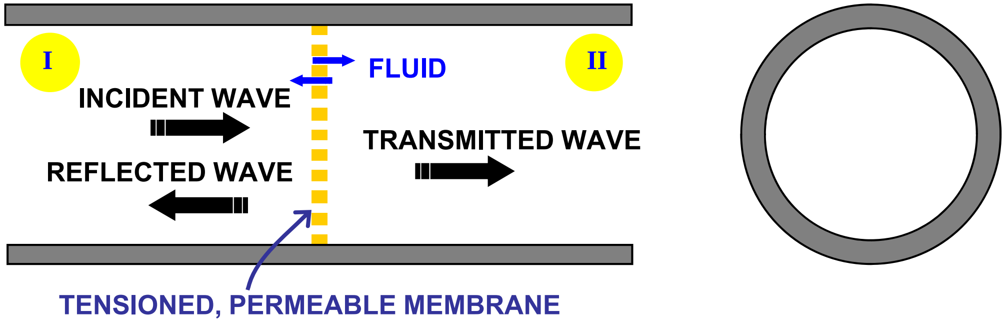
Material Properties

- Tension
- Loss factor
- Membrane Density
- Surface Film Density
- Porosity
- Flow Resistance

Unit cell



Theoretical Model - Permeable Membrane



Assumed Solutions

- Sound Pressures in Acoustic Cavities:

$$P_{\mathrm{I}}(r,z) = e^{-jkz} + \sum_n B_n J_{\mathrm{o}}(k_{r_n} r) e^{jk_{z_n} z}$$

$$P_{\mathrm{II}}(r,z) = \sum_n C_n J_{\mathrm{o}}(k_{r_n} r) e^{-jk_{z_n} z}$$

- Membrane Displacement (Solid Component):

$$y(r,t) = \sum_n A_n J_o(k_{0_n} r)$$

- Membrane Displacement (Fluid Component):

$$u(r,t) = \sum_n F_n J_o(k_{0_n} r) + F_o$$

Theoretical Model – Solution Method

- Boundary Conditions

- The Continuities of Velocity at the Both Side of a Membrane:

$$-\frac{1}{j\omega\rho_{\mathrm{o}}}\frac{\partial P_{\mathrm{I}}}{\partial z}\bigg|_{z=0} = (1-\Omega)\frac{\partial y}{\partial t}+\Omega\frac{\partial u}{\partial t}$$

$$-\frac{1}{j\omega\rho_{\mathrm{o}}}\frac{\partial P_{\mathrm{II}}}{\partial z}\bigg|_{z=0} = (1-\Omega)\frac{\partial y}{\partial t}+\Omega\frac{\partial u}{\partial t}$$

- The Force Equilibrium Equation in the Membrane:

$$\nabla^2 y-\frac{\rho_s}{T}\frac{\partial^2 y}{\partial t^2}-\frac{R_f}{T}\frac{\partial(y-u)}{\partial t} = -\frac{(1-\Omega)}{T}(P_{\mathrm{I}}-P_{\mathrm{II}})$$

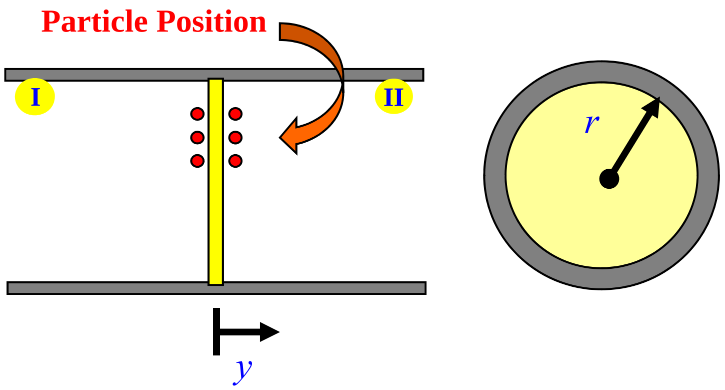
$$\rho_{\mathrm{o}}\Omega h\frac{\partial^2 u}{\partial t^2}-R_f\frac{\partial(y-u)}{\partial t} = \Omega(P_{\mathrm{I}}-P_{\mathrm{II}})$$

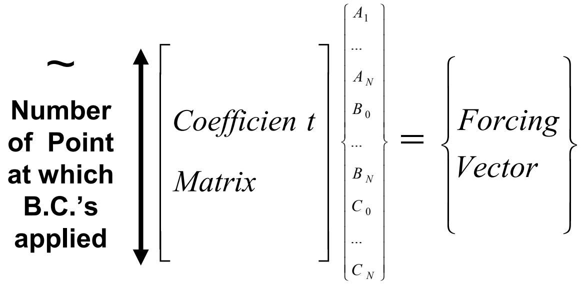
where

$$T=T_{\mathrm{o}}(1+j\eta) \qquad \Omega=N\pi a^2/A \qquad P_{front}-P_{back}=R_f v_f$$

- Solution Method

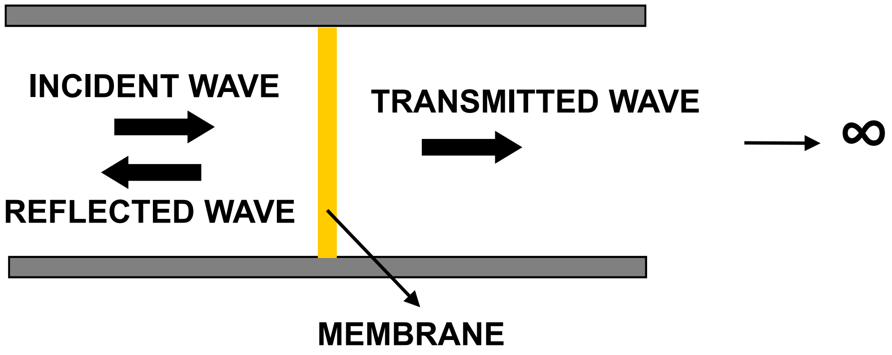
Apply four boundary conditions on a point-by-point basis across the membrane





$$\underbrace{\begin{bmatrix} Coefficient \\ Matrix \end{bmatrix}}_{\text{Number of Point at which B.C.'s applied}} \begin{Bmatrix} A_1 \\ \cdots \\ A_N \\ B_0 \\ \cdots \\ B_N \\ C_0 \\ \cdots \\ C_N \end{Bmatrix} = \begin{Bmatrix} Forcing \\ Vector \end{Bmatrix}$$

Energy dissipation by Membrane



Measurement

Sound Pressure from microphones

Estimation

Fourier Bessel coeff. of Incident / Transmitted Waves

Normal Incident Reflection coeff.: R

Transfer Impedance of Membrane :

$$Z_m = (1+R) / (1-R) - \rho_o c$$

Transfer Matrix Method

- Membrane & Air Cavity Transfer Matrix

$$[T_m] = \begin{pmatrix} 1 & Z_m \\ 0 & 1 \end{pmatrix} \qquad [T_a] = \begin{pmatrix} \cos(k\cdot(l_2-l_1)) & i\rho_o c\sin(k\cdot(l_2-l_1)) \\ \dfrac{i}{\rho_o c}\sin(k\cdot(l_2-l_1)) & \cos(k\cdot(l_2-l_1)) \end{pmatrix}$$

- Total Transfer Matrix

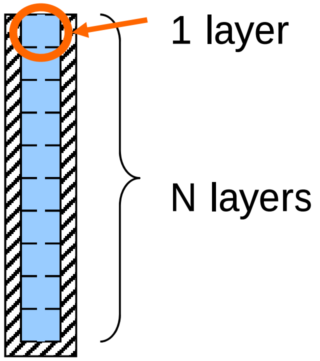
$$\begin{Bmatrix} P_{Top} \\ u_{Top} \end{Bmatrix} = \left[T_{total}\right] \begin{Bmatrix} P_{Bottom} \\ u_{Bottom} \end{Bmatrix} \qquad [T_{total}] = \overbrace{\underbrace{[T_{m_s}][T_a]}_{\text{1 layer}}[T_m][T_a]\;\cdots\cdots\;[T_m][T_a]}^{\text{N layers}}$$

- Reflection Coefficient

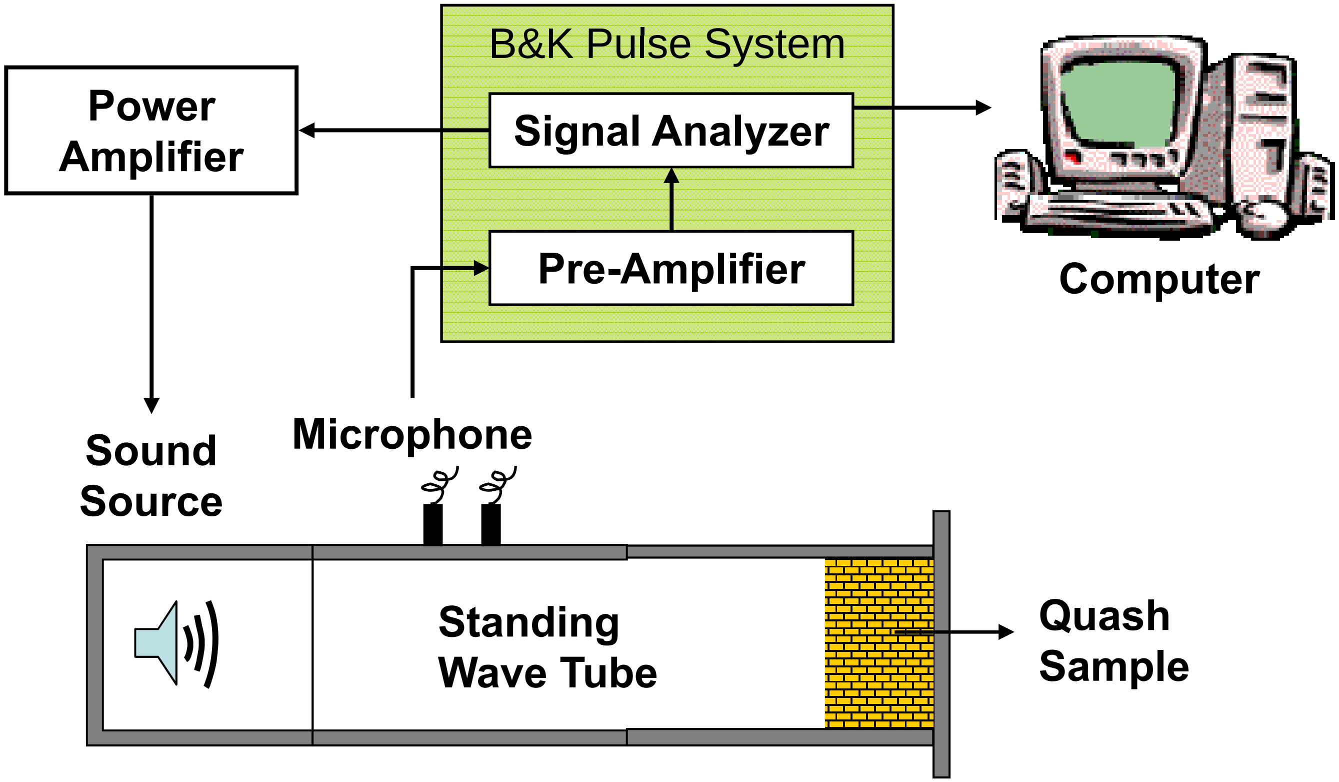
$$R_{Top} = \frac{Z_{Top} - \rho_o c_o}{Z_{Top} + \rho_o c_o}$$

- Absorption Coefficient

$$\boxed{\alpha = 1 - \left|R_{Top}\right|^2}$$

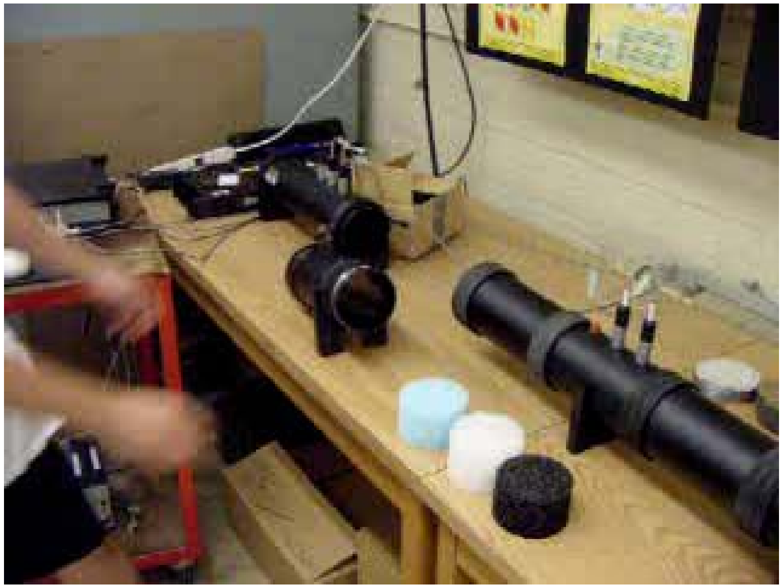


Experimental Set-up



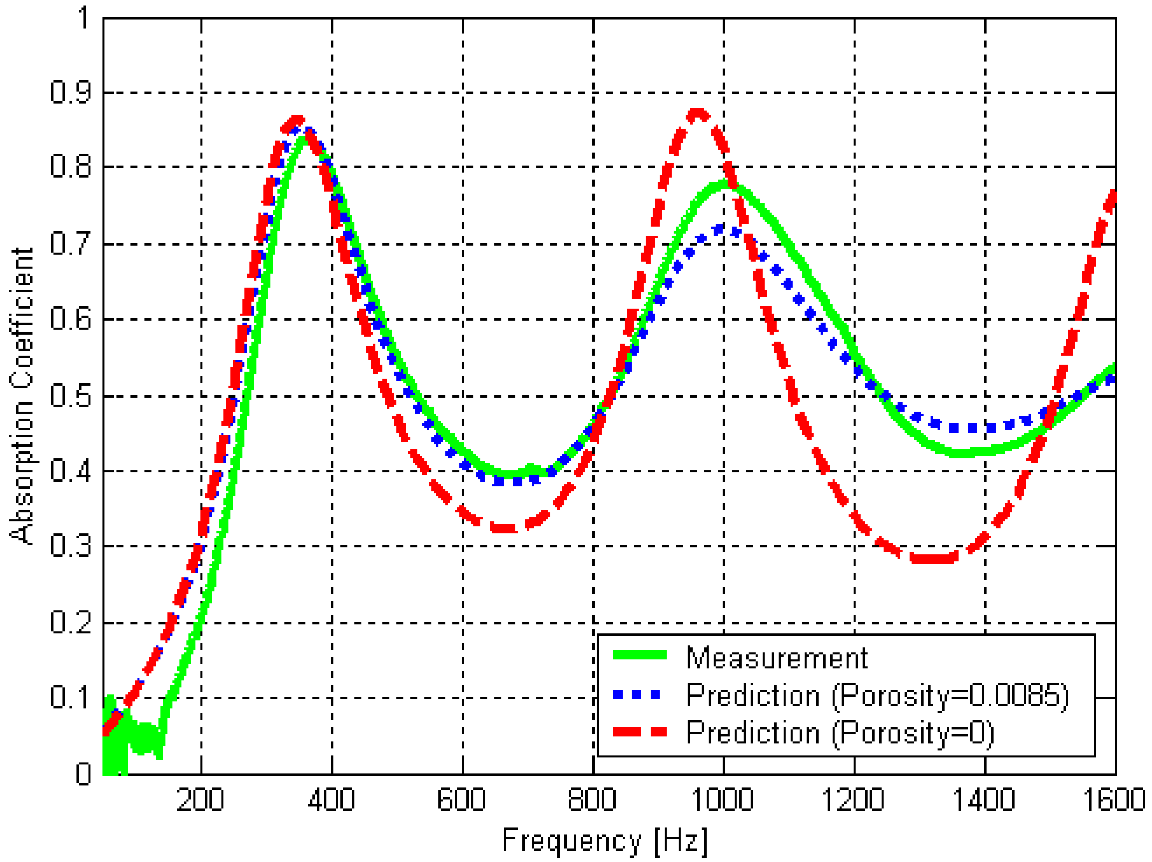
Experimental Set-up

<u>Loading Quash Sample</u>



<u>Measurement Set-up</u>

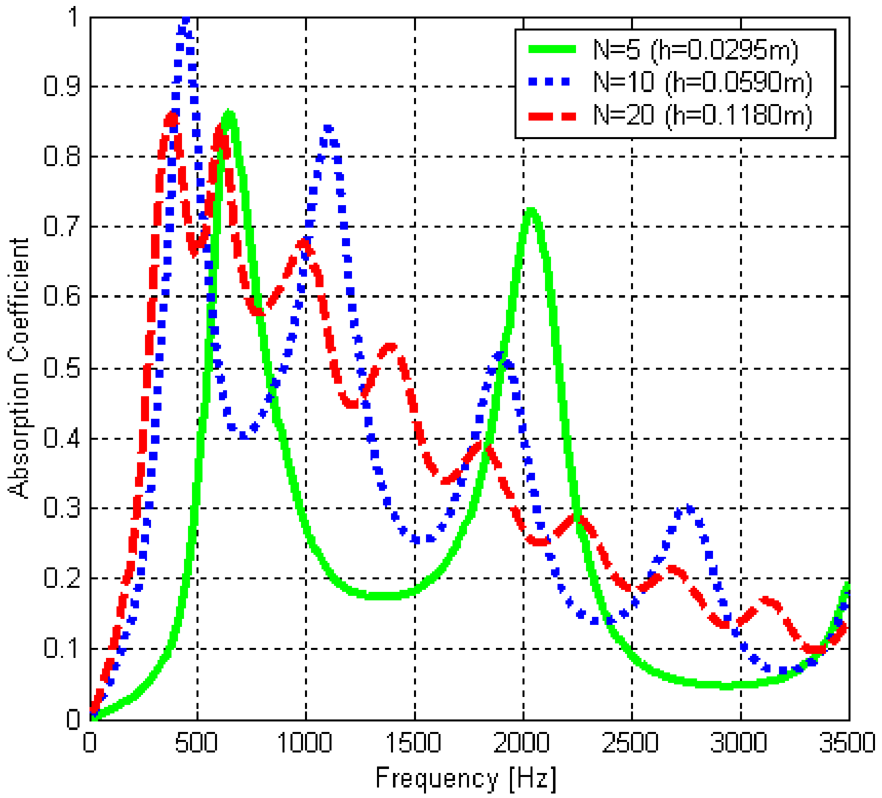
Comparison of Measurement and Prediction



ρ_m=0.0885 kg/m^2, T_o=0.13 N/m, η=1.6, m_s=0.1586 kg/m^2, Ω=0.0085,
R_f=0.286 Rayls, t=0.0002 m, d_o=0.00486 m, h=0.05832 m, N=12.

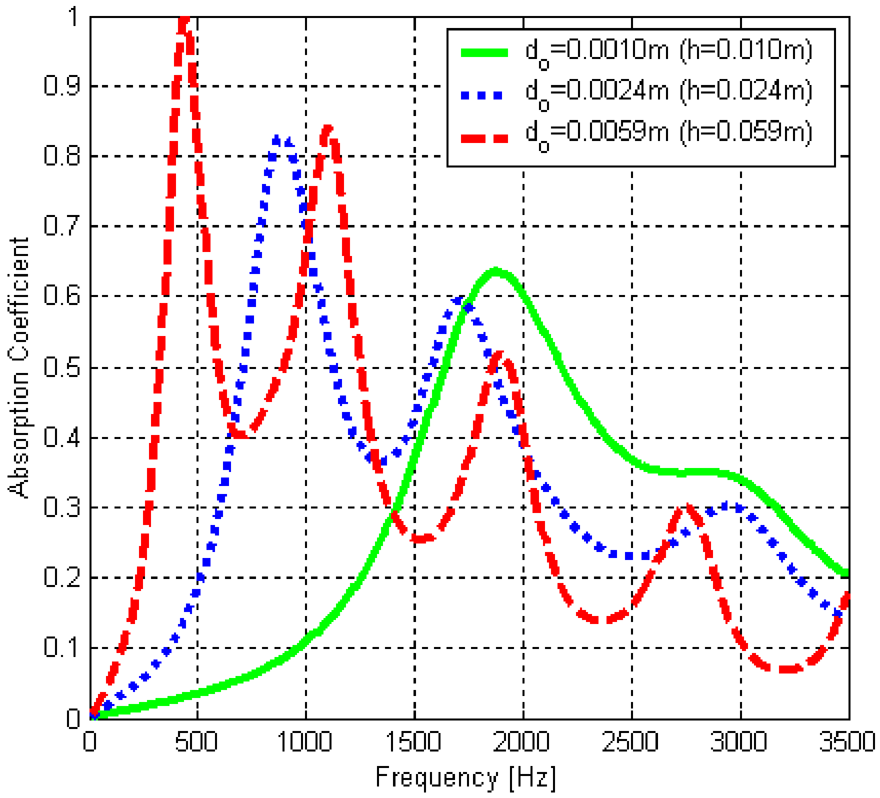
Parameter Effects on Sound Absorption

Foam Thickness



ρ_m=0.07 kg/m^2, To=0.5 N/m, η=0.7, m_s=0.2 kg/m^2, Ω=0.01, R_f=0.2 Rayls, t=0.0002 m, d_o=0.0059 m,

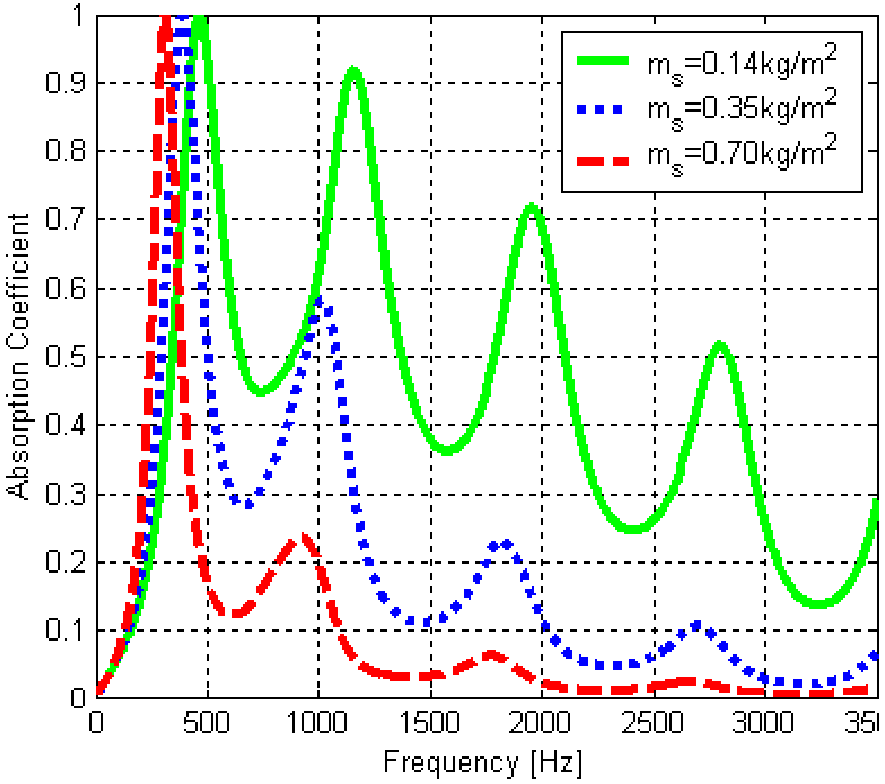
Membrane Size



ρ_m=0.07 kg/m^2, To=0.5 N/m, η=0.7, m_s=0.2 kg/m^2, Ω=0.01, R_f=0.2 Rayls, t=0.0002 m, N=10

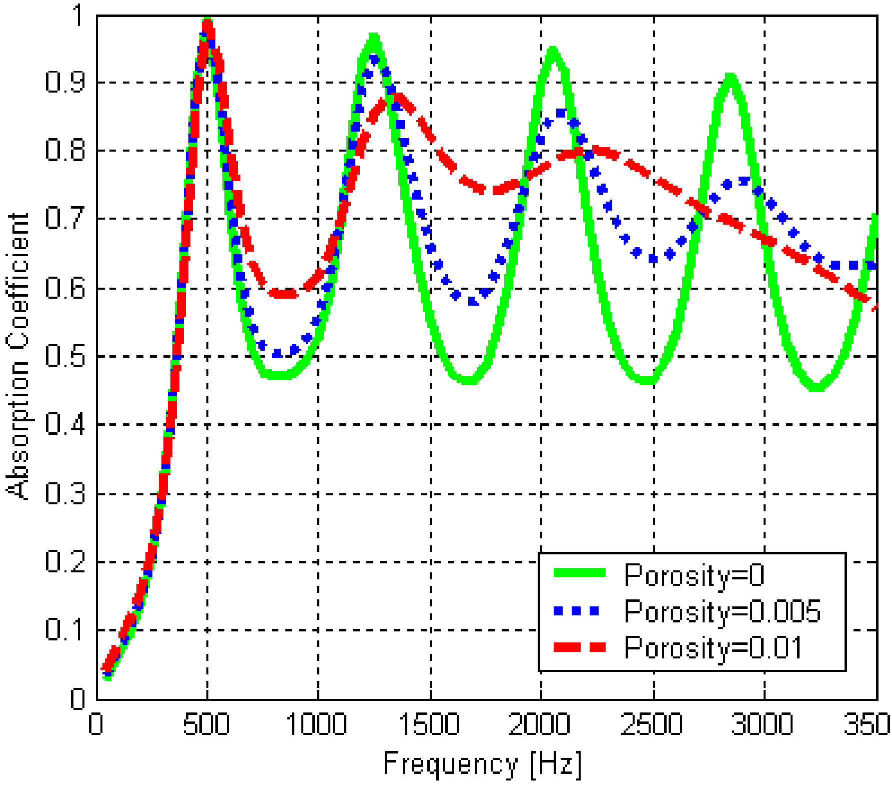
Parameter Effects on Sound Absorption

Surface Mass



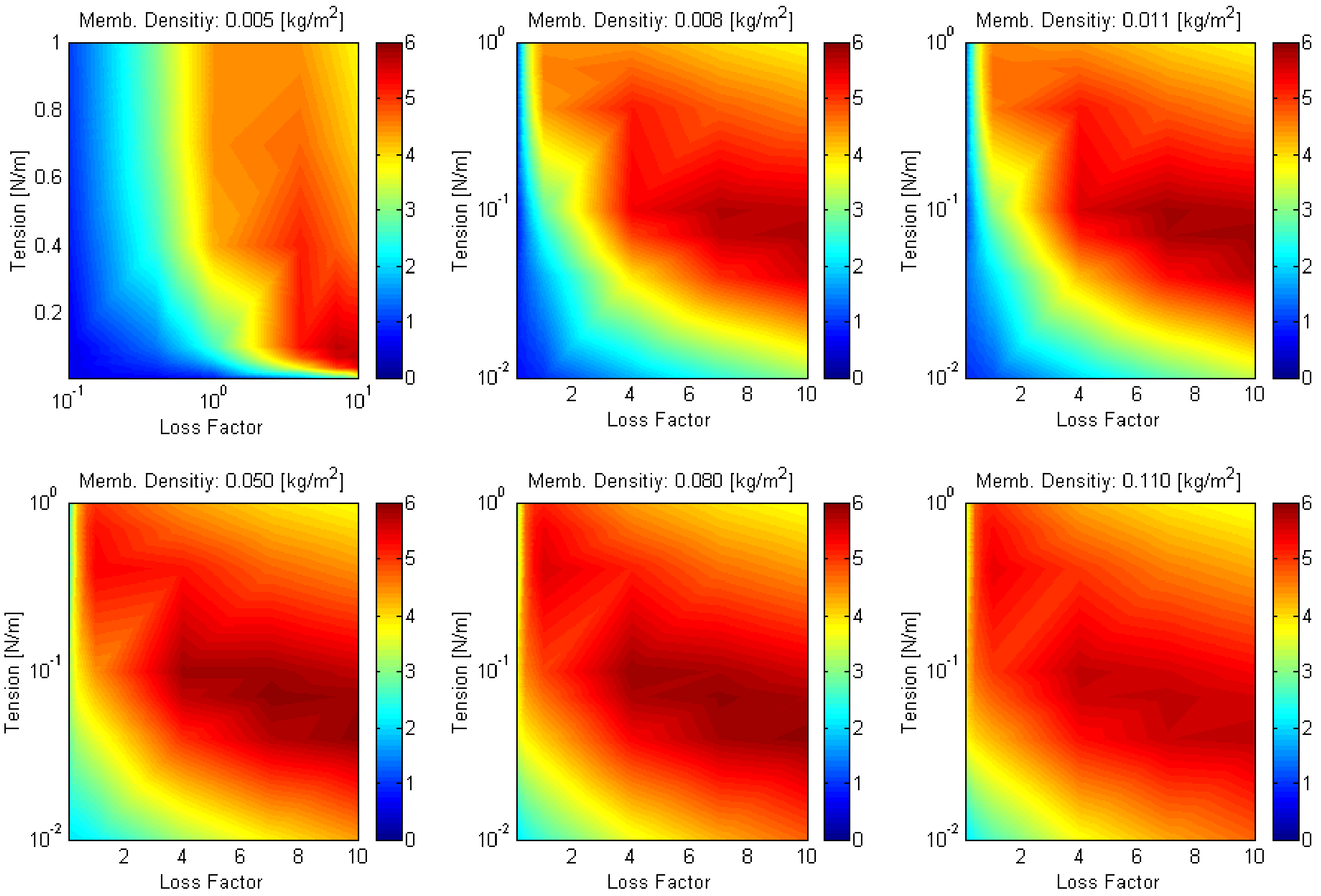
ρ_m=0.07 kg/m^2, To=0.5 N/m, η=0.7, Ω=0.01,
R_f=0.2 Rayls, t=0.0002 m, d_o=0.0059 m, N=10

Membrane Porosity



ρ_m=0.07 kg/m^2, To=0.5 N/m, η=0.7, m_s=0.07 kg/m^2,
R_f=0.2 Rayls, t=0.0002 m, d_o=0.0059 m, N=10

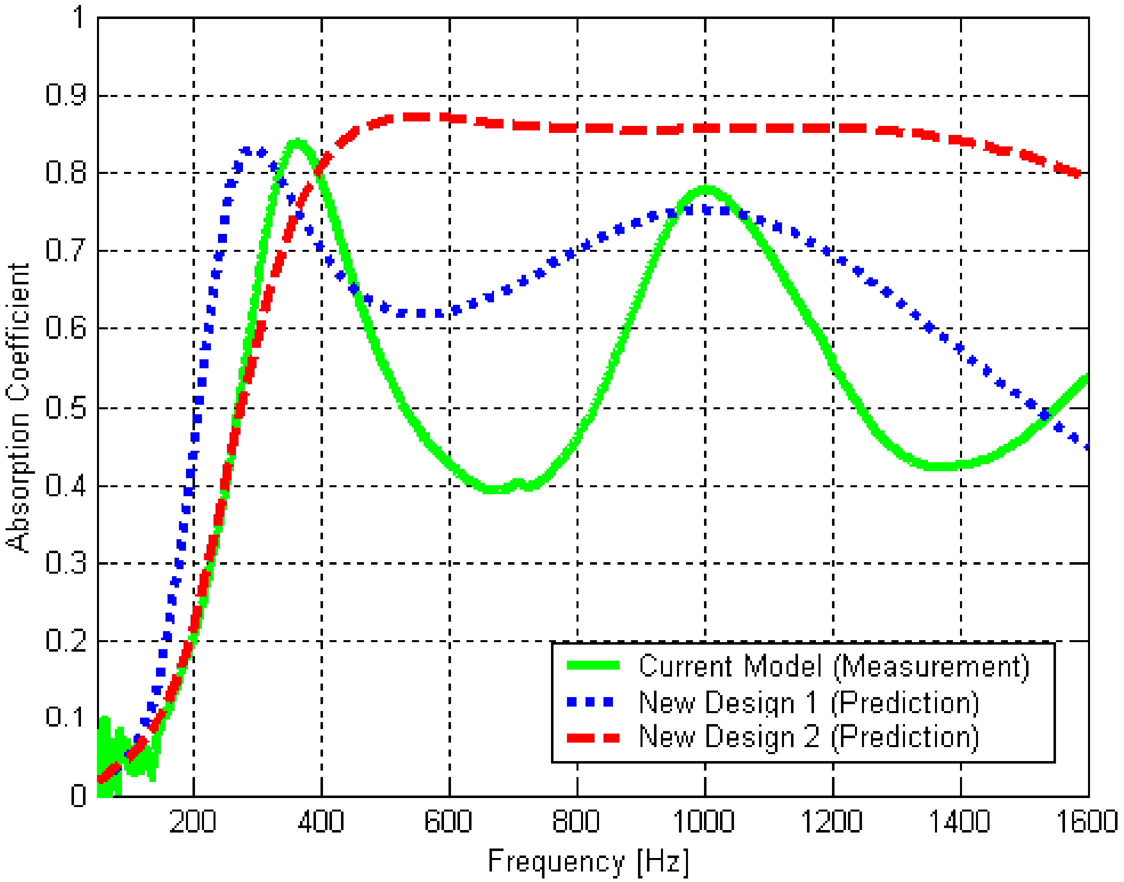
Parameter Effects on Sound Absorption



m_s=0.2135 kg/m^2, Ω=0.0, R_f=0.2 Rayls, t=0.0002 m, d_o=0.0056 m, h=0.056 m, N=12

(1/3-octave band normal incidence absorption averaged from 125 Hz to 1600 Hz)

Some High Absorption Designs



New Design 1

ρ_m=0.2213 kg/m^2(↑),
T_o=0.065 N/m (↓), η=1.6,
m_s=0.1941 kg/m^2(↑), Ω=0.02(↑),
R_f=0.286 Rayls, t=0.0002 m,
d_o=0.00583 m(↑), h=0.0583 m,
N=10(↓)

New Design 2

ρ_m=0.1770 kg/m^2(↑),
T_o=0.13 N/m, η=1.6,
m_s=0.0970 kg/m^2 (↓), Ω=0.03(↑),
R_f=0.286 Rayls, t=0.0002 m,
d_o=0.00583 m(↑), h=0.0583 m,
N=10 (↓)

Conclusions & Future Work

- An acoustical model for membrane-based sound absorbing materials was presented and was verified experimentally on the basis of acoustical measurements.
- It has been found that the theoretical model can accurately reproduce the acoustical behavior of the particular foam studied here.
- It was shown that the choice of particular combinations of material properties can result in improved sound absorption.
- The present work can provide the foundation necessary to design membrane-based sound absorbing materials having enhanced sound absorption capacity.
- The present work implies that alternative stiffness mechanisms of membrane systems such as flexural stiffness, membrane curvature, bulk elasticity, and membrane inhomogeneity, can also result in sound dissipation in membrane-based foams; this work will be presented in the future.