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Sound Absorption Characteristics of Membrane-Based Sound Absorbers

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Seogwipo, Jeju, Korea
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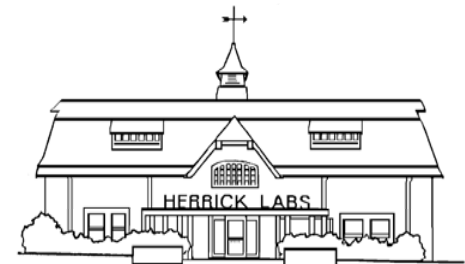
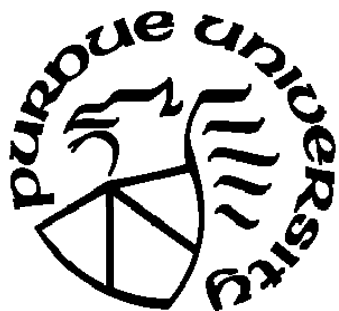
Sound Absorption Characteristics of Membrane-Based Sound Absorbers

August 28th, 2003

Jinho Song and J. Stuart Bolton

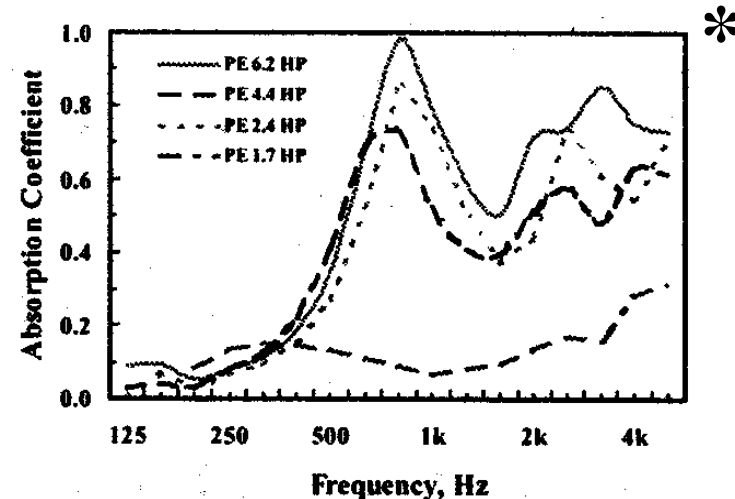
Ray W. Herrick Laboratories

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.*



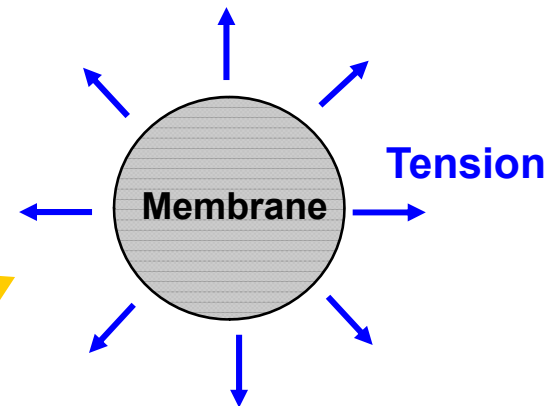
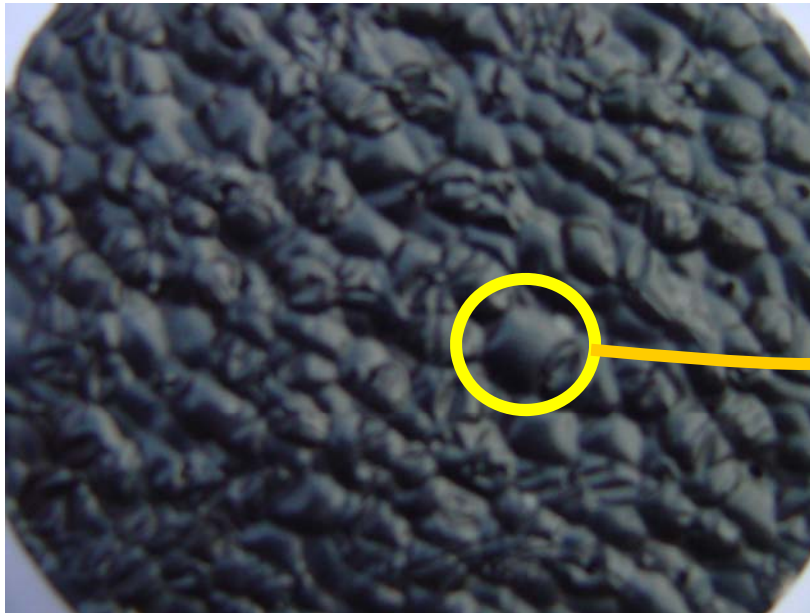
- How does this sound absorption arise?
- How do you model this effect?

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

Quash Membrane Model

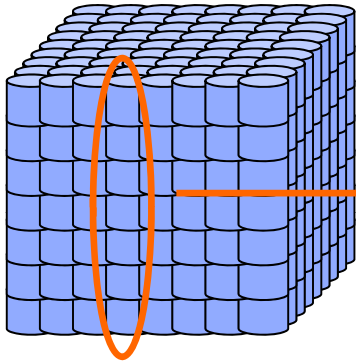
- To this point, model is based on tensioned membranes
- Stiffness of this model is provided by tension of membrane

Top View of Quash

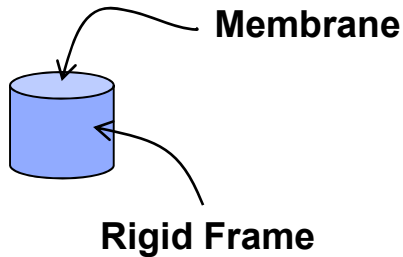


Foam Modeling Procedure

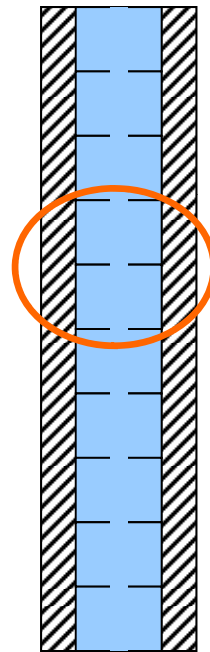
3-D Model



Unit cell



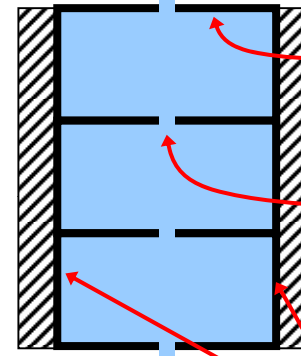
2-D Model



Material Properties

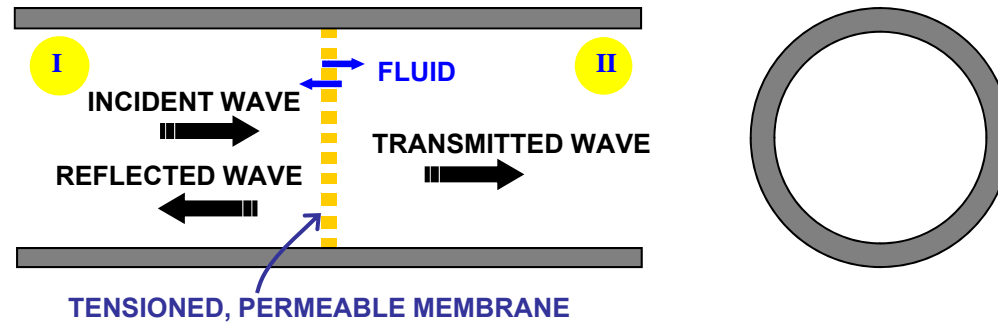
- Tension
- Loss factor
- Membrane Density
- Surface Film Density
- Porosity
- Flow Resistance

Sound Energy Loss Mechanisms



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

Theoretical Model - Permeable Membrane



Assumed Solutions

- Sound Pressures in Acoustic Cavities:

$$P_I(r, z) = e^{-jkz} + \sum_n B_n J_0(k_{r_n} r) e^{jk_{z_n} z}$$

$$P_{II}(r, z) = \sum_n C_n J_0(k_{r_n} r) e^{-jk_{z_n} z}$$

- Membrane Displacement (Solid Component):

$$y(r, t) = \sum_n A_n J_0(k_{0_n} r)$$

- Membrane Displacement (Fluid Component):

$$u(r, t) = \sum_n F_n J_0(k_{0_n} r) + F_o$$

Theoretical Model – Solution Method

- Boundary Conditions

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

$$-\frac{1}{j\omega\rho_0} \frac{\partial P_I}{\partial z} \Big|_{z=0} = (1-\Omega) \frac{\partial y}{\partial t} + \Omega \frac{\partial u}{\partial t}$$

$$-\frac{1}{j\omega\rho_0} \frac{\partial P_{II}}{\partial z} \Big|_{z=0} = (1-\Omega) \frac{\partial y}{\partial t} + \Omega \frac{\partial u}{\partial t}$$

- The Force Equilibrium Equation in the Membrane:

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

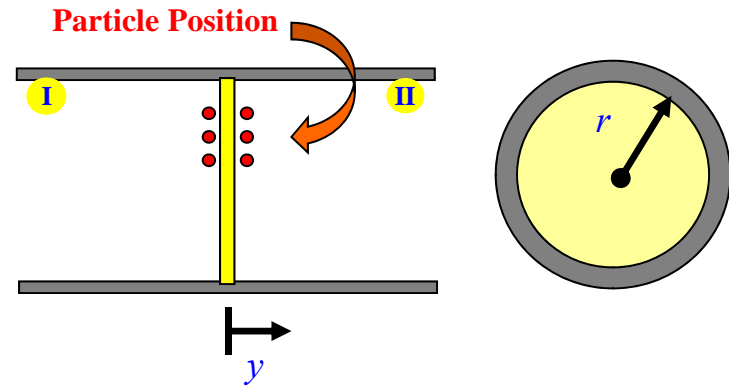
$$\rho_0 \Omega h \frac{\partial^2 u}{\partial t^2} - R_f \frac{\partial(y-u)}{\partial t} = \Omega (P_I - P_{II})$$

where

$$T = T_0(1 + j\eta) \quad \Omega = N\pi a^2 / A \quad P_{front} - P_{back} = R_f v_f$$

- Solution Method

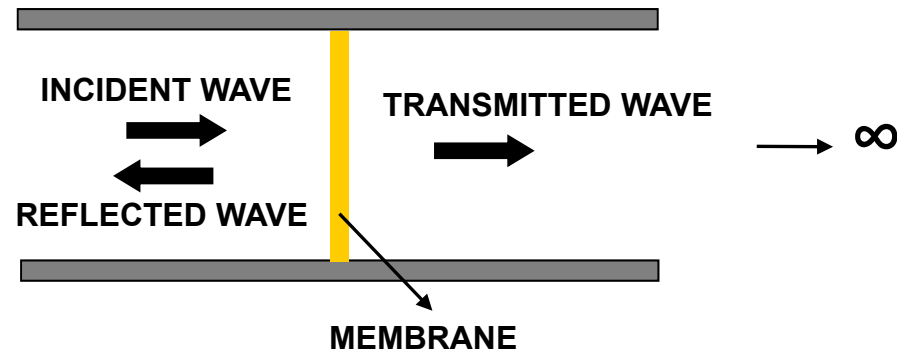
Apply four boundary conditions on a point-by-point basis across the membrane



$$\sim \begin{matrix} \uparrow \\ \text{Number of Point} \\ \text{at which} \\ \text{B.C.'s} \\ \text{applied} \end{matrix} \left[\begin{matrix} \text{Coefficient} \\ \text{Matrix} \end{matrix} \right] = \left\{ \begin{matrix} \text{Forcing} \\ \text{Vector} \end{matrix} \right\}$$

$$\left[\begin{matrix} A_1 \\ \dots \\ A_N \\ B_0 \\ \dots \\ B_N \\ C_0 \\ \dots \\ C_N \end{matrix} \right]$$

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 :**

$$Z_m = (1+R) / (1-R) - \rho_0 c$$

Transfer Matrix Method

- Membrane & Air Cavity Transfer Matrix

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

- Total Transfer Matrix

$$\begin{Bmatrix} P_{Top} \\ u_{Top} \end{Bmatrix} = [T_{total}] \begin{Bmatrix} P_{Bottom} \\ u_{Bottom} \end{Bmatrix} \quad [T_{total}] = \underbrace{[T_{m_s}][T_a][T_m][T_a]}_{1 \text{ layer}} \cdots \cdots [T_m][T_a]$$

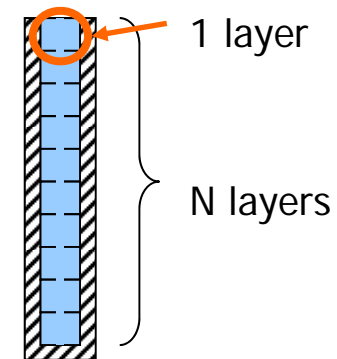
N layers

- Reflection Coefficient

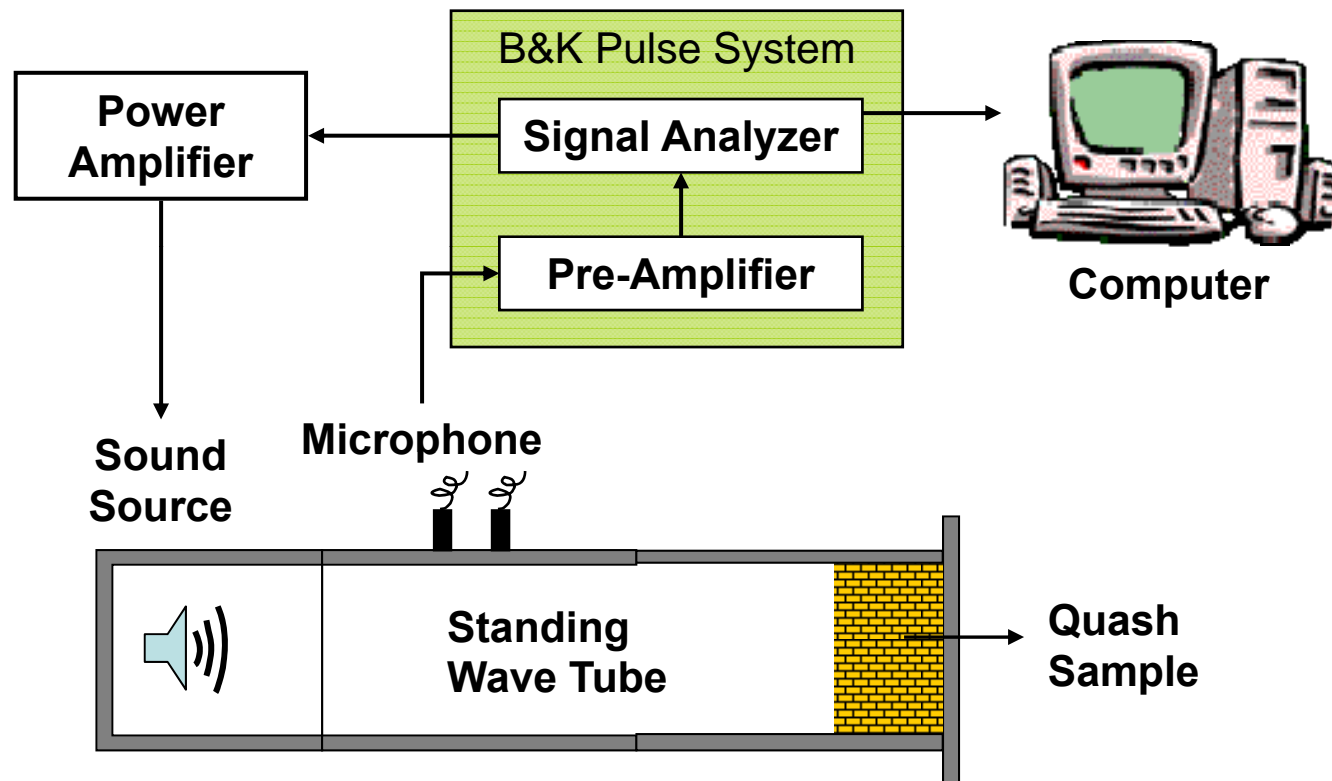
$$R_{Top} = \frac{Z_{Top} - \rho_o c_o}{Z_{Top} + \rho_o c_o}$$

- Absorption Coefficient

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



Experimental Set-up



Experimental Set-up

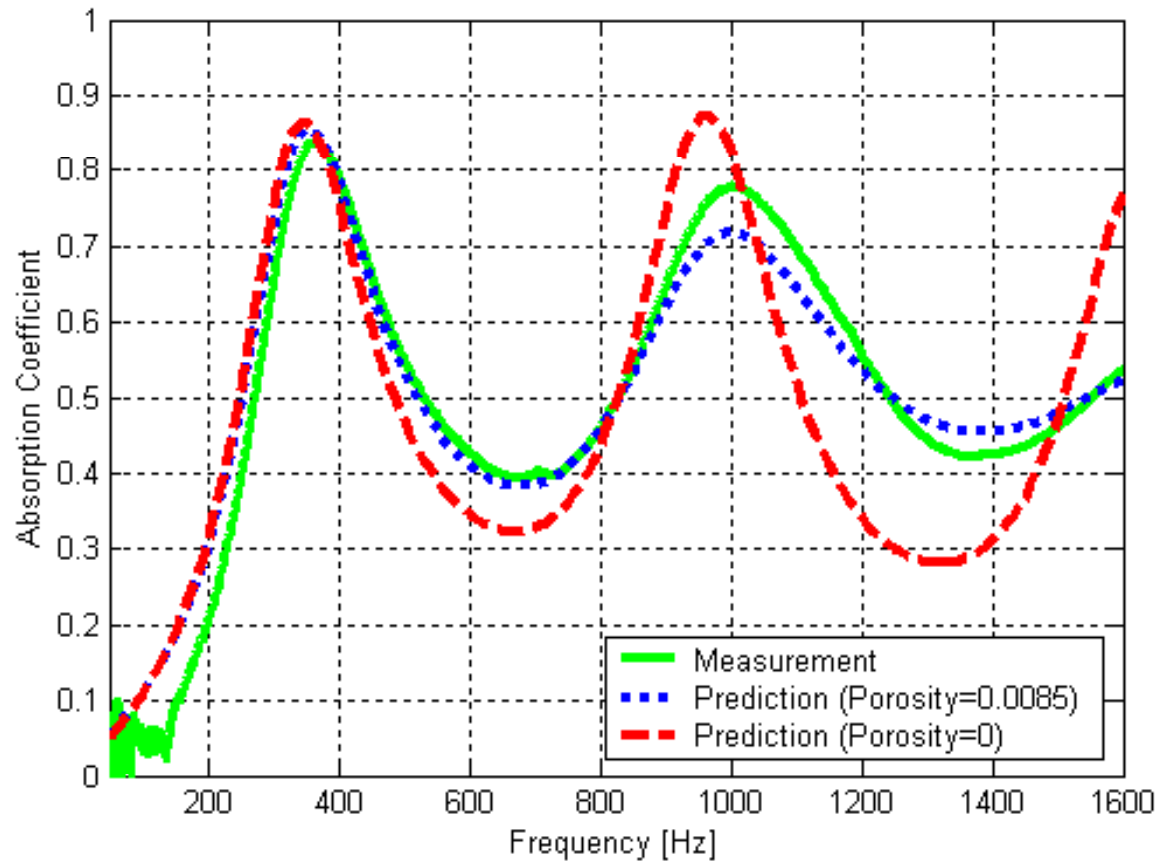
Loading Quash Sample



Measurement Set-up



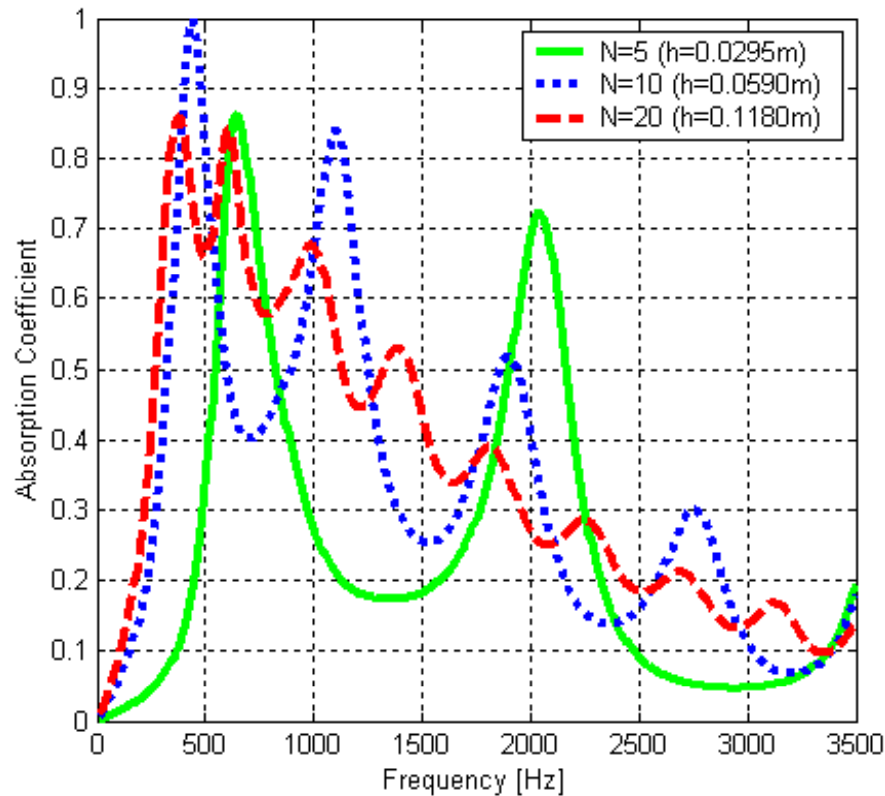
Comparison of Measurement and Prediction



$\rho_m=0.0885 \text{ kg/m}^2$, $T_o=0.13 \text{ N/m}$, $\eta=1.6$, $m_s=0.1586 \text{ kg/m}^2$, $\Omega=0.0085$,
 $R_f=0.286 \text{ Rays}$, $t=0.0002 \text{ m}$, $d_o=0.00486 \text{ m}$, $h=0.05832 \text{ m}$, $N=12$.

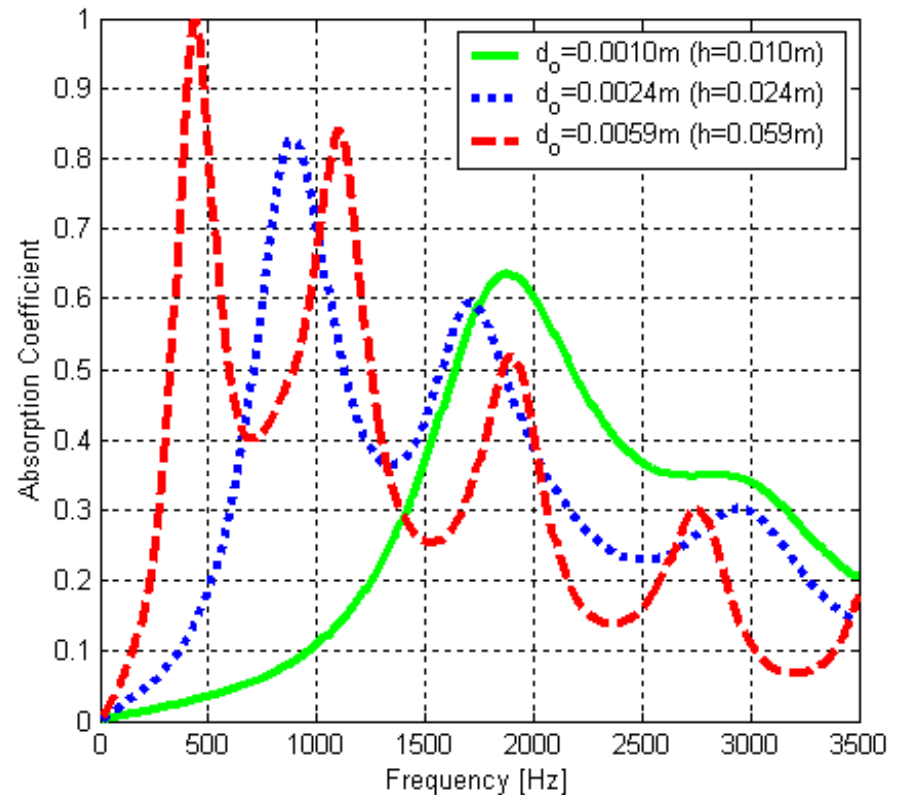
Parameter Effects on Sound Absorption

Foam Thickness



$\rho_m=0.07 \text{ kg/m}^2$, $T_o=0.5 \text{ N/m}$, $\eta=0.7$, $m_s=0.2 \text{ kg/m}^2$,
 $\Omega=0.01$, $R_f=0.2 \text{ Rayls}$, $t=0.0002 \text{ m}$, $d_o=0.0059 \text{ m}$,

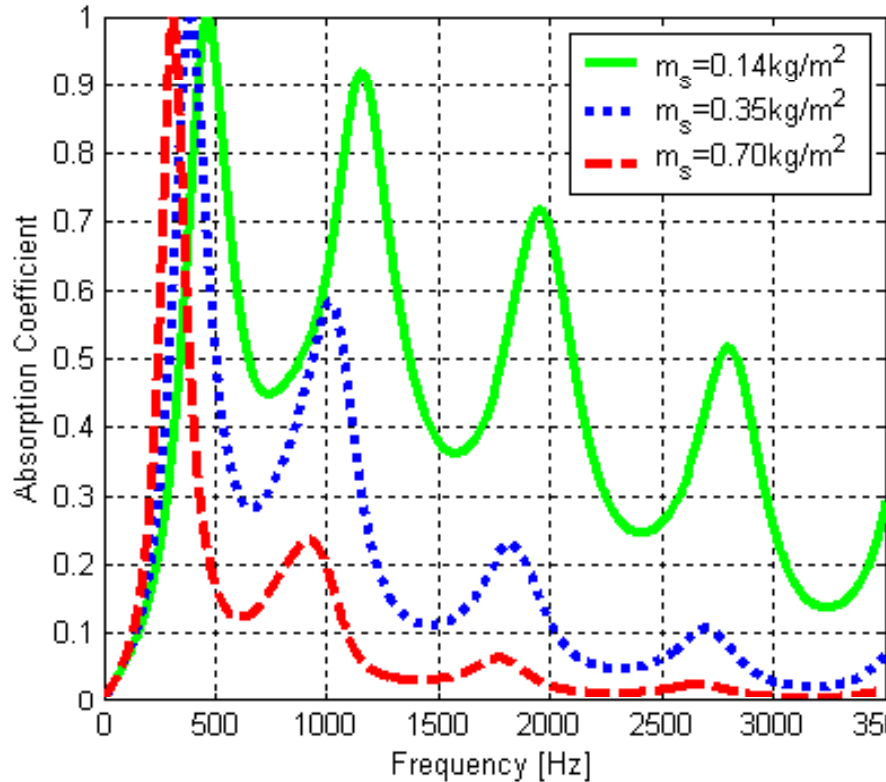
Membrane Size



$\rho_m=0.07 \text{ kg/m}^2$, $T_o=0.5 \text{ N/m}$, $\eta=0.7$, $m_s=0.2 \text{ kg/m}^2$,
 $\Omega=0.01$, $R_f=0.2 \text{ Rayls}$, $t=0.0002 \text{ m}$, $N=10$

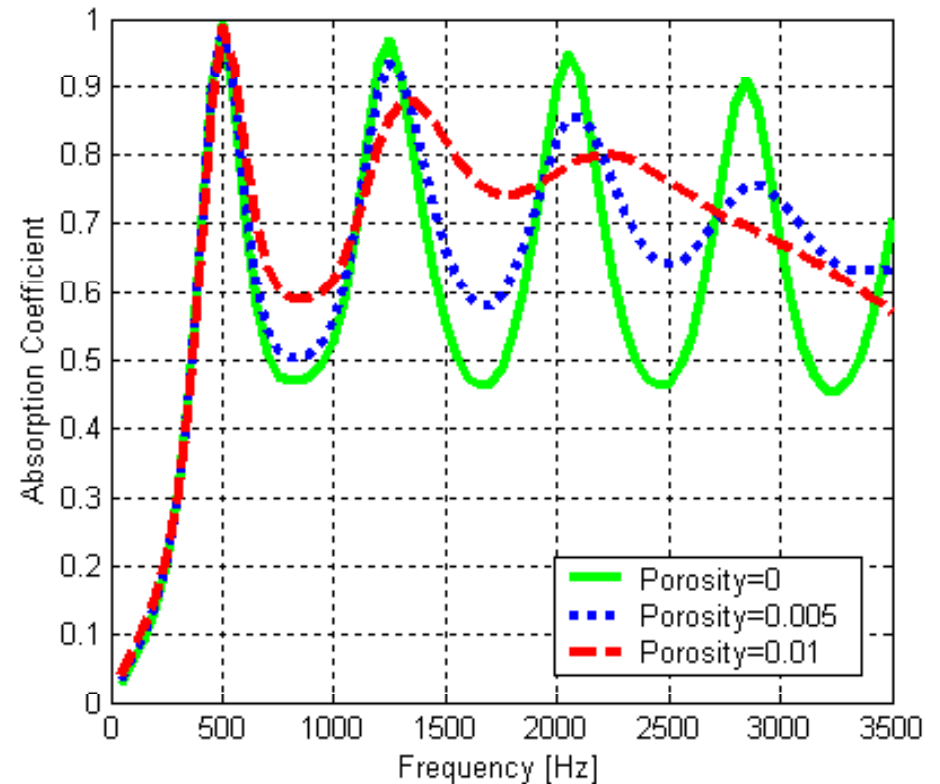
Parameter Effects on Sound Absorption

Surface Mass



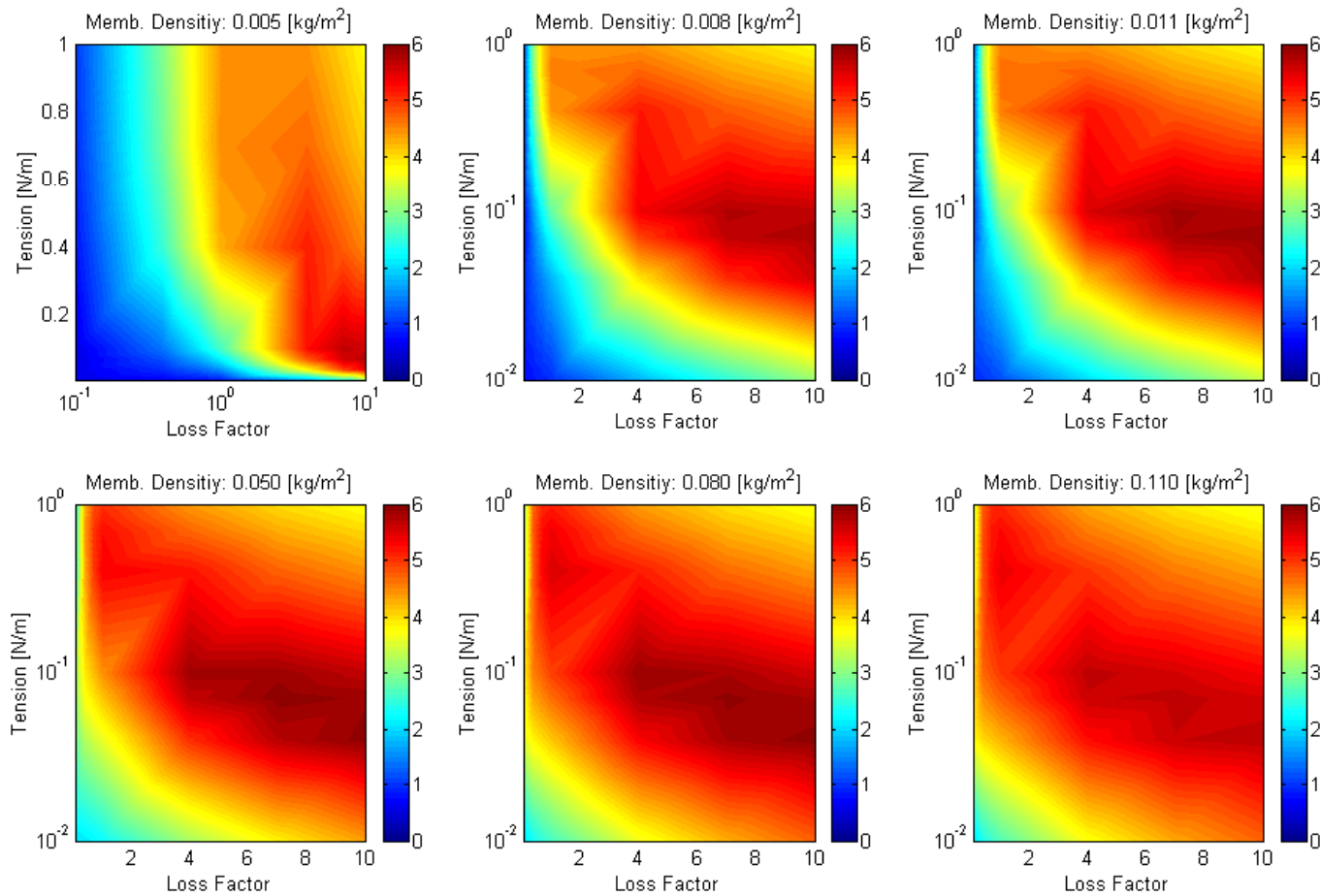
$\rho_m=0.07 \text{ kg/m}^2$, $T_o=0.5 \text{ N/m}$, $\eta=0.7$, $\Omega=0.01$,
 $R_f=0.2 \text{ Rays}$, $t=0.0002 \text{ m}$, $d_o=0.0059 \text{ m}$, $N=10$

Membrane Porosity



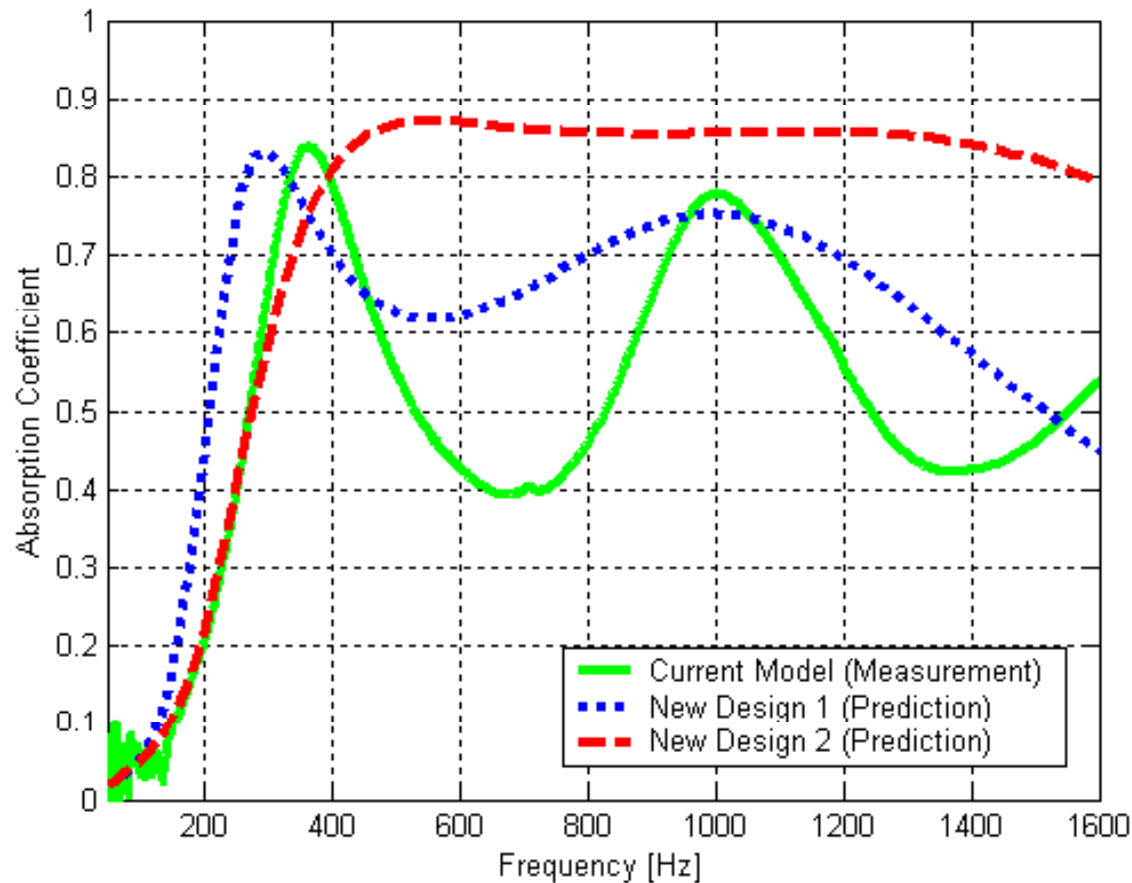
$\rho_m=0.07 \text{ kg/m}^2$, $T_o=0.5 \text{ N/m}$, $\eta=0.7$, $m_s=0.07 \text{ kg/m}^2$,
 $R_f=0.2 \text{ Rays}$, $t=0.0002 \text{ m}$, $d_o=0.0059 \text{ m}$, $N=10$

Parameter Effects on Sound Absorption



$m_s=0.2135 \text{ kg/m}^2$, $\Omega=0.0$, $R_f=0.2 \text{ Rayls}$, $t=0.0002 \text{ m}$, $d_o=0.0056 \text{ m}$, $h=0.056 \text{ m}$, $N=12$
(1/3-octave band normal incidence absorption averaged from 125 Hz to 1600 Hz)

Some High Absorption Designs



New Design 1

$\rho_m=0.2213$ kg/m²(↑),
 $T_o=0.065$ N/m (↓), $\eta=1.6$,
 $m_s=0.1941$ kg/m²(↑), $\Omega=0.02$ (↑),
 $R_f=0.286$ Rayls, $t=0.0002$ m,
 $d_o=0.00583$ m(↑), $h=0.0583$ m,
 $N=10$ (↓)

New Design 2

$\rho_m=0.1770$ kg/m²(↑),
 $T_o=0.13$ N/m, $\eta=1.6$,
 $m_s=0.0970$ kg/m² (↓), $\Omega=0.03$ (↑),
 $R_f=0.286$ 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.