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The Effect of Flexibility on the Acoustical Performance of Microperforated Materials

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WITH THANKS TO: Jinho Song (Otis Elevator), Taewook Yoo (3M/EAR), Ryan Schultz (Sandia) and Yangfan Liu (Purdue)

ASA Fall meeting, Kansas City, 10/22/12

Great Ape House – National Zoo

Micro-perforated film in a modular, tile-based design

Installed in exhibit

Absorption performance

Introduction

- Solid phase of microperforated materials having superficial densities less than 500 g/m^2 may be driven into motion by the incident sound field (direct pressure + viscous drag)
- Energy is dissipated by flexure of the solid phase and relative motion of the fluid in the pores and the solid phase – motion of the solid phase affects this process
- Two extremes considered here: membrane-like performance modified by porosity; rigid microperforated performance modified by flexibility of the solid phase

Finite-Size, Impermeable Membrane

● Solution Method

Apply two velocity continuity boundary conditions and membrane equation of motion on a point-by-point basis across the membrane

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Number of Point at which B.C.'s applied

Coefficient Matrix

$$\begin{bmatrix} A_1 \\ \dots \\ A_N \\ B_0 \\ \dots \\ B_N \\ C_0 \\ \dots \\ C_N \end{bmatrix} = \begin{Bmatrix} \text{forcing} \\ \text{Vector} \end{Bmatrix}$$

● System Response (Membrane Displacement)

Finite-Size, Impermeable Membrane – Velocity Measurement

Vibrational Modes

Theory

1st

2nd

Experiment

Finite-Size, Impermeable Membrane – Transmission Loss

Finite-Size, Impermeable Membrane – Transmission Loss

- Given experimental results as input, Find appropriate material properties (T_o , ρ_s , η)

Tensioned Membrane

$$T = 82 \text{ Pa} \quad \eta = 0.0040 \quad \rho_s = 0.0870 \frac{\text{kg}}{\text{m}^2}$$

Note : Mass-law trend with large peaks associated with zero volume velocity modes

Sound Dissipation Mechanism – Impermeable Membrane

- Membrane with finite-depth backing space

$$T = 75 \text{ Pa} \quad \eta = 0.0063 \quad \rho_s = 0.19 \frac{\text{kg}}{\text{m}^2} \quad l = 0.1192 \text{ m}$$

- Absorption peaks when $\text{Im}\{Z_n\} = 0$
- Significant sound absorption in narrow frequency regions produced by dissipation in the membrane

Theoretical Model – Permeable Membrane

Assumed Solutions

- Sound Pressures in Acoustic Cavities:
- Membrane Displacement (Solid Component):
- Membrane Displacement (Fluid Component):

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

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

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

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

Membrane Permeability: Measurement

A duct with a tensioned, permeable membrane

Membrane

- ❑ Each pore had a diameter of approximately 0.5 mm and the total number of pores ranged from 24 to 120 increasing in steps of 24: the pores were uniformly distributed over the membrane.
- ❑ Flow resistance controls “background” level of energy dissipation

Sound Dissipation Mechanism – Effect of Flow Resistance

Sound Power Dissipation from Membrane

Sound Power Dissipation from Fluid

$$a=0.05 \text{ m}, \rho_s=0.174 \text{ kg/m}^2, T_0=85 \text{ N/m}, \eta=0.005, \Omega=0.0018, h=0.2 \text{ mm}$$

- Viscous energy dissipation controlled by flow resistance of membrane

Micro-perforated Panel

- ❑ Relatively heavy ($> 300 \text{ g/m}^2$), not tensioned but flexurally stiff
- ❑ Advantages over fibrous material
 - stiffness (self supporting), robust, weatherproof
- ❑ Energy dissipates when sound moves through small holes
 - $d=0.1\sim 0.9 \text{ mm}$, $t=0.1\sim 2 \text{ mm}$, $N=10^3\sim 10^6 \text{ per m}^2$

Equations of Motion and Velocity Conditions

Volume velocity continuity at $x=0$

$$\begin{cases} -\frac{1}{j\omega\rho_o} \frac{\partial p_I}{\partial x} \Big|_{x=0} = (1-\Omega) \frac{\partial d_s}{\partial t} + \Omega \frac{\partial d_f}{\partial t} \\ -\frac{1}{j\omega\rho_o} \frac{\partial p_{II}}{\partial x} \Big|_{x=0} = (1-\Omega) \frac{\partial d_s}{\partial t} + \Omega \frac{\partial d_f}{\partial t} \end{cases}$$

Force equilibrium at $x=0$

$$\begin{cases} \text{Solid} & p_I - p_{II} + R_t \frac{\Omega^2}{1-\Omega} \frac{\partial(d_f - d_s)}{\partial t} = D \nabla^4 d_s - T \nabla^2 d_s + \rho_s \frac{\partial^2 d_s}{\partial t^2} \\ \text{Fluid} & p_I - p_{II} - R_t \Omega \frac{\partial(d_f - d_s)}{\partial t} = j\omega\rho_o h' \frac{\partial d_f}{\partial t} \end{cases}$$

p_I : Pressure at source side
 p_{II} : Pressure behind the panel
 d_s : Displacement of solid part
 d_f : Displacement of fluid part
 ρ_s : Membrane mass per unit area
 R_t : Flow resistance
 D : Flexural stiffness
 T : Tension
 h' : Effective thickness
 Ω : Porosity

Micro-perforated Panel

□ 3-dimensional model

Only symmetric modes exist

Sound pressure in each region

$$P_I = e^{-jkx} + \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} B_{mn} \cos(k_{2m}z) \cos(k_{2n}y) e^{jk_{x2m2n}x}$$

$$P_{II} = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} C_{mn} \cos(k_{2m}z) \cos(k_{2n}y) \left(e^{-jk_{x2mn}x} + e^{jk_{x2mn}(x-2L)} \right)$$

$$k_{2m} = \frac{2m\pi}{L_z} \quad k_{2n} = \frac{2n\pi}{L_y} \quad k_{x2m2n} = \sqrt{k^2 - k_{2m}^2 - k_{2n}^2} \quad (k > k_{2n} + k_{2m})$$

$$(m, n = 0, 1, 2, \dots) \quad = -j\sqrt{k^2 - k_{2m}^2 - k_{2n}^2} \quad (k < k_{2n} + k_{2m})$$

Displacement of membrane

for simply supported BC

Solid part $d_s = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} A_{mn} \sin(k_{2m-1}z) \sin(k_{2n-1}y)$

Fluid part $d_f = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} F_{mn} \cos(k_{2m}z) \cos(k_{2n}y)$

for clamped BC

Solid part $d_s = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} A_{mn} \{\cos(k_{2m}z) - 1\} \{\cos(k_{2n}y) - 1\}$

Fluid part $d_f = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} F_{mn} \cos(k_{2m}z) \cos(k_{2n}y)$

$$k_{2m-1} = \frac{(2m-1)\pi}{L_z}, \quad k_{2n-1} = \frac{(2n-1)\pi}{L_y} \quad (m, n = 1, 2, \dots)$$

Measurement of Plexiglass Samples

Sample 1 (x100)

Sample 2 (x50)

Sample 3 (x50)

	d (nominal) [mm]	t [mm]	ρ_s [kg/m ²]	N
Sample 1	0.254	1.588	1.584	722500
Sample 2	0.2667	1.588	1.627	291600
Sample 3	0.4064	1.588	1.631	160000

6.5 cm by 6.5 cm

Comparison between Predictions and Measurements

- ❑ Rigid perforated behavior slightly modified by flexibility

	d (nominal) [mm]	d (adjusted) [mm]	t [mm]	$D /$ loss factor [N·m ²]	T [N]	ρ_s [kg/m ²]	N
S 1	0.254	0.305	1.588	0.7/ 0.07	0	1.584	722500
S 2	0.2667	0.35	1.588	0.7/ 0.07	0	1.627	291600
S 3	0.4064	0.45	1.588	0.7/ 0.07	0	1.631	160000

Flexural Stiffness Effect

d [mm]	t [mm]	D [N·m ²]	loss factor in D	T [N]	Mass/area [kg/m ²]	N	Size [mm]
0.45	1.588	1, 0.6, 0.4, 0.3, 0.2, 0.1, 0.01, 0.0001	0.05	0	0.1631	160000	63.5 x 63.5

- Depending on the flexural stiffness, the absorption performance can be enhanced with an appropriate loss factor
- Absorption bandwidth can be increased
- Performance is reduced if stiffness is too low

3D Clamped-clamped Displacement of Fluid and Solid Parts

10 Hz

200 Hz

1250 Hz

d [mm]	t [mm]	D [N·m ²]	loss factor	T [N]	ρ_s [kg/m ²]	N	Size [mm]
0.15	0.4	0.0001	0.001	0	0.1631	756589	63.5 x 63.5

Energy Dissipation

$$W_I = \frac{1}{2} \text{Re} \left\{ \iint P_I u_I^* dy dz \right\}$$

$$W_{II} = \frac{1}{2} \text{Re} \left\{ \iint P_{II} u_{II}^* dy dz \right\}$$

From sound fields

$$W_{\text{E.D.}_{\text{field}}} = W_I - W_{II}$$

$$W_{\text{E.D.}_{\text{solid}}} = \frac{1-\Omega}{2} \text{Re} \left\{ \iint \left(D \nabla^4 d_s - T \nabla^2 d_s + \rho_s \frac{\partial^2 d_s}{\partial t^2} - R_t \frac{\Omega^2}{1-\Omega} \frac{\partial (d_f - d_s)}{\partial t} \right) \left(\frac{\partial d_s}{\partial t} \right)^* dy dz \right\}$$

$$W_{\text{E.D.}_{\text{fluid}}} = \frac{\Omega}{2} \text{Re} \left\{ \iint \left(R_t \Omega \frac{\partial (d_f - d_s)}{\partial t} + j \omega \rho_o h' \frac{\partial d_f}{\partial t} \right) \left(\frac{\partial d_f}{\partial t} \right)^* dy dz \right\}$$

From displacements of
solid and fluid parts

$$W_{\text{E.D.}_{\text{disp.}}} = W_{\text{E.D.}_{\text{solid}}} + W_{\text{E.D.}_{\text{fluid.}}}$$

$$W_{\text{E.D.}_{\text{field}}} = W_{\text{E.D.}_{\text{disp.}}}$$

Energy Dissipation

d [mm]	t [mm]	Number of holes per unit area	Mass/area [kg/m ²]	Tension / loss factor	Flexural Stiffness/ loss factor	Panel size
0.15	0.4	756,589	0.174	85.41/0.05	0	63.5 x 63.5 mm

Conclusions

1. Very lightweight tensioned, permeable membranes acts like impermeable membranes, but energy dissipation (and absorption) can be increased by control of porosity and flow resistance
2. Relatively heavy, flexurally stiff, microperforated materials act essentially like rigid microperforated materials but additional absorption features attributable to flexing of the panel appear, and can increase absorption bandwidth if stiffness is not too low
3. Energy dissipation by flexure of the microperforated panel can be comparable to the energy dissipation due to viscous losses in the pores

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Presentations available at Herrick Labs epub site:

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