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Effect of Lining Anisotropy on Sound Attenuation in Lined Ducts

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Introduction

Car door system

Grazing Incidence Applications

- Porous materials are often used to line “channels”
- previous work show that the properties that control grazing direction attenuation are somewhat different from those that control normal absorption.

Here introduce **anisotropic theory** to account for **different flow resistivity** of the lining material in normal and grazing directions.

Duct lining geometry and coordinate system for poro-elastic lining

Transversely isotropic poro-elastic displacement and stress field

$$u_x = e^{-jk_x x} \left(\sum_{i=1}^4 \alpha_i C_i e^{-jk_{iz} z} + \sum_{i=5}^6 C_i e^{-jk_{iz} z} \right)$$

$$u_z = e^{-jk_x x} \left(\sum_{i=1}^4 C_i e^{-jk_{iz} z} + \sum_{i=5}^6 \alpha_i C_i e^{-jk_{iz} z} \right)$$

$$U_x = e^{-jk_x x} \left(\sum_{i=1}^6 \beta_i C_i e^{-jk_{iz} z} \right)$$

$$U_z = e^{-jk_x x} \left(\sum_{i=1}^6 \gamma_i C_i e^{-jk_{iz} z} \right)$$

$$\begin{aligned} \sigma_z &= -j e^{-jk_x x} \left[\sum_{i=1}^4 \{k_x (F \alpha_i + Q \beta_i) + k_{iz} (C + Q \gamma_i)\} C_i e^{-jk_{iz} z} \right. \\ &\quad \left. + \sum_{i=5}^6 \{k_x (F + Q \beta_i) + k_{iz} (C \alpha_i + Q \gamma_i)\} C_i e^{-jk_{iz} z} \right] \\ \tau_{xz} &= -j e^{-jk_x x} \left[\sum_{i=1}^4 \{k_x (F \alpha_i + Q \beta_i) + k_{iz} (C + Q \gamma_i)\} C_i e^{-jk_{iz} z} \right. \\ &\quad \left. + \sum_{i=5}^6 \{k_x (F + Q \beta_i) + k_{iz} (C \alpha_i + Q \gamma_i)\} C_i e^{-jk_{iz} z} \right] \\ s &= -j e^{-jk_x x} \left[\sum_{i=1}^4 \{k_x (F \alpha_i + Q \beta_i) + k_{iz} (C + Q \gamma_i)\} C_i e^{-jk_{iz} z} \right. \\ &\quad \left. + \sum_{i=5}^6 \{k_x (F + Q \beta_i) + k_{iz} (C \alpha_i + Q \gamma_i)\} C_i e^{-jk_{iz} z} \right]. \end{aligned}$$

Boundary condition: fully-lined model

- 2-D porous formulation of the free-wave solution in a lined duct.
- Rigid wall boundary condition
- Simplified by symmetric condition
- Solve for k_x to find attenuation rate in lining.

at $y = -d$

$$(1) u_{x(symm)} = 0$$

$$(2) u_{y(symm)} = 0$$

$$(3) U_{y(symm)} = 0$$

at $y = d$

$$(4) u_{x(symm)} = 0$$

$$(5) u_{y(symm)} = 0$$

$$(6) U_{y(symm)} = 0$$

- The characteristic dispersion equation

$$\mathbf{A}_f \mathbf{X}_f = 0$$

$$\det(\mathbf{A}_f) = 0$$

$$\mathbf{X}_f = [c_1^* \quad c_3^* \quad c_5^*]^T$$

Boundary condition: partially-filled model (FA)

- 2-D porous formulation of the free-wave solution in a lined duct
- Rigid wall boundary condition
- Solve for k_x to find attenuation rate in lining.

at $y = 0$

$$(1) u_{x,1} = 0$$

$$(2) u_{y,1} = 0$$

$$(3) U_{y,1} = 0$$

at $y = L_1$

$$(4) -\Omega_p P = s$$

$$(5) -(1 - \Omega_p)P = \sigma_y$$

$$(6) v_y = j\omega(1 - \Omega_p)u_y + j\omega\Omega_p U_y$$

$$(7) \tau_{yx} = 0$$

at $y = L_2$

$$(8) v_y = 0$$

$$\mathbf{A}_p \mathbf{X}_p = 0$$

- The characteristic dispersion equation

$$\det(\mathbf{A}_p) = 0$$

$$\mathbf{X}_p = [C_1 \quad C_2 \quad C_3 \quad C_4 \quad C_5 \quad C_6 \quad A_1 \quad A_2]^T$$

Square duct system and glass fiber layer

0.5m
Sample length

- 4-microphone transfer matrix method used to measure attenuation at grazing incidence

Effect of Material Anisotropy

Measurement of TL in two configurations for glass fiber (green)

Case 1:

9 pieces layered in vertical direction

Case 2:

9 pieces layered in horizontal direction

- Acoustic properties depend on material orientation – flow resistivity larger in normal direction

Anisotropic Duct Lining

- Prediction and measurement for **Yellow glass fiber** by using anisotropic poro-elastic model

- Different flow resistivities [MKS Rayls/m] in x- and y-directions

$$\sigma_x = 7500 \quad \sigma_y = 15000$$

Sensitivity to transverse flow resistivity

Yellow glass fiber

Green glass fiber

Conclusions

- A free wave propagation model based on a transversely isotropic poro-elastic theory was implemented for both fully-lined and partially-lined duct systems
- Performed experimental measurements of lined duct attenuation rates in x- and y-directions.
- Showed good agreement between predictions and measurements for partially-lined duct case.
- The study of flow resistivity shows that the x-direction is more effective than that of y-direction for controlling the sound attenuation performance in the duct system.
- Comparison of isotropic and anisotropic models shows that anisotropic model is more effective for predicting anisotropic real behavior of the lining materials.