9-2014

Effect of Thermal Losses and Fluid-Structure Interaction on the Transfer Impedance of Microperforated Films

Thomas Herdtle
3M Company

J Stuart Bolton
Purdue University, bolton@purdue.edu

Herdtle, Thomas and Bolton, J Stuart, "Effect of Thermal Losses and Fluid-Structure Interaction on the Transfer Impedance of Microperforated Films" (2014). *Publications of the Ray W. Herrick Laboratories.* Paper 119.
http://docs.lib.purdue.edu/herrick/119

Advancing the Technology and Practice of Noise Control Engineering

Effect of Thermal Losses and Fluid-Structure Interaction on the Transfer Impedance of Microperforated Films

Thomas Herdtle, SEMS Predictive Engineering, 3M
J. Stuart Bolton, Ray W. Herrick Laboratories, Purdue University

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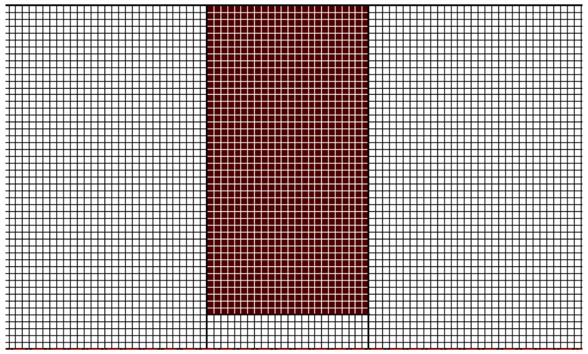
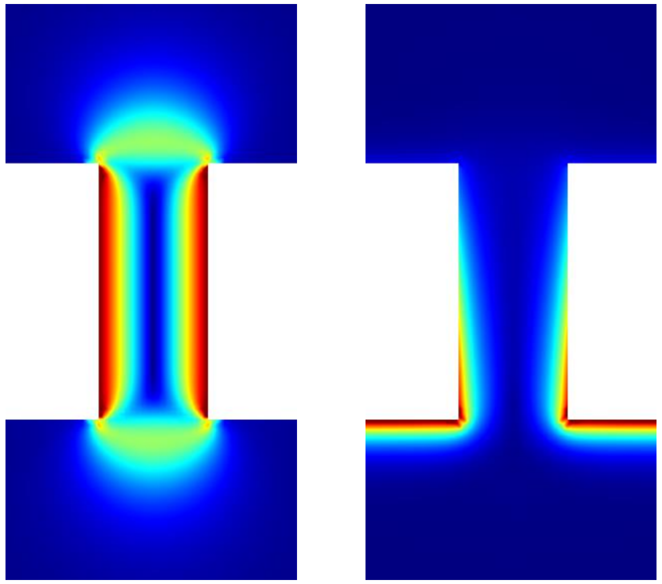
Microperforated Films

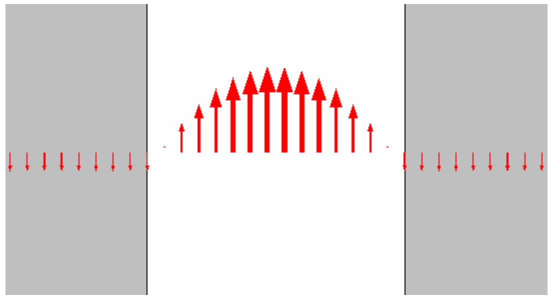
- Introduction and Review
  - Perforated Films
  - Computational Fluid Dynamics (CFD) vs. Acoustic Modeling

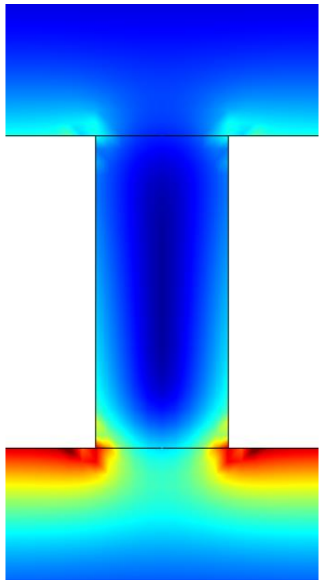


- Rigid Film
  - Viscous Effects
  - Thermal Effects – *Turn out to be small*
  - Frequency-dependant Velocity Profiles



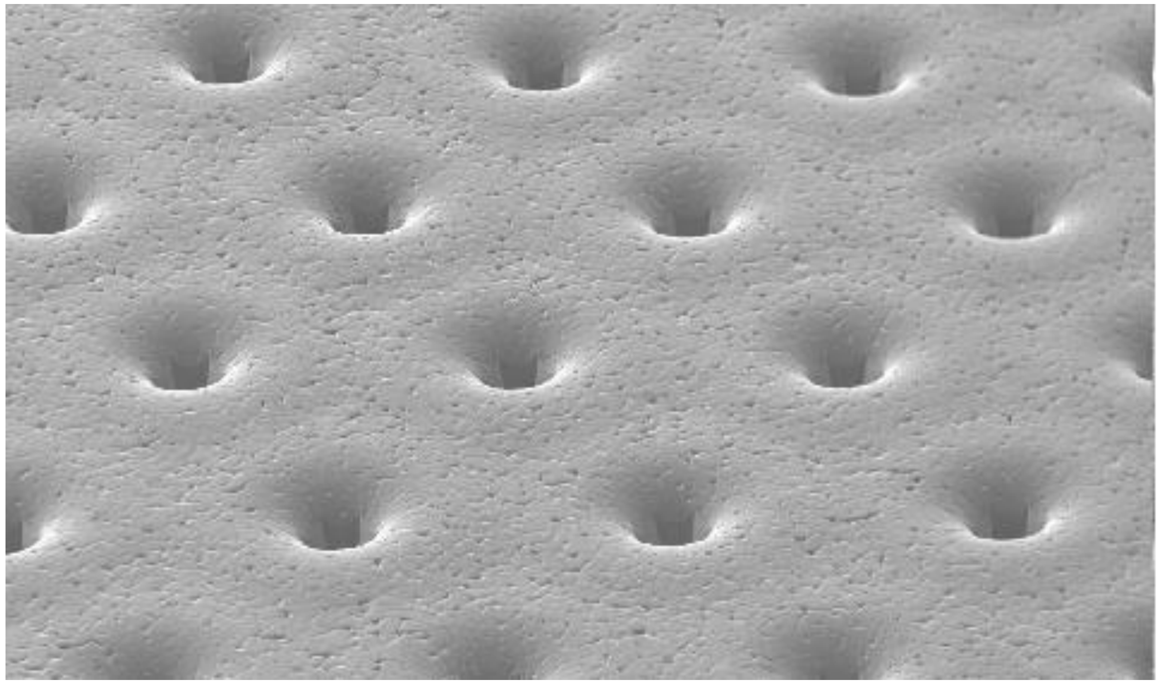
- Fluid-Structure Interaction (FSI) Models – Limp Films
  - Mass Law for a Solid Film
  - Microperforated Limp Films – *Solid and fluid impedance add in parallel*
- Summary and Conclusions





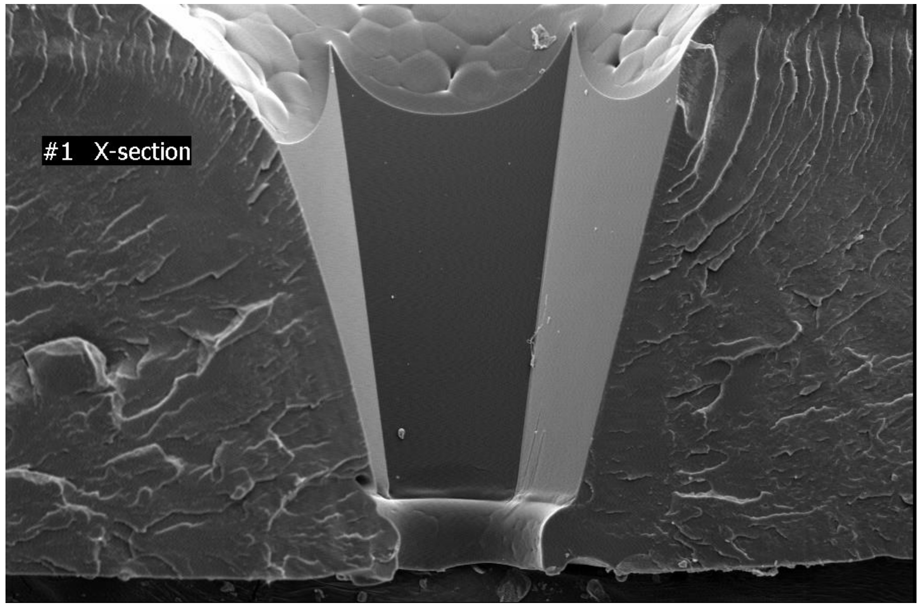
Microperforated Films

- Suggested by Maa in 1975
  - Used for sound absorption
  - Proposed different formulas for thermally conducting and non-conducting boundaries
- Models needed for design and prediction
  - Film transfer impedance needed for transmission matrix calculations
  - Need to model non-cylindrical pores



Top view of a microperforated film

Installed microperforated panels in the Great Ape House of the Smithsonian National Zoo

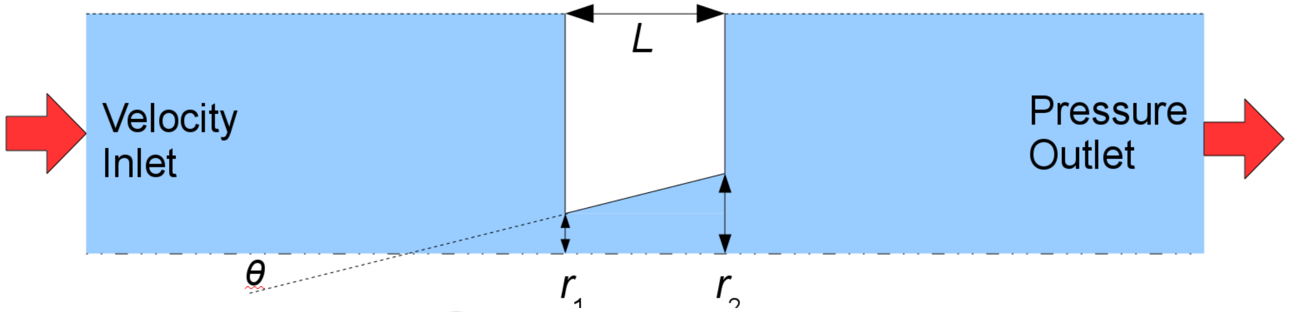


Cross-section of a microperforated film

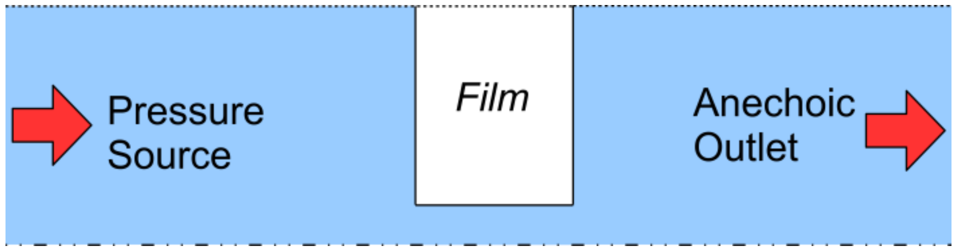
Model Comparison – Model Setup

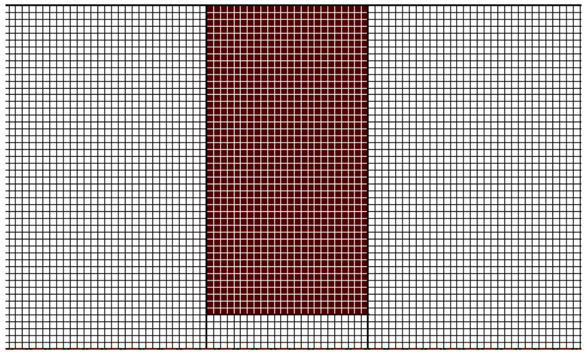
- **CFD Models** – *InterNoise 2011*
  - Time domain
  - Incompressible
  - Isothermal
  - 2D axisymmetric
  - Inlet: Hann-windowed, 5 kHz half-sine
  - Maximum velocity of 1 mm/s
  - Outlet pressure set of 0 Pa
  - Run for at least 0.5 ms

- **Acoustic Models** – *NoiseCon 2014*
  - Frequency domain, harmonic waves
  - Compressible
  - Including energy equation
  - 2D axisymmetric
  - Non-reflecting inlet with 1 Pa incident
  - Resulting face velocity up to 2.4 mm/s
  - Anechoic outlet
  - Run from 50 to 10,000 Hz




Inlet velocity profile




Typical mesh

Model Comparison – Model Equations

- **CFD Models** – *InterNoise 2011*
  - Incompressible Navier-Stokes equations
    - Momentum and Continuity

p	pressure
u	velocity
ρ	density *(constant)*
μ	dynamic viscosity
I	unit vector

$$\rho\frac{\partial \mathbf{u}}{\partial t}+\rho(\mathbf{u}\cdot\nabla)\mathbf{u}=\nabla\cdot\left[-p\mathbf{I}+\mu\left(\nabla\mathbf{u}+(\nabla\mathbf{u})^T\right)\right]$$

$$\nabla\cdot\mathbf{u}=0$$

- At the surface of the film: $\mathbf{u}=0$

- **Acoustic Models** – *NoiseCon 2014*
  - Linearized, harmonic Navier-Stokes equations
    - Momentum, Continuity, and Energy

$$\boxed{a\rightarrow a_0+a\,e^{i\omega t}}$$

p	pressure
u	velocity
T	temperature
ρ	density
k	thermal conductivity
μ	dynamic viscosity
C_P	specific heat at constant pressure
I	unit vector

$$i\omega\rho_0\mathbf{u}=\nabla\cdot\left[-p\mathbf{I}+\mu\left(\nabla\mathbf{u}+(\nabla\mathbf{u})^T\right)-\frac{2\mu}{3}(\nabla\cdot\mathbf{u})\mathbf{I}\right]$$

$$\frac{i\omega}{\rho_0}\left(p\left.\frac{\partial\rho_0}{\partial p}\right|_T+T\left.\frac{\partial\rho_0}{\partial T}\right|_p\right)+\rho_0\nabla\cdot\mathbf{u}=0$$

$$i\omega\rho_0C_PT=\nabla\cdot(k\nabla T)-i\omega p\frac{T_0}{\rho_0}\frac{\partial\rho_0}{\partial T}$$

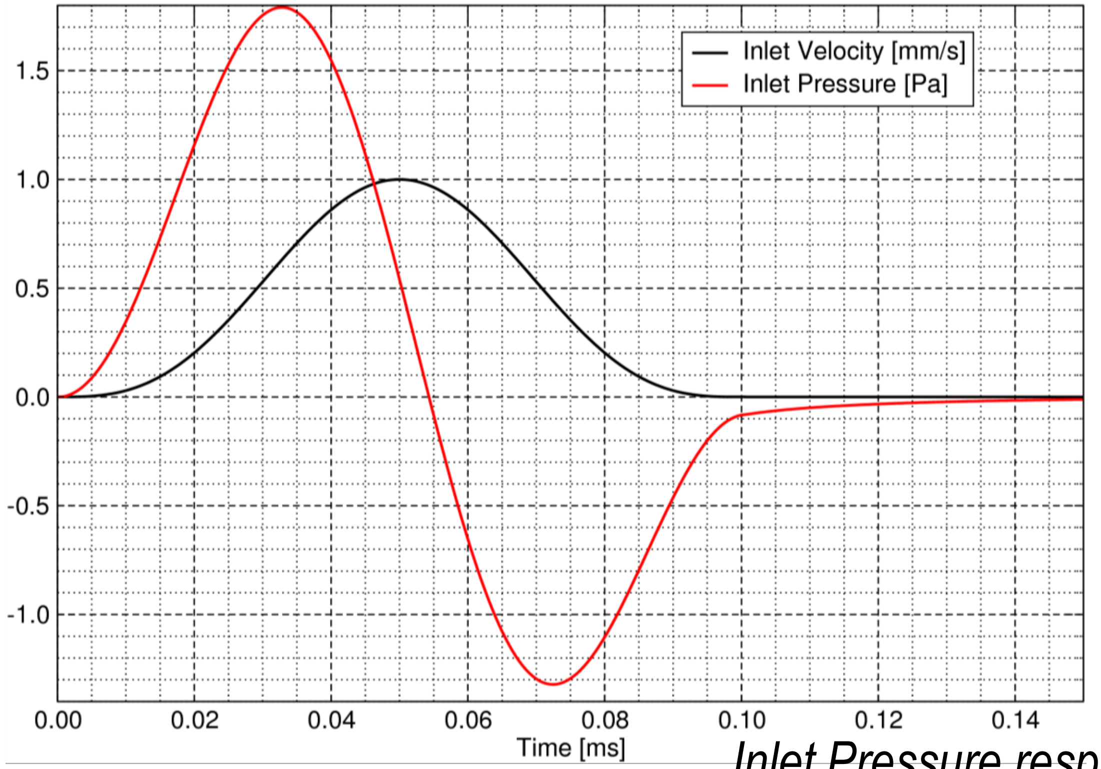
- At the surface of the film: $\mathbf{u}=\mathbf{u}_{film}$

Model Comparison – Transfer Impedance Calculation

- **CFD Models** – *InterNoise 2011*
  - Pressure taken at inlet and outlet
    - 1.7 mm and 5.0 mm away from film
  - Fourier transform for impedance

$$Z_{Trans} = \frac{P_{in} - P_{out}}{V_{in}}$$

$$V = V_0 \frac{1 - \cos(4\pi f t)}{2} \sin(2\pi f t)$$



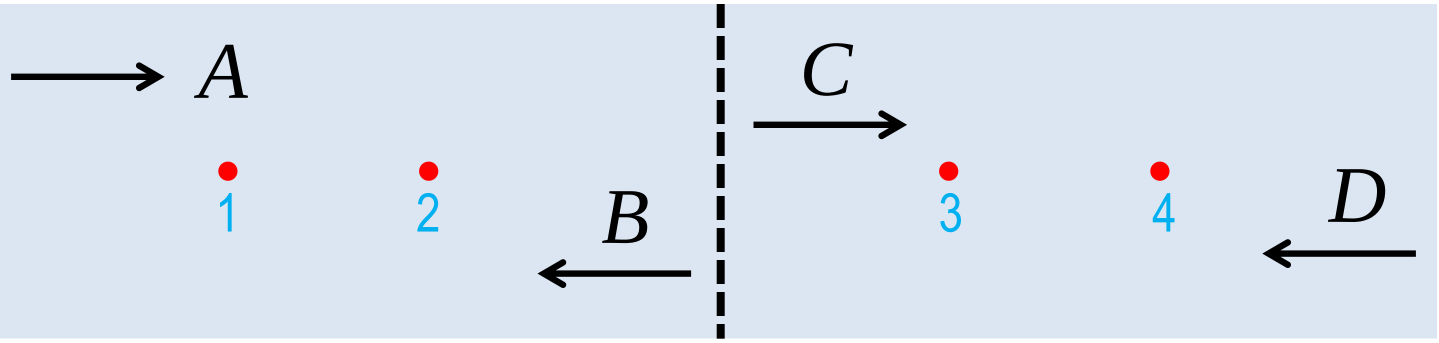
*Inlet Pressure response (**red**)*
*to the prescribed inlet Velocity (**black**)*

- **Acoustic Models** – *NoiseCon 2014*
  - Pressure probes spaced away from film
    - 2.50 mm and 3.75 mm up- and down- stream
  - Already in Fourier space
  - Pressure and Velocity on front and back surfaces of film were determined from incident, reflected, and transmitted waves
  - Transfer impedance computed using the 4-probe method from ASTM E2611-09

$$Z_{Trans} = \frac{P_0}{V_0} - \frac{P_L}{V_L}$$

Model Comparison – Four-Probe Method

- Analogous to ASTM E2611-09 with a single load



k	wave number
r_{in}	radius upstream
r_{out}	radius downstream
A	incoming wave
B	reflected wave
C	transmitted wave
D	reflected from termination = *0 for anechoic*
p_*	pressure measured at points 1-4
x_*	position of points 1-4 from left side of film
L	thickness of film
I_*	intensity of waves A, B, C, or D
ρ_{air}	density of air
c	speed of sound
r	reflection coefficient
τ	transmission coefficient
α	absorption coefficient
P_*	pressure at film surfaces
V_*	velocity at film surfaces
Z_{trans}	transfer impedance

$$k = \omega / c \qquad r_{in} = r_{out}$$

$$A = \frac{i\left(p_1 e^{+ikx_2} - p_2 e^{+ikx_1}\right)}{2\sin k\left(x_1 - x_2\right)} \qquad I_A = \frac{|A|^2 \pi r_{in}^2}{\rho_{air} c}$$

$$B = \frac{i\left(p_2 e^{-ikx_1} - p_1 e^{-ikx_2}\right)}{2\sin k\left(x_1 - x_2\right)} \qquad I_B = \frac{|B|^2 \pi r_{in}^2}{\rho_{air} c}$$

$$C = \frac{i\left(p_3 e^{+ikx_4} - p_4 e^{+ikx_3}\right)}{2\sin k\left(x_3 - x_4\right)} \qquad I_C = \frac{|C|^2 \pi r_{out}^2}{\rho_{air} c}$$

$$D = \frac{i\left(p_4 e^{-ikx_3} - p_3 e^{-ikx_4}\right)}{2\sin k\left(x_3 - x_4\right)} \qquad I_D = \frac{|D|^2 \pi r_{out}^2}{\rho_{air} c}$$

$$r = I_B / I_A \qquad \tau = I_C / I_A \qquad \alpha = 1 - r - \tau$$

$$P_0 = A + B \qquad V_0 = \left(A - B\right) / \rho_{air} c \qquad Z_0 = P_0 / V_0$$

$$P_L = Ce^{-ikL} + De^{+ikL} \qquad V_L = \left(Ce^{-ikL} - De^{+ikL}\right) / \rho_{air} c \qquad Z_L = P_L / V_L$$

$$Z_{trans} = Z_0 - Z_L$$

Rigid Film – Transfer Impedance

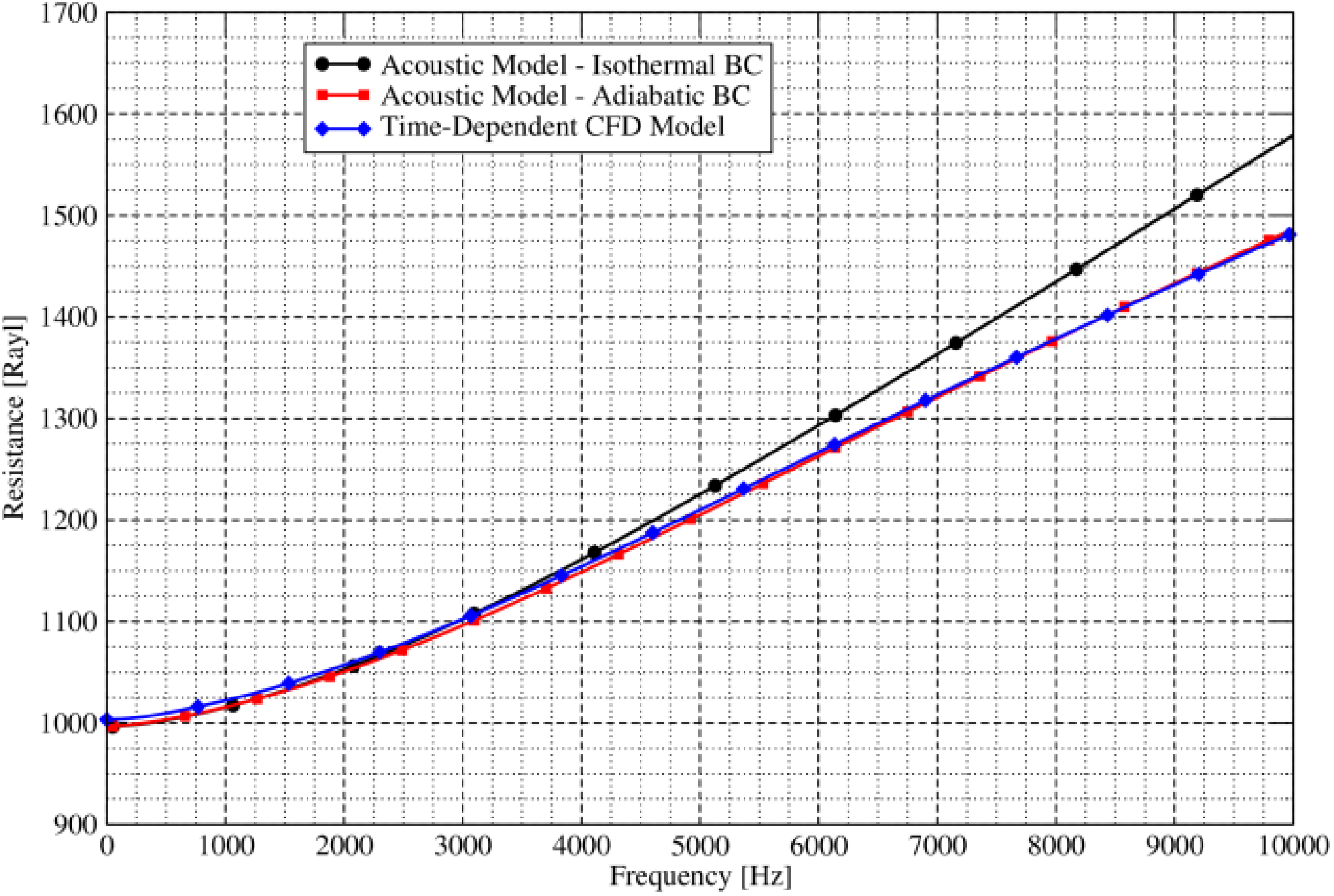
- Thermal losses affect the Resistance only
  - There are no thermal losses at an adiabatic boundary
  - Acoustic and CFD models match when adiabatic boundary conditions are applied
- CFD calculations require additional correction
  - Need to account for the reactance of the air in the inlet and outlet regions

$$Z_{Trans} = Z_{CFD} - j\omega\rho_{air}\left(L_{in} + L_{out}\right)$$

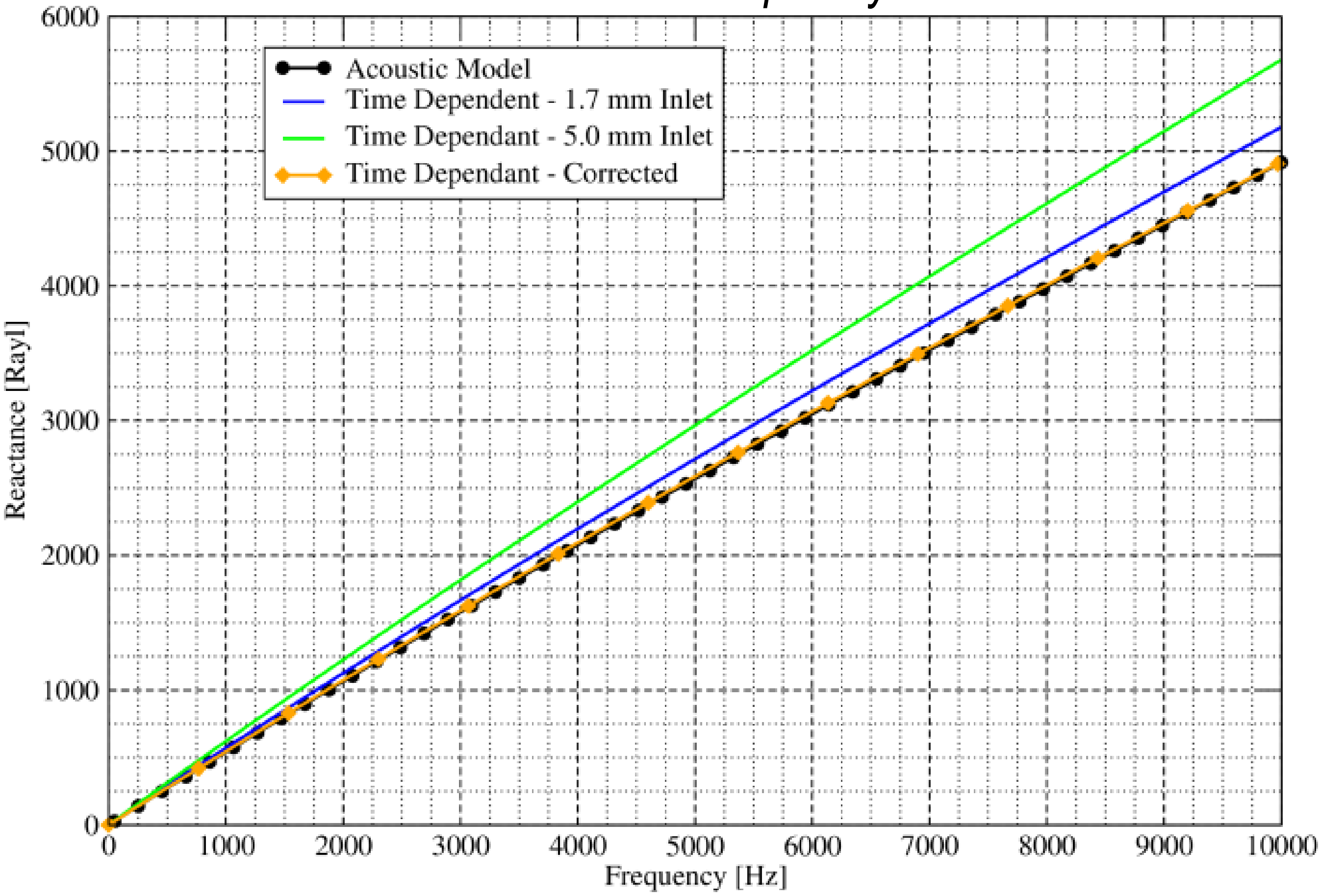
Film Properties

• Film Thickness	400 µm
• Hole Diameter	170 µm
• Porosity	1%

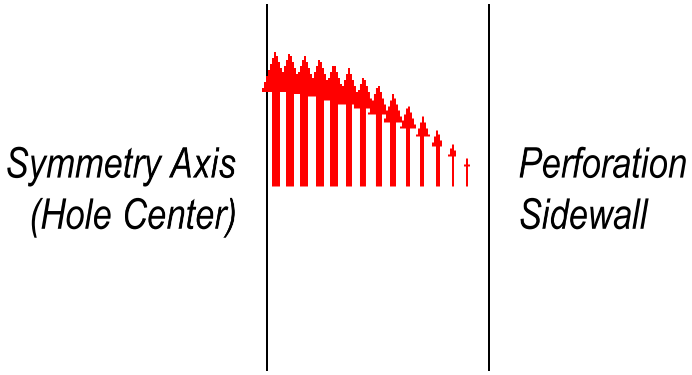
Resistance vs. frequency



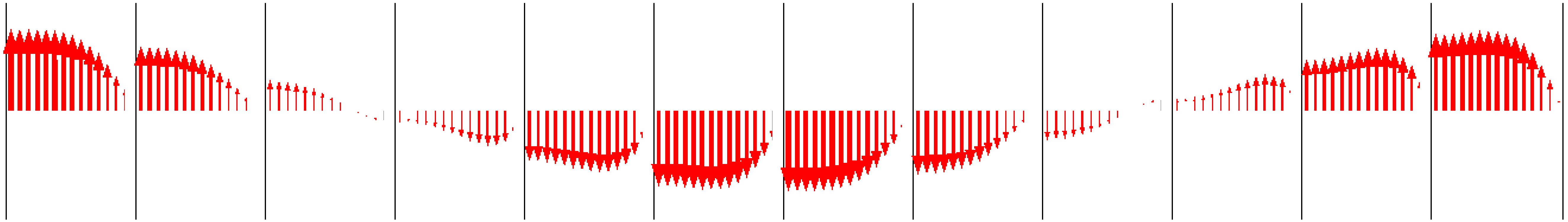
Reactance vs. frequency



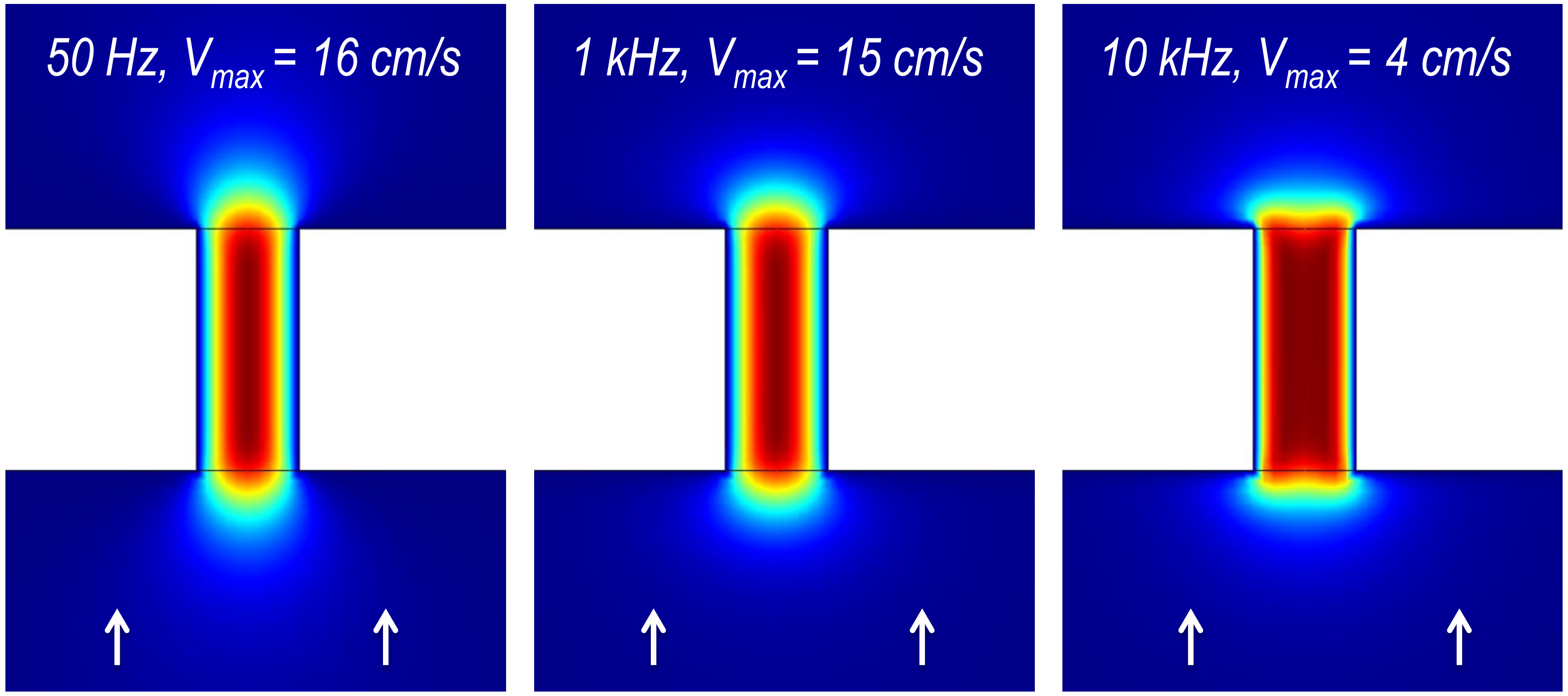
Rigid Film – Velocity Profiles



- Low frequency velocity profile is like Poiseuille flow
  - Parabolic in shape
- High frequencies may deviate significantly from parabolic
  - Velocity vectors every 30º of phase (symmetry axis on the left, wall on the right),10 kHz



- Velocity distribution also changes with frequency *(not on equal color scales)*

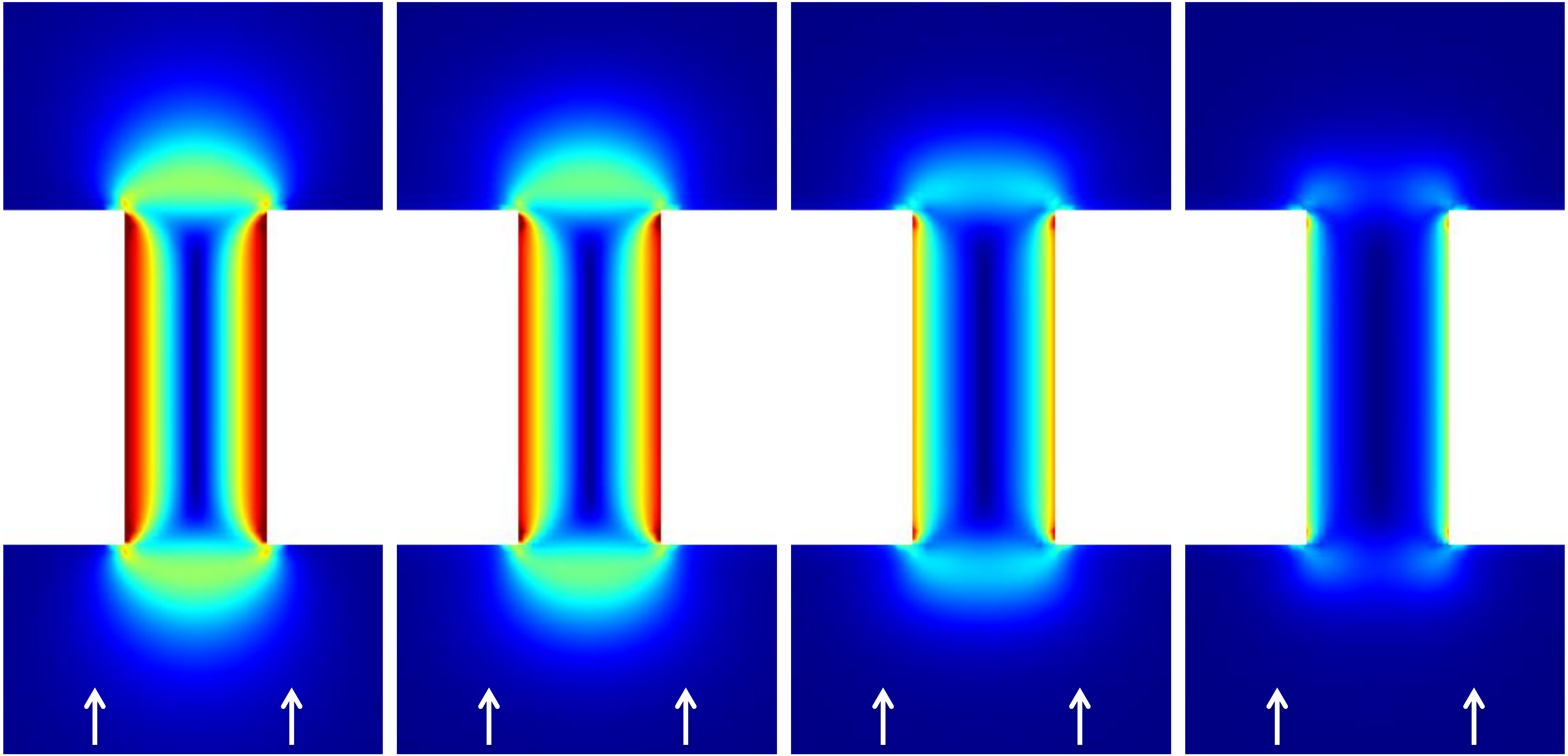


Incident pressure wave from below

Rigid Film – Viscous Losses

$$\langle E_{loss}\rangle_{\mu} = \mu\left\langle |\nabla u|^{2}\right\rangle$$

- Viscous energy losses are proportional to the shear rate squared
  - Losses are concentrated along perforation walls and at the inlet/outlet *(resistive end correction)*
  - Losses are symmetric front-to-back in linear regime *(acoustic wave is incident from below)*
  - Losses decrease as the frequency increases



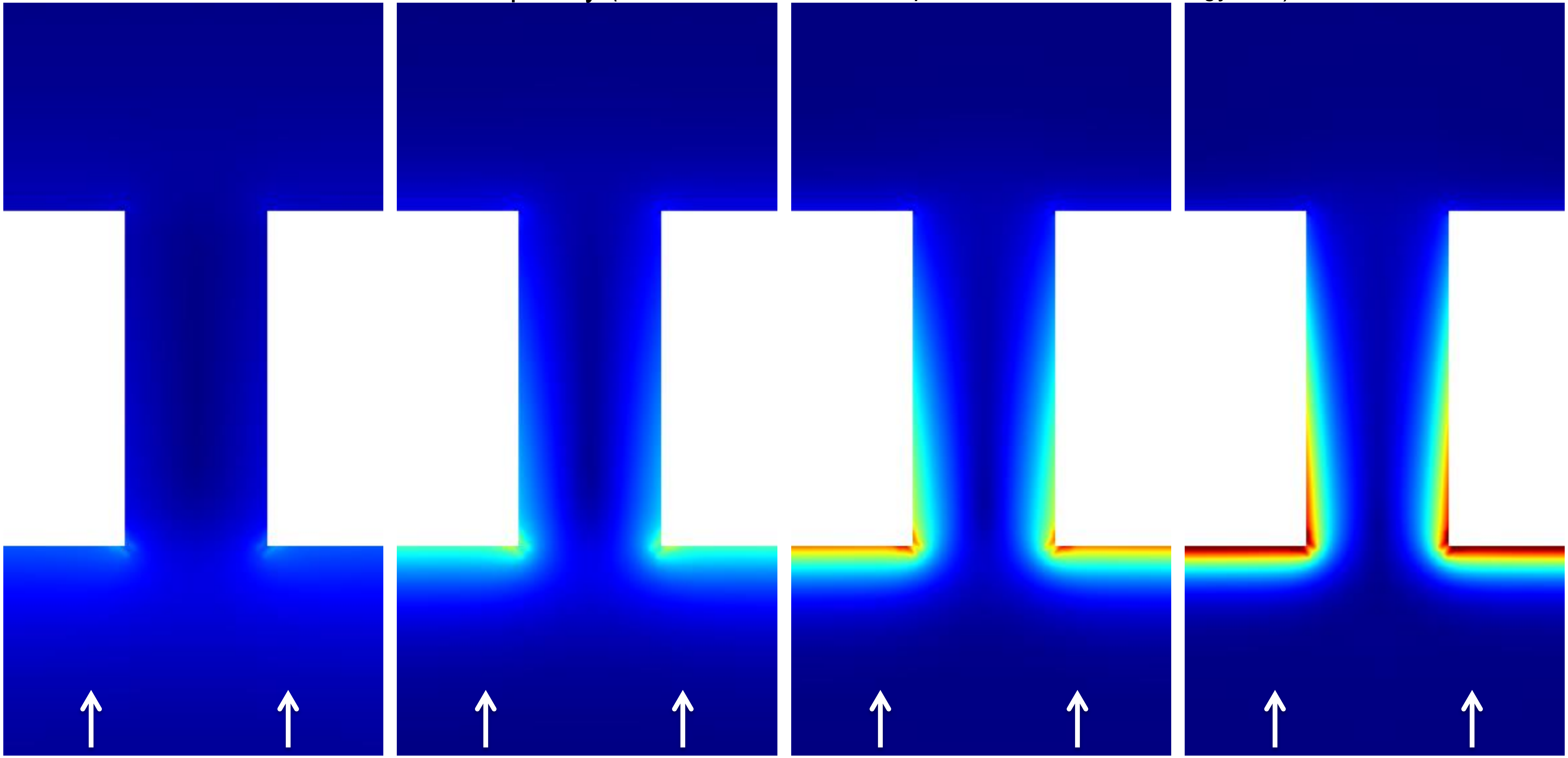
500 Hz *2,000 Hz* *5,000 Hz* *10,000 Hz*

Plots of the square root of viscous losses on a scale from 0 to 15 $\sqrt{W/m^3}$

Rigid Film – Thermal Losses

$$\langle E_{loss} \rangle_k = \frac{k}{T} \langle |\nabla T|^2 \rangle$$

- Thermal energy losses are proportional to the temperature gradient squared
  - Losses are concentrated over whole front surface, and only a little within the perforation *(unlike Maa who modeled thermal losses occurring within the perforation)*
  - Losses are asymmetric front-to-back *(acoustic wave is incident from below)*
  - Losses increase with the frequency *(Scale is 1/30th of viscous plots, so 1/900th the energy loss)*

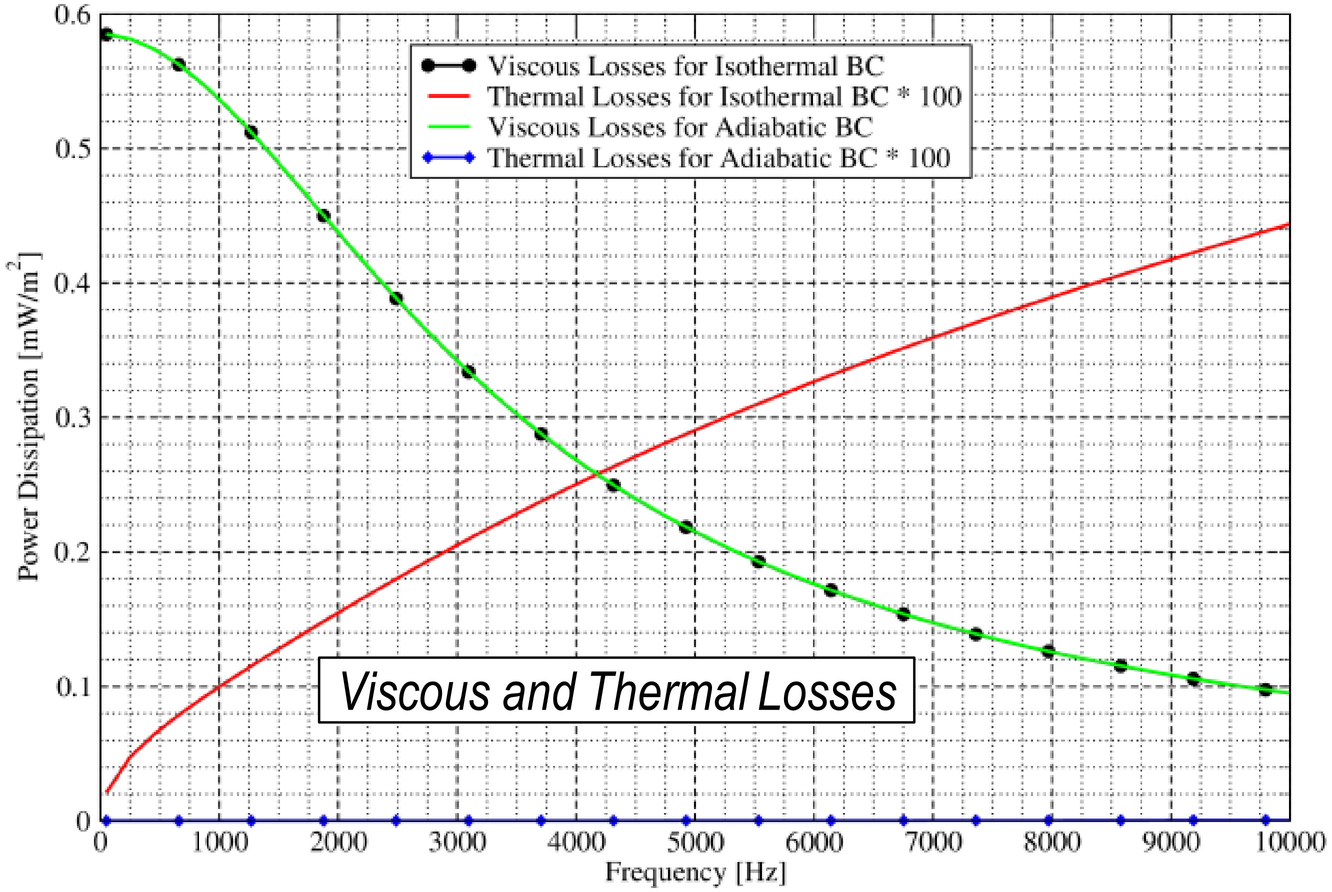


500 Hz *2,000 Hz* *5,000 Hz* *10,000 Hz*

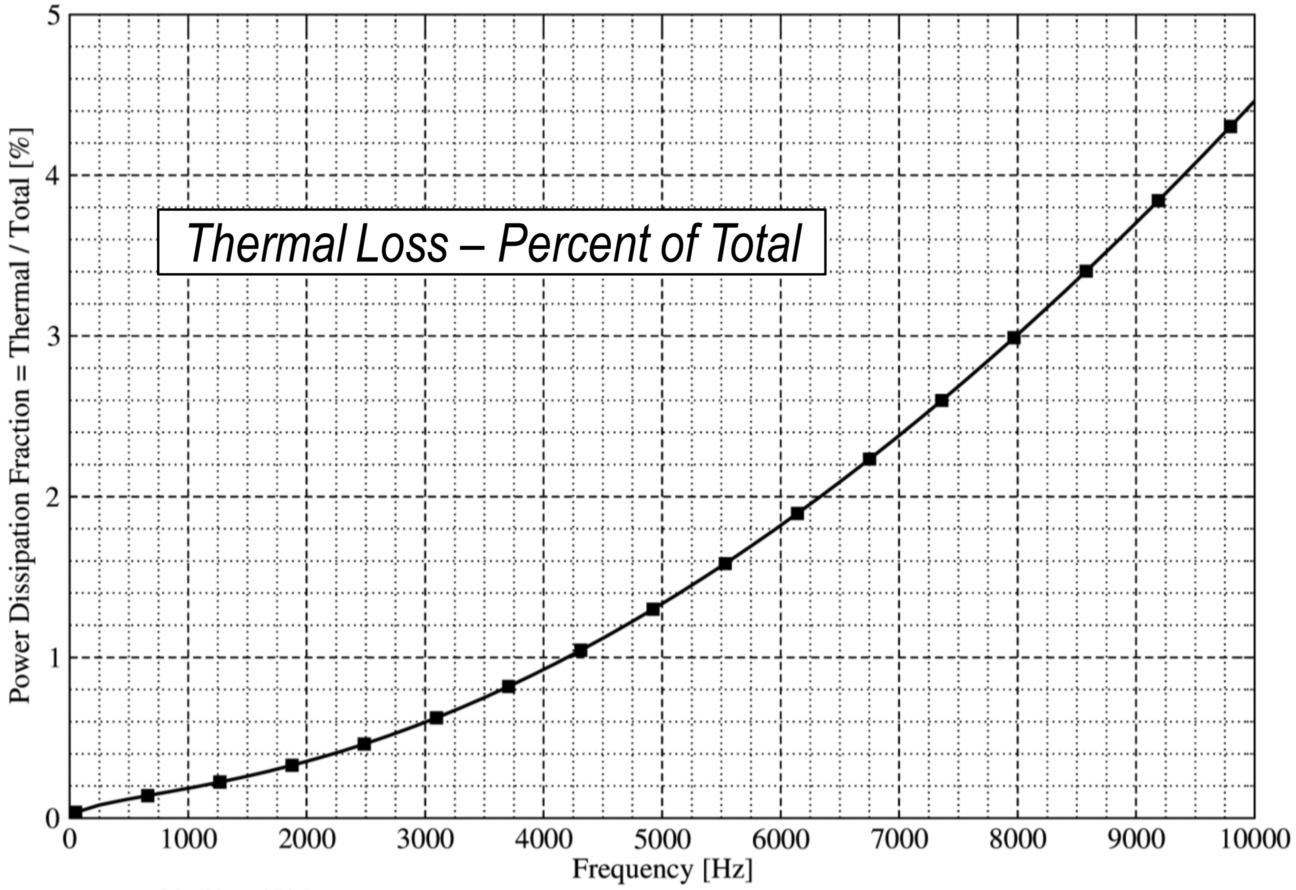
Plots of the square root of thermal losses on a scale from 0 to 0.5 $\sqrt{W/m^3}$

Rigid Film – Losses Compared and Effective Absorption

- Thermal losses are significantly smaller than viscous losses *(< 5% up to 10 kHz)*

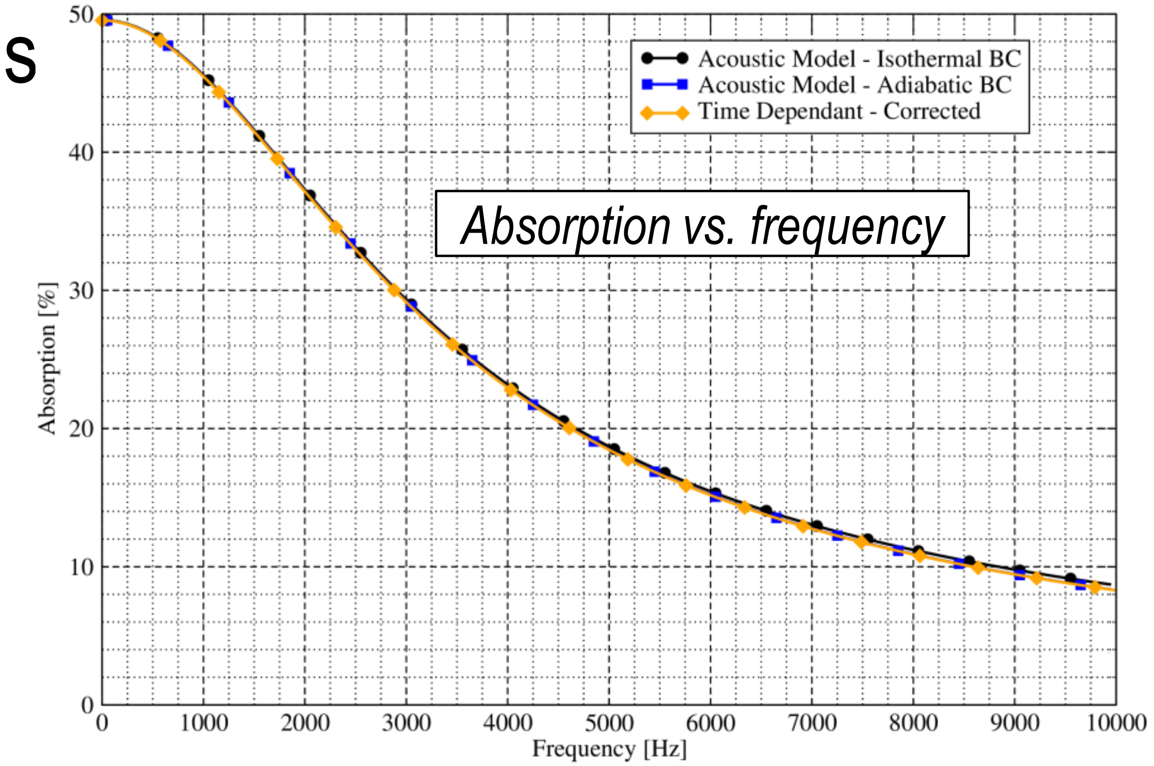


Viscous and Thermal Losses



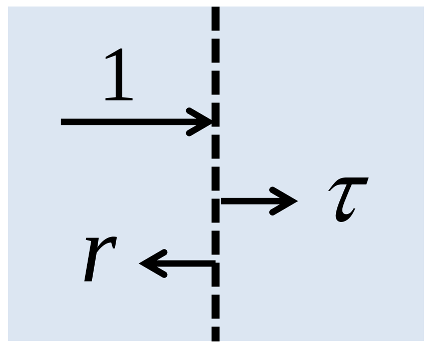
Thermal Loss – Percent of Total

- Thermal boundary conditions (**adiabatic** vs. **isothermal**) are <u>not significant</u> for absorption
  - Infinite film in free space
  - Film in impedance tube with anechoic termination



Absorption vs. frequency

$$\alpha = 1 - r - \tau$$



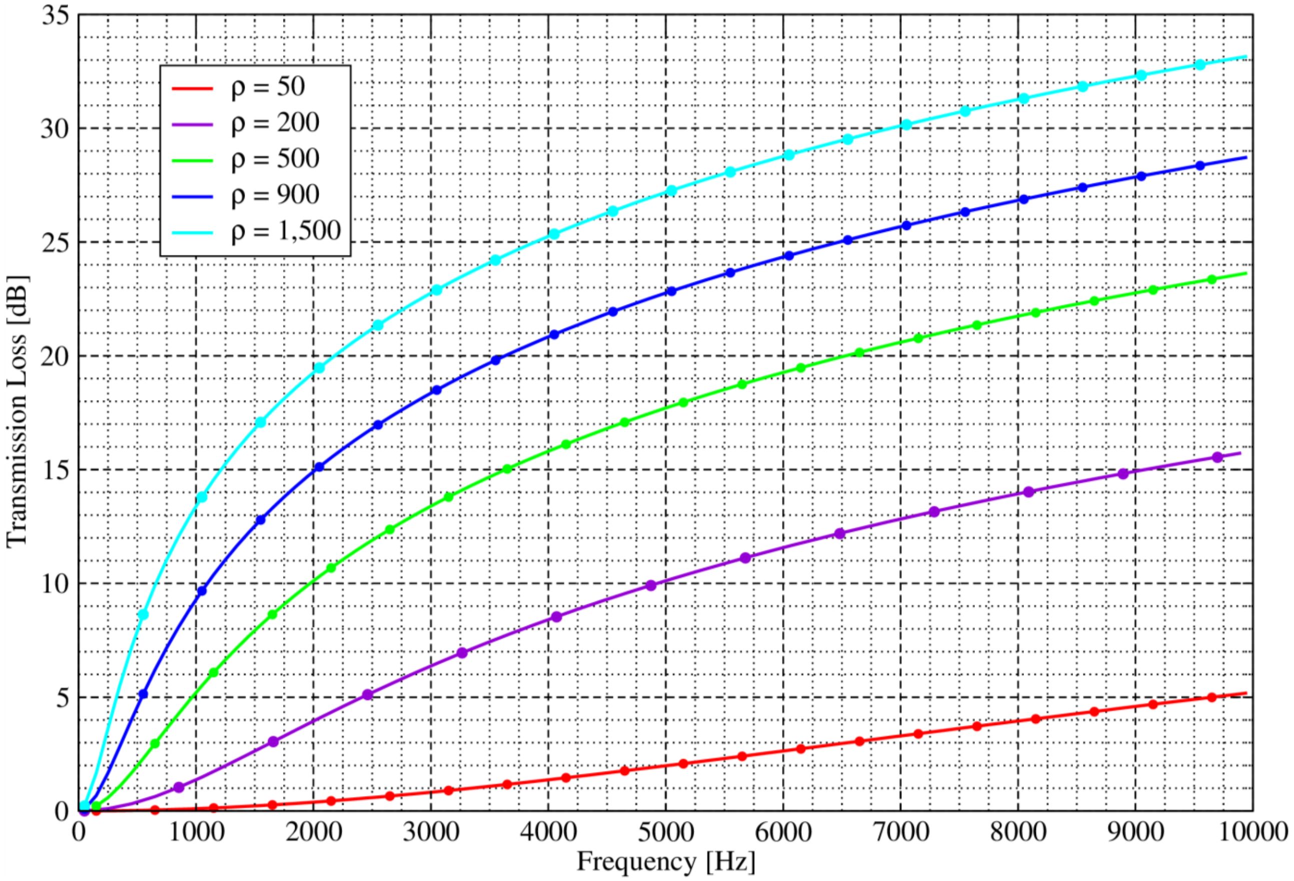
***Absorption** is the fraction of normally incident acoustic intensity not reflected or transmitted by the film.*

Solid Limp Film – Mass Law

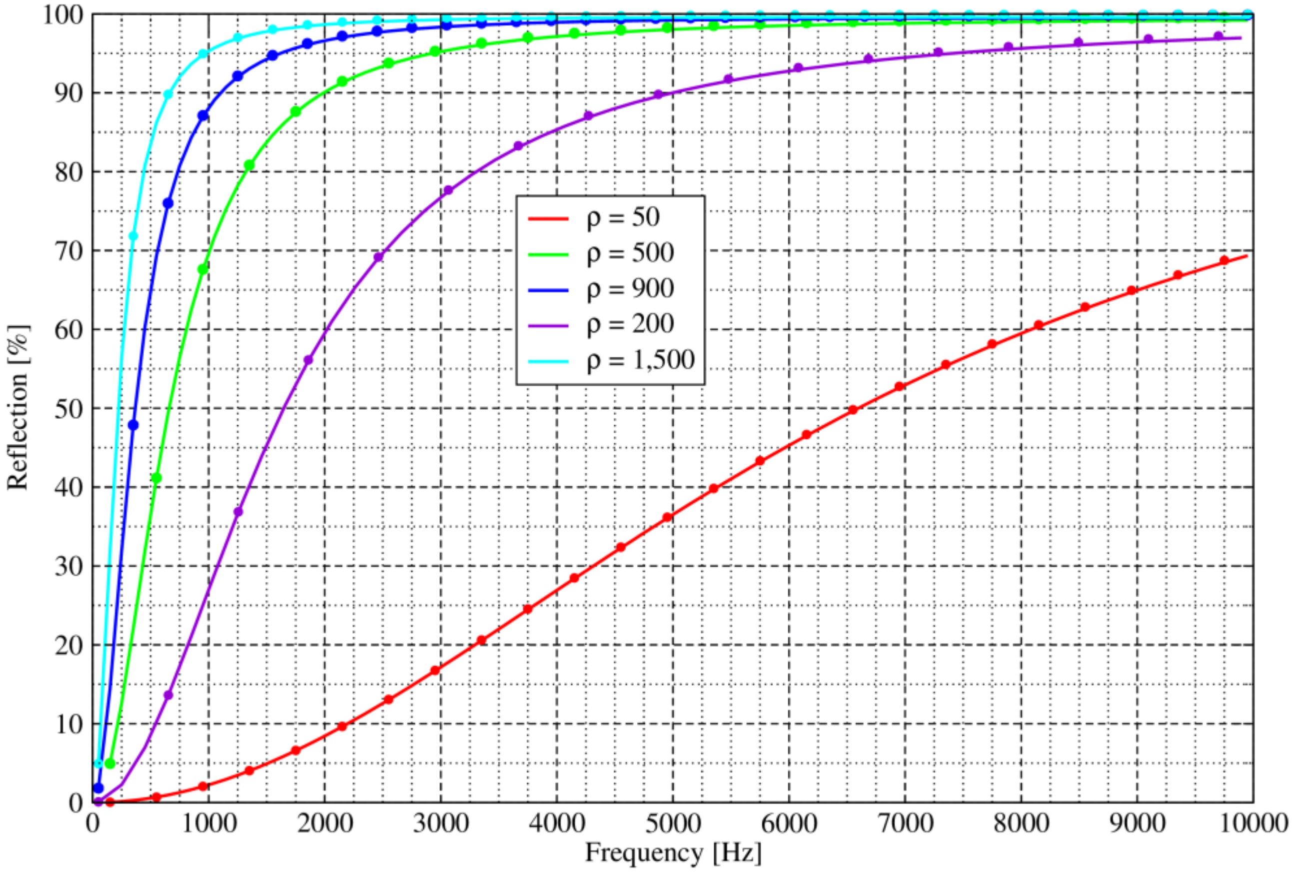
- *Impedance* for an (acoustically) thin impermeable layer is determined from its mass $$Z_{Sheet} = j\omega m = j\omega\rho_{film}L$$
- Transmission loss and Reflection coefficient increase with the mass
  - Exact agreement with numerical model *(Markers on plots)*

$$\tau = \frac{1}{1+\left(\frac{\omega m}{2\rho_{air}c}\right)^2} \qquad TL = 10\log_{10}\left[1+\left(\frac{\omega m}{2\rho_{air}c}\right)^2\right]$$

Transmission Loss



Reflection Coefficient



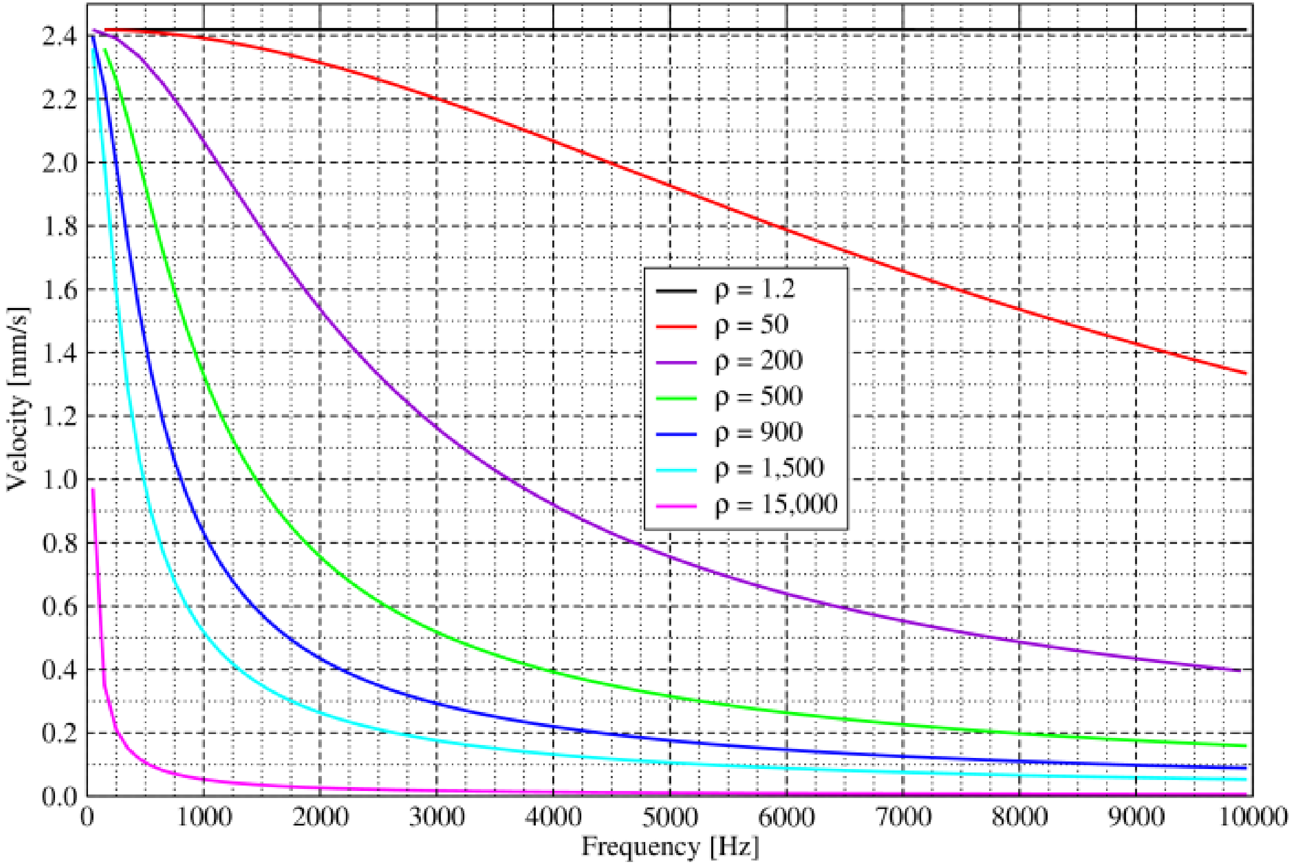
Solid Limp Film – Model Details

- Velocity of the film depends on the film's mass / density
  - Film moves as one solid block, in unison
  - Film was modeled as an elastic solid
- Negligible thermal absorption *(< 0.3%)*
  - Prediction by Pierce for normal-incidence absorption at a rigid surface *(markers on plot)*
    - Allen D. Pierce, "**Acoustics: An Introduction to Its Physical Principles and Applications",** ASA, 1989.

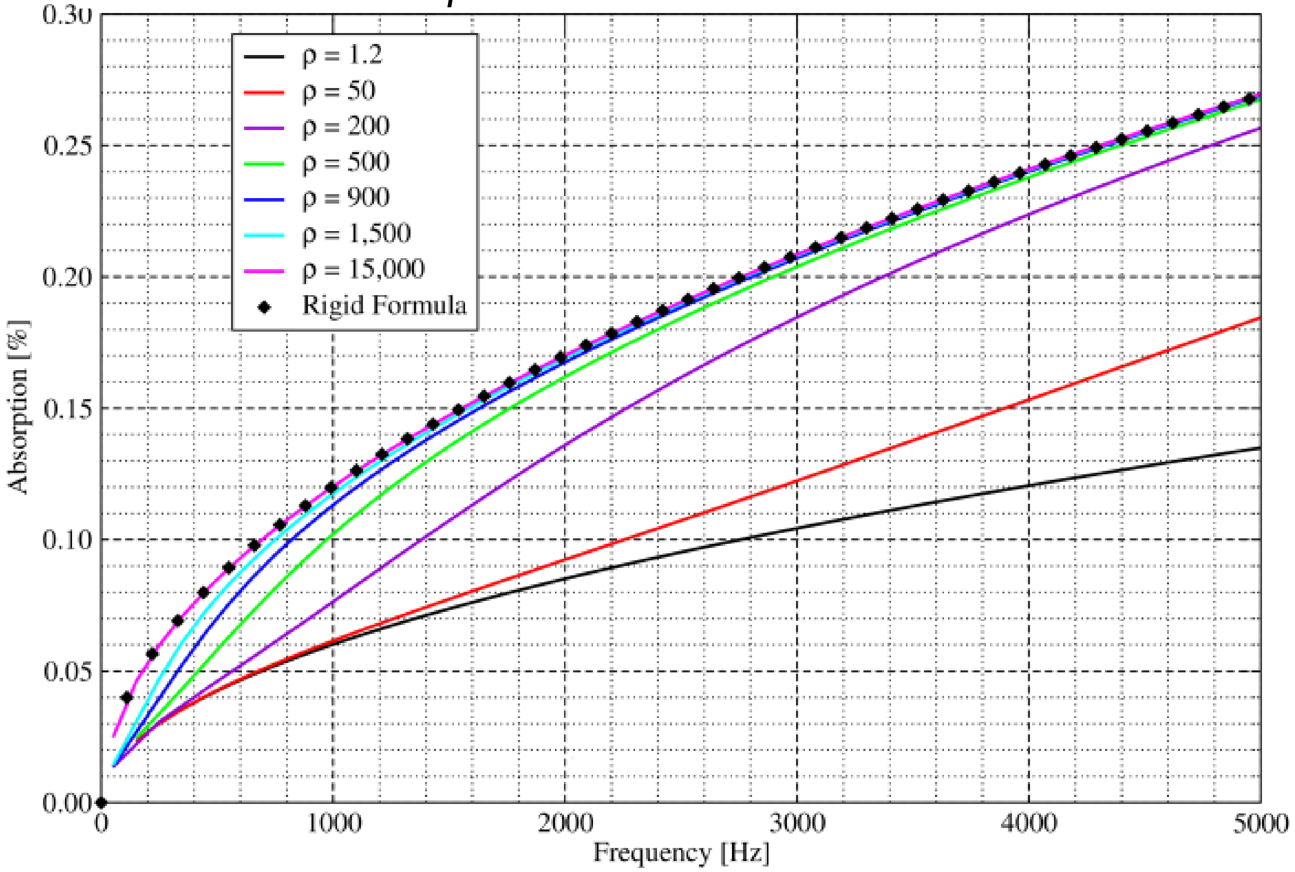
Film Properties

• Film Thickness	400 μm
• Elastic Modulus	10^9 Pa
• Poisson's Ratio	0.4

Film Velocity



Absorption from Thermal Losses



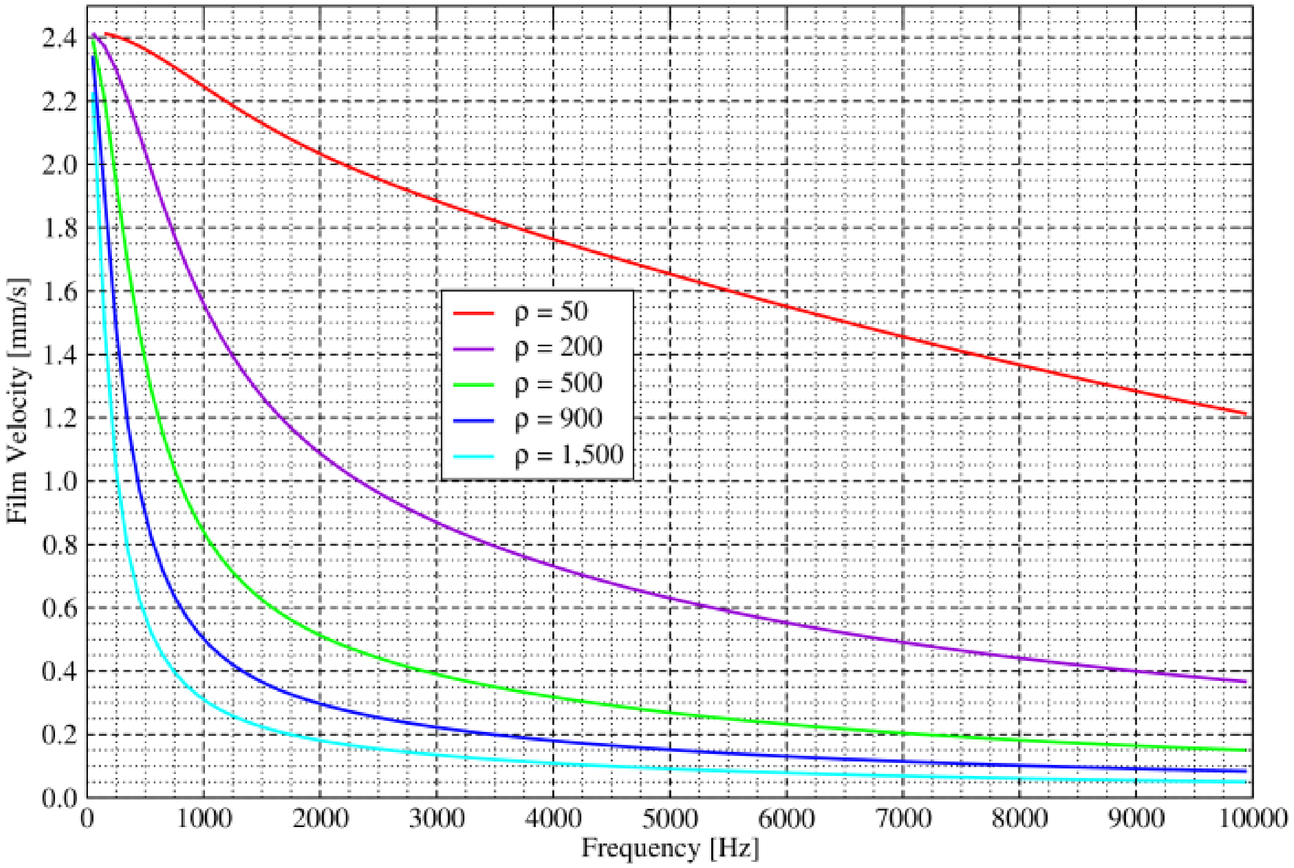
Limp Perforated Film – Velocity magnitude

Film Properties

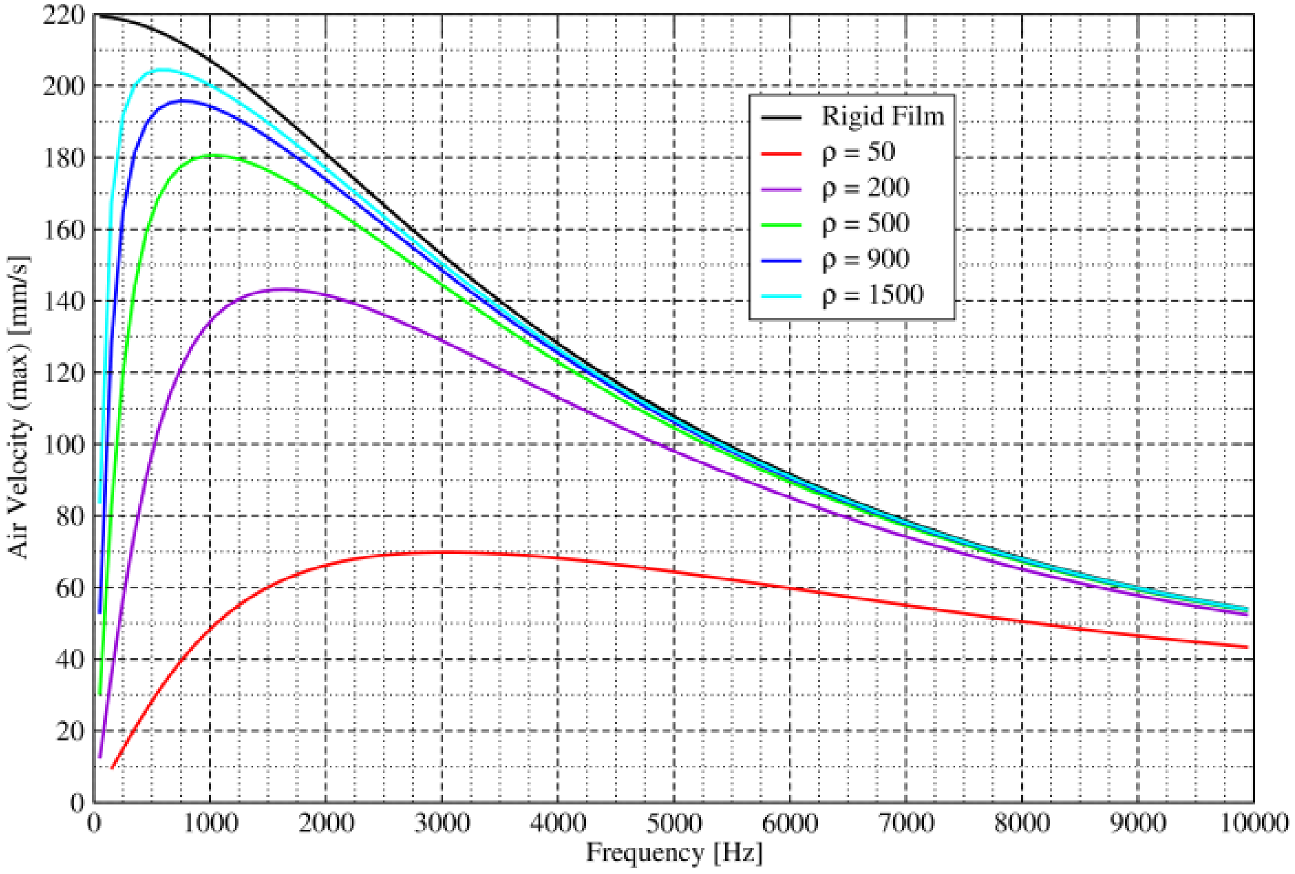
• Film Thickness	400 μm
• Hole Diameter	170 μm
• Porosity	1%
• Elastic Modulus	10^9 Pa
• Poisson's Ratio	0.4

- Film velocities are reduced, compared to a solid film
  - Airflow through the perforations reduces the surface pressure
  - For example at 1 kHz, film velocities dropped by about 35%
- Air velocities through the perforations are reduced, compared to a rigid film
  - Due to the film moving with the air
  - Peak air velocity shifts to higher frequencies as the film mass decreases
  - Air velocities are typically two orders of magnitude greater than film velocity

Film Velocity

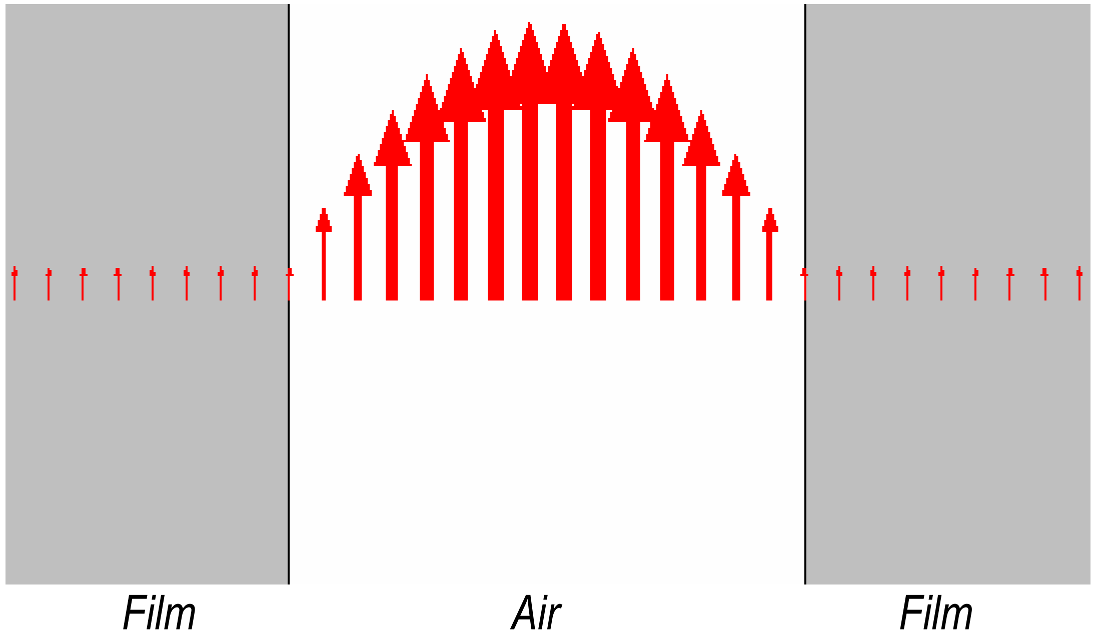


Air Velocity within perforation

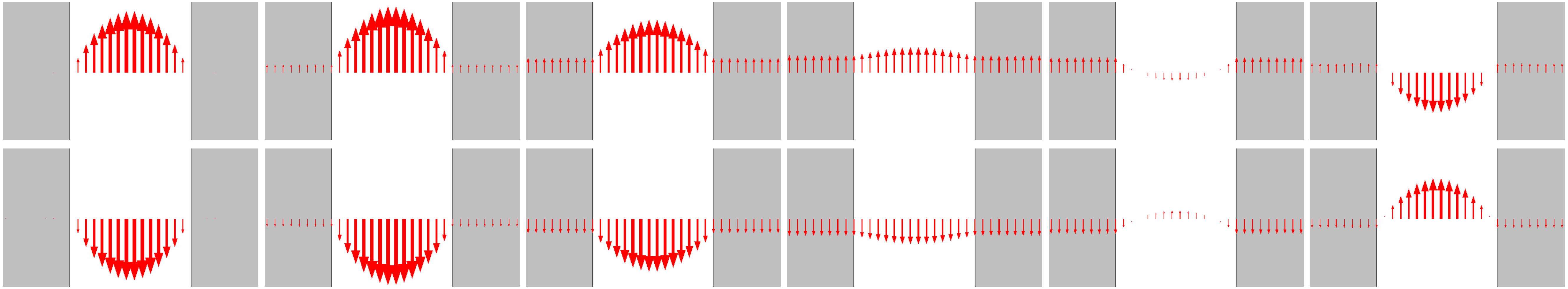


Limp Perforated Film – Velocity and Phase

- Relative motion
  - Most significant for light films at low frequency
  - Shown here for a density of 50 kg/m^3 at 150 Hz



Fluid-structure interaction



Film and air velocity shown every 30º of phase

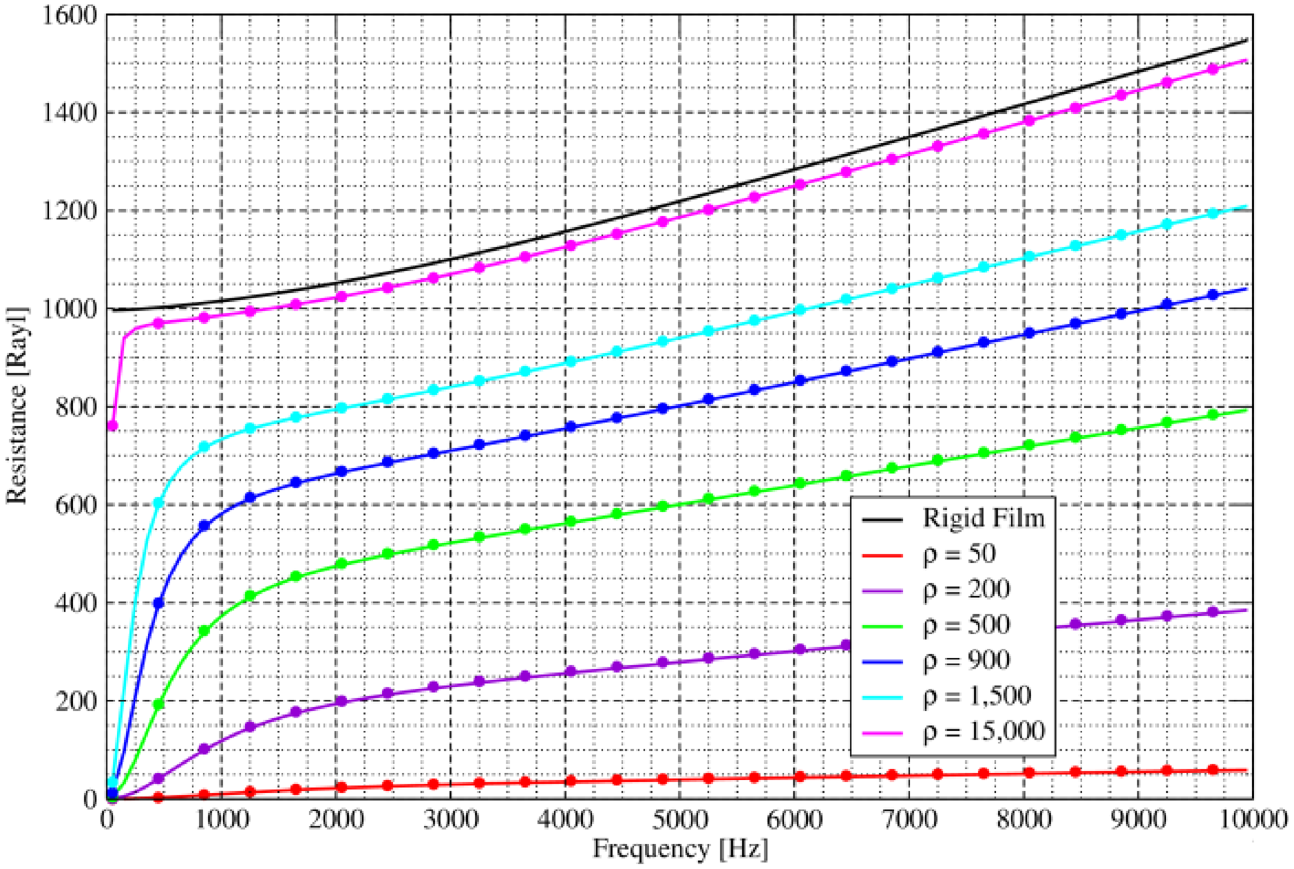
Limp Perforated Film – Impedance

- Mass Law impedance for limp impervious sheet **added in parallel** to the impedance of a rigid perforated plate predicts response very well *(markers)*
  - Resistance drops as mass decreases
  - Reactance changes in non-intuitive manner
    - Low-frequency has an increase of reactance with mass
    - High-frequency approaches rigid results more directly

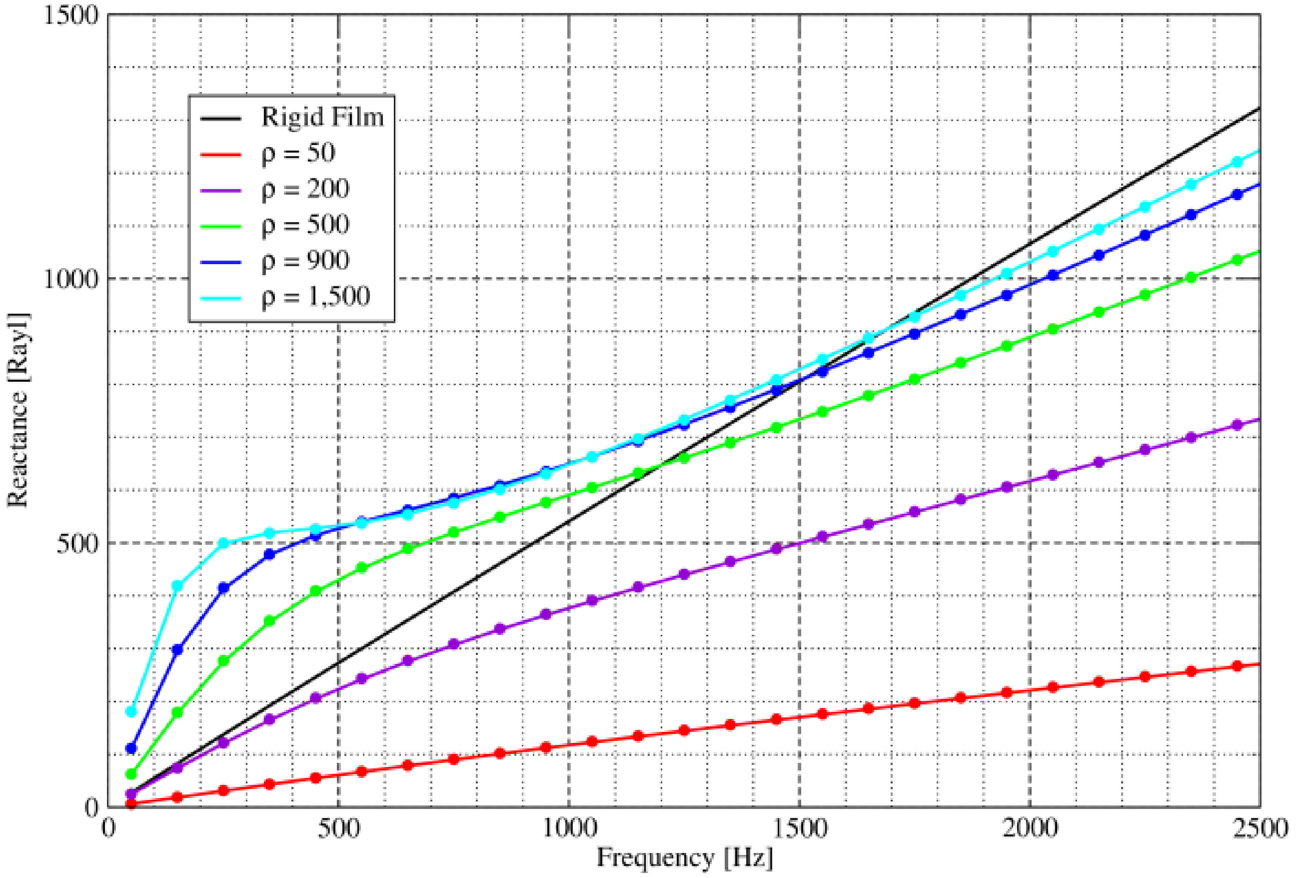
$$\boxed{Z_{Film} = \frac{1}{\dfrac{1}{Z_{Rigid}} + \dfrac{1}{Z_{Sheet}}} = \frac{j\omega m \cdot Z_{Rigid}}{Z_{Rigid} + j\omega m}}$$

Coupling effects neglected

Film Resistance – FSI models compared to formula



Film Reactance – FSI models compared to formula

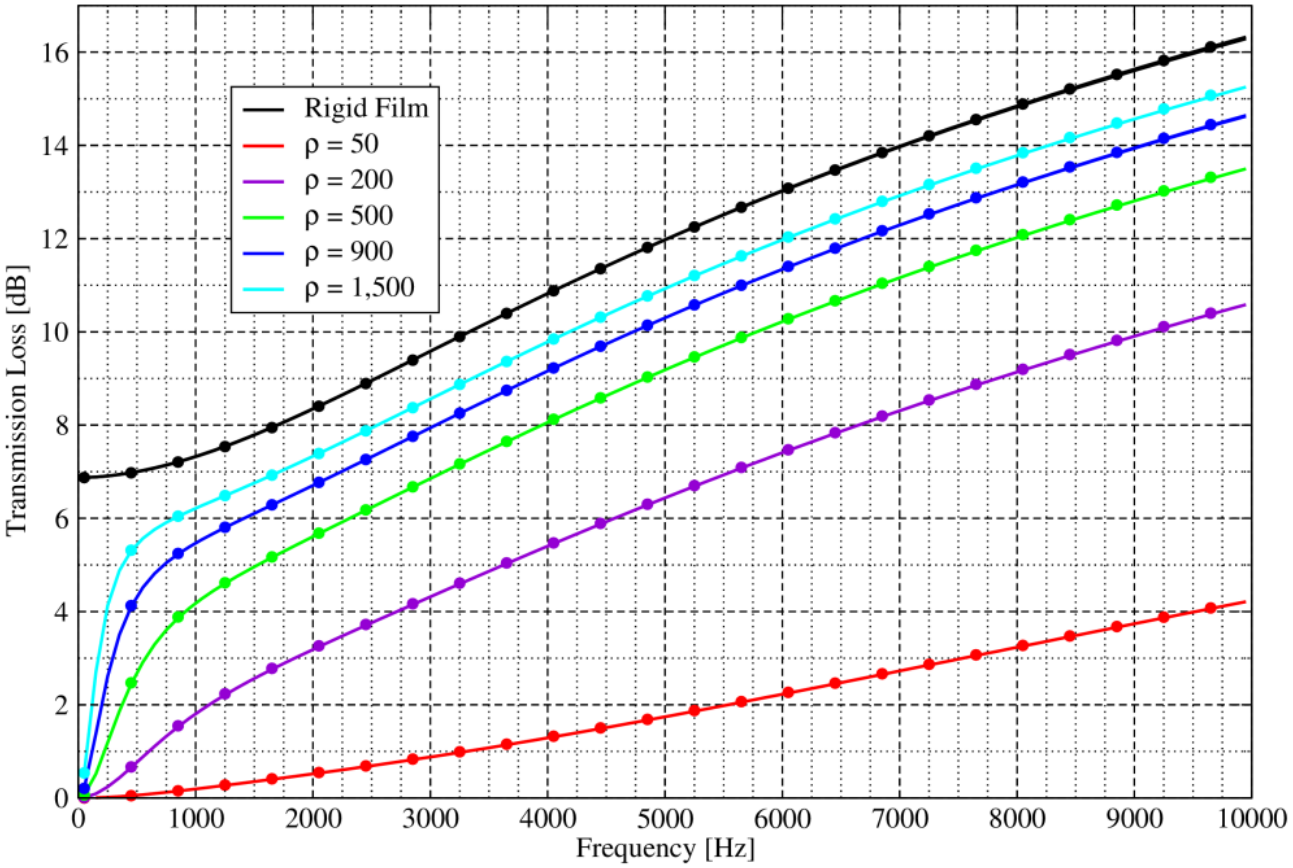


Limp Perforated Film – Transmission Loss

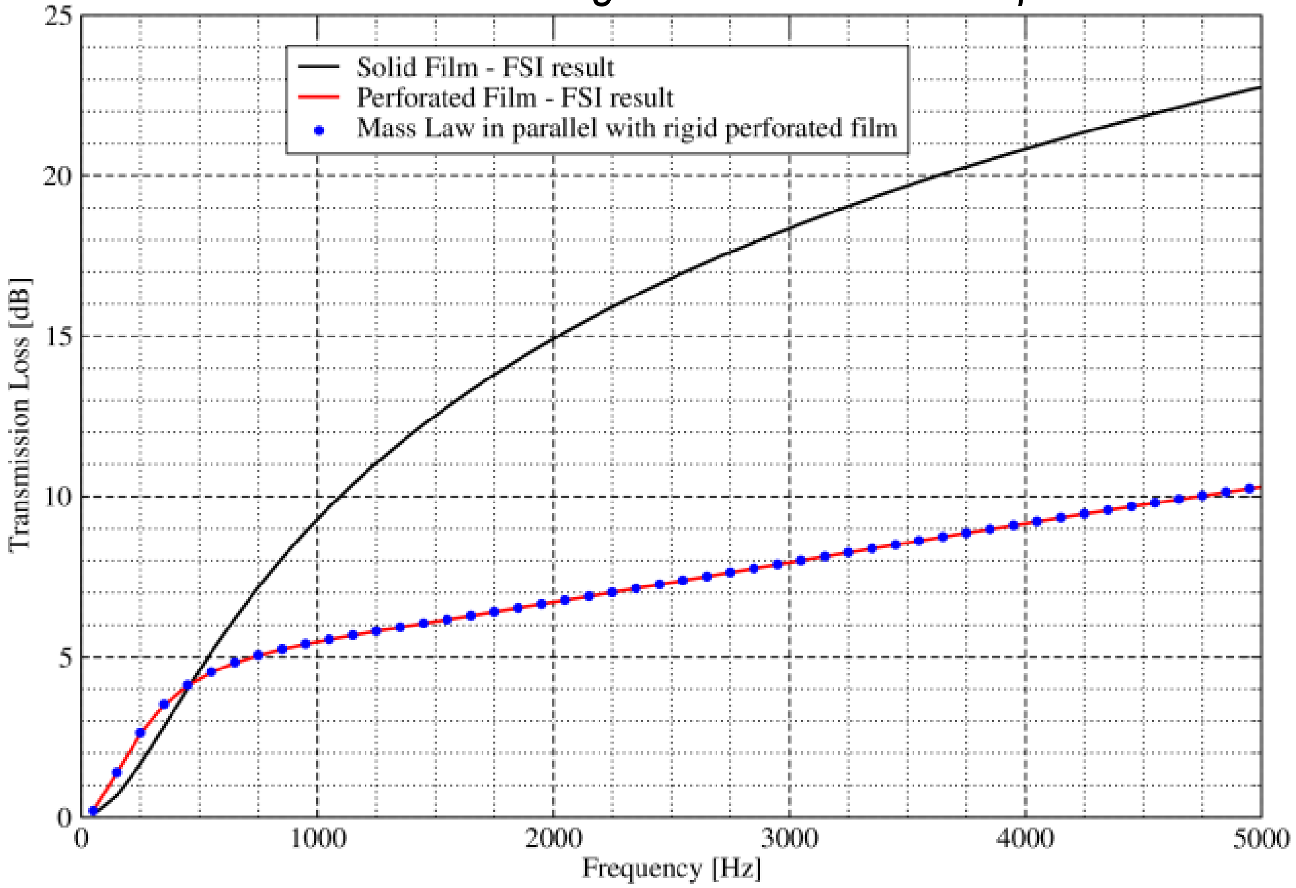
- Transmission loss decreases for lighter films, as expected
- Transmission loss for perforated film is significantly less than for solid film
- Parallel impedance formula *(markers)* predicts response very well

$$TL = 20\log_{10}\left|1+\frac{Z_{Film}}{2\rho_{air}c}\right|$$

Transmission Loss from FSI models compared to equation



Transmission Loss for 900 kg/m^3 with and without perforations

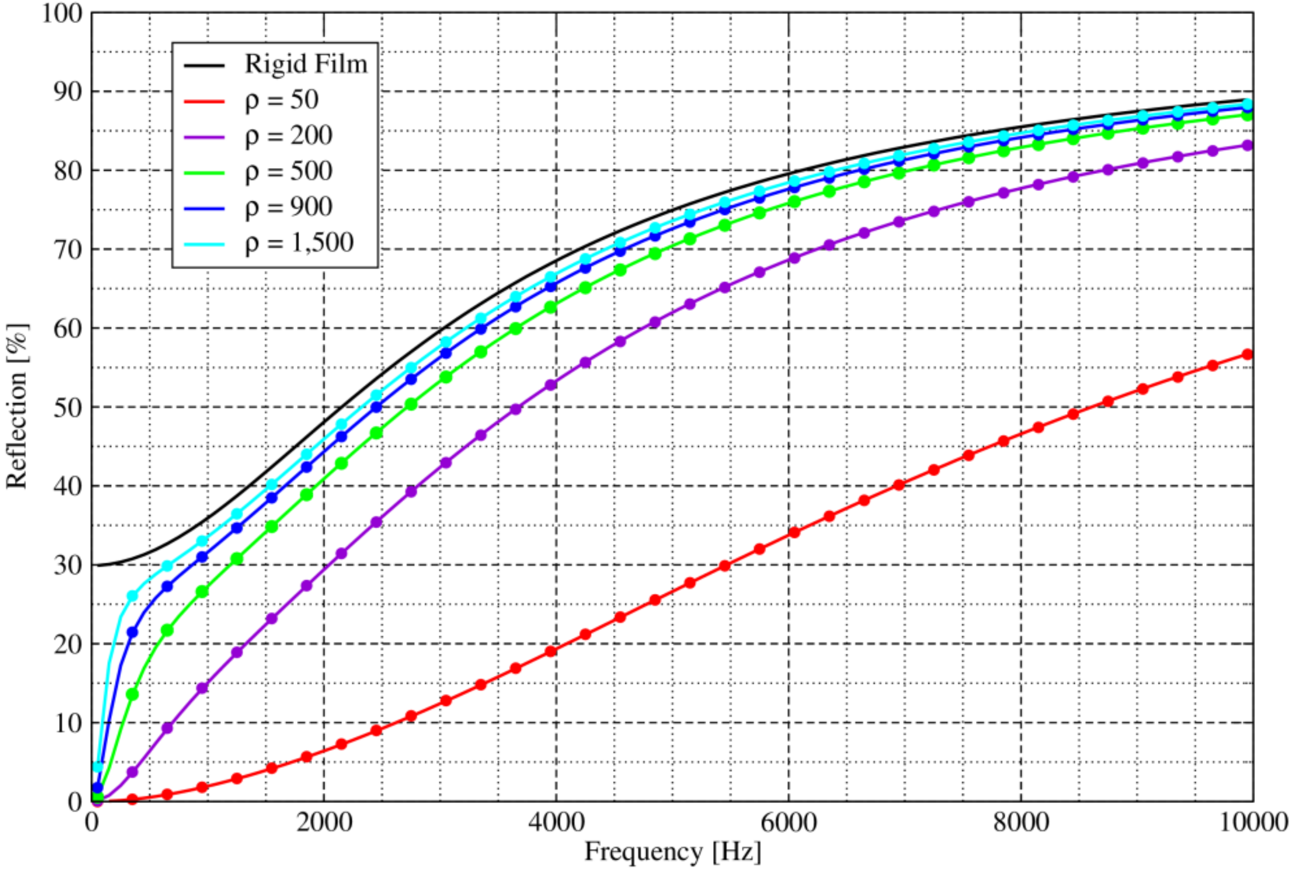


Perforated Film with Relative Motion – Reflection & Transmission

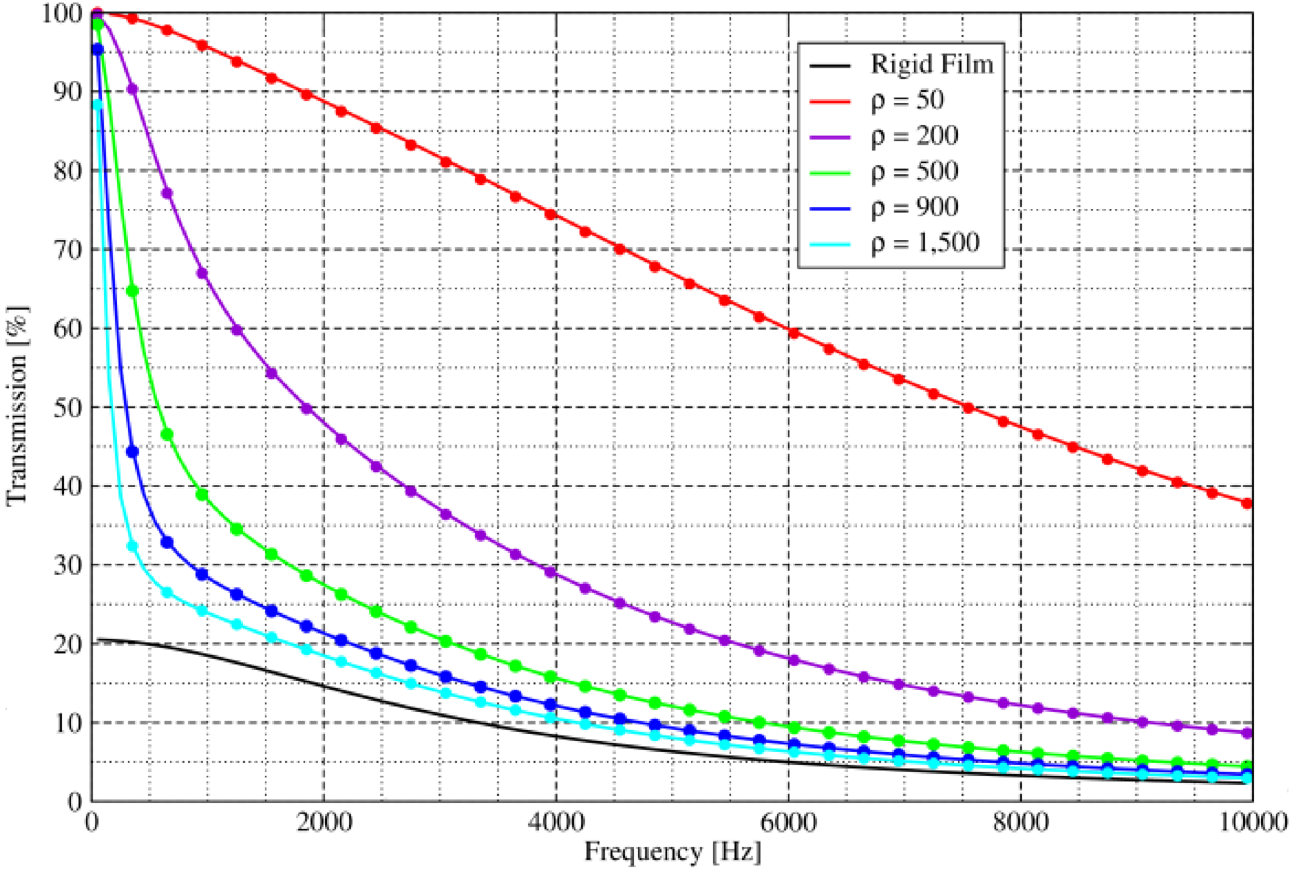
- Reflection and Transmission coefficients can similarly be calculated
- Parallel impedance formula *(markers)* predicts response very well *(anechoic term.)*
  - Reflection increases with the film mass, limited by that for a rigid film
  - Transmission decreases with the film mass, limited by that for a rigid film

$$r = \left| \frac{Z_{Film}}{Z_{Film} + 2\rho_{air}c} \right|^2 \qquad \tau = \left| \frac{2\rho_{air}c}{Z_{Film} + 2\rho_{air}c} \right|^2$$

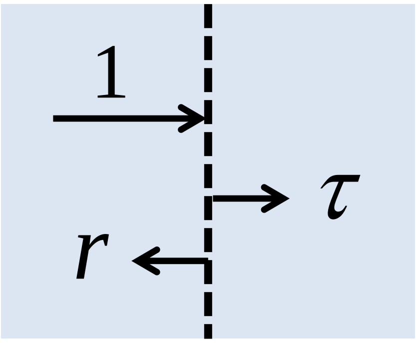
Reflection from FSI models compared to equation



Transmission from FSI models compared to equation

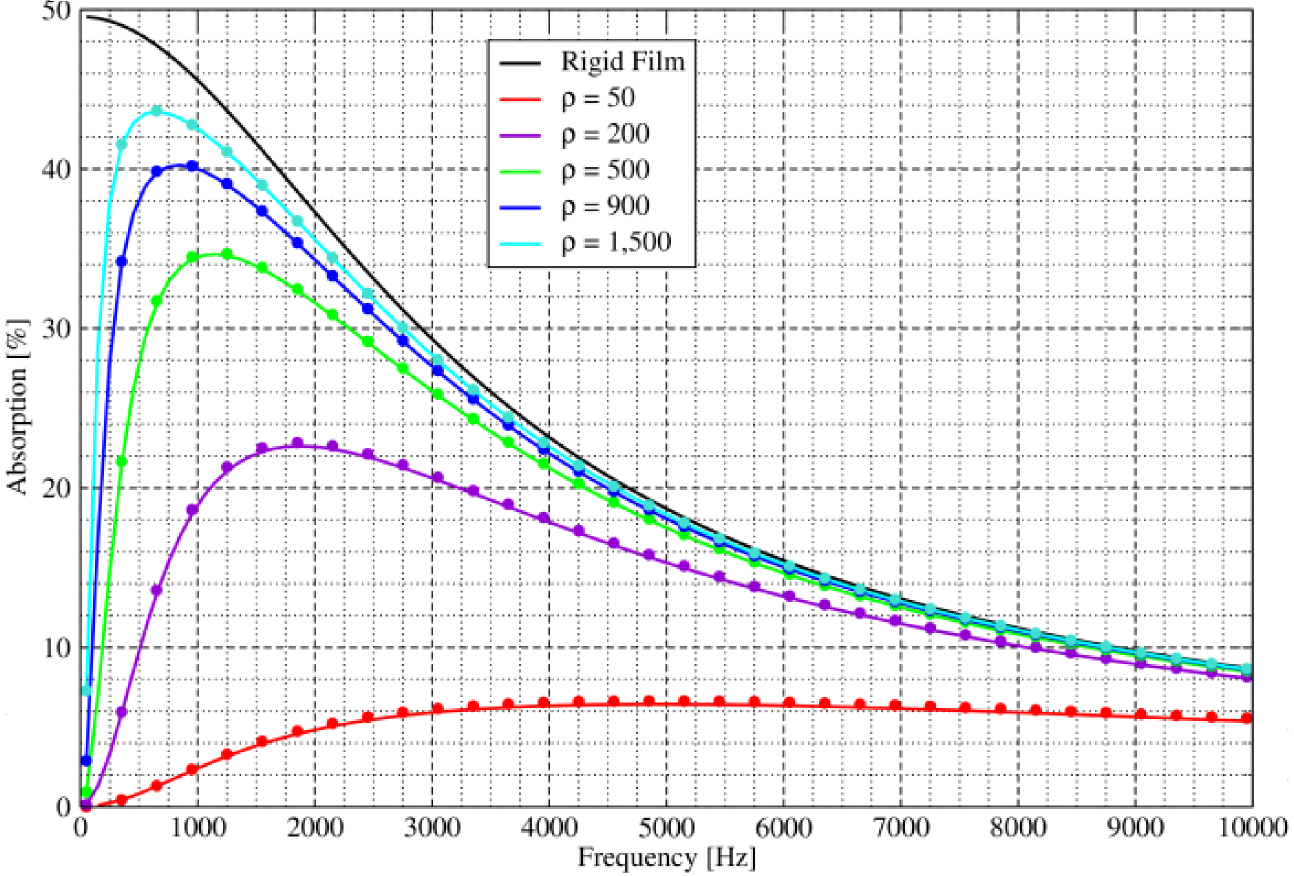


Film Perforated Film – Dissipation of Energy

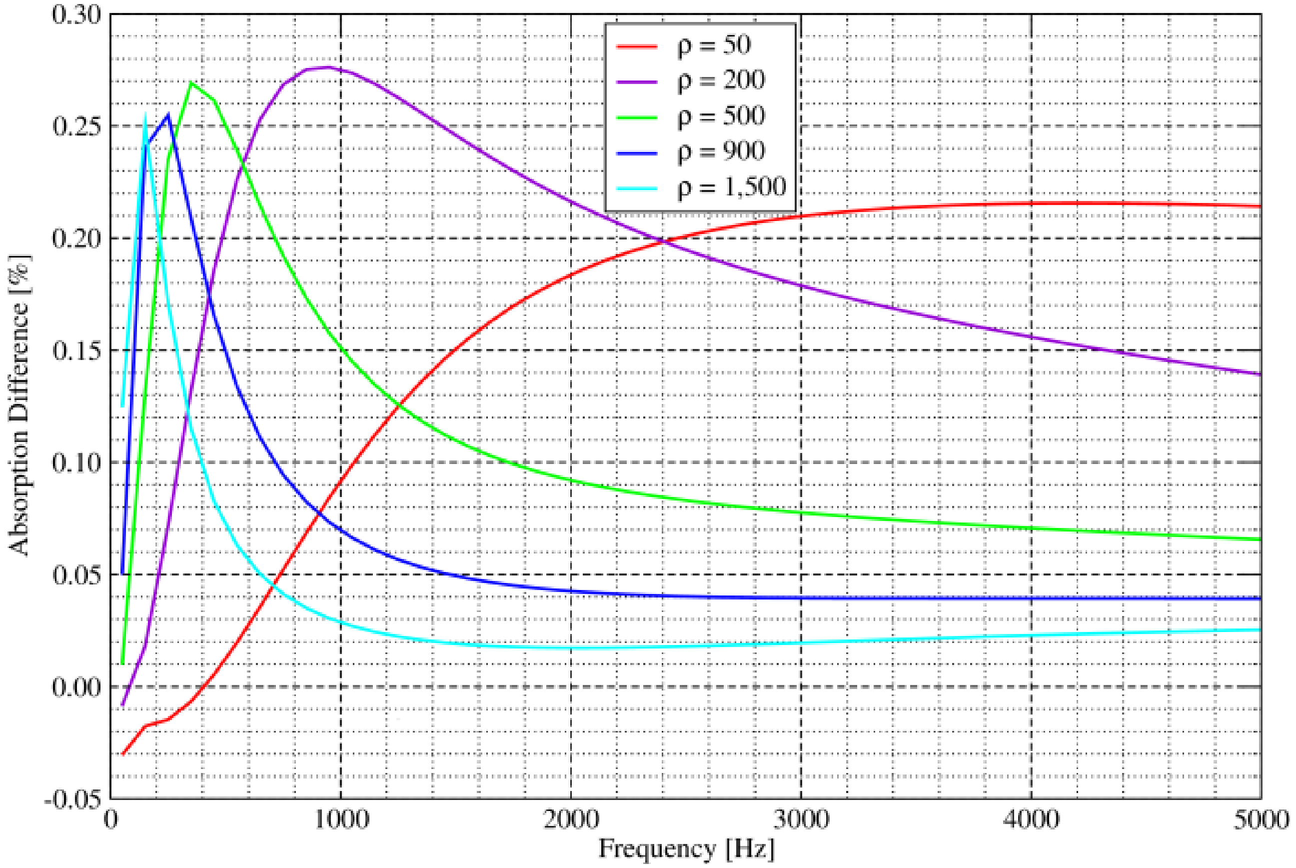


Absorption *is the fraction of normally incident acoustic intensity not reflected or transmitted by the film.*

- Total energy absorption coefficient
  - Calculated from the reflection and transmission: $\alpha = 1 - r - \tau$
- Parallel impedance formula *(markers)* predicts response very well
- The difference between the FSI model and the approximate equation < 0.30%
  - The maximum difference occurs at about half the frequency for peak absorption



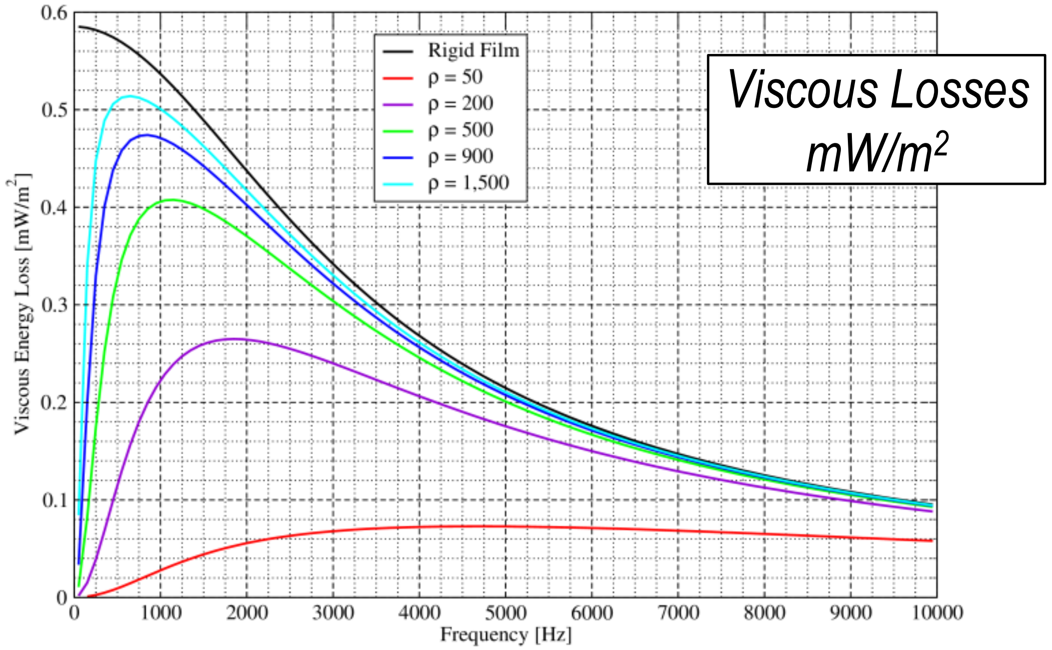
Absorption from FSI models compared to equation



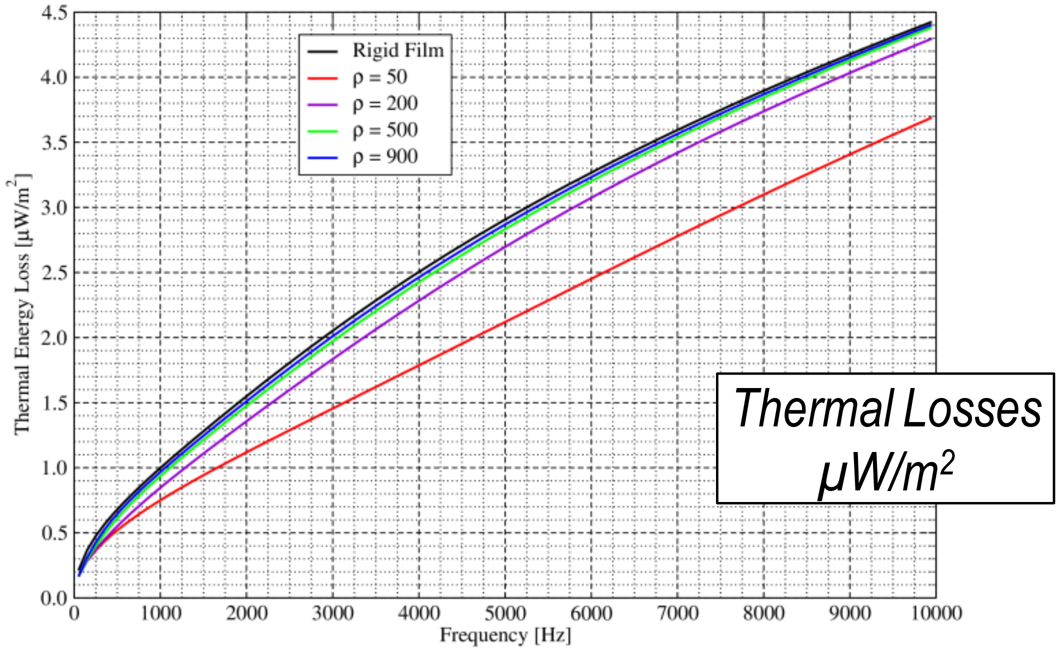
Difference between FSI model and equation

Limp Perforated Film – Energy Loss

- Thermal losses are much less than viscous losses, again < 5% even at 10kHz

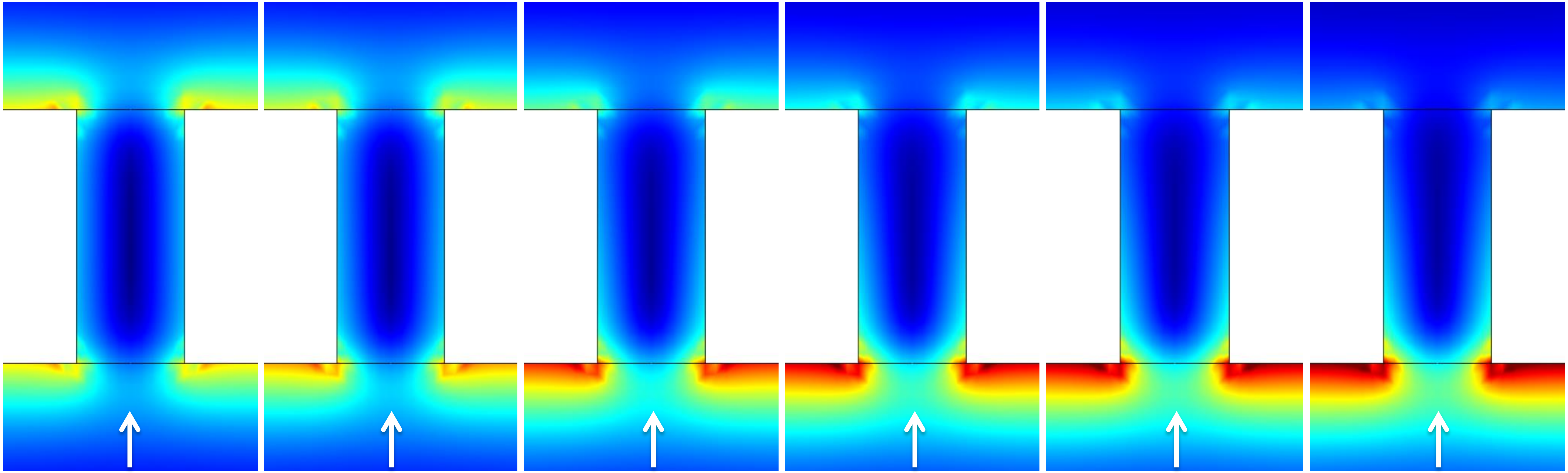


Viscous Losses
mW/m²



Thermal Losses
μW/m²

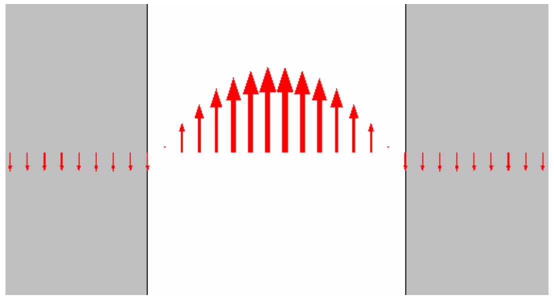
- For a film *(shown at 450 Hz)*, thermal losses can occur on both sides of the film *(total < rigid)*



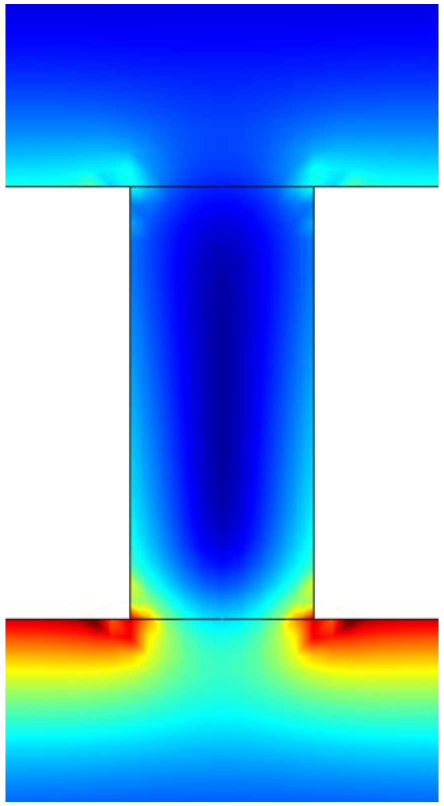
50 *200* *500* *900* *1,500* *Rigid*

Film density given in kg/m³; color scale is from 0 to 0.1 $\sqrt{W/m^3}$

Summary and Conclusions



- Fluid-Structure-Interaction (FSI) acoustic models were created
  - 2D axisymmetric models of one hole of a microperforated film
  - Viscous and thermal losses were investigated as well as their effect on absorption
- Thermal losses:
  - Increase with frequency
  - Occur over the full incident face of the film
    - Contributions from within the perforations are negligible
    - For moving films, losses occur on both sides of the film
      but the total thermal loss is almost identical to that of a rigid wall
  - Contribute to the acoustic resistance, but not the reactance
  - **Are less than 5% of the total energy loss for practical films below 10 kHz**
    - **Have no significant affect on the predicted absorption**



- Relative motion
  - Air velocity through the perforations are <u>much greater</u> than the film velocity
    - Only comparable at low frequencies for light films, but absorption is very low under these conditions anyway
  - **Transfer impedance of a flexible microperforated film can be determined by <u>adding in parallel</u> that of a rigid perforated plate and a limp impervious sheet**

$$Z_{Film} = \frac{1}{\dfrac{1}{Z_{Rigid}} + \dfrac{1}{Z_{Sheet}}}$$

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