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Frequency Reduction and Attenuation of the Tire Air Cavity Mode due to a Porous Lining

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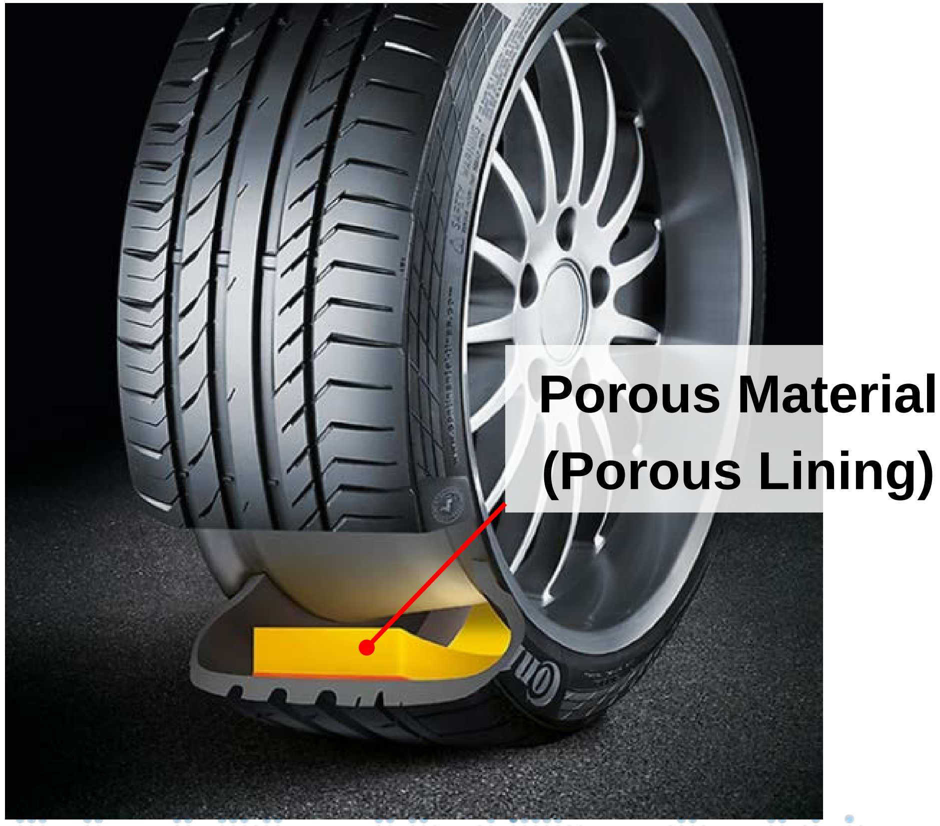
NOISE-CON 2023
May 15-18 | Grand Rapids, MI

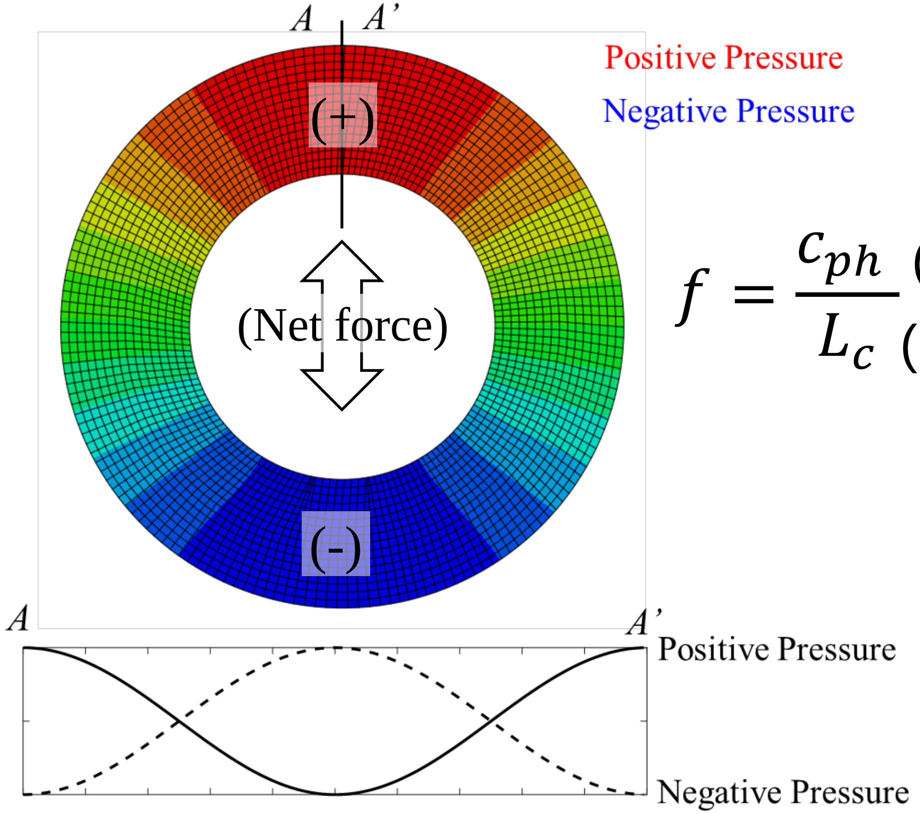
Electric Vehicles Road Noise

Q. What do these vehicles have in common?

A. They have **acoustic polyurethane foam** pasted on the inner side of their tires

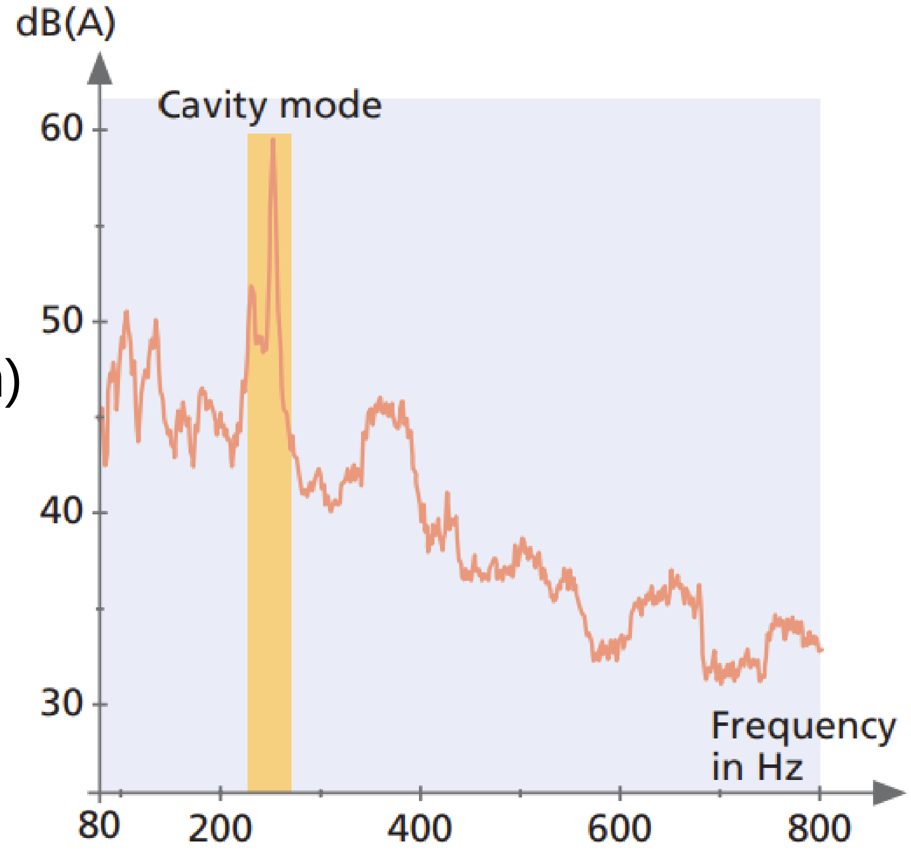


Tire Air Cavity Resonance (TACR)



Pressure distribution
in the first air cavity resonance of a tire.

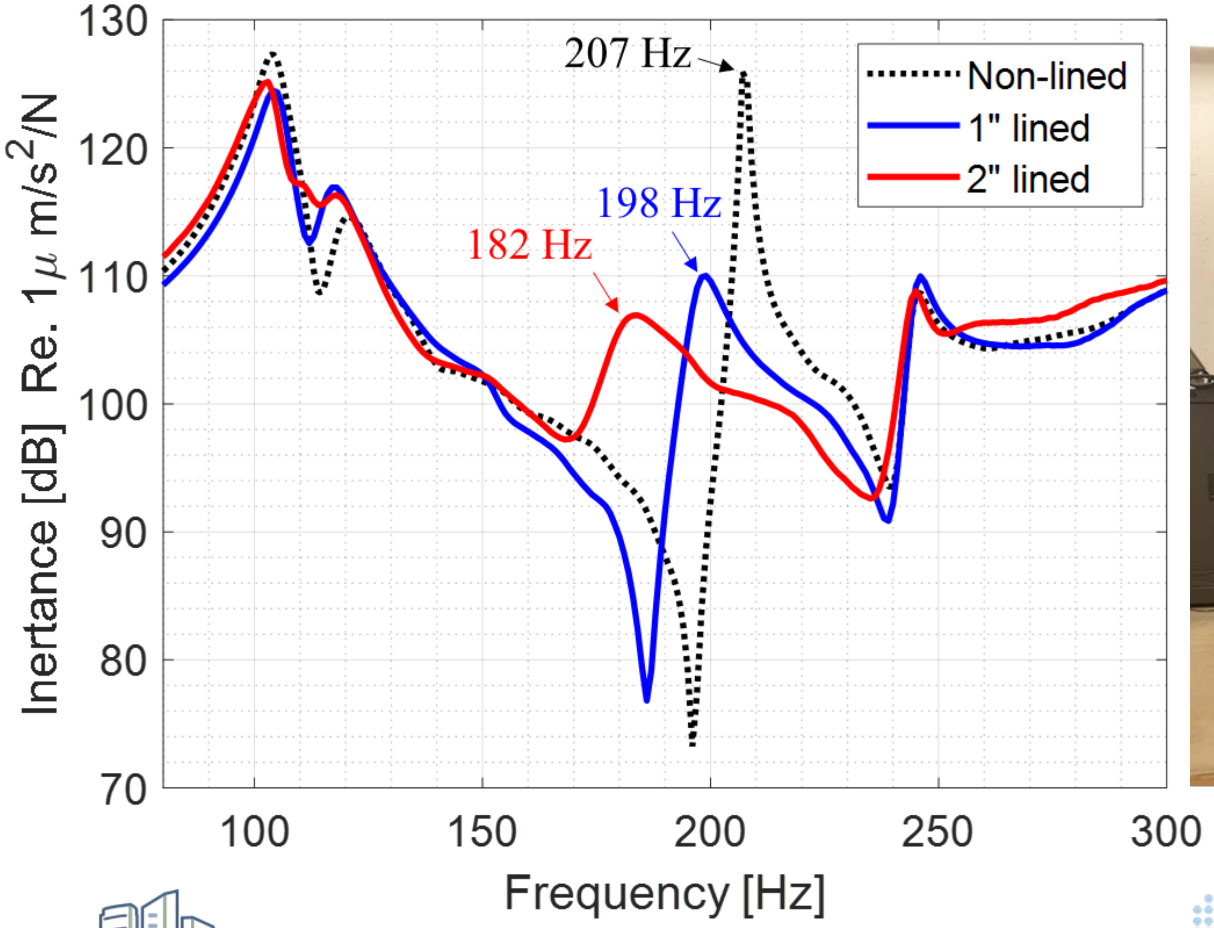
$$f = \frac{c_{ph}}{L_c}$$ (Phase Speed) / (Circum. Length)

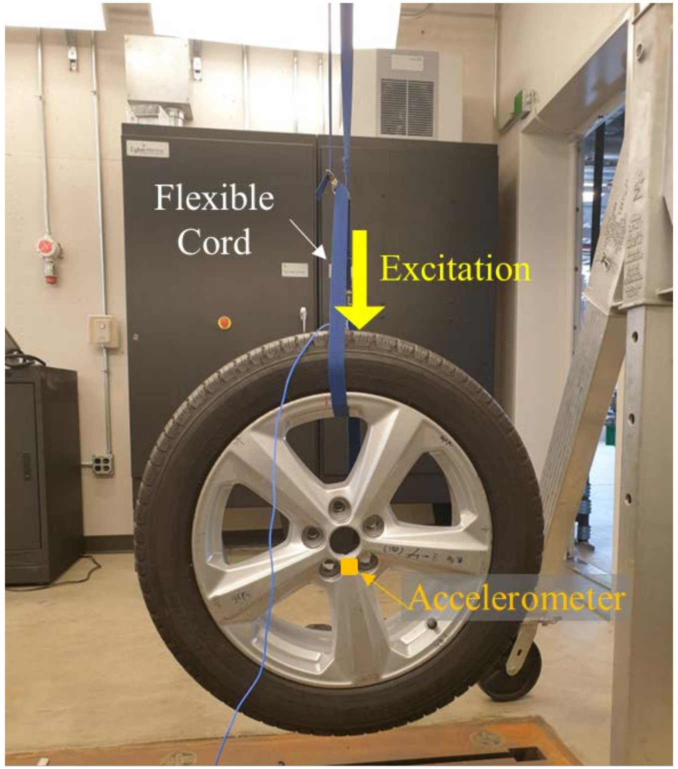


Frequency spectrum
of typical road noise [1]

Frequency Reduction and Mode Attenuation

Measurement of Acceleration of a Tire under Free Boundary Condition





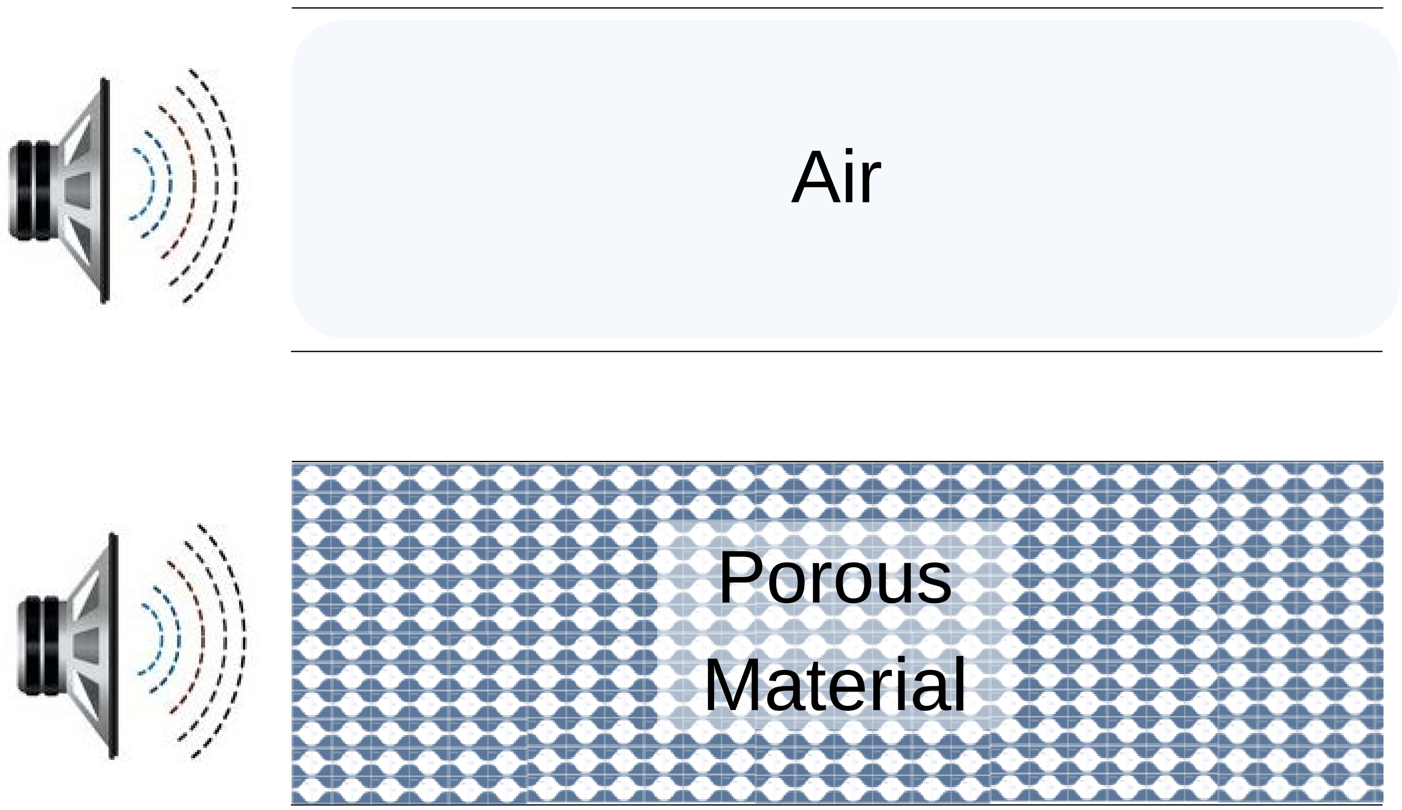
Internal sound of a tire

Non-lined

1 inch lined

Sound Propagation within Porous Material (P.M.)

Description of sound propagation within porous: Speed of Sound



$$c_{ph} = \sqrt{\frac{B}{\rho}} = 345\ \text{m/s}$$

B = Bulk Modulus of air [Pa]

ρ = Density of air [kg/m^3]

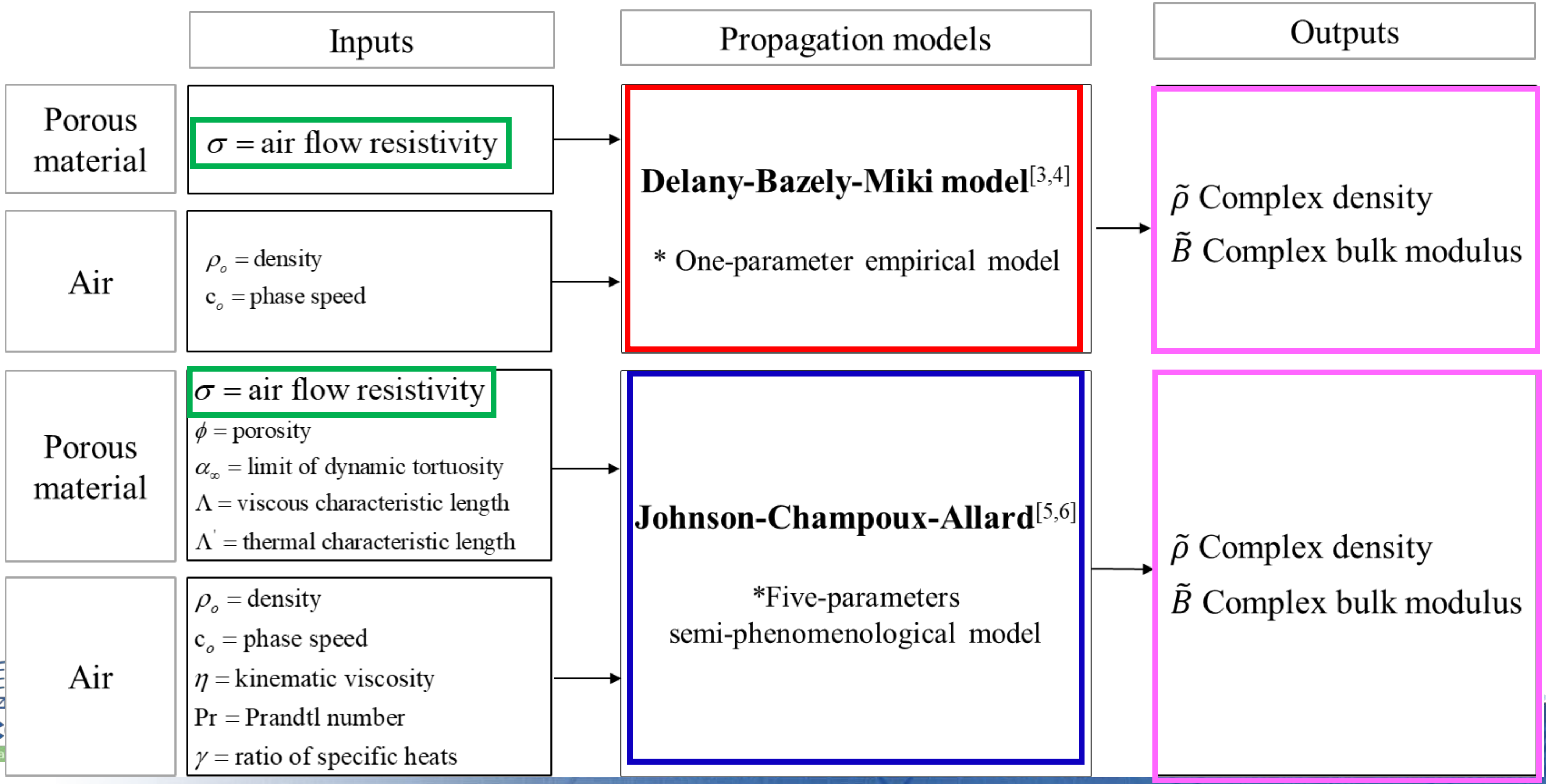
$$c_{ph} = \sqrt{\frac{\tilde{B}}{\tilde{\rho}}} = ?$$

$\tilde{B}$ = Bulk Modulus of P. M.

$\tilde{\rho}$ = Density of P. M.

Sound Propagation within Porous Material

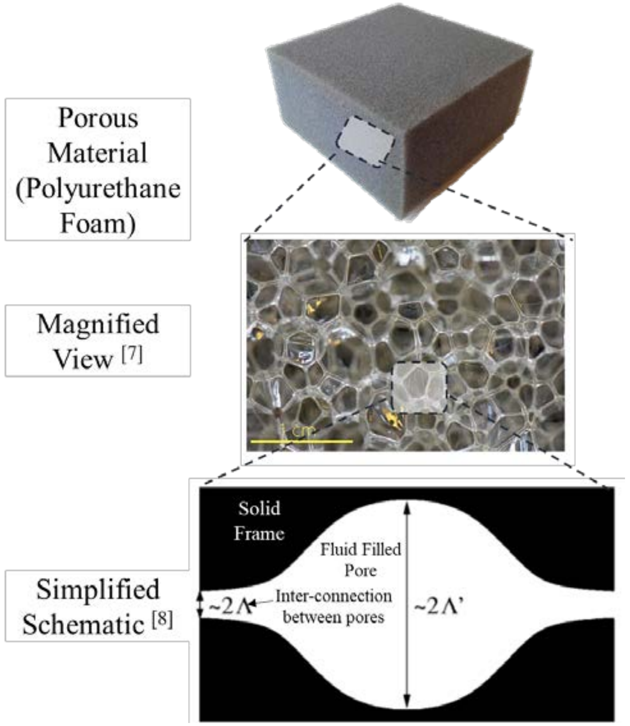
Description of sound propagation within porous

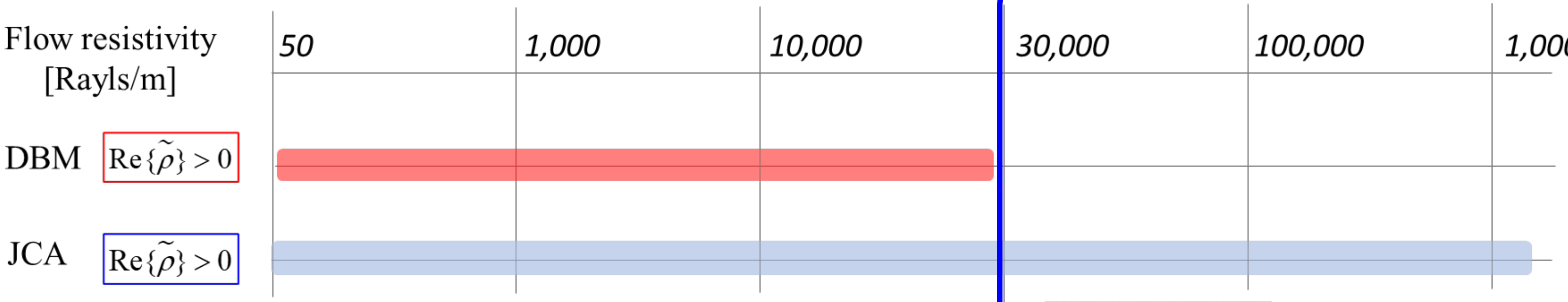


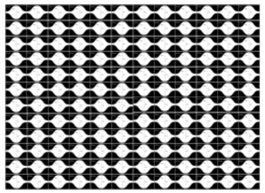
Research Objective

- To investigate the effect of high FR porous material on the sound attenuation of TACR.
- To identify the sound attenuation and frequency reduction mechanisms.

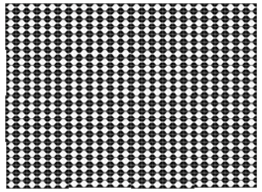
Flow Resistivity (FR), σ *** Key design parameter**
: Resistance of porous material to steady state air flow







Schematic of Relatively low FR Porous Material

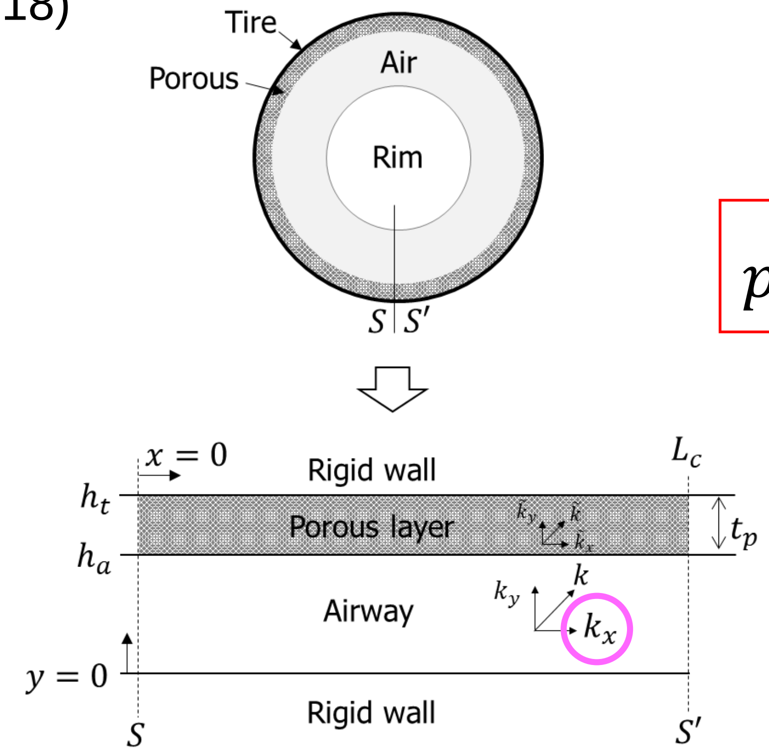


Schematic of Relatively High FR Porous Material

Theoretical and FE Analysis of a lined tire

Theoretical acoustic model of unfolded tire

(235/50R18)



$$p_{o,\,x-dir} = e^{-jk_x x}$$

Complex axial wavenumber calculated

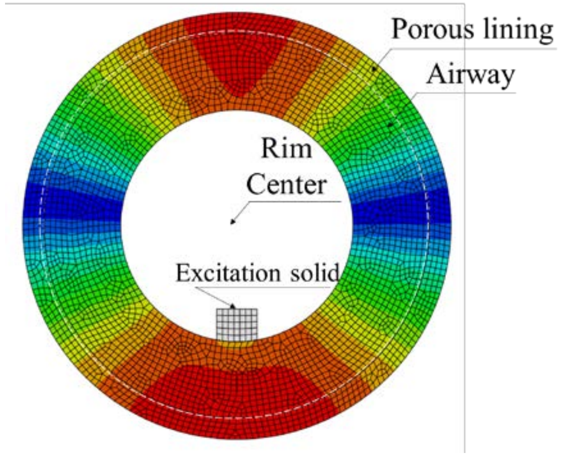
$$k_x = \beta - j\alpha$$

First cavity frequency ↔ First cavity frequency

Rate of attenuation ↔ Attenuated pressure

FE acoustic model

(235/50R18)



Part	Material type	Density [kg/m³]	Modulus	Poisson's ratio
Rim	Solid	7850	2e+11 (Elastic)	0.3
Air	Acoustic medium	1.1615	138,710 (Bulk)	-
Porous Material	Acoustic medium	Complex Density $\tilde{\rho}$ from JCA model (Frequency dependent)	Complex Bulk Modulus $\tilde{B}$ from JCA model (Frequency dependent)	-

Sound pressure computed

$$p_o = e^{-jk_x x}$$

Complex axial wavenumber

- The fact that the wavenumber, k_x, is complex is important.
- The imag. part of k_x represents the **rate of pressure attenuation** along the tire cavity.

Pressure distribution in airway

$$p_{o,x-dir} = e^{-jk_x x} \quad \ldots (1)$$

Complex axial wavenumber calculated

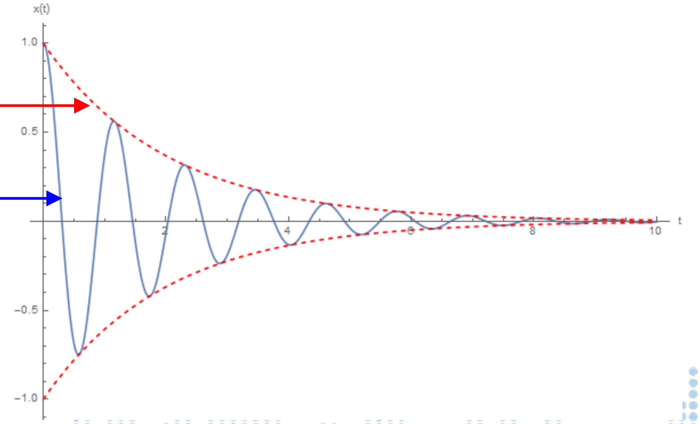
$$k_x = \beta - j\alpha \quad \ldots (2)$$

Combining eq.(2) and eq.(1) yields

$$p_{o,x-dir} = e^{-j\beta x} e^{-\alpha x}$$

Attenuation: Decaying rate

Propagation: Oscillatory frequency



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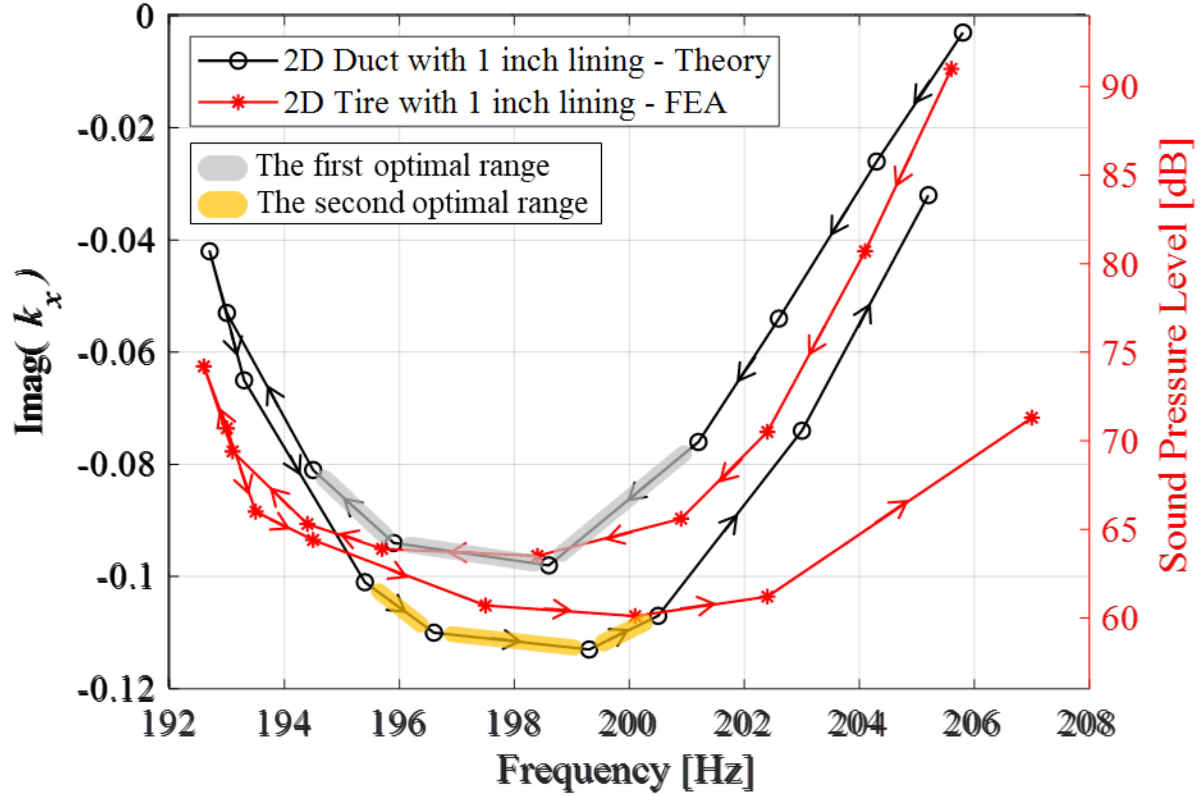
Behavior of mode attenuation and frequency reduction

Comparison between theoretical result and simulation result

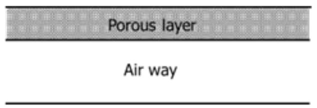


Flow Resistivity	1 inch				Error of Real(f_1)
	Theory		FEA		
σ [Rayls/m]	Imag(k_x)	Real(f_1) [Hz]	SPL [dB]	Real(f_1) [Hz]	
0	0	207.0	107.6	207.0	-
1	-0.003	205.8	91.0	205.6	-0.1%
100	-0.026	204.3	80.7	204.1	-0.1%
500	-0.054	202.6	70.5	202.4	-0.1%
1,000	-0.076	201.2	65.6	200.9	-0.1%
2,000	-0.098	198.6	63.5	198.4	-0.1%
3,500	-0.094	195.9	63.9	195.7	-0.1%
5,000	-0.081	194.5	65.3	194.4	-0.1%
10,000	-0.053	193.0	69.4	193.1	0.1%
50,000	-0.042	192.7	74.2	192.6	-0.1%
100,000	-0.065	193.3	70.7	193.0	-0.2%
200,000	-0.101	195.4	66.0	193.5	-0.9%
250,000	-0.110	196.6	64.4	194.5	-0.6%
400,000	-0.113	199.3	60.7	197.5	-0.9%
500,000	-0.107	200.5	60.1	200.1	-0.7%
1,000,000	-0.074	203	61.2	202.4	-0.4%
5,000,000	-0.032	205.2	71.3	207	0.9%

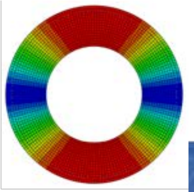
Low FR

High FR

Theoretical Model

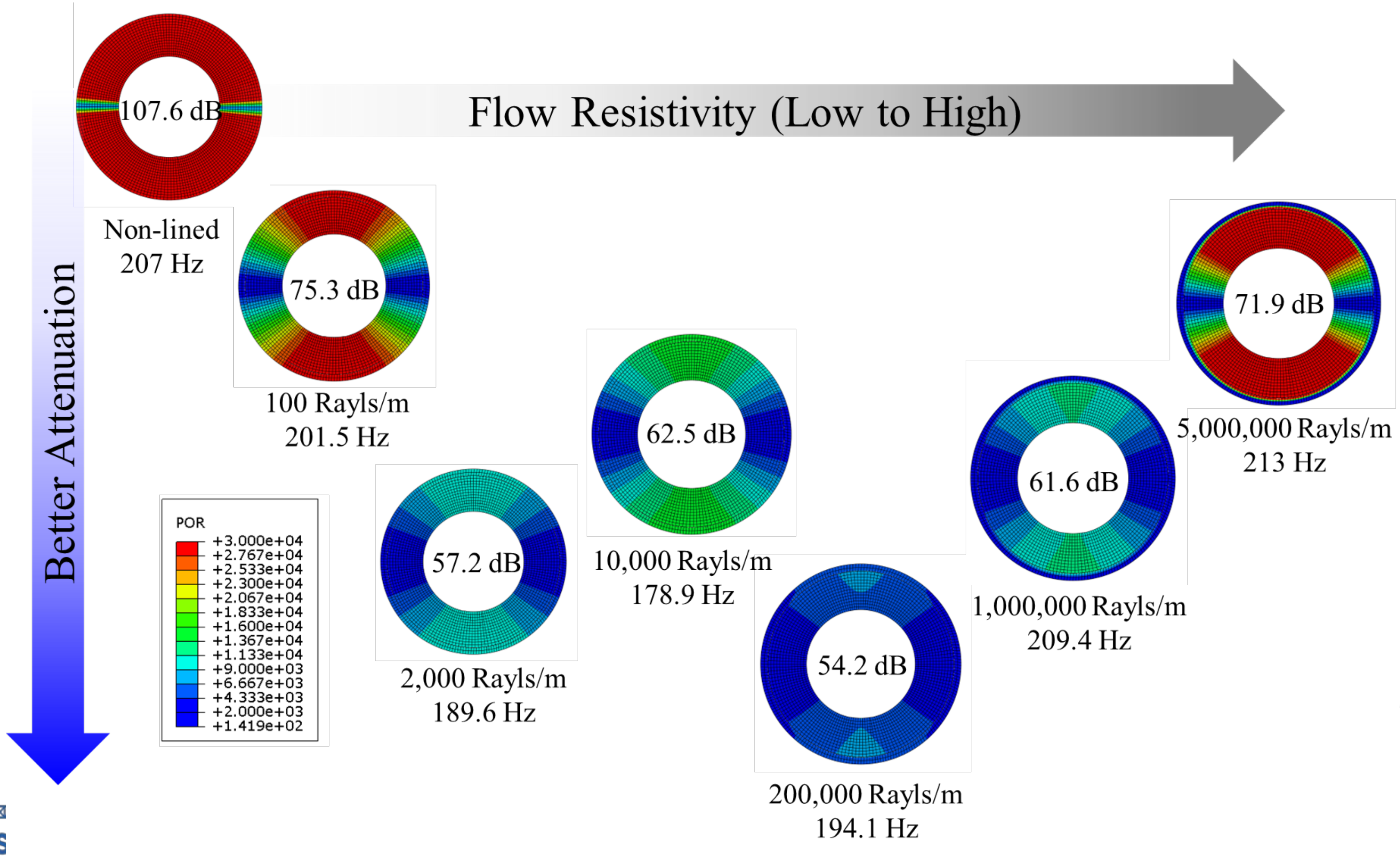


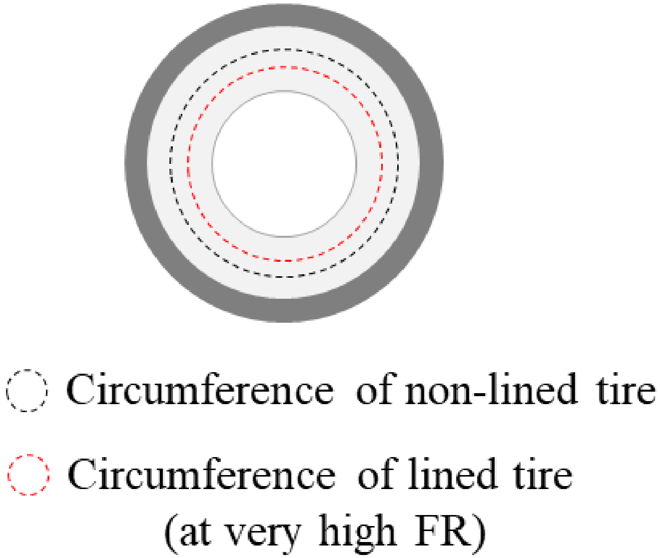
FE Model



Behavior of mode attenuation

Behavior of mode attenuation with respect to change in flow resistivity

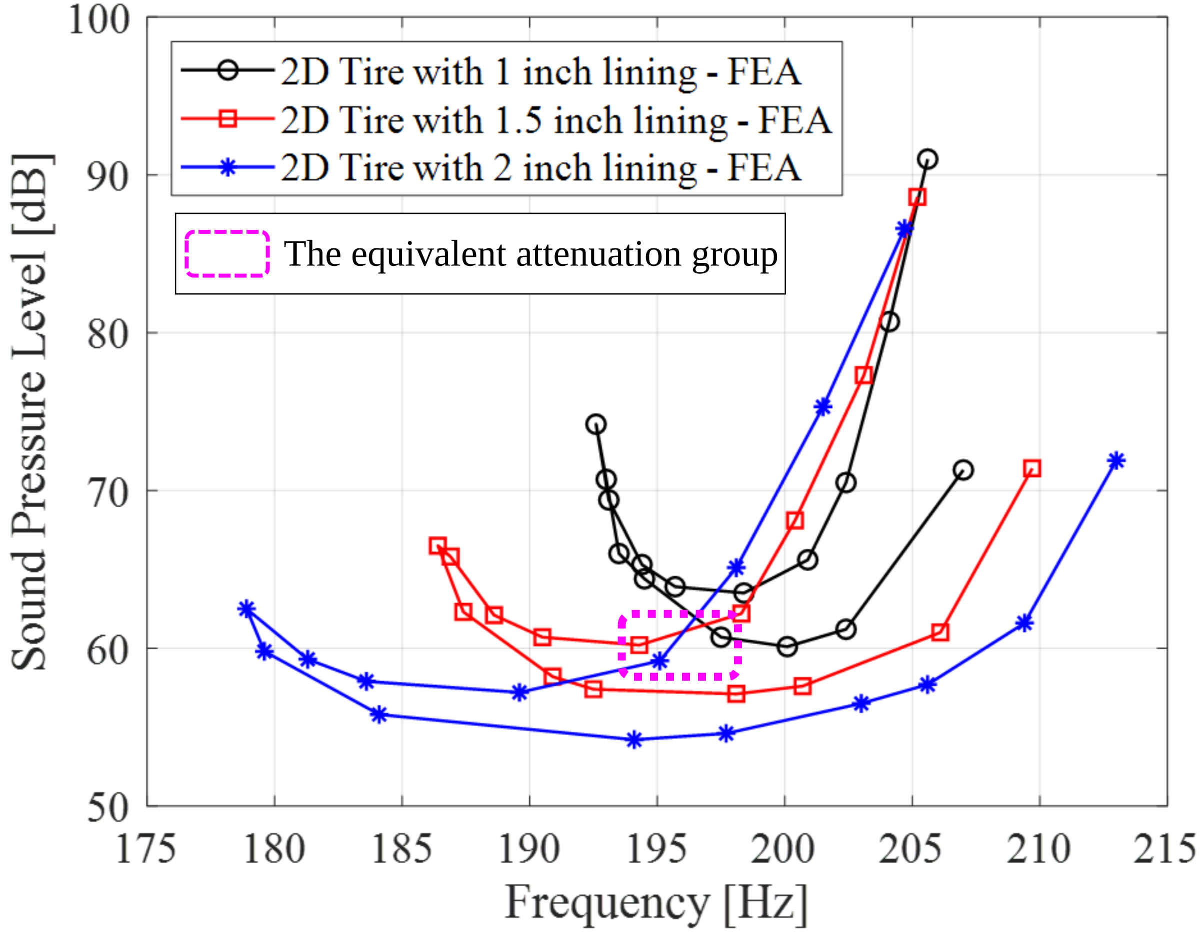


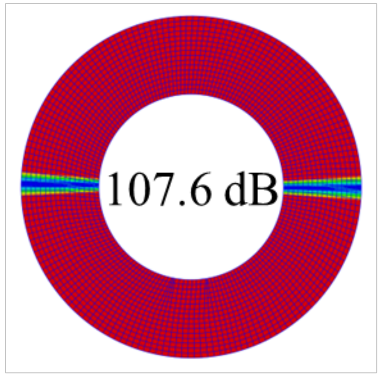


$$f = \frac{c_{ph}}{L_c} \quad \begin{matrix}\text{(Phase Speed)} \\ \text{(Circum. Length)}\end{matrix}$$

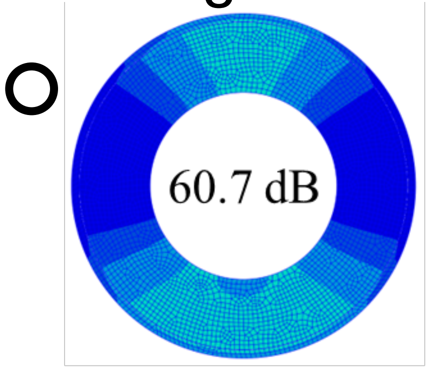
Case study

Case study of the equivalent level of attenuation with thinner porous lining

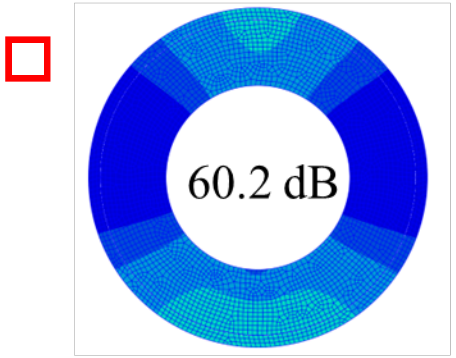




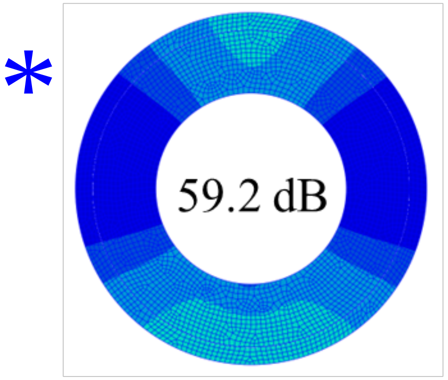
Non-lined 206.3 Hz



1 inch lining 198.6Hz
2nd optimal (400,000 Rayls/m)



1.5 inch lining 194.3 Hz
1st optimal (2,000 Rayls/m)



2 inch lining 195 Hz
Normal (1,000 Rayls/m)

Pressure distribution and dispersion diagram

Pressure distribution and dispersion diagram (FEA with 3,500 Rayl/m of FR, 1st optimal range)

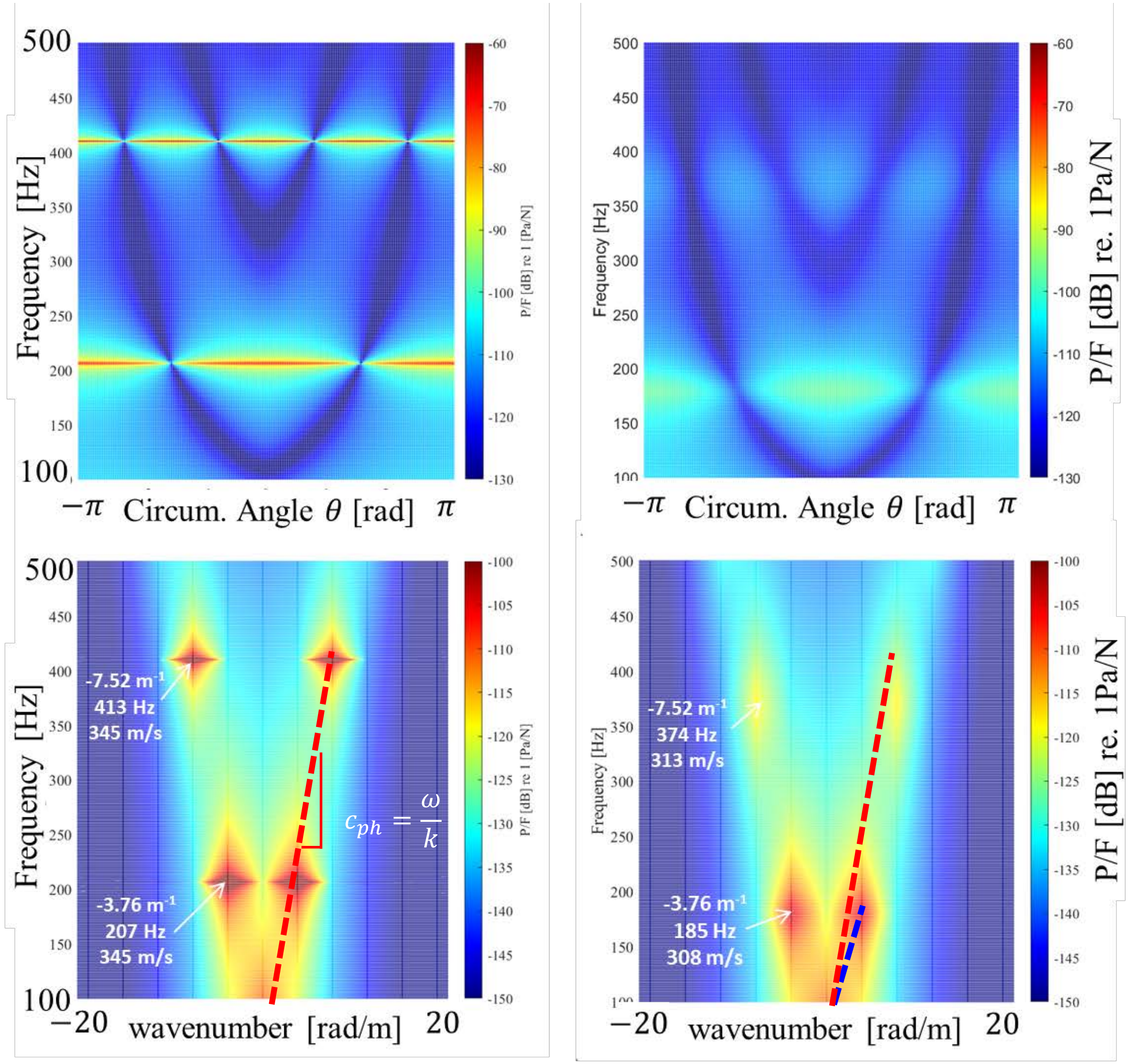
Pressure (non-lined)

Resonance
1st : 207 Hz

Dispersion (non-lined)

Phase speed
1st : 345 m/s

$c_{ph} = \frac{\omega}{k}$



Pressure (2 inch lined)

Resonance
1st : 185 Hz

Dispersion (2 inch lined)

Phase speed
1st : 308 m/s

$c_{ph} = \frac{\omega}{k}$

$$f = \frac{c_{ph}}{L_c}$$

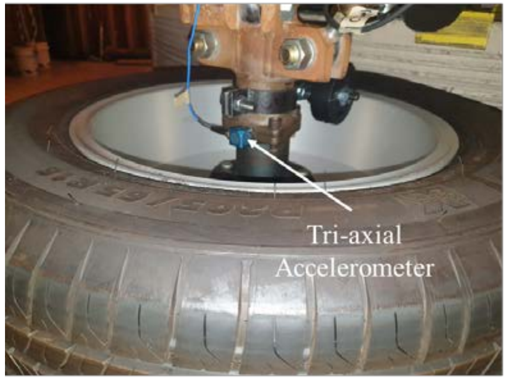
$$k = \frac{\omega}{c_{ph}} \Rightarrow c_{ph} = \frac{\omega}{k}$$

Validation under Dynamic Boundary Condition

Measurement of Force and Internal Sound of a Rolling Tire

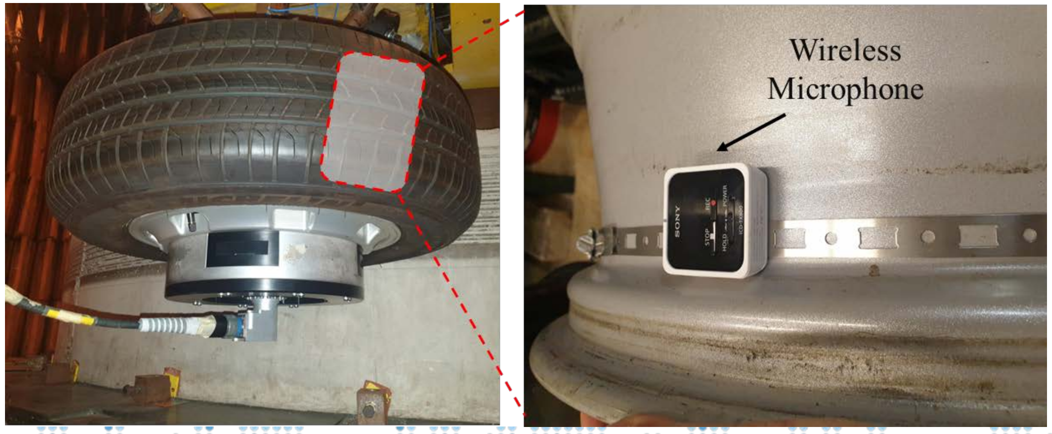
Test set-up
- Tire Pavement Test Apparatus (TPTA)
- 10~30 mph of speed with 1,000 lbs of load.

Sensors
- Wheel force transducer
- Wireless microphone fixed on the rim.



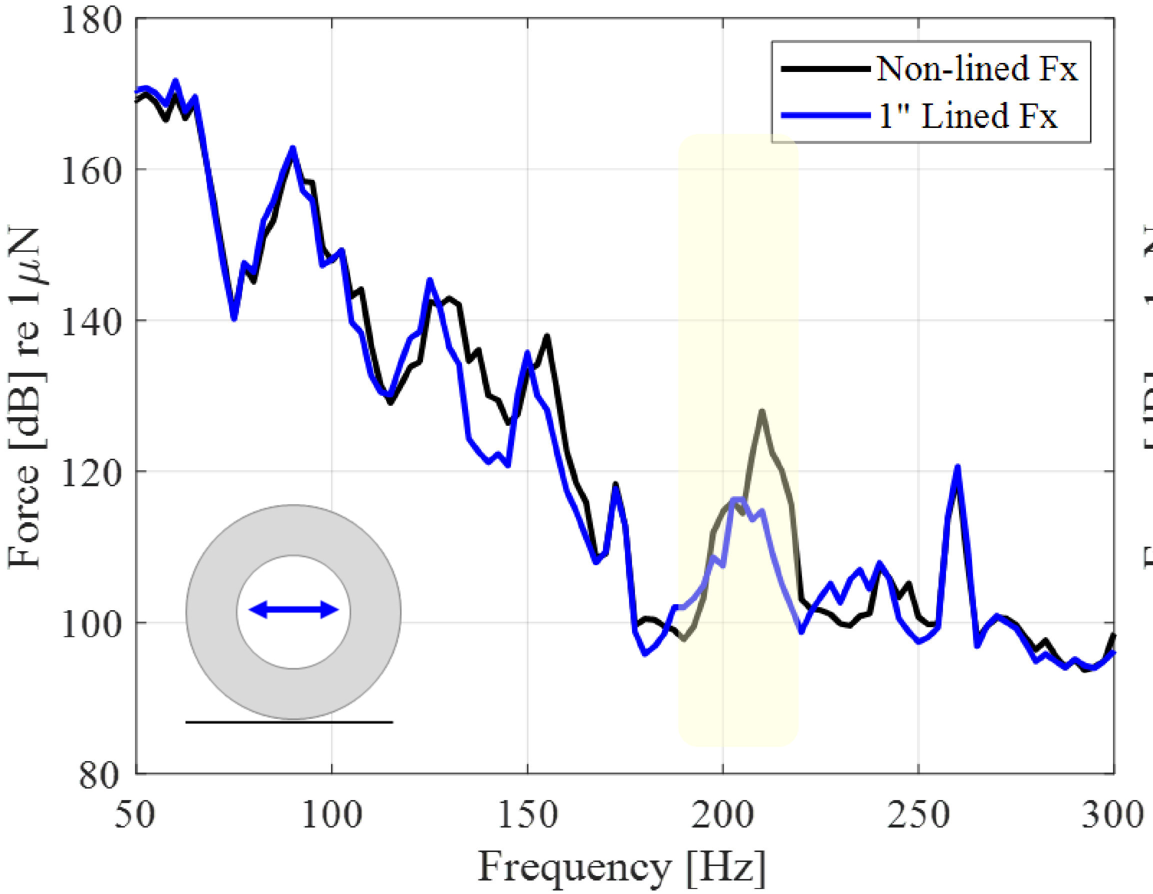
(a) Acceleration Measurement

(b) Force and Moment Measurement

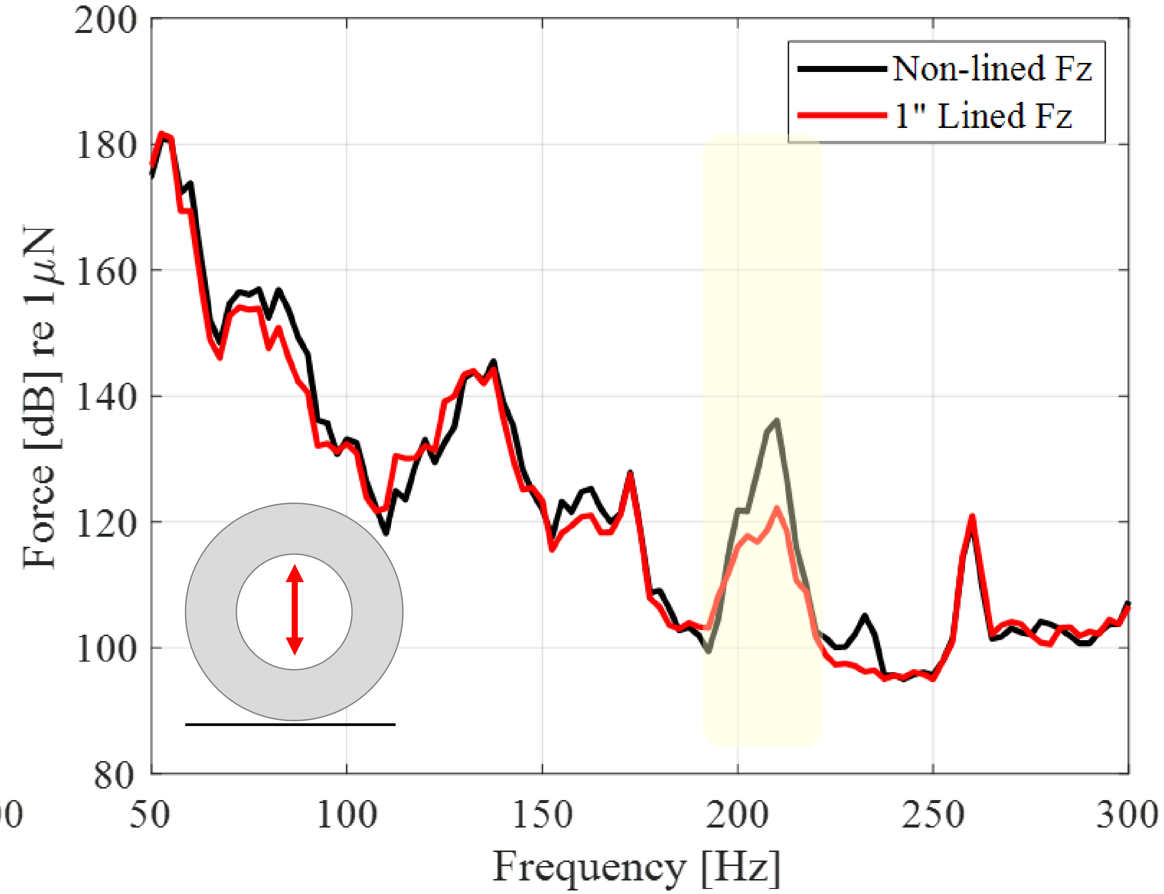


Validation under Dynamic Boundary Condition

Measurement of the Force of a Rolling Tire at 30 mph



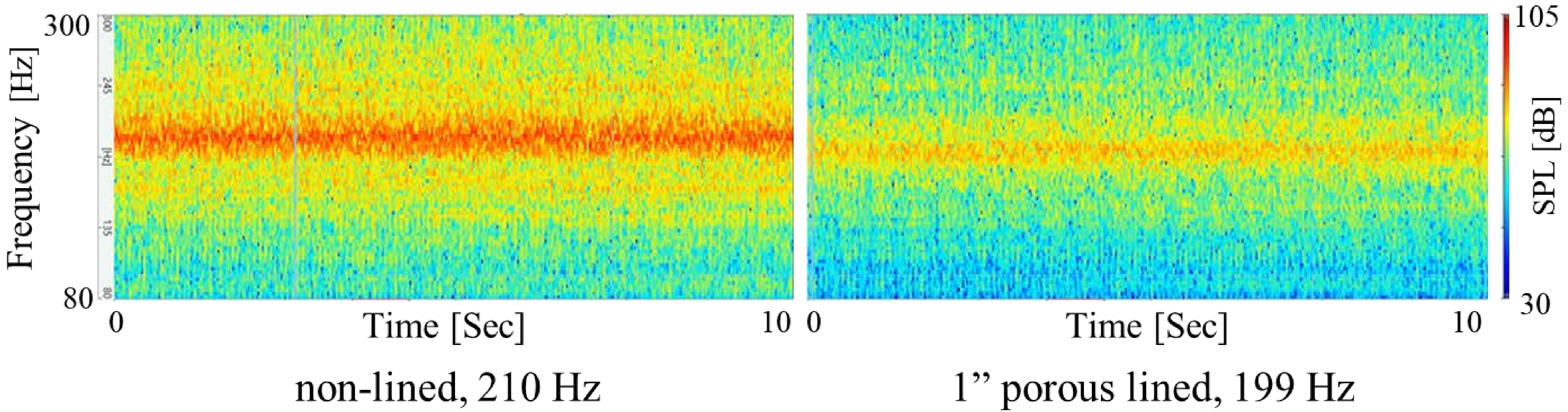
(a) Longitudinal Force at 30 mph



(b) Vertical Force at 30 mph

Validation under Dynamic Boundary Condition

Measurement of the Internal Sound of a Rolling Tire at 10 mph



Conclusion

- The **frequency reduction and attenuation of the tire cavity resonance** due to a porous lining was investigated.

- The **JCA model** was adopted in the theoretical analysis to describe the sound propagation in the porous lining, thus allowing for a **broader working boundary of design parameters** and consideration of **visco-inertial and thermal effects.**

- An important finding was the existence of not only the first optimal range previously identified by other researchers, but also **a second optimal range that performed better in terms of attenuation.**

- The frequency reduction was a result of the **slowed phase speed**, and the mode attenuation was caused by the **complex wavenumber** due to the presence of the porous lining

Thank you for your attention.

Q & A

Contact Information

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- Affiliation: Ray W. Herrick Labs, Purdue University
- Email: choo7@purdue.edu

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