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# Design of Lightweight Fibrous Vibration Damping Treatments to Achieve Optimal Performance in Realistic Applications

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# NOISE AND VIBRATION

CONFERENCE & EXHIBITION

# DESIGN OF LIGHTWEIGHT FIBROUS VIBRATION DAMPING TREATMENTS TO ACHIEVE OPTIMAL PERFORMANCE IN REALISTIC APPLICATIONS

(SAE Technical Paper 2019-01-1524, Student Competition)

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PURDUE MECHANICAL ENGINEERING

RAY W. HERRICK LABORATORIES

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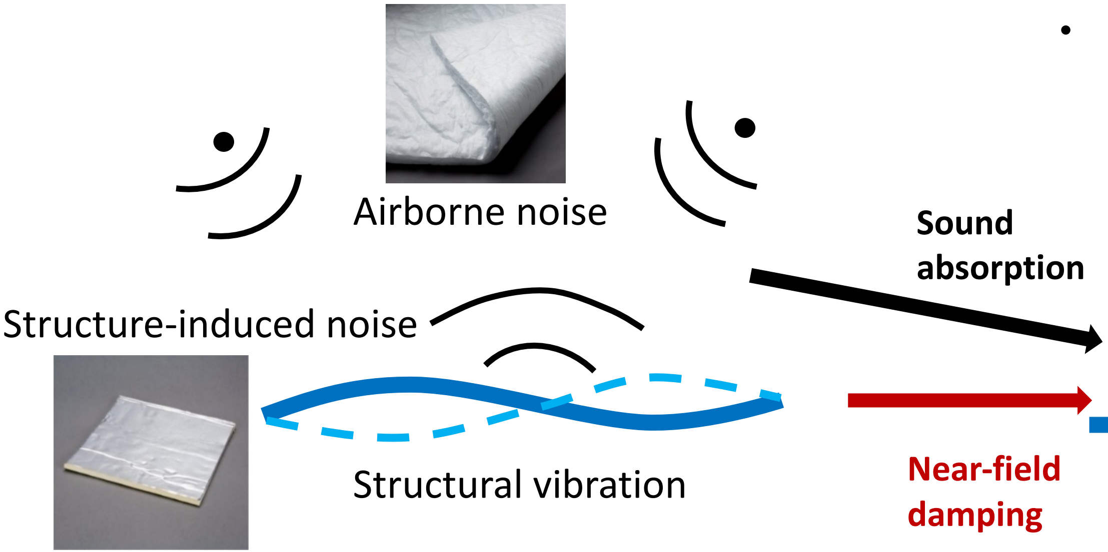
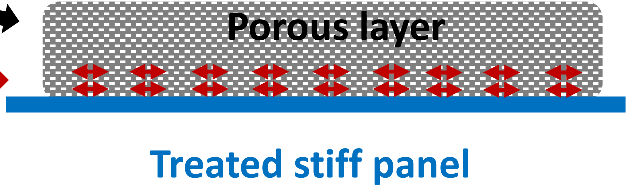
# CHALLENGE

- **Advanced Noise Control Materials[1]**
  - **What's important about a noise control material?**
    - **Cost**
    - **Safety**
    - **Weight**
    - **Volume**
    - **Recyclability**
    - **…**
    - **…**
    - **Acoustical Performance**

# OBJECTIVE: MULTIFUNCTIONALITY

- **Near-field damping:** dissipating power through viscous interaction between the porous medium and the evanescent acoustical near-field of the panel associated with sub-critical panel motion[2–7]

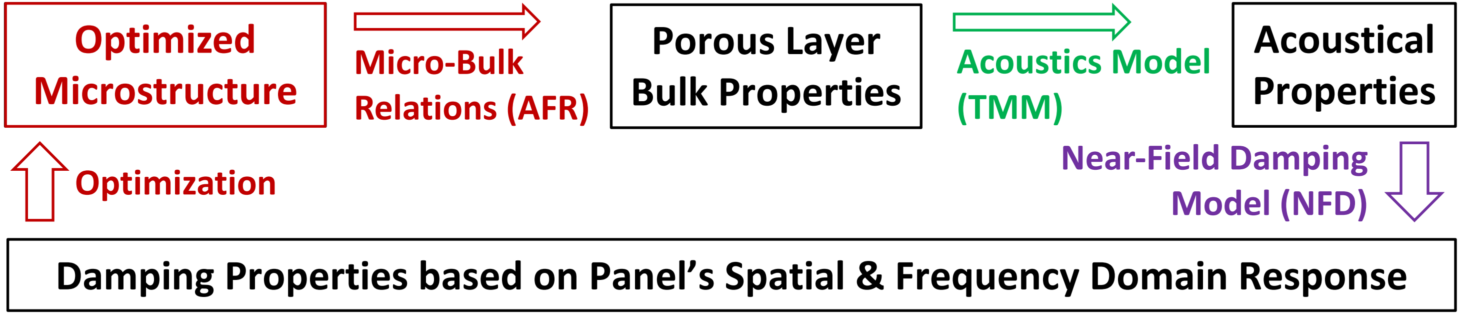



- **Objectives: modeling, predicting and optimizing** the near-field damping performance of conventional sound absorbing materials (fiber, foam, *etc.*), so that a properly-designed porous layer can achieve both structural damping and sound absorption at the same time
  → **save weight and cost**

# ANALYTICAL MODELING

- Connecting damping material's properties and performance




- **AFR:** micro-bulk relations for porous media made of fibers[8]
- **TMM:** bulk-acoustical relations[9,10] including Johnson-Champoux-Allard (JCA) model[11], Biot theory[11–15] and B.C.s interpretation[13,16]
- **NFD:** acoustical-damping relations including Euler-Bernoulli beam theory, wavenumber-space Fourier transform[17] and power analysis[18]

➢ **TMM** + **NFD** + **AFR** provides an micro-damping model to maximize fibrous media's damping performance by optimizing their microstructures

# MODELING OF REGULAR STRUCTURES

- **Porous damping treatments in the analytical model[2,5,6]**

**Limp porous layer**

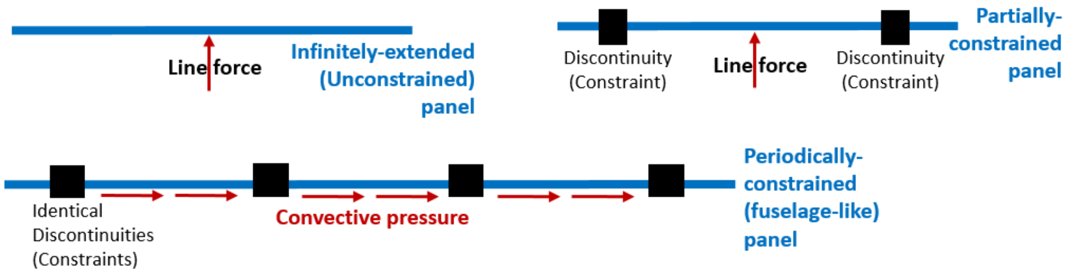
**Negligible bulk elasticity of frame**

- -Flow resistivity
- -Porosity
- -Tortuosity
- -Viscous characteristic length
- -Thermal characteristic length
- -Bulk density
- -In vacuo bulk modulus
- -Poisson's ratio
- -Shear modulus
- -Loss factor (mechanical)

**Poro-elastic layer**

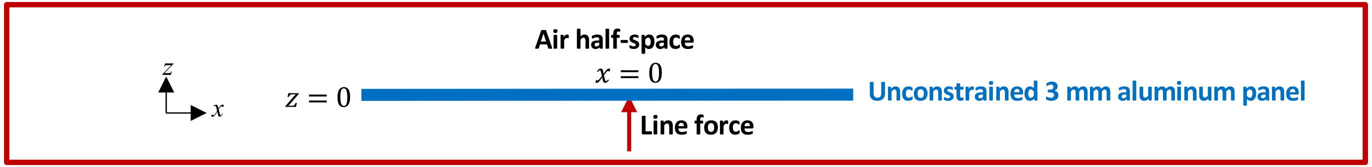
**Non-negligible bulk elasticity of frame**

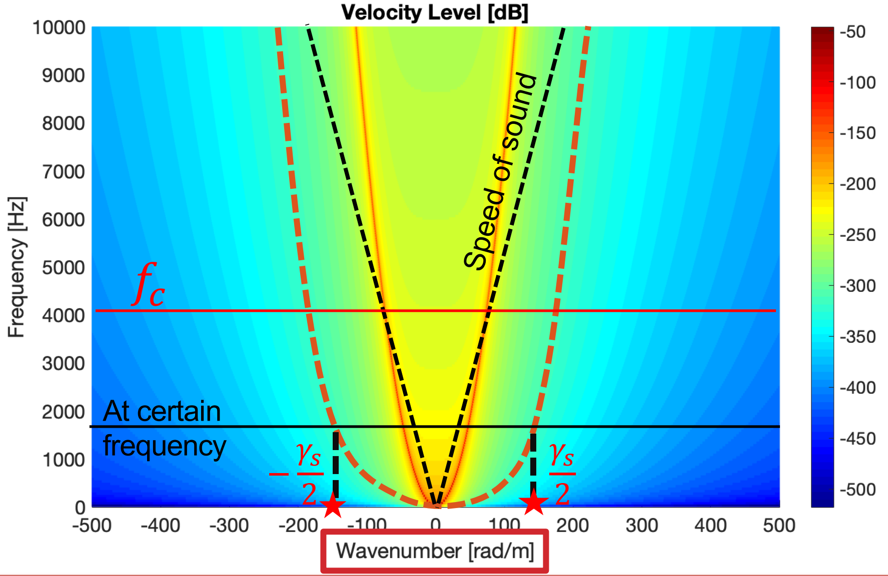
- **Vibrating panels in the analytical model[2,5,6]**

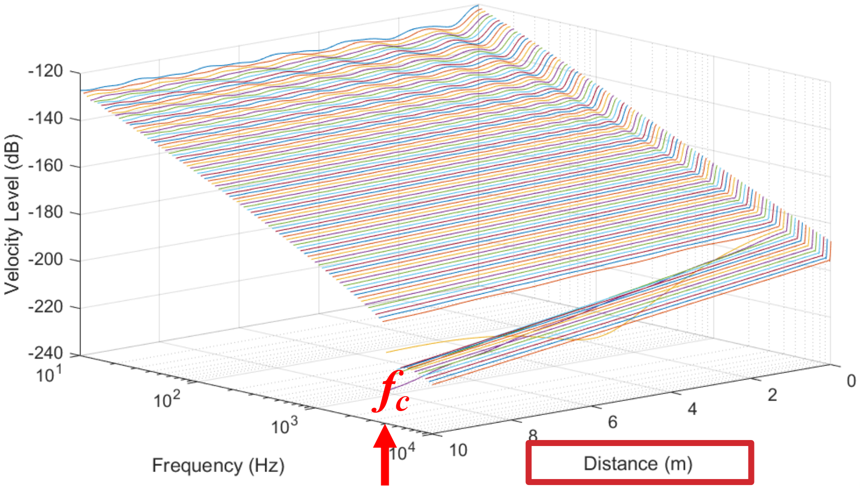



# WAVENUMBER-SPACE FOURIER TRANSFORM

- An example to show wavenumber ←→ spatial domains Fourier transform[2]

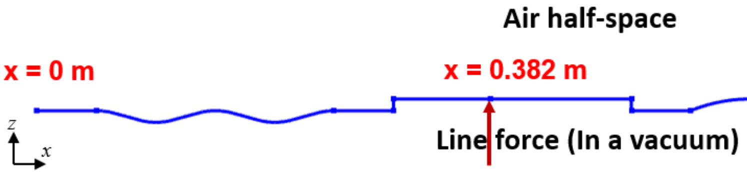


# A VEHICLE FLOOR PAN-LIKE STRUCTURE

- Optimizing fibrous damping for a more realistic vibrating structure



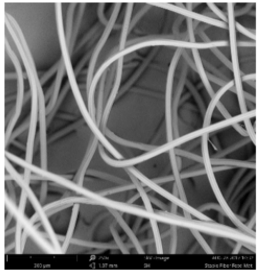

A line-driven, floor pan-like panel modeled by COMSOL Multiphysics

- Target material

Limp fibrous layer

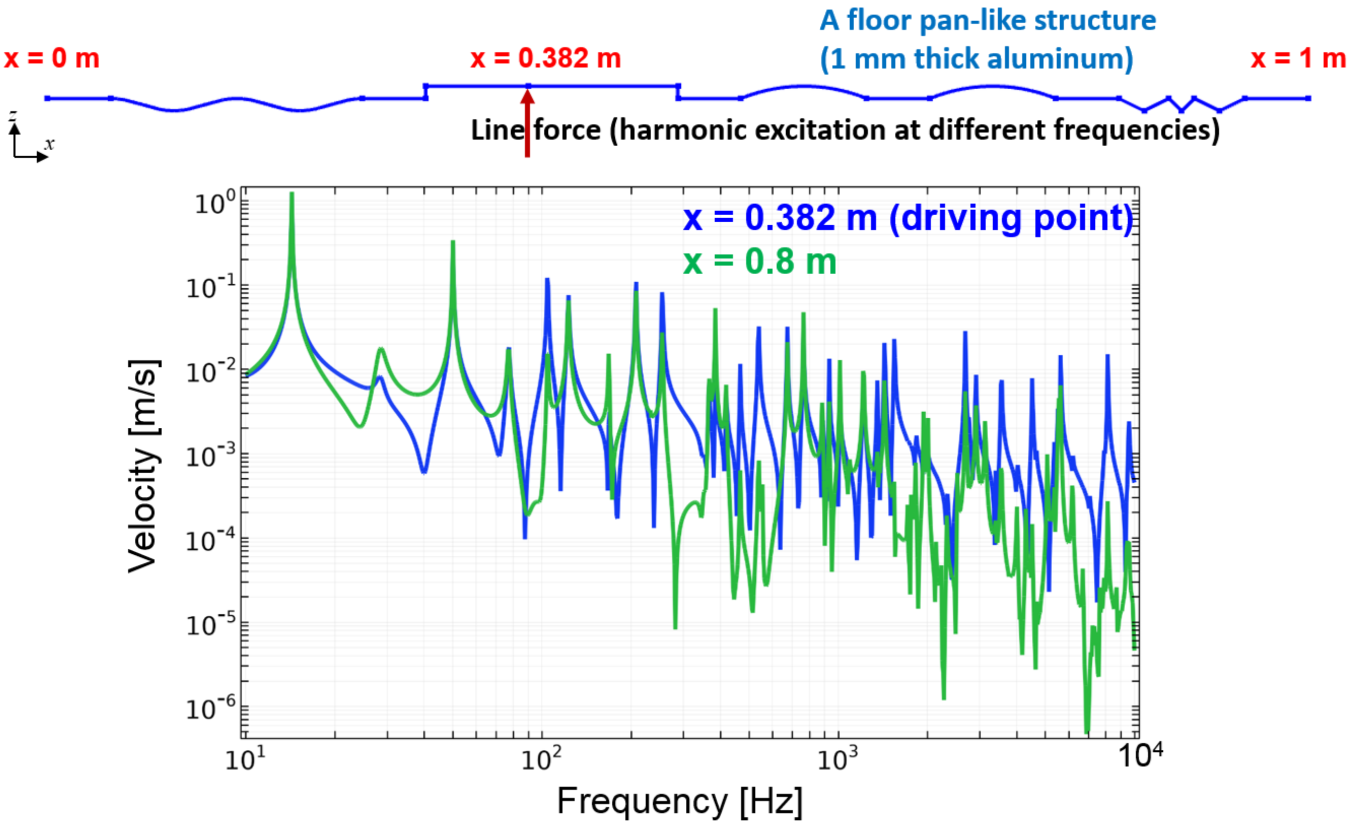
Negligible bulk elasticity of frame

- -Flow resistivity
- -Porosity
- -Tortuosity
- -Viscous characteristic length
- -Thermal characteristic length
- -Bulk density
- -In vacuo bulk modulus
- -Poisson's ratio
- -Shear modulus
- -Loss factor (mechanical)

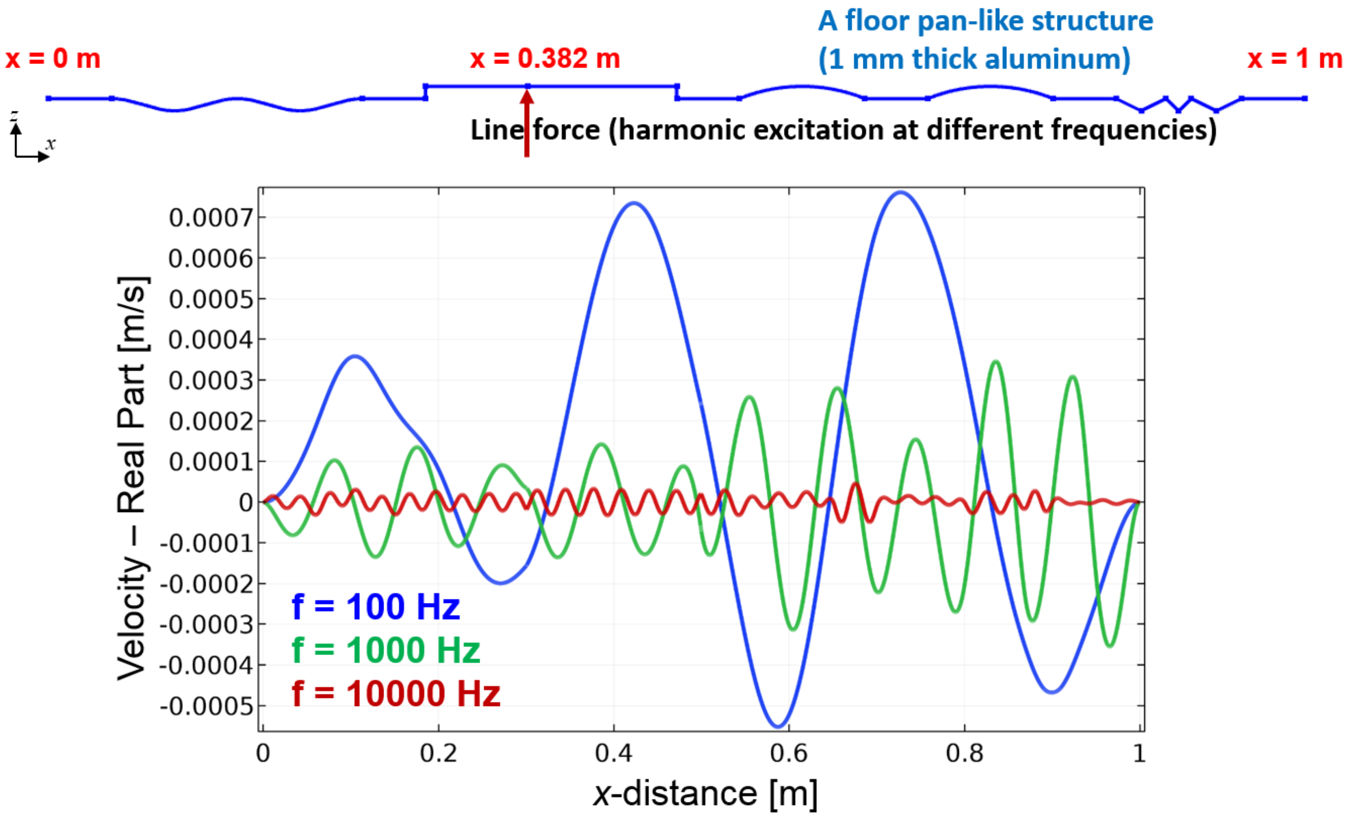


Made of single fiber component with uniform fiber size

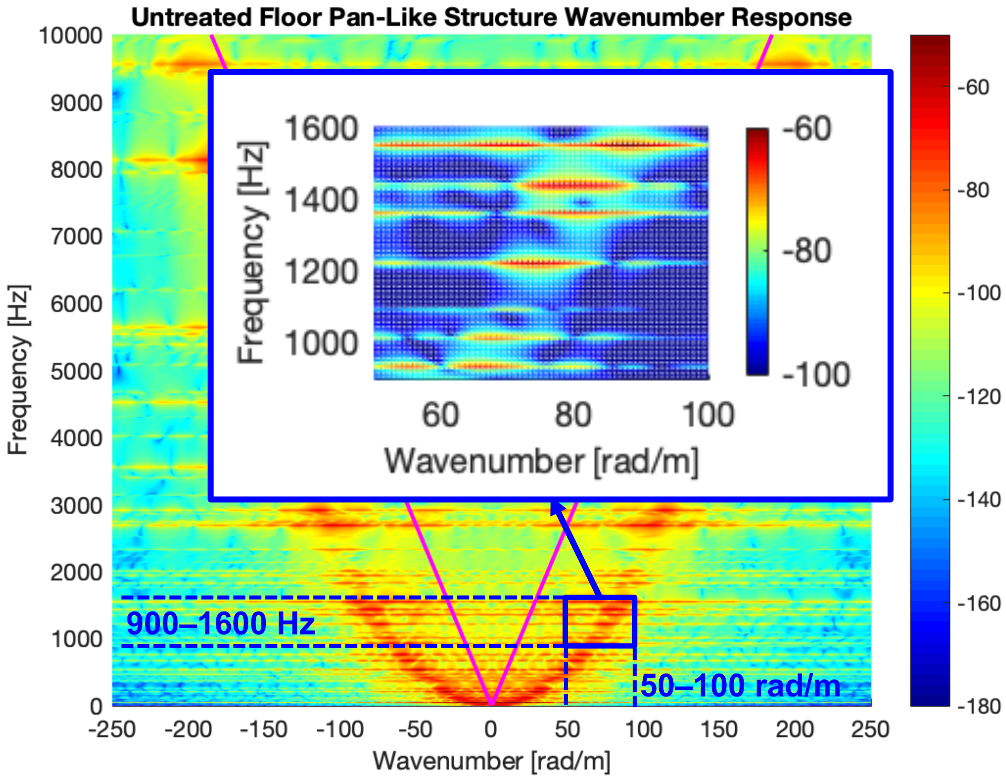
# VELOCITY RESPONSE SPECTRA OF THE FLOOR PAN



# SPATIAL RESPONSE OF THE FLOOR PAN



# WAVENUMBER RESPONSE MAPPING OF THE FLOOR PAN

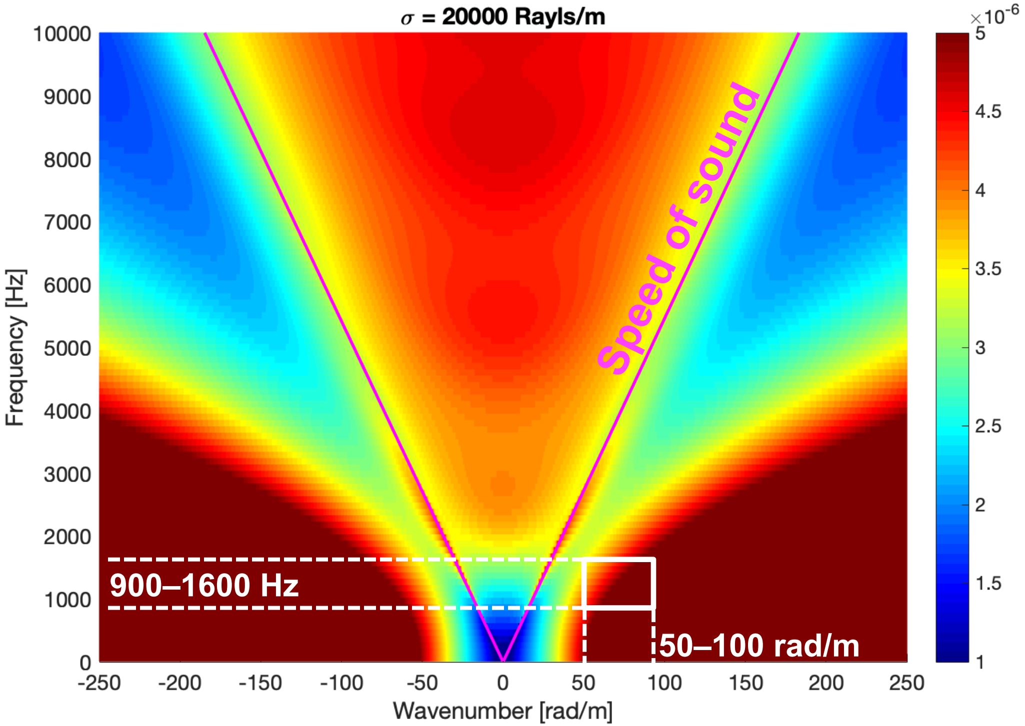


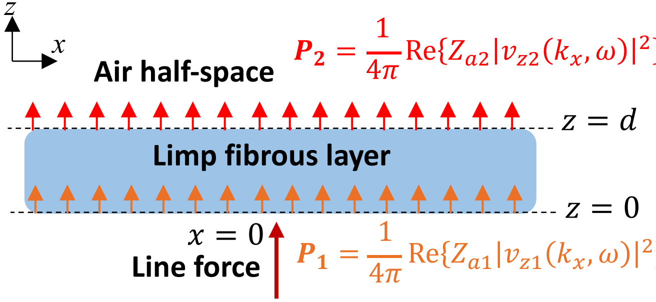

- Interpolating and zero-padding the spatial response, then Discrete Fourier Transforming (DFT) it to wavenumber domain at each frequency

- **As an example, define a target wavenumber/frequency region with strong vibrations that we wish to suppress**

# POWER DISSIPATION OF THE DAMPING TREATMENT

- Mapping the power dissipation ($P_d$) of the limp fibrous layer by $P_d = P_1 - P_2$




$$P_2 = \frac{1}{4\pi}\mathrm{Re}\{Z_{a2}|v_{z2}(k_x,\omega)|^2\}$$

$$P_1 = \frac{1}{4\pi}\mathrm{Re}\{Z_{a1}|v_{z1}(k_x,\omega)|^2\}$$

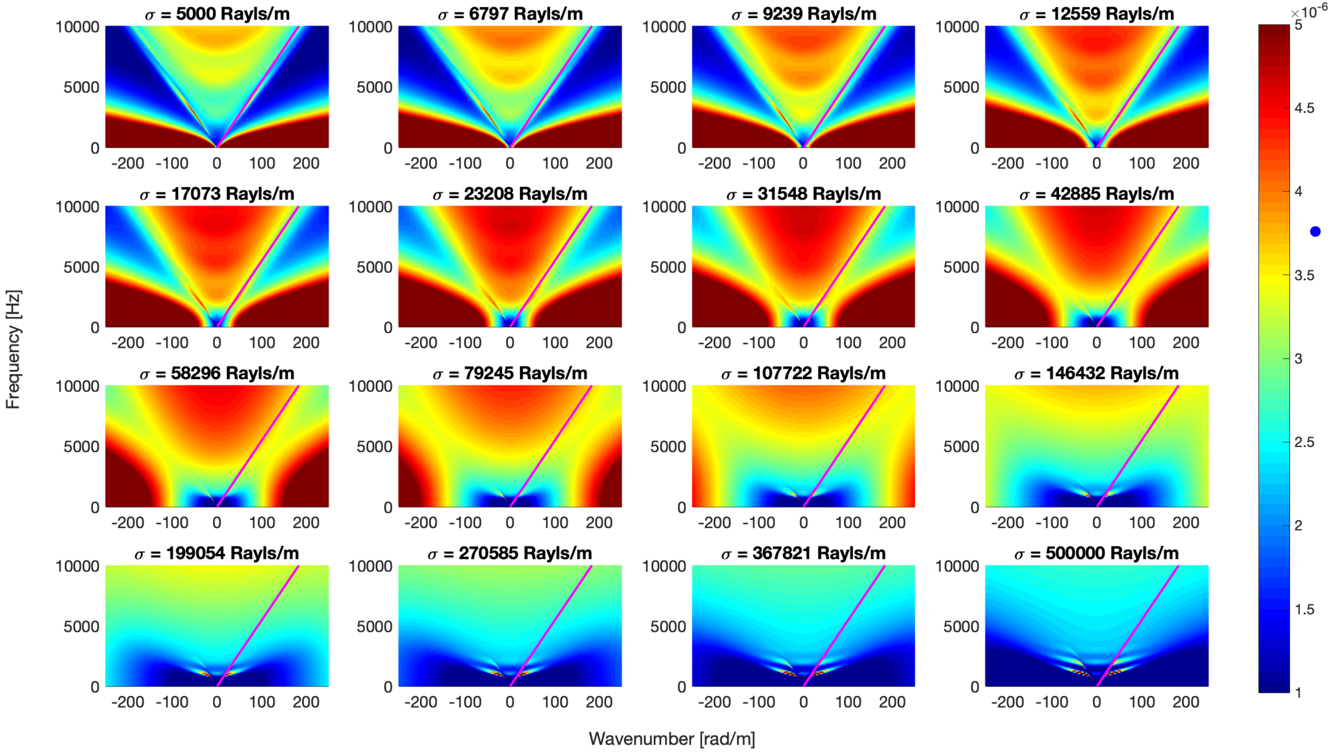
- Fibrous layer bulk properties:

Thickness $d$ = 5 cm
Airflow resistivity $\sigma$ = 20000 Rayls/m
Bulk density $\rho_b$ = 10 kg/m$^3$
Mass/unit area $m_s$ = 500 g/m$^2$

- **Parametric study on fibrous damping within the target region**

# AIRFLOW RESISTIVITY OPTIMIZATION OF THE TREATMENT

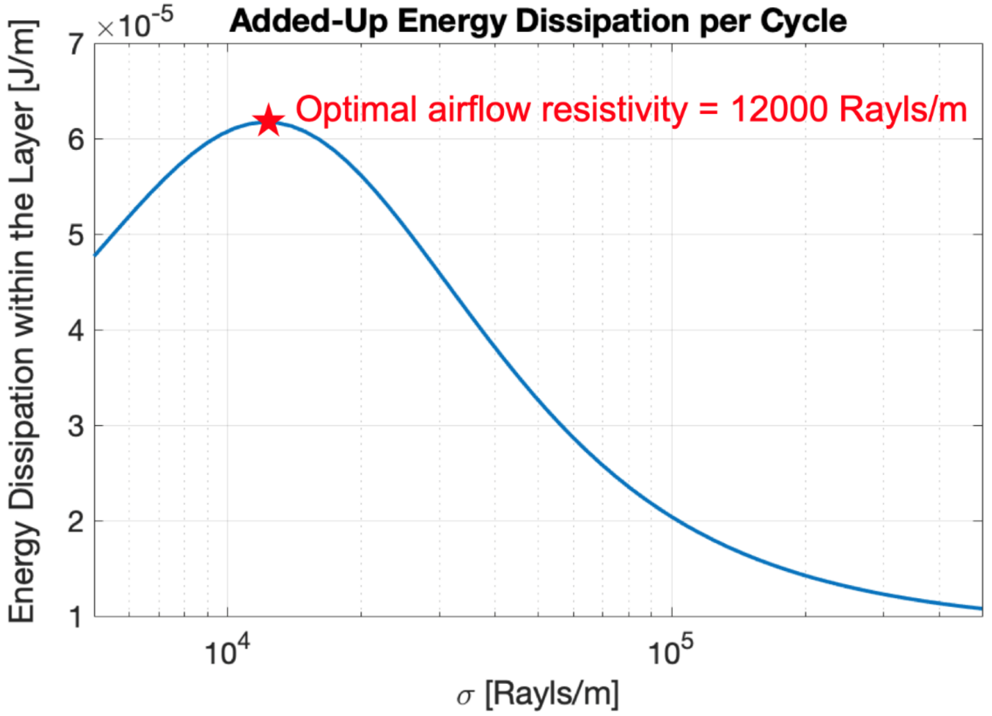
- Parametric study of airflow resistivity effect on power dissipation




- **Integrate power dissipation within target "box" for each airflow resistivity**

# AIRFLOW RESISTIVITY OPTIMIZATION OF THE TREATMENT

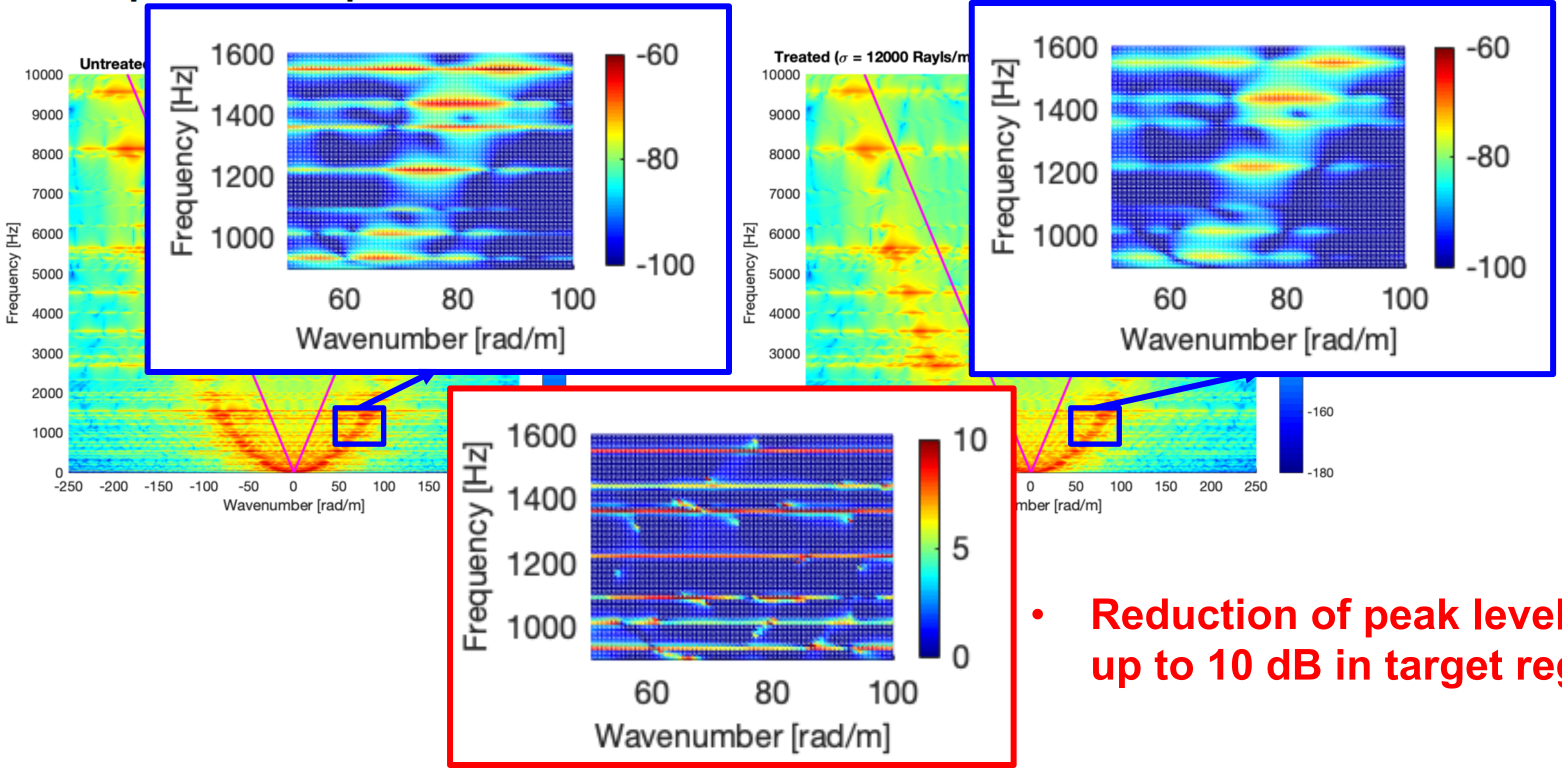
- **Parametric study of airflow resistivity effect on damping**




- **An optimal airflow resistivity could be identified, which resulted in the largest damping performance within the target "box"**

# AIRFLOW RESISTIVITY OPTIMIZATION OF THE TREATMENT

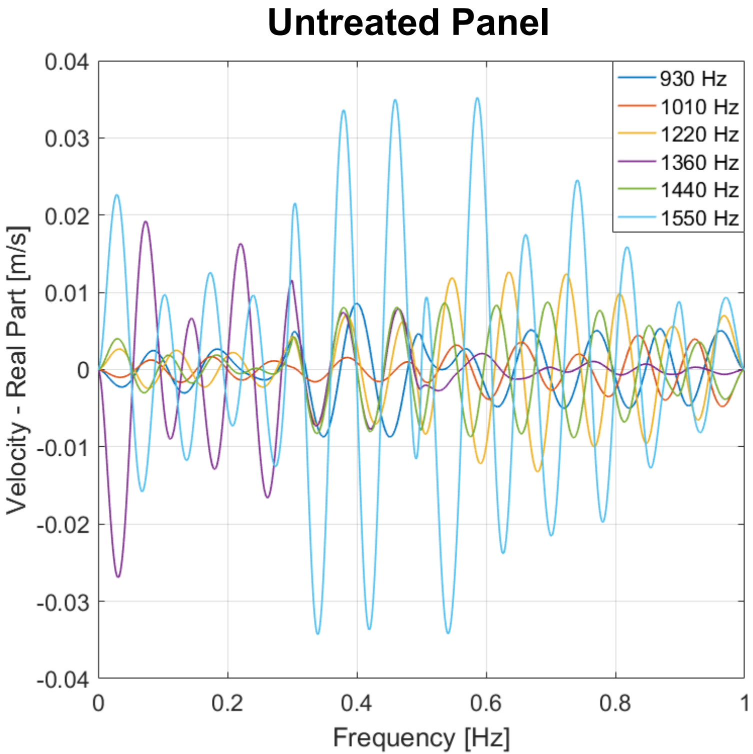
- **Responses comparison – wavenumber domain**

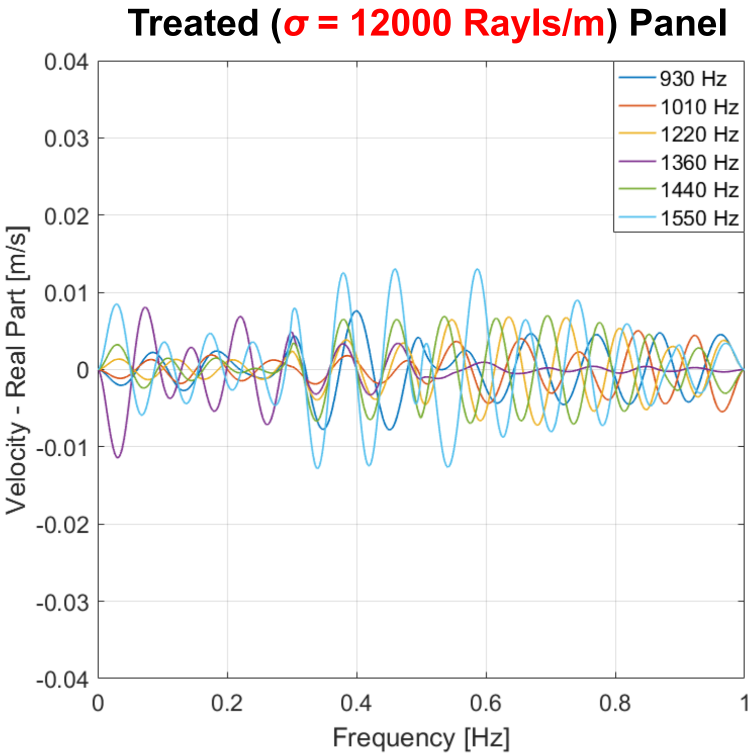



- **Reduction of peak level by up to 10 dB in target region**

# AIRFLOW RESISTIVITY OPTIMIZATION OF THE TREATMENT

- **Responses comparison – spatial domain**



# MICROSTRUCTURAL OPTIMIZATION OF THE TREATMENT

- **Fiber inputs:**

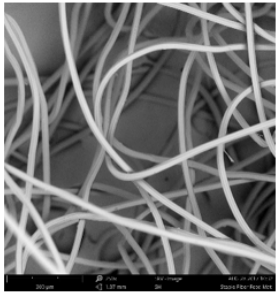
➢ **Solid material density $\rho_1 = 910\ \mathrm{kg/m^3}$** (made of polymer);

➢ Fibrous layer bulk density $\rho_b = 10\ \mathrm{kg/m^3}$

➢ Optimal airflow resistivity to maximize the power dissipation $\sigma = 12000\ \mathrm{Rayls/m}$

- **Optimization results**

➢ Optimization target → optimal fiber radius $r_1 = 3.6\ \mu\mathrm{m}$ was found by using the AFR micro-bulk relation[8] model and optimization



**Target material: made of single fiber component with uniform fiber size**

- **Fiber size was optimized to achieve the largest damping for certain wavenumber/frequency region & panel of interests**
- **Different result would be obtained for different wavenumber/frequency region**

# CONCLUSIONS

- **Lightweight fibrous damper parametric study on macro/microscopic properties**

  - **Significant levels of damping can be achieved by properly designed fibrous treatment → multifunctional (absorbing & damping) fibrous layer saves weight, space and cost**

  - **The design process can be based on analytical modeling and parametric studies to optimize bulk properties or microstructures for fibrous dampers applied on idealized structures (partially-constrained or periodically-constrained panels)**

  - **Combined with finite element model, the design process can also be conducted on more realistic structures such as a floor pan-like structure**

  - **In the future, extend the analysis to two-dimensional structures**

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- **Relevant work can be found online (http://docs.lib.purdue.edu/herrick/)**

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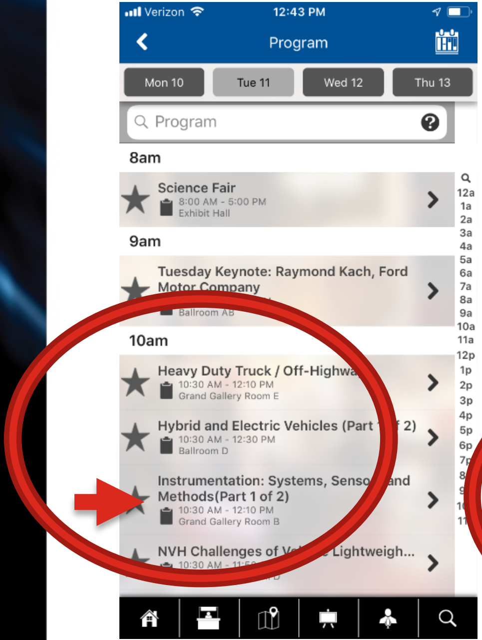


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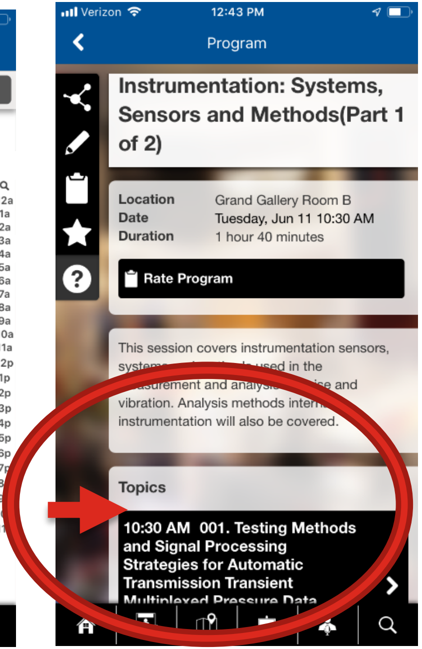


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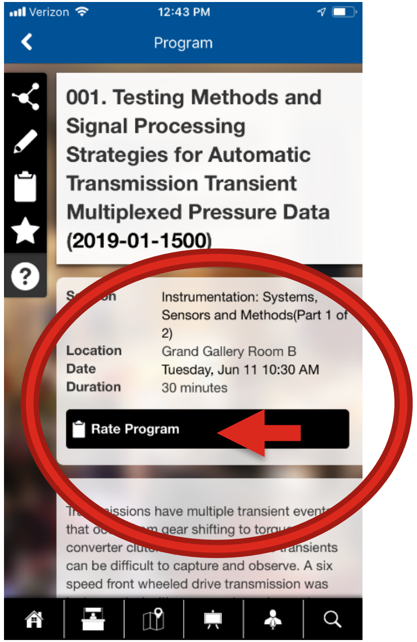


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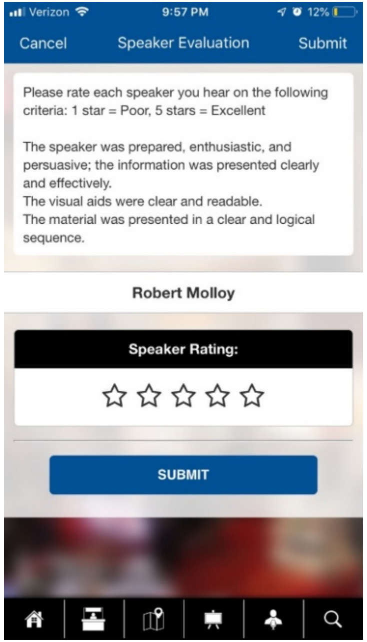


4. Rate speaker based on 3 criteria