ICCS24 - 24th International Conference on Composite Structures
FEUP - Faculty of Engineering, University of Porto, Portugal, 14 - 18 June 2021

DESIGN OF LOCALLY RESONANT METAMATERIAL CURVED DOUBLE WALL WITH EMBEDDED RESONATORS TO IMPROVE SOUND INSULATION AT RING AND MASS-SPRING-MASS RESONANCE

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My Background

Born:
Shijiazhuang

1989-2007

Bachelor:
BIT, Beijing

2007-2011

Master:
NUDT, Changsha

2011-2014

PhD:
KTH, Stockholm

2014-2019

Research engineer:

- **Yiduo Co. Ltd.**
- **Tongji University**
- **SYSU**
- **Tsinghua…**

2019-2021

Postdoc at Tsinghua

2021-2023?

Background and experiences:

- **Acoustic metamaterials, smart structure design and application;**
- **Sound insulation and absorption/NVH control;**
- **Acoustic/elastic waves;**
- **Tribology**

DESIGN OF METAMATERIAL PANELS: BACKGROUND

Turbine noise

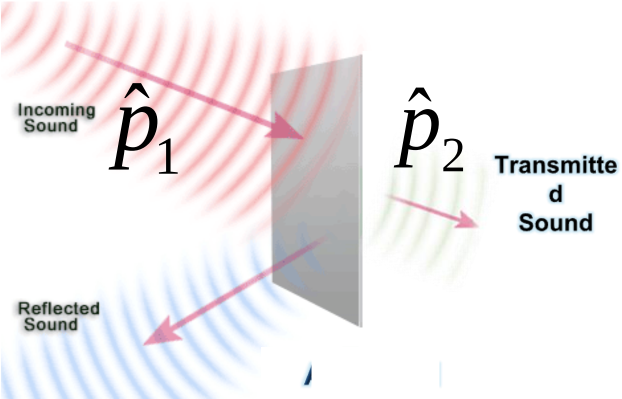
Fan noise

- Lightweight
- Bad insulation in particular frequency regions
- Limitations in traditional method

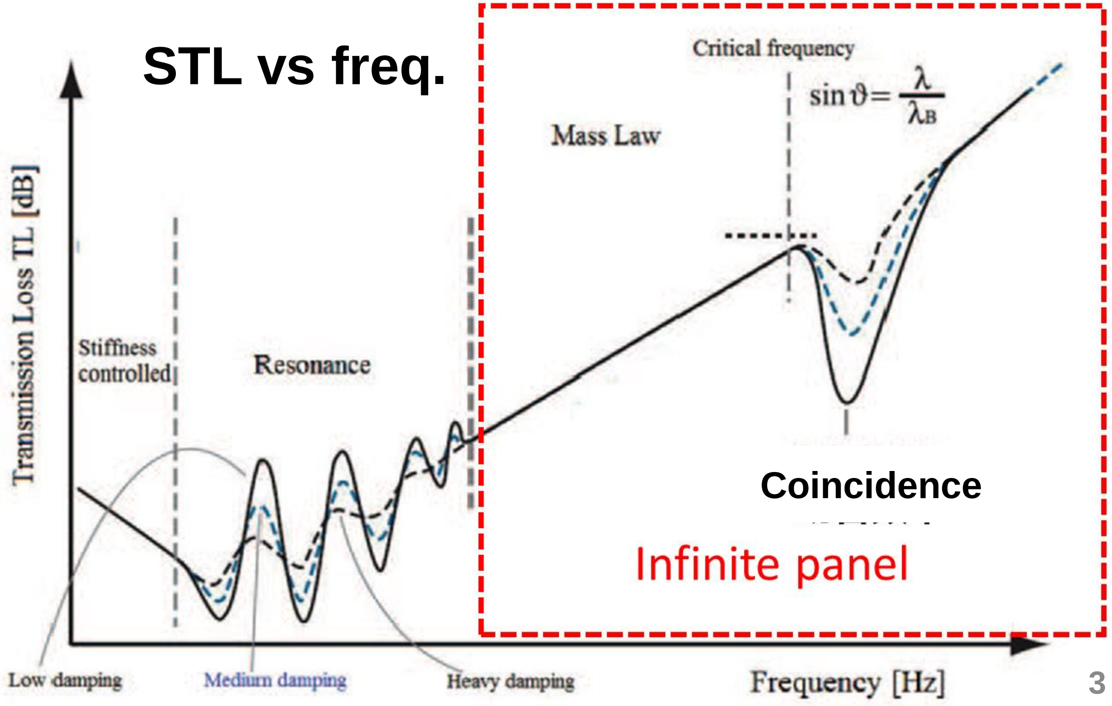
New treatment desired to improve the sound insulation properties of different types of panels

Environmental noise

Depiction of sound transmission



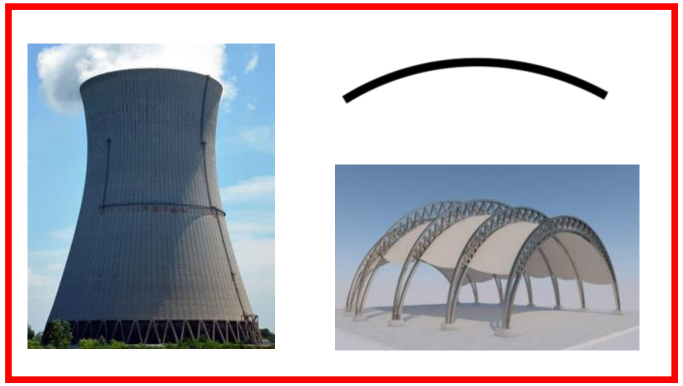
STL vs freq.



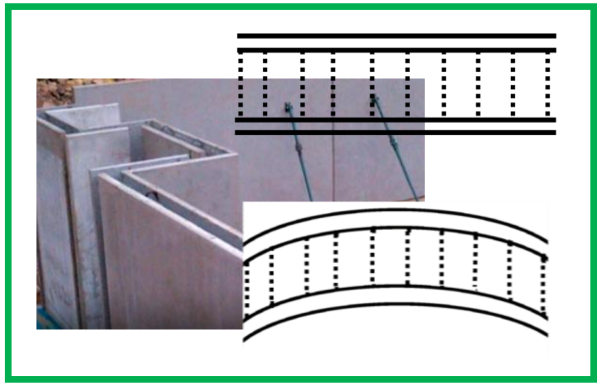
DESIGN OF METAMATERIAL PANELS: BACKGROUND

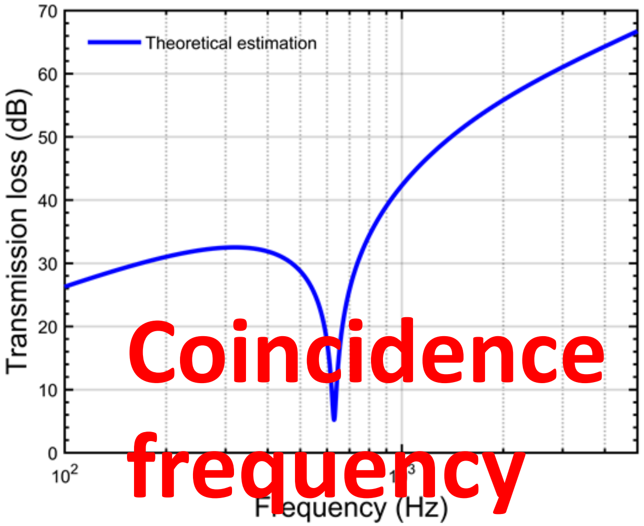
Sandwich structures

Cylindrical shells

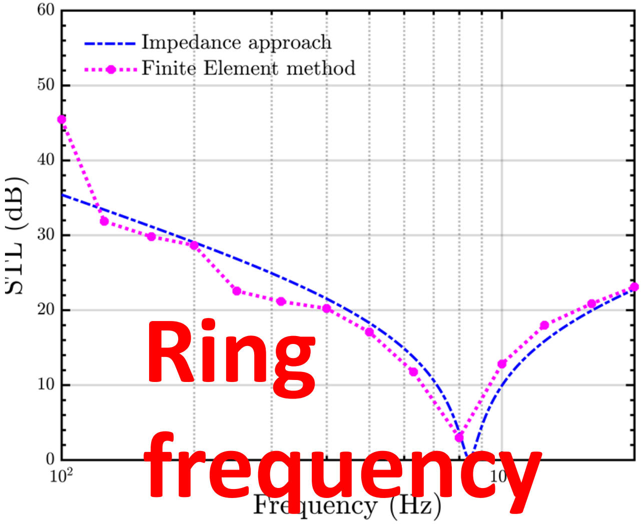


Double walls

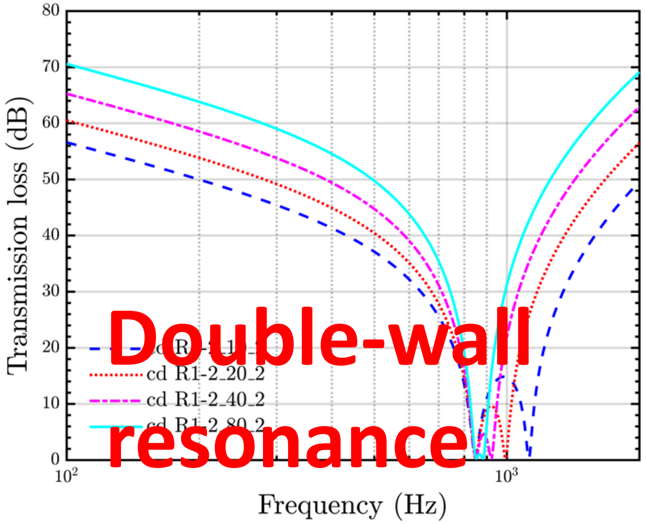




Coincidence frequency



Ring frequency



Double-wall resonance

NEEDS:

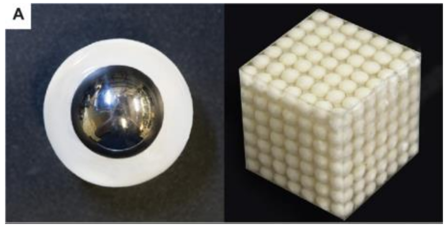
To improve

- Coincidence for sandwiches
- Ring frequency for shells
- Double-wall resonance

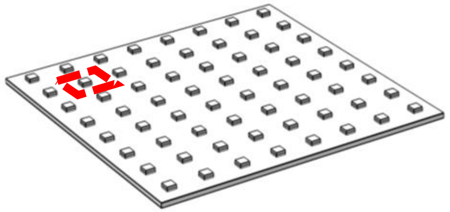
DESIGN OF METAMATERIAL PANELS: SCIENTIFIC PROBLEM

- Acoustic metamaterials (AM)
  - Nontrivial behaviour
  - Limited working frequency region
- Locally resonant AM
  - Host panel
  - Resonators

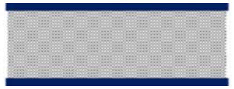
Locally resonant AM



AM panel

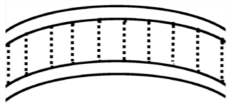


Sandwich



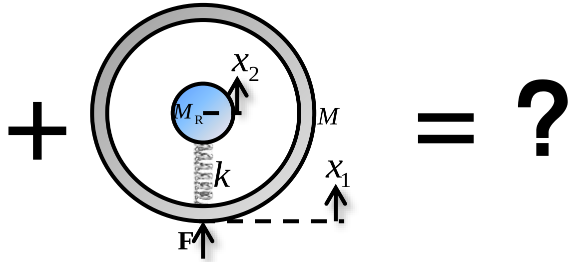
Shell

Double wall



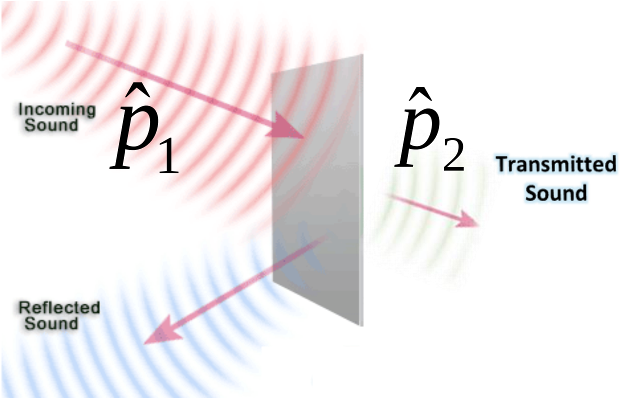
- Unexpected results
- Limited working frequency region

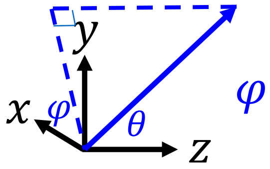
Resonators



- Investigate the physical insights;
- Explore the potential ways to improve the sound insulation behavior in the relevant specific frequency regions.

Design of metamaterial panels: Background





$\varphi = 0; \theta = \frac{\pi}{3}$

- $\hat{p}_1 = \hat{p}_{\text{inc}} + \hat{p}_{\text{ref}}$
- $\hat{p}_2 = \hat{p}_{\text{trans}}$

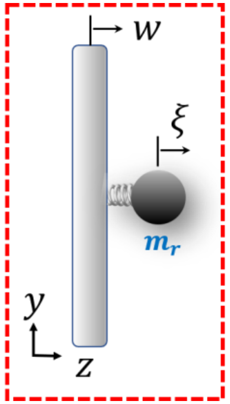
Under the Thin Plate Assumption:

- Continuity of Velocity: $\rho_0 \dfrac{\partial \vec{v}_z}{\partial t} = -\vec{\nabla}_z \hat{p}$
- Newton's second law: $\hat{p}_1 - \hat{p}_2 = Z \cdot \hat{v}$

Z **Impedance of the panel**

- Transmission coefficient: $\tau = \dfrac{P_{\text{trans}}}{P_{\text{inc}}} \to \left| 1 + \dfrac{Z\cos\theta}{2\rho_0 c_0} \right|^{-2}$
- Sound transmission loss: $\text{STL} = 10\log\left(\dfrac{1}{\tau}\right)$

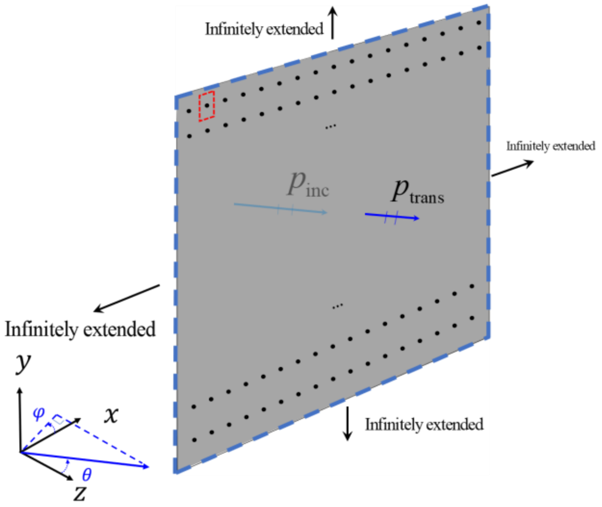
DESIGN OF METAMATERIAL PANELS: BACKGROUND



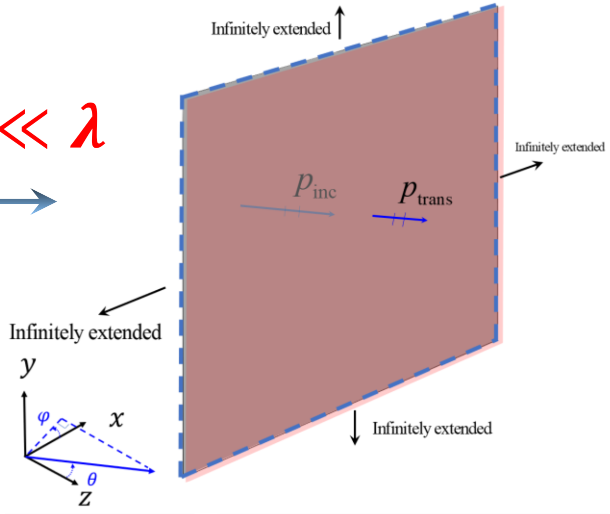
- For metamaterial panels:
  - $\mathrm{STL} = \frac{1}{\tau}, \quad \tau = \left| 1 + \frac{\boxed{Z_{\mathrm{eff}}} \cos\theta}{2\rho_0 c_0} \right|^{-2}$

$$Z_{\mathrm{eff}} = Z + \boxed{Z_{\mathrm{eq}}^{\mathrm{r}}}$$

$$Z_{\mathrm{eq}}^{\mathrm{r}} = \mathrm{j}\omega m_{\mathrm{r}} \frac{1}{1 - f^2 / f_{\mathrm{res}}^2}$$



Distance $\ll \lambda$



DESIGN OF METAMATERIAL PANELS: METAMATERIAL SANDWICH

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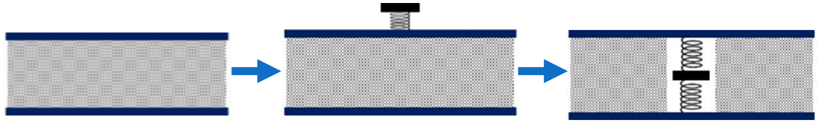
Metamaterial sandwich with embedded resonators:

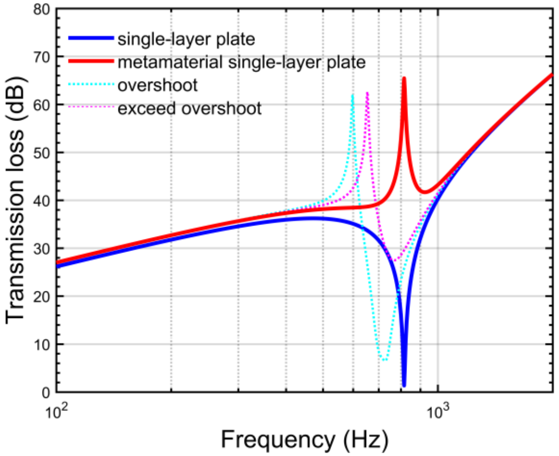


- A systematic tuning criterion

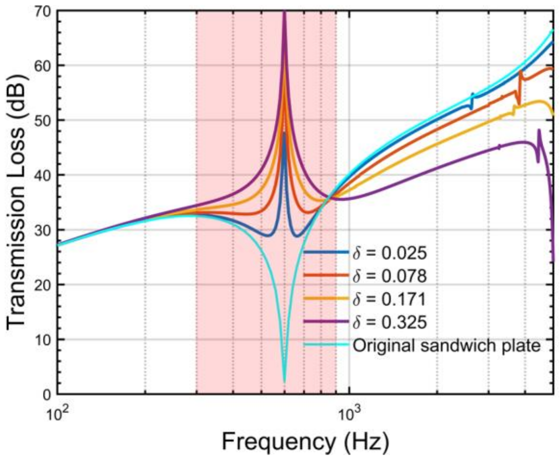
$$f_{\mathrm{co}}\left(\sqrt{1+\frac{\delta}{2}}-\sqrt{\frac{\delta}{2}}\right)\le f_{\mathrm{res}}\le f_{\mathrm{co}}\left(\sqrt{1+\frac{\delta}{2}}+\sqrt{\frac{\delta}{2}}\right)$$

- where δ is the ratio of the resonator to the host panel $\delta = \frac{m_r}{m}$

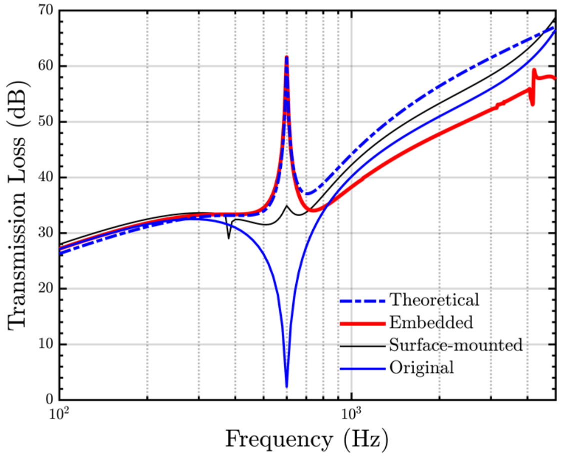
- Working frequency range: $\sim \sqrt{\delta}$



Overcome the coincidence effect



Broaden the working frequency range

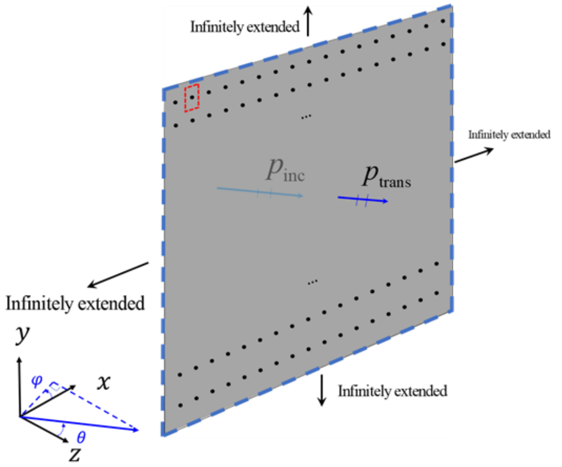


Suppress the radiation from the resonators

Advantages:

- **Coincidence effect**
- **Radiation from the resonators**
- **Working frequency range**
- **Practicability**

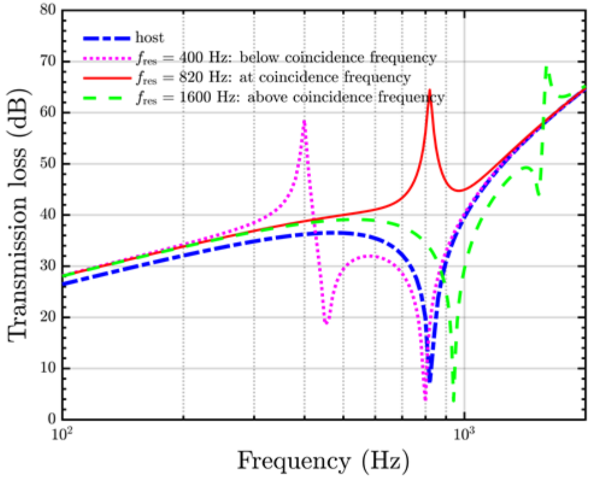
DESIGN OF METAMATERIAL PANELS: METAMATERIAL SHELL

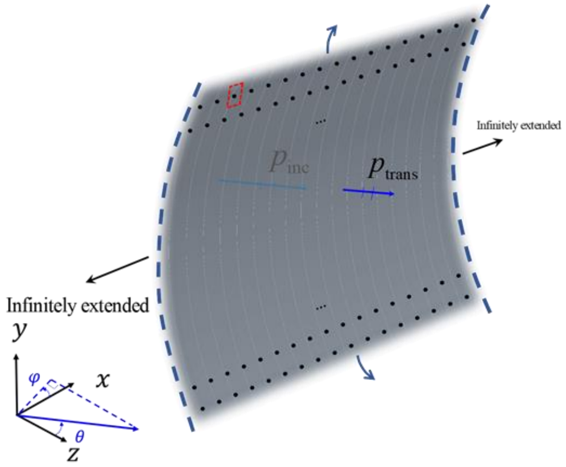


- **Coincidence:**

$$Z = \mathrm{j}\omega m\left(1 - \frac{f^2}{f_{\mathrm{co}}^2}\right)$$

$$Z_{\mathrm{eff}} = Z + Z_{\mathrm{eq}}^{\mathrm{r}}$$



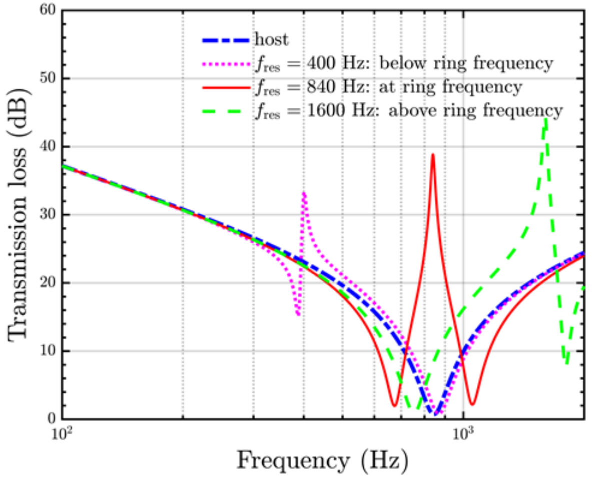


- **Ring:**

$$Z = \mathrm{j}\omega m\left(1 - \frac{f^2}{f_{\mathrm{co}}^2} - \frac{f_{\mathrm{ri}}^2}{f^2}\right)$$

$$Z_{\mathrm{eff}} = Z + Z_{\mathrm{eq}}^{\mathrm{r}}$$

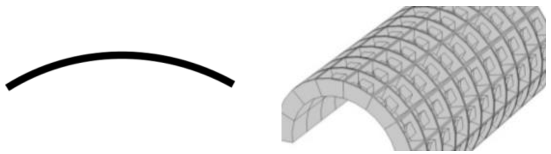
  - *'Side effects'*



DESIGN OF METAMATERIAL PANELS: METAMATERIAL SHELL

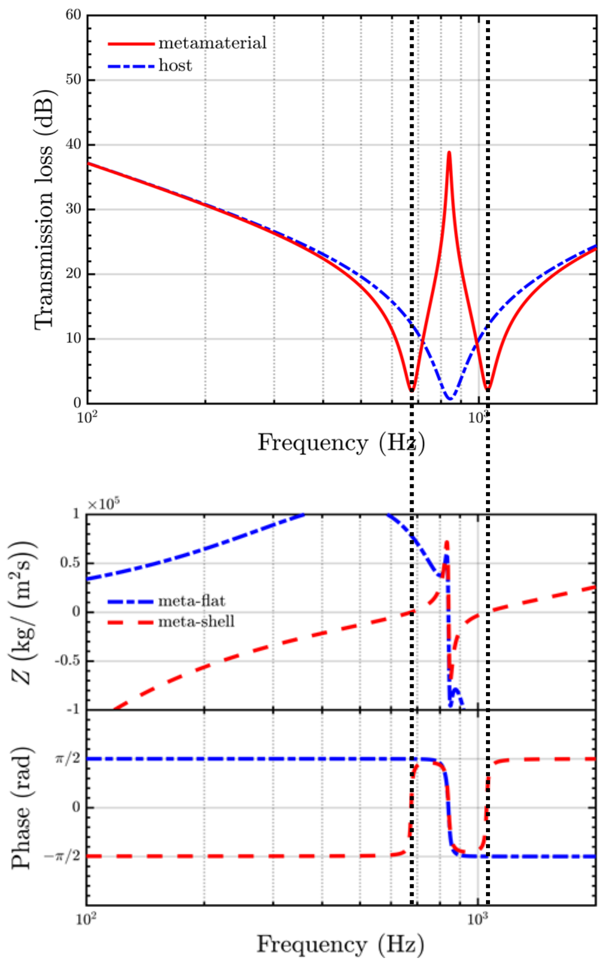
Journal of Applied Physics **125**, 115105 (2019); https://doi.org/10.1063/1.5081134

Metamaterial cylindrical shell

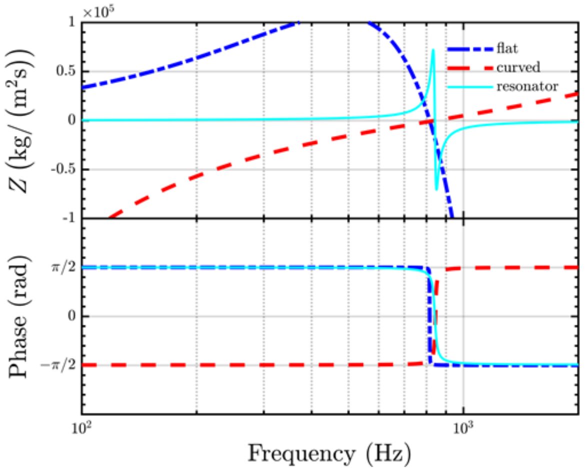


Tuning conventional resonators to the ring frequency of curved panels generates two side dips despite a sharp improvement.

Z	Resonator	Flat	Shell
Below the freq.	+	+	-
Above the freq.	-	-	+



The 'side effects' from the resonators



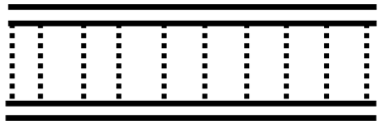
Physical insights: Phase change

Resonators: mass- to stiffness-controlled

Shell at ring: stiffness- to mass-controlled

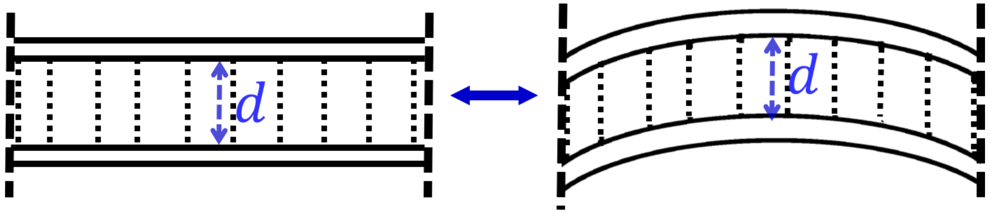
- **Effective impedance approach;**
- **Allow for the design of suitable resonators to resolve the ring frequency effect.**

Design of metamaterial panels: Metamaterial curved double wall

- **Double wall:** 

    - Double-wall resonance

- **Curved double walls**



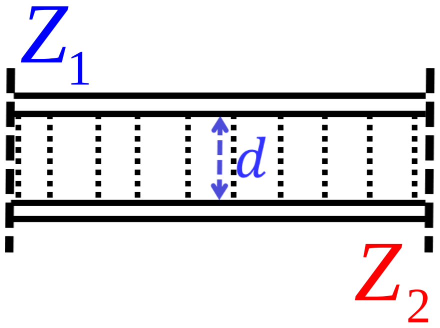
- Ring frequency effect
- Mass-spring-mass resonance effect

→ *More Critical*

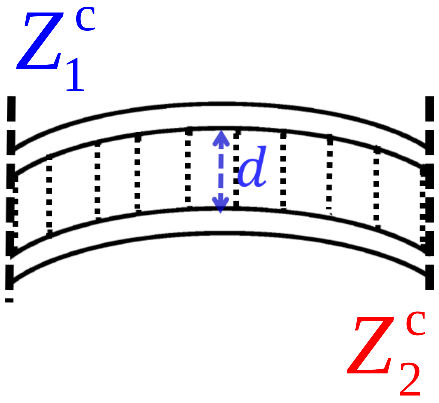
Side wall of an aircraft fuselage

Design of metamaterial panels: Metamaterial curved double wall

- Transmission coefficient: $\tau = \left|1 + \dfrac{Z}{2Z_a}\right|^{-2}$

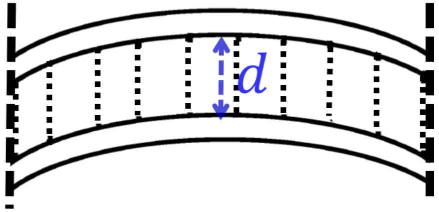


$$Z^{d} = Z_1 + Z_2 + \frac{j\omega}{s}\left(Z_1 + Z_a\right)\left(Z_2 + Z_a\right)$$



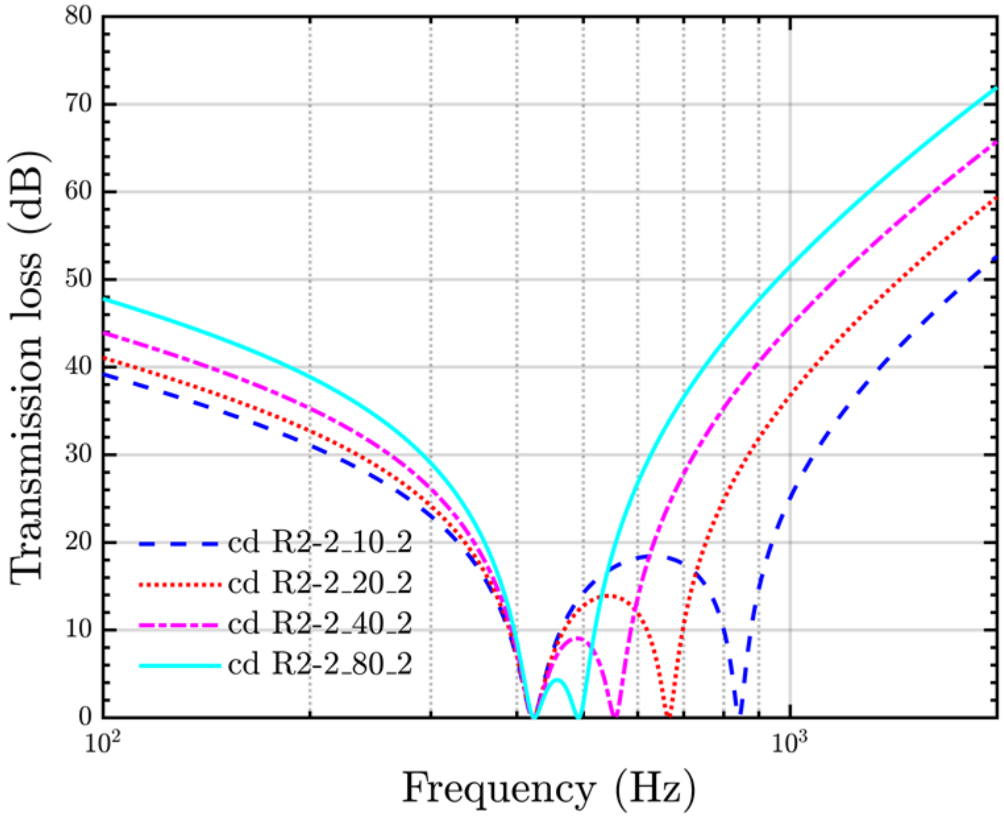
$$Z^{cd} = Z_1^{c} + Z_2^{c} + \frac{j\omega}{s}\left(Z_1^{c} + Z_a\right)\left(Z_2^{c} + Z_a\right)$$

- **Estimation of characteristic frequencies:**



$$f_1^{\mathrm{cd}} = f_{\mathrm{ri}}$$

$$f_2^{\mathrm{cd}} = \sqrt{{f_{\mathrm{msm}}^{\mathrm{d}}}^2 + {f_{\mathrm{ri}}}^2}$$



Design of metamaterial panels: Metamaterial curved double wall

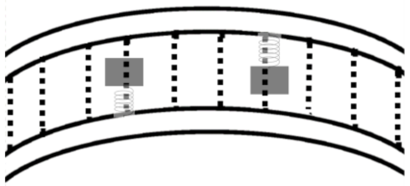
- **Curved double walls → Broad 'valley' → can be narrowed**
- **Metamaterials → Limited working frequency range**
- ***Design method***
    1. *Narrow the 'valley'*
    2. *Mount tuned resonators*

DESIGN OF METAMATERIAL PANELS: METAMATERIAL CURVED DOUBLE WALL

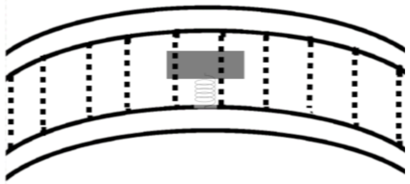
- ***Design approach***

  1. *Narrow the 'valley'*
  2. *Mount tuned resonators*

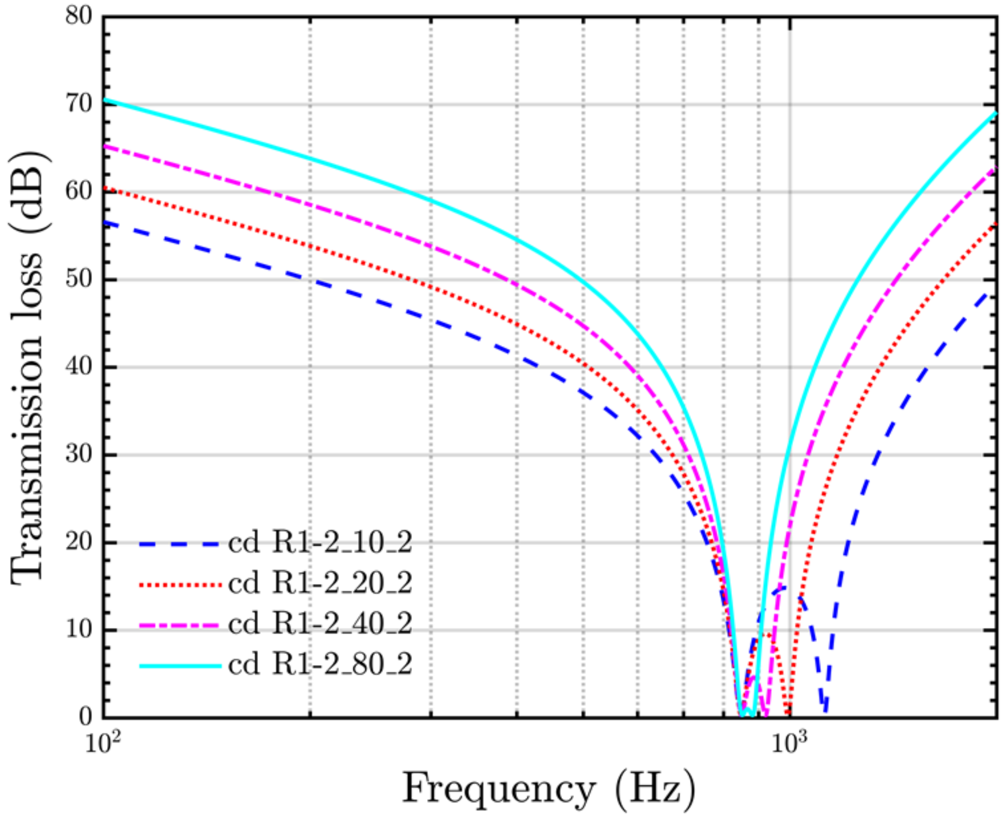
1. *Resonators on both panels*



2. *Resonators on one panel*

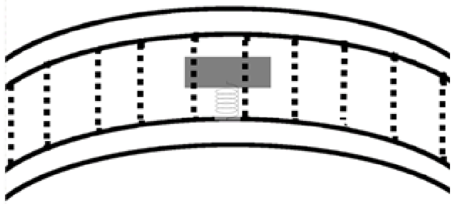


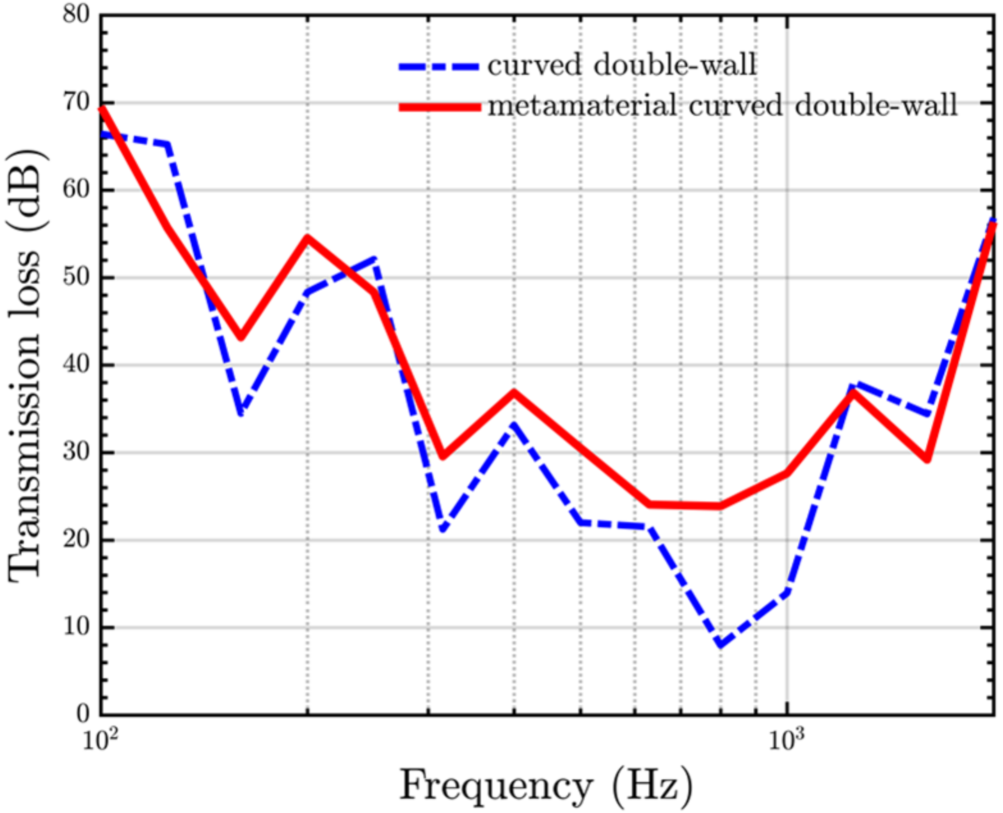
The total added mass is kept constant



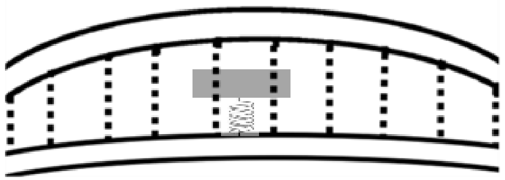
DESIGN OF METAMATERIAL PANELS: METAMATERIAL CURVED DOUBLE WALL

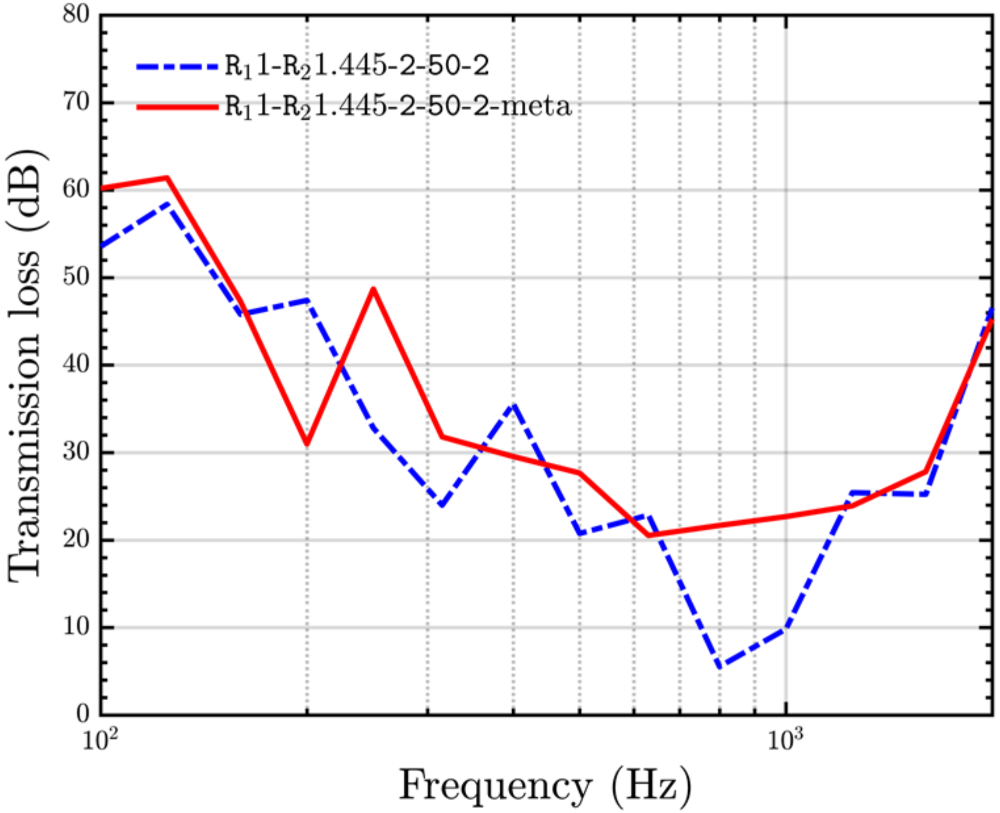
Identical:





Non-identical:





DESIGN OF METAMATERIAL PANELS: METAMATERIAL CURVED DOUBLE WALL

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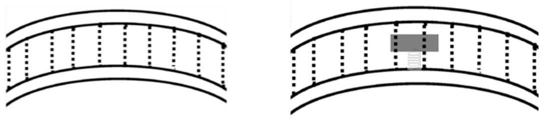
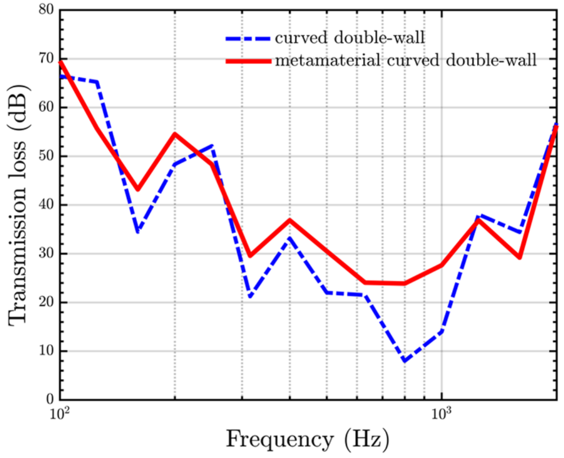
Volume 149, 15 February 2021, 107179

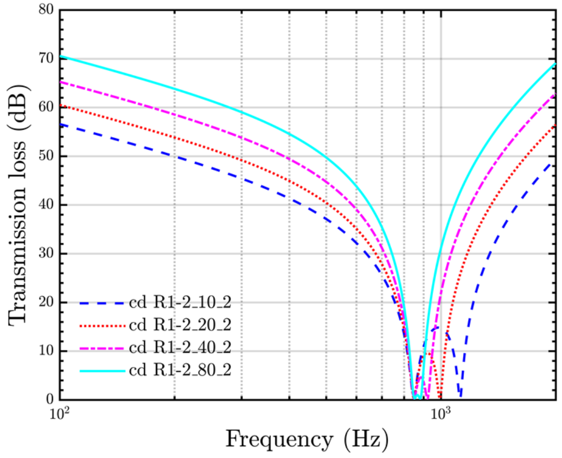
Curved double wall



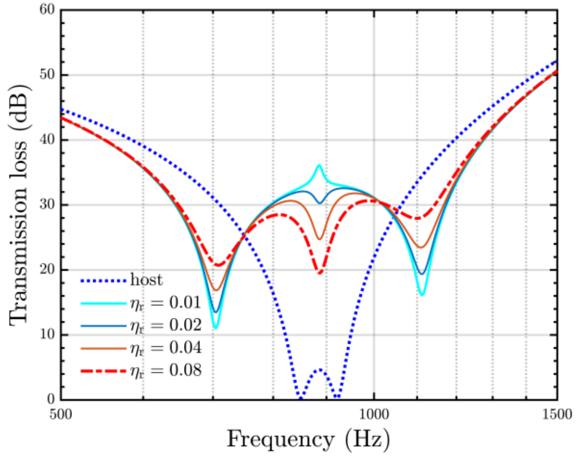
'Apparent Impedance' formula

$$Z^{\mathrm{cd}} = Z_1^{\mathrm{c}} + Z_2^{\mathrm{c}} + \frac{\mathrm{j}\omega}{s}\left(Z_1^{\mathrm{c}} + Z_{\mathrm{a}}\right)\left(Z_2^{\mathrm{c}} + Z_{\mathrm{a}}\right)$$





Step 1. Design of the host panel: narrowed 'valley'



Step 2. Mounted with damped resonators

- **Apparent impedance approach introduced, validated against the Finite Element method.**
- **Improvement of sound transmission loss performance around characteristic frequencies.**

Thank you for your attention!

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