Respondent	Zibo Liu
Examen	Teknologie doktor
Avhandlingens titel	Design of soundproof panels via metamaterial concept
Ämne på forskarnivå och eventuell inriktning	Farkostteknik
Huvudhandledare	Universitetslektor Leping Feng
Ordförande	Docent Susann Boij
Fakultetsopponent	Professor Jean-François Deü, Conservatoire National des Arts et Metiers, Frankrike
Ledamöter i betygsnämnden	Professor Sergio De Rosa, Università degli Studi di Napoli, Italien Docent Patrik Höstmad, Chalmers Tekniska Högskola, Göteborg Dr. Elke Deckers, Katholieke University Leuven, Belgien Ersättare: Professor Mats Åbom, KTH, Stockholm

Design of soundproof panels via metamaterial concept

Zibo Liu

Supervisors: Leping Feng; Romain Rumpler

Content

- **Introduction**
- **Methodology**
- **Coincidence effect**
- **Ring frequency problem**
- **Curved double walls**
- **Conclusions**

- *Song, Y., Feng, L., **Liu, Z.**, Wen, J., & Yu, D. (2019). Suppression of the vibration and sound radiation of a sandwich plate via periodic design. International Journal of Mechanical Sciences, 150, 744-754.*
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Background and motivation

- Urbanization
- Industrialization
- Transportation
- etc.

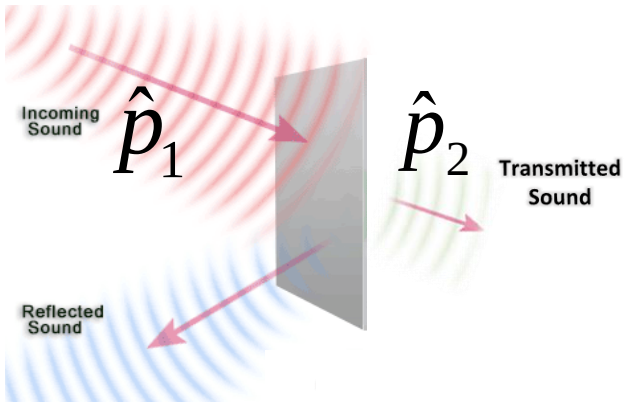
Noise reduction engineering

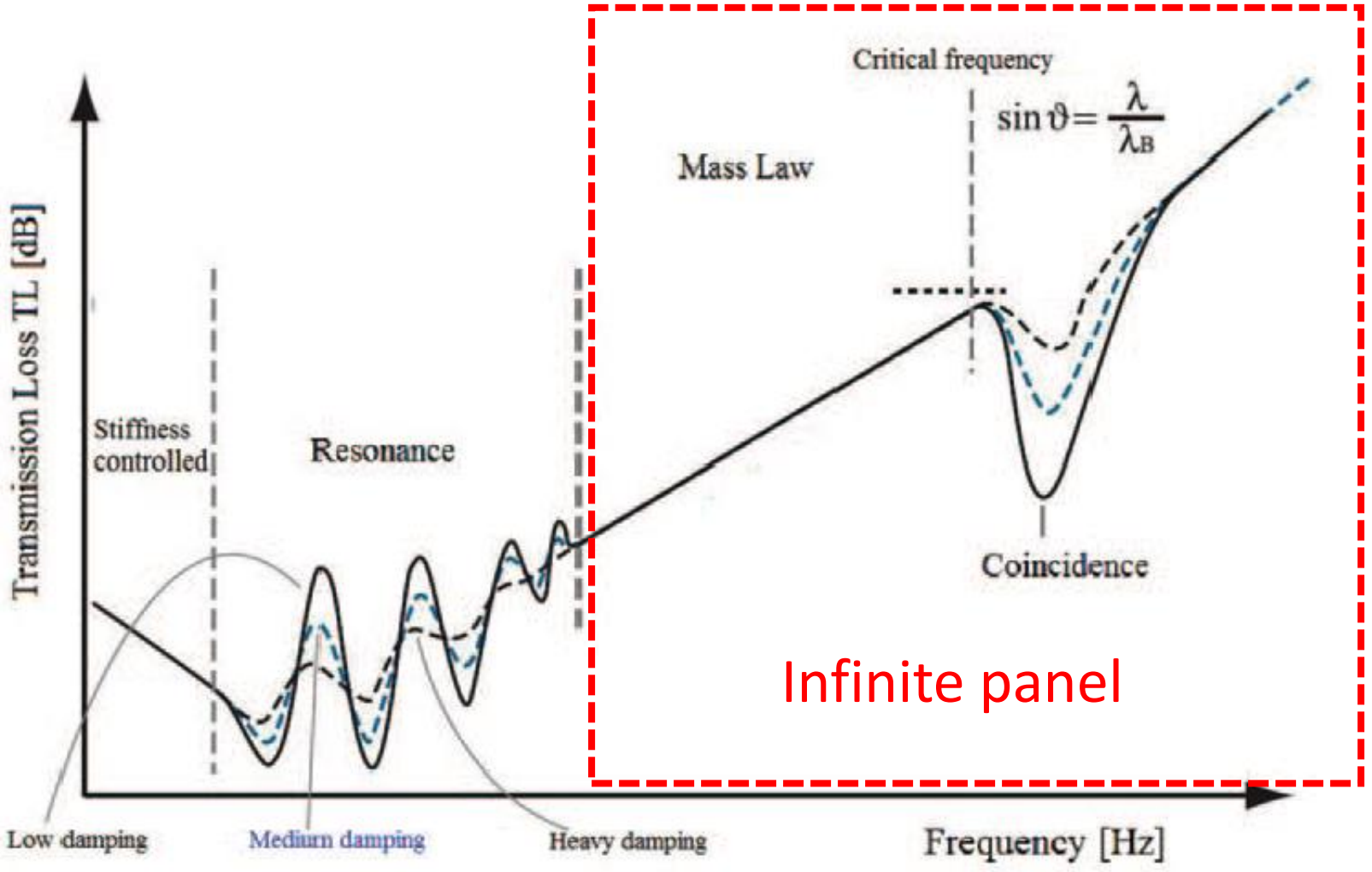
Isolation for sound transmission path

Sound insulation/sound transmission loss properties

1. *Fritschi, Lin, Lex Brown, Rokho Kim, Dietrich Schwela, and Stylianos Kephalopoulos. "Burden of disease from environmental noise: Quantification of healthy life years lost in Europe." WHO regional office for Europe (2011).*

Background and motivation





1. *D'Alessandro, V., Petrone, G., Franco, F., & De Rosa, S. (2013). A review of the vibroacoustics of sandwich panels: Models and experiments. Journal of Sandwich Structures & Materials, 15(5), 541-582.*

Background and motivation

Coincidence frequency:

$$\lambda_{\mathbf{trace}} = \lambda_{\mathbf{bending}}$$

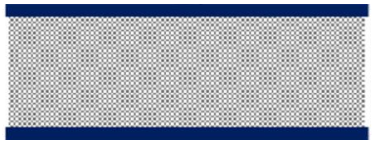
Ring frequency:

$$\mathbf{circumference} = \lambda_{\mathbf{longitudinal}}$$

Double-wall resonance:

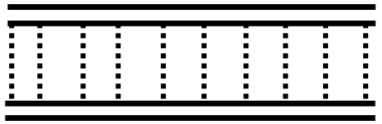
$$\mathbf{double\ wall\ resonance} = \frac{1}{2\pi}\sqrt{s\left(\frac{1}{m_1}+\frac{1}{m_2}\right)}$$

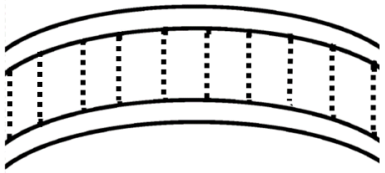
- **Sandwich:**



- **Curved:**

- **Double wall:**





Background and motivation

- Acoustic Metamaterial
  - Unusual properties
  - Limited frequency range
- Locally resonant metamaterial panels
  - Host panel
  - Resonators

Initial realizations of locally resonant acoustic metamaterials

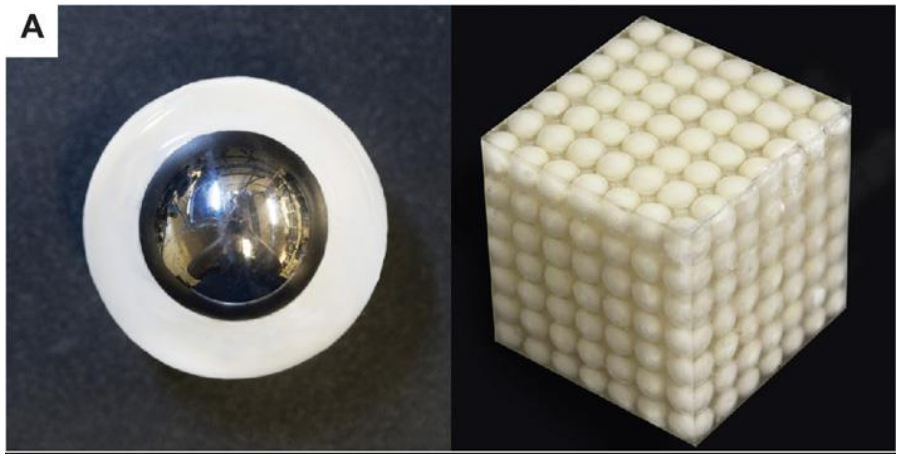
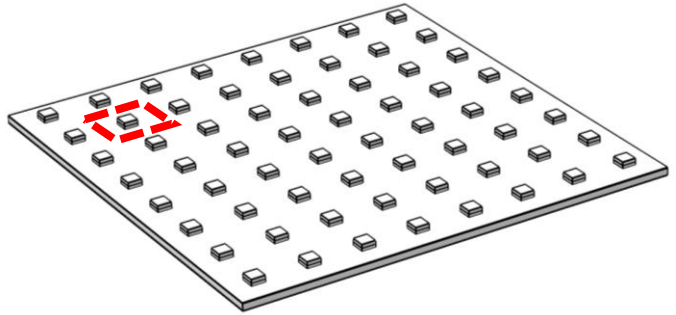


Illustration of a locally resonant metamaterial panel

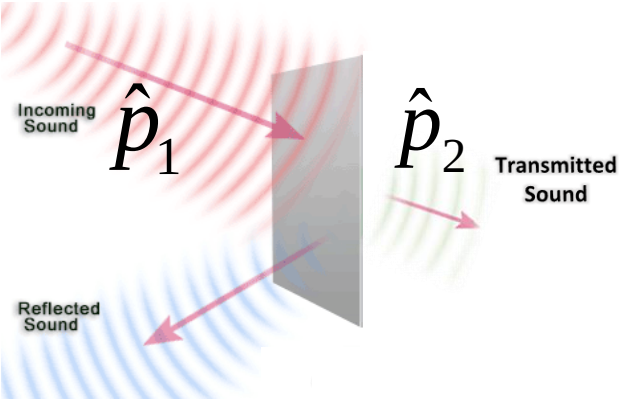


1. *Ma, Guancong, and Ping Sheng. "Acoustic metamaterials: From local resonances to broad horizons." Science advances2, no. 2 (2016): e1501595.*

Methodology

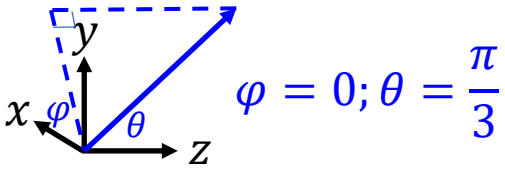
- **Impedance approach**
- **Finite Element Method**

Impedance approach



Under the Thin Plate Assumption:

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



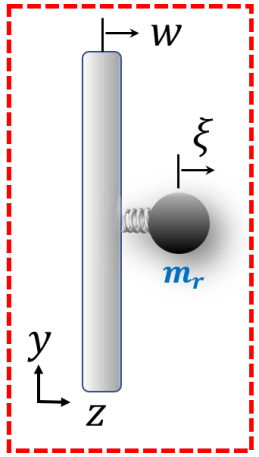
$\varphi = 0; \theta = \frac{\pi}{3}$

Z **Impedance of the panel**

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

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

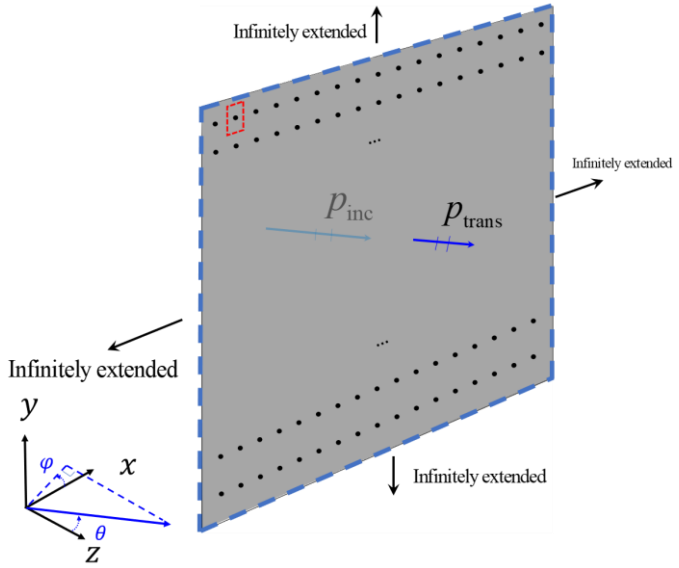
Impedance approach



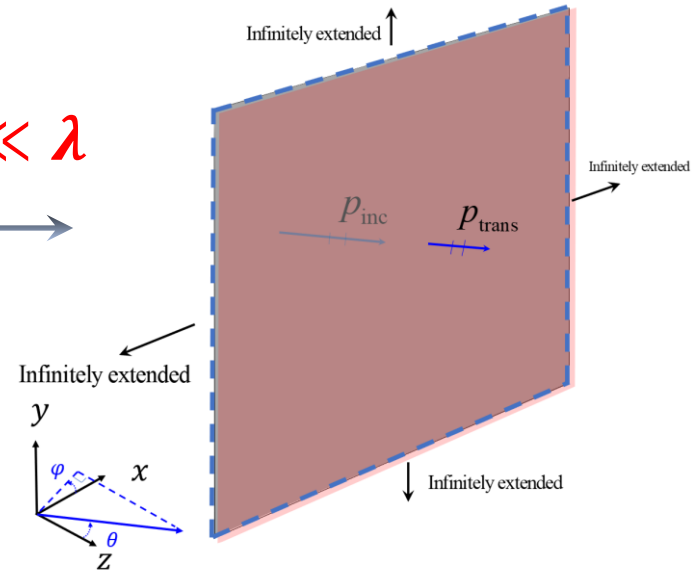
- For metamaterial panels:
  - $\mathrm{STL} = \frac{1}{\tau}, \quad \tau = \left| 1 + \frac{Z_{\mathrm{eff}} \cos\theta}{2\rho_0 c_0} \right|^{-2}$

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

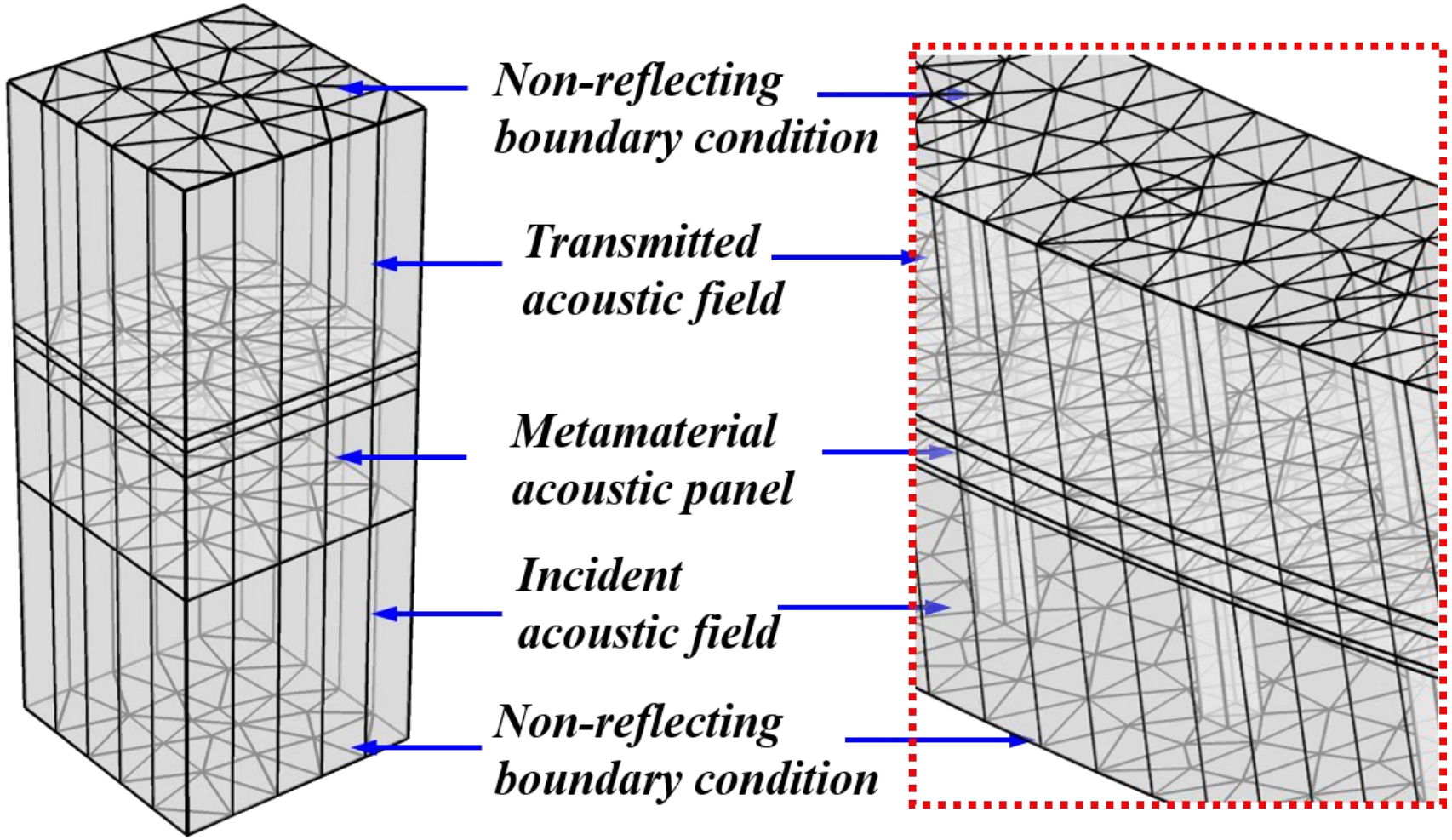
$$Z_{\mathrm{eq}}^{\mathrm{r}} = \mathrm{j}\omega m_{\mathrm{r}} \frac{1}{1 - f^2 / f_{\mathrm{res}}^2}$$



Distance $\ll \lambda$



Finite Element Method



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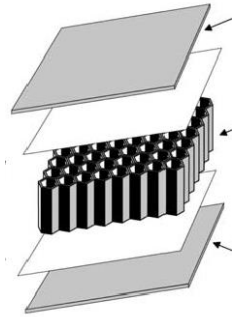
Introduction to sandwich panels

Advantage:

- low mass
- high stiffness

Disadvantage:

- bad sound insulation properties
  - ➢ Broad coincidence region
  - ➢ Low frequency range



Early works:

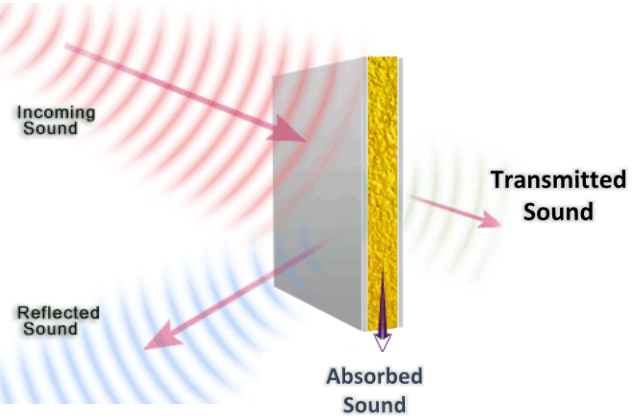
- Shear wall
- Coincidence wall
- etc…

Solution of interest:

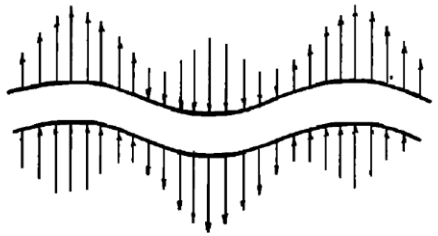
Metamaterial sandwich

1. *Moore, J. A., and R. H. Lyon. "Sound transmission loss characteristics of sandwich panel constructions." The Journal of the Acoustical Society of America 89, no. 2 (1991): 777-791.*

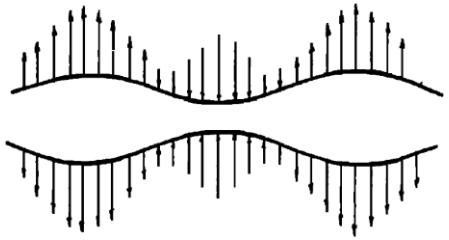
Sound transmission through sandwich panels



In-phase Mode:

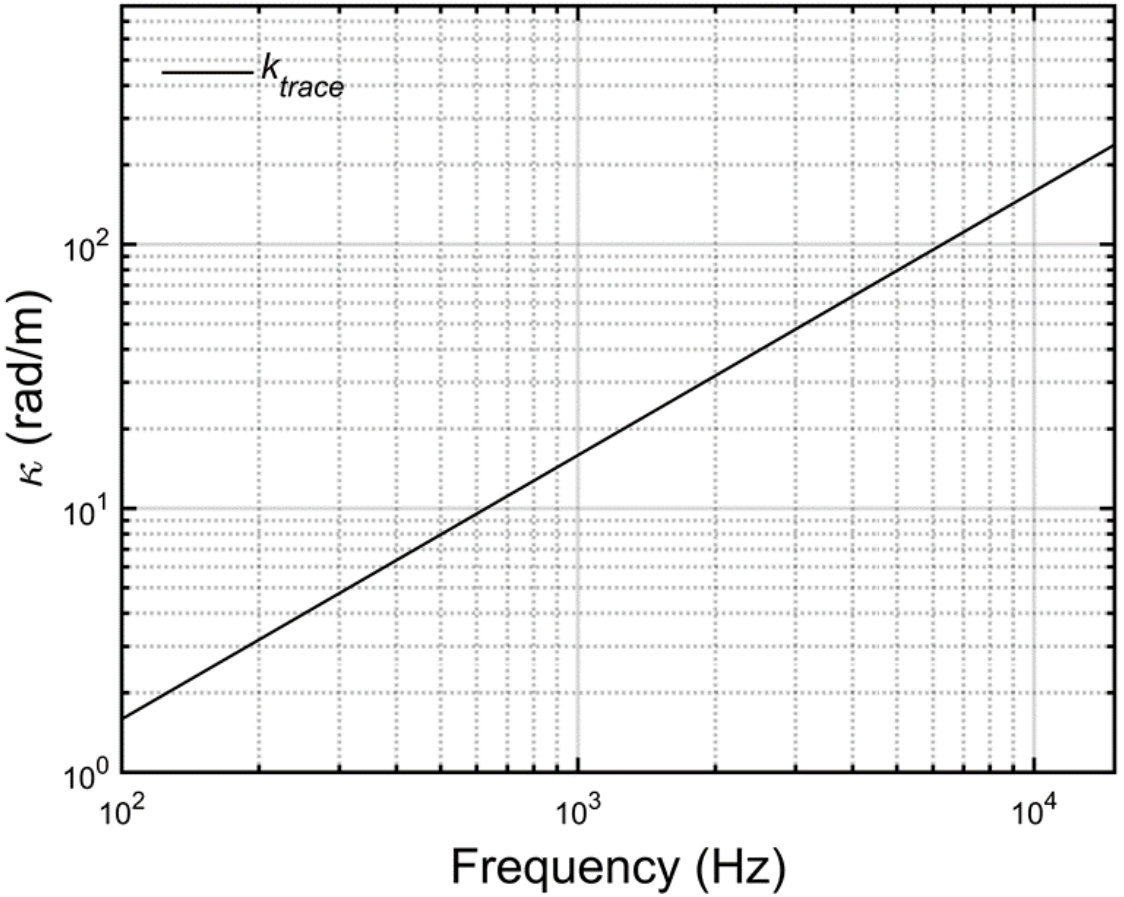


Anti-phase Mode:

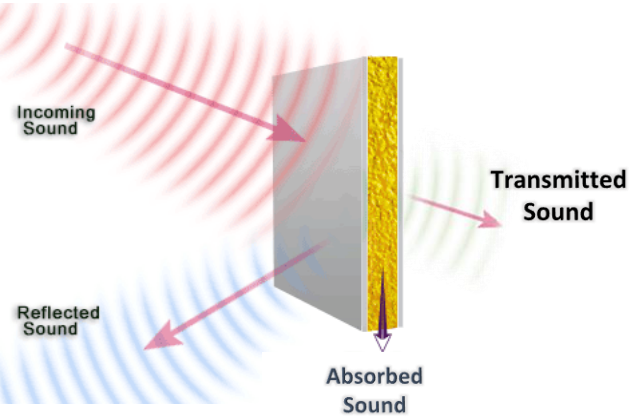


- **Equation of In-phase motion**

→ **Dispersion**



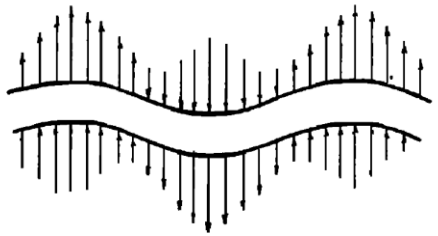
Sound transmission through sandwich panels



- **Equation of In-phase motion**

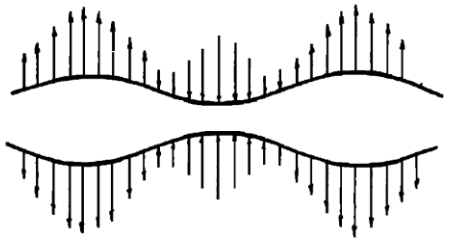
→ **Dispersion**

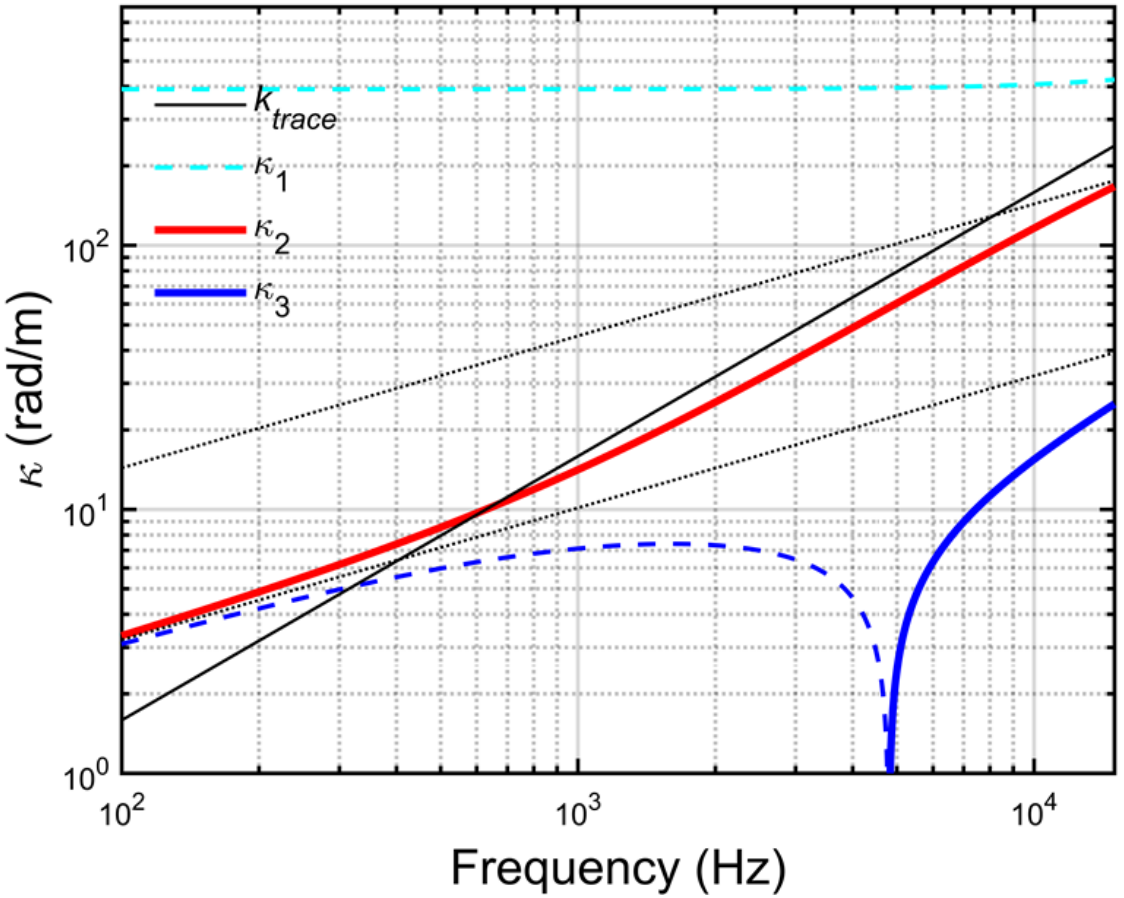
In-phase Mode:



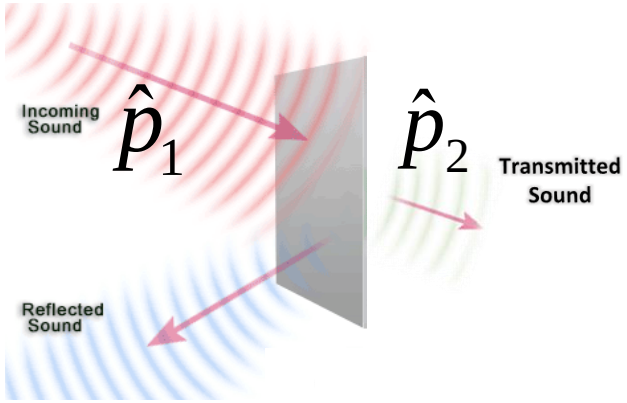
$\kappa_1 \quad \kappa_2 \quad \kappa_3$

Anti-phase Mode:



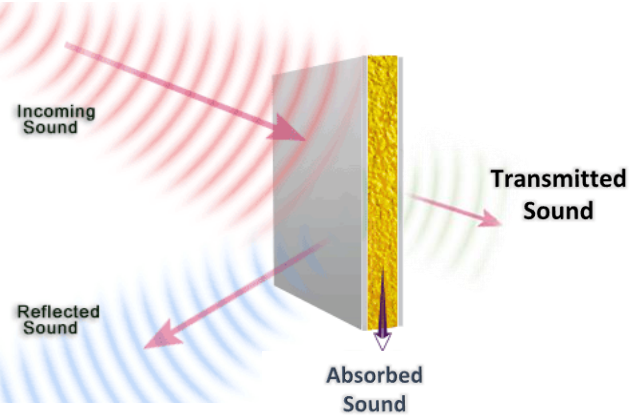


Sound transmission through sandwich panels

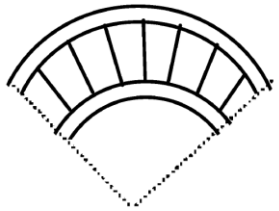


- **Recall: Impedance of single-leaf:**

$$Z = \mathrm{j}\omega m\left(1-\frac{k^4}{\kappa^4}\sin^4\theta\right) = \mathrm{j}\omega m\left(1-\frac{f^2}{f_{\mathrm{co}}{}^2}\right)$$



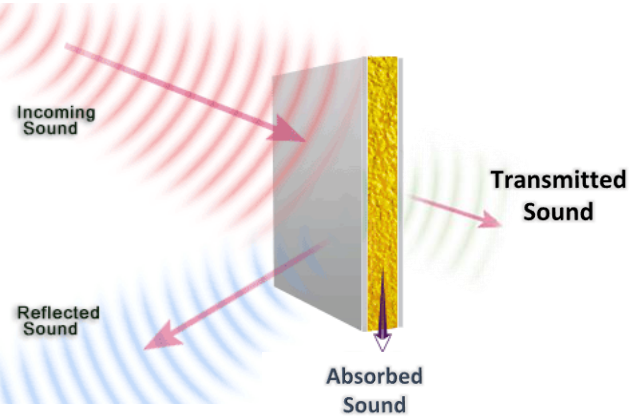
- **Impedance of sandwich:**



Bending, wavenumber $\kappa_2(f)$

$$Z = \mathrm{j}\omega m\left(1-\frac{k^4}{\kappa_2(f)^4}\sin^4\theta\right) = \mathrm{j}\omega m\left(1-\frac{f^2}{f_{\mathrm{Sco}}{}^2}\right)$$

Sound transmission through sandwich panels

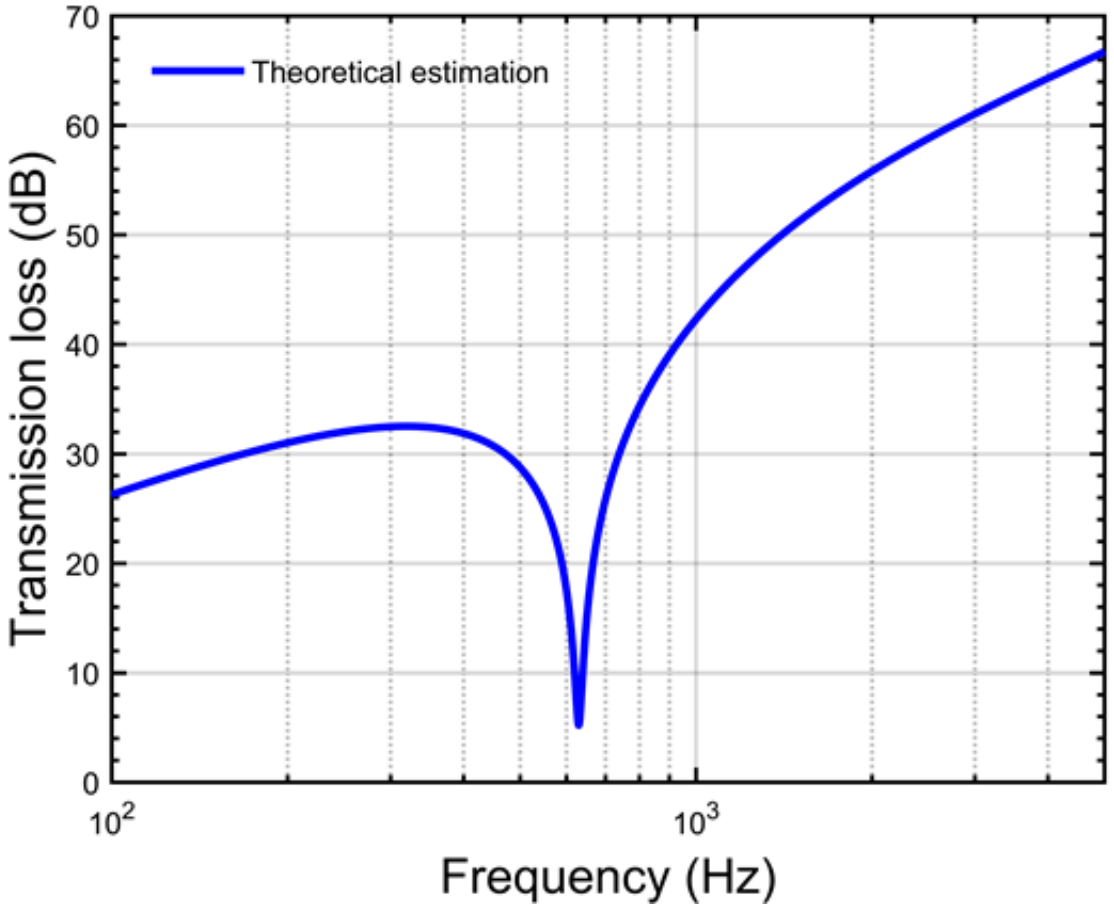


- **Impedance of sandwich:**

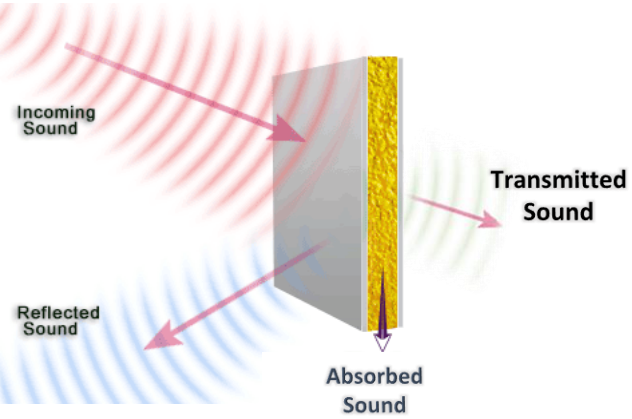
$$Z = \mathrm{j}\omega m\left(1-\frac{f^2}{f_{\mathrm{Sco}}{}^2}\right)$$

$$\downarrow$$

$$f_{\mathrm{Sco}} = \frac{1}{2\pi}\frac{c_0}{\sin^2\theta}\frac{\kappa_2{}^2}{k}$$



Sound transmission through sandwich panels

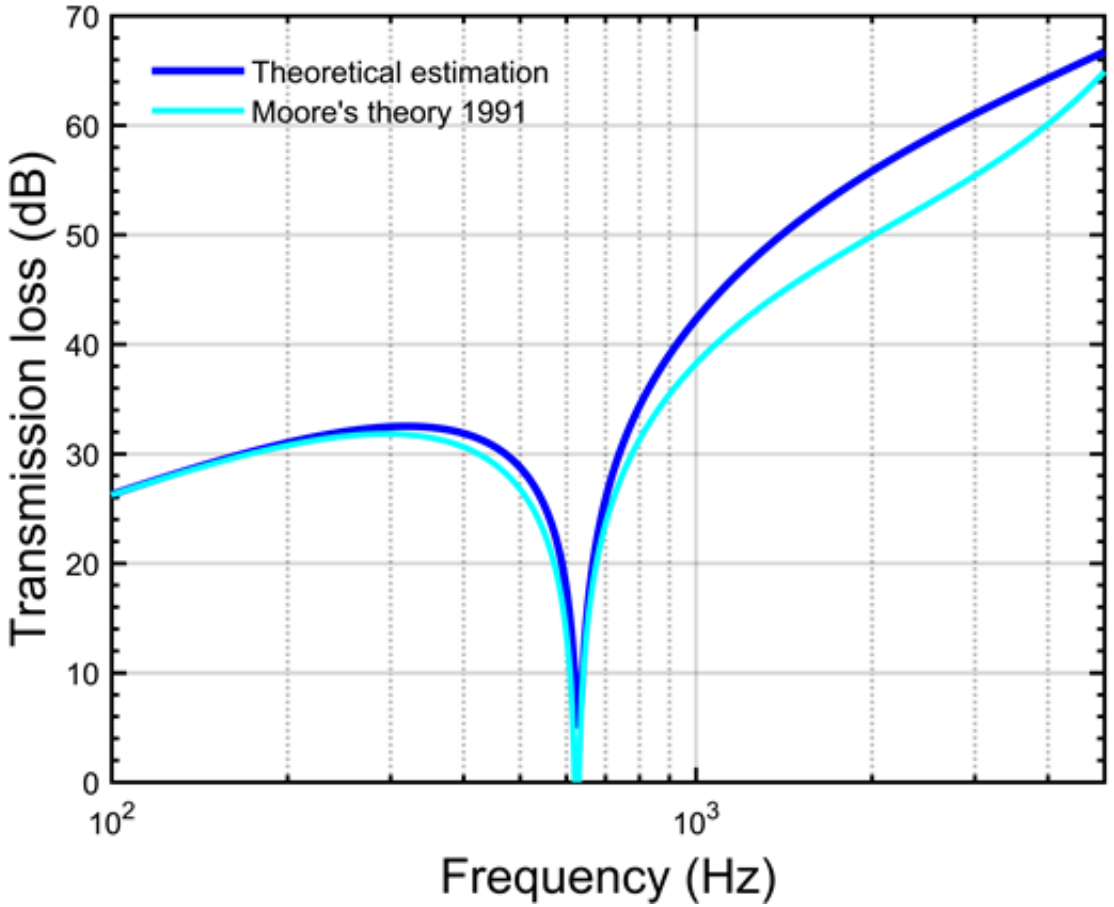


- **Impedance of sandwich:**

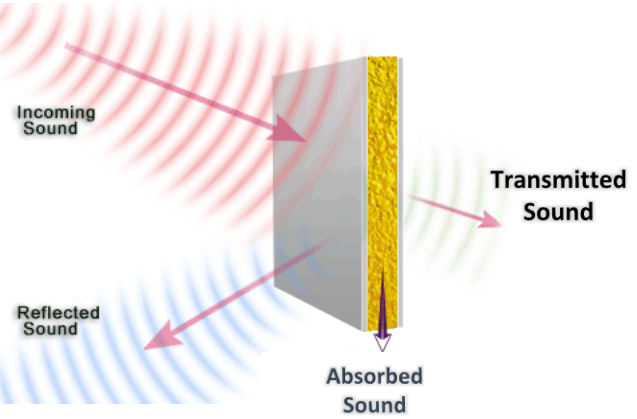
$$Z = \mathrm{j}\omega m\left(1-\frac{f^2}{f_{\mathrm{Sco}}{}^2}\right)$$

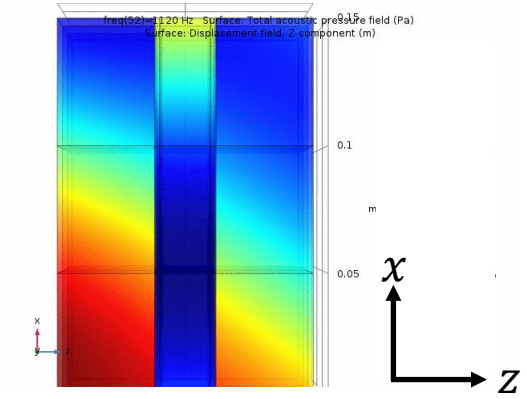
$$\downarrow$$

$$f_{\mathrm{Sco}} = \frac{1}{2\pi}\frac{c_0}{\sin^2\theta}\frac{\kappa_2{}^2}{k}$$



Sound transmission through sandwich panels



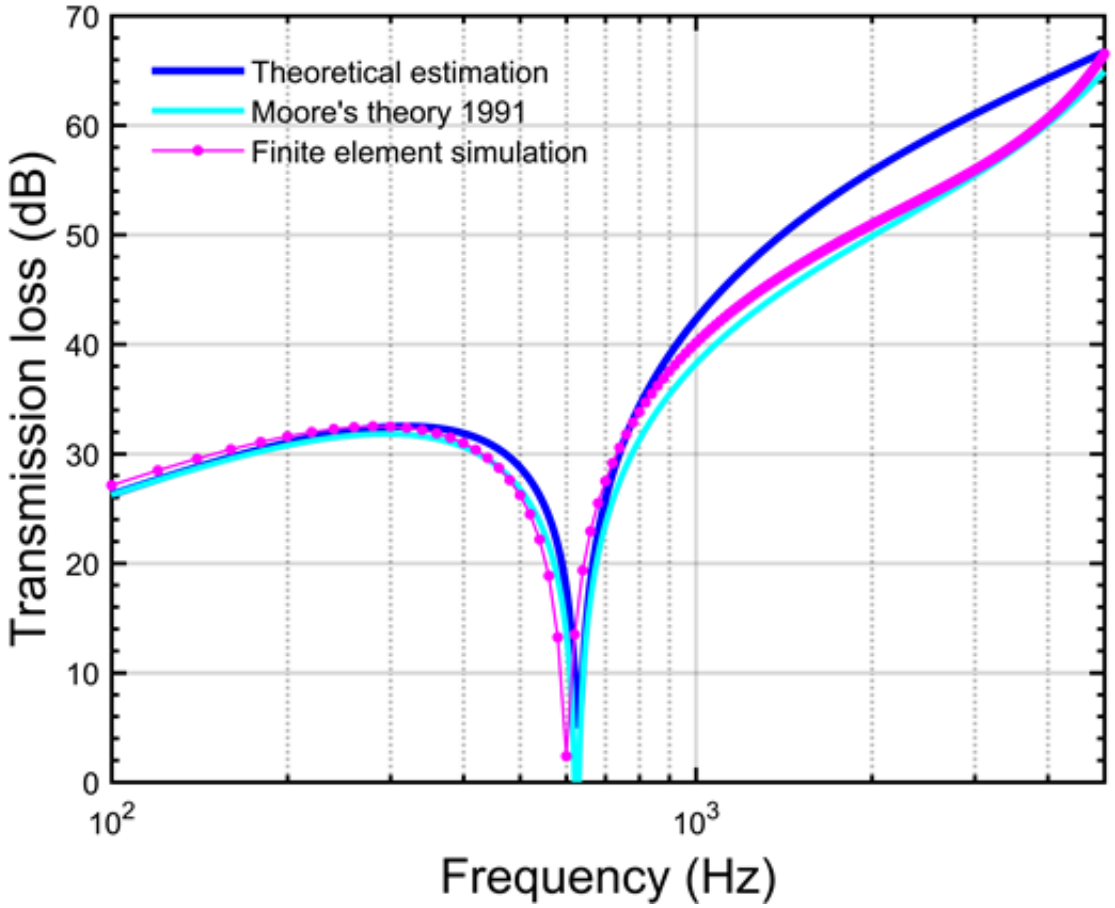


Single-leaf: $$Z = \mathrm{j}\omega m\left(1-\frac{f^2}{f_{\mathrm{co}}{}^2}\right)$$

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

Intention:

- **Integrate the effect of resonators**

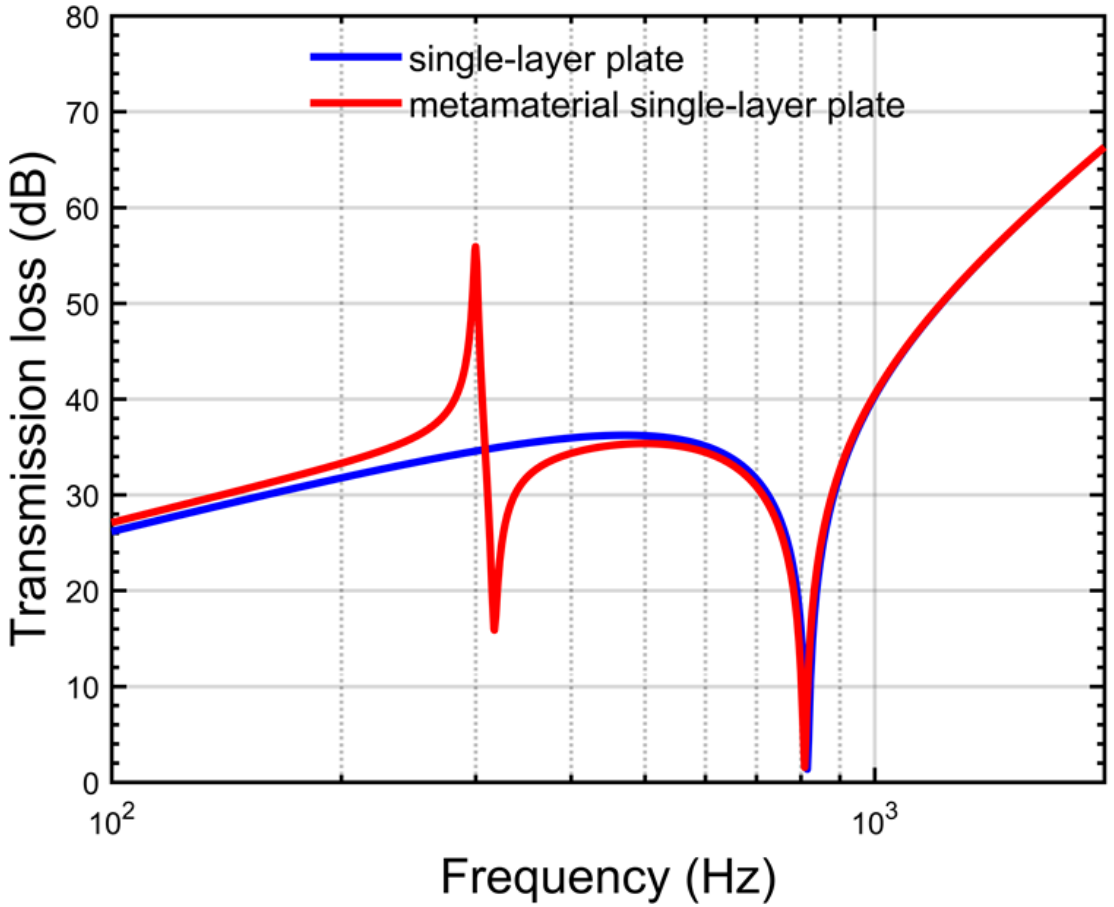


A systematic tuning criterion

Overcome coincidence effect using resonators

A systematic tuning criterion

⟶ **Single-leaf panel**



A systematic tuning criterion

- *Improved STL :* $Z_{\text{eff}} \geq Z$

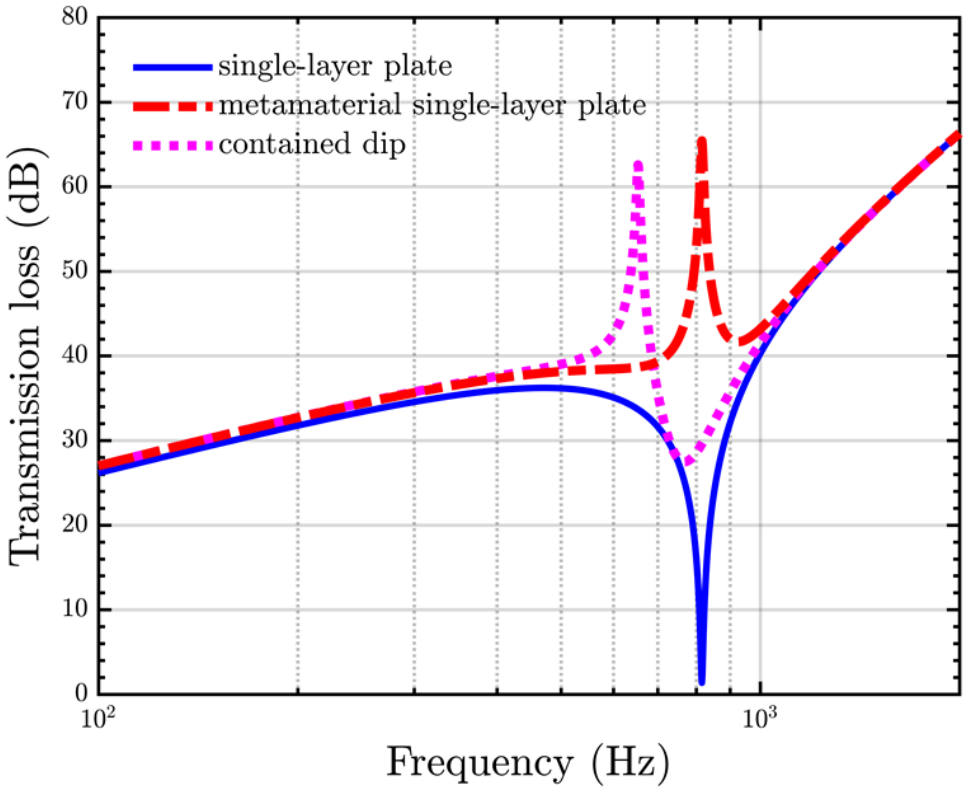
$$Z_{\text{eff}} = Z + Z_{\text{eq}}^{\text{r}}$$

- *Condition:*

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

$$\text{with} \quad \delta = \frac{m_{\text{r}}}{m}$$

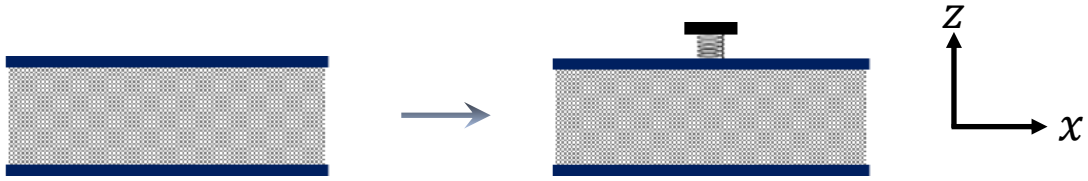
- *Working frequency range:* $\sim \sqrt{\delta}$

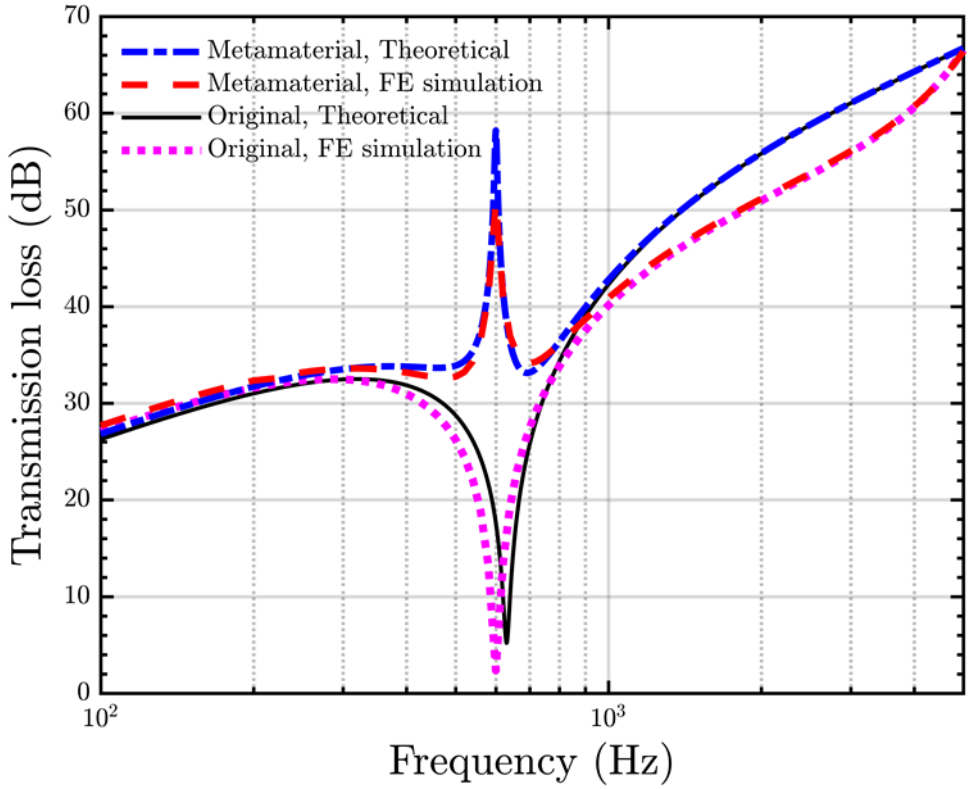


⟶ ***Criterion applicable to the sandwich panel***

Design of metamaterial sandwich

- *Metamaterial sandwich – **surface mounted***



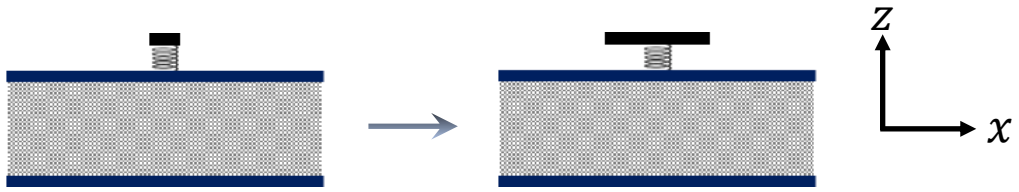


- Sharp improvement of STL at coincidence
- BUT: lower STL for FE simulation

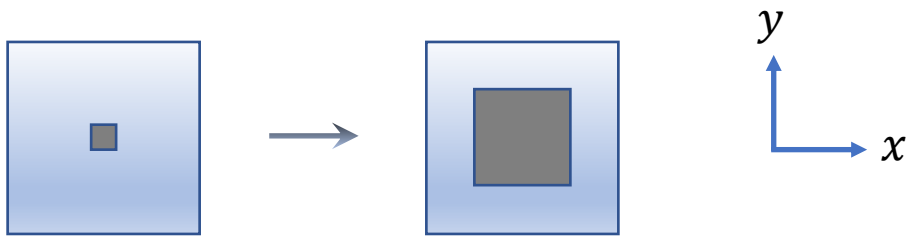
→ ***Radiation from the resonators ?***

Design of metamaterial sandwich

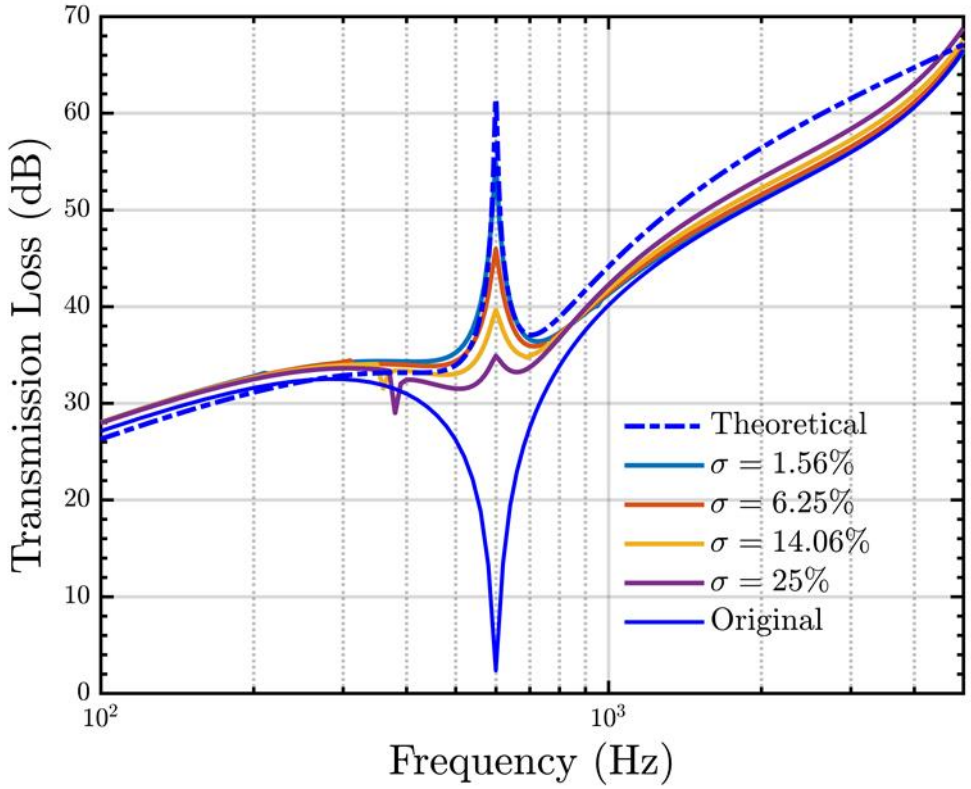
- **Effect of radiation: parametric study**



- ***Surface ratio σ***
- ***Constant mass ratio***



$\sigma = 1.56\%$ $\sigma = 25\%$

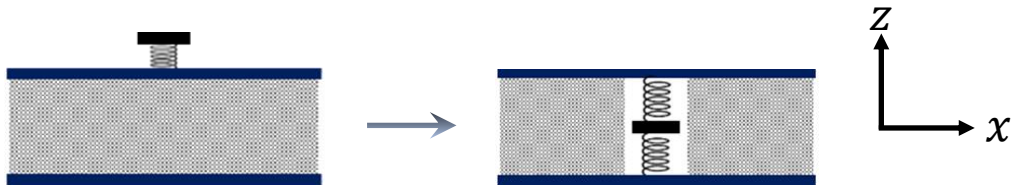


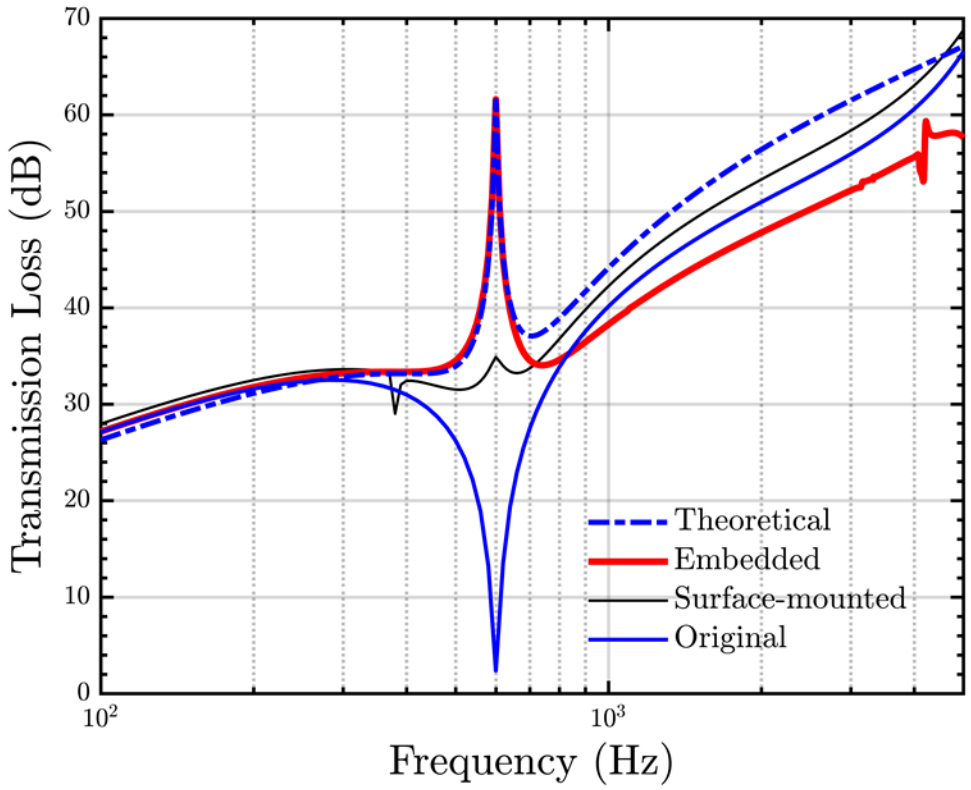
→ ***Radiation from resonators reduces the performance***

Design of metamaterial sandwich

- *Additional drawbacks of the surface mounting*
  - Radiation from the resonators
  - Increased mass
  - Impractical

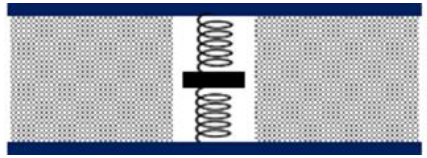
→ ***Proposed design: embedded resonators***





Design of metamaterial sandwich

- ***Embedded resonators***



Advantages:

- Coincidence effect → **Overcome**
- Radiation from resonators → **Suppressed**
- Mass ratio → **Working frequency range**
- Mechanical properties → **Maintained**
- Flat surface → **Functional**

Content

- Introduction
- Methodology
- Coincidence effect
- **Ring frequency problem**
- Curved double walls
- Conclusions

- *Song, Y., Feng, L., **Liu, Z.**, Wen, J., & Yu, D. (2019). Suppression of the vibration and sound radiation of a sandwich plate via periodic design. International Journal of Mechanical Sciences, 150, 744-754.*
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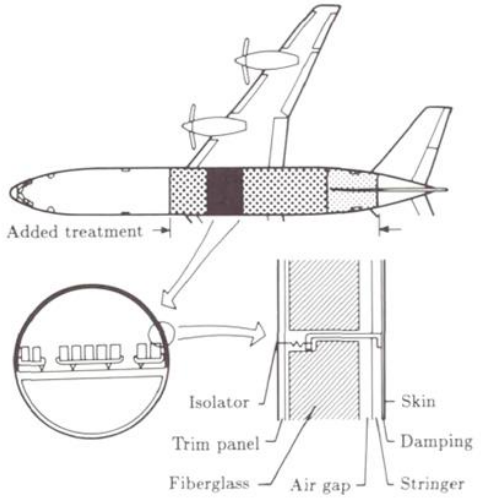
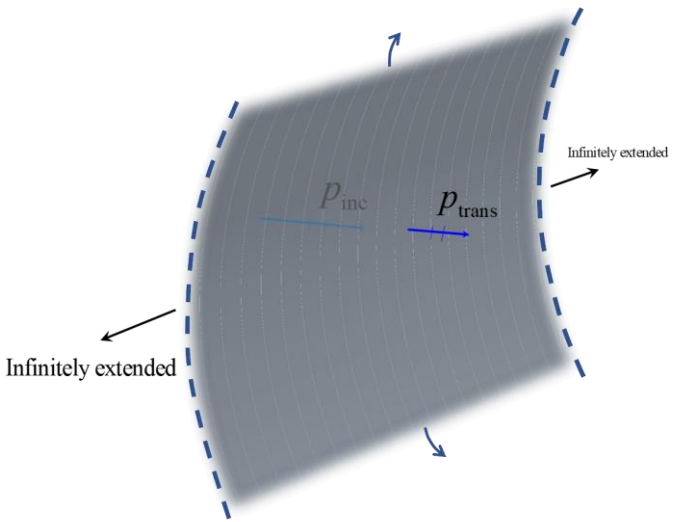
Curved panels





Curved panel:

- Aeronautical/aerospace engineering

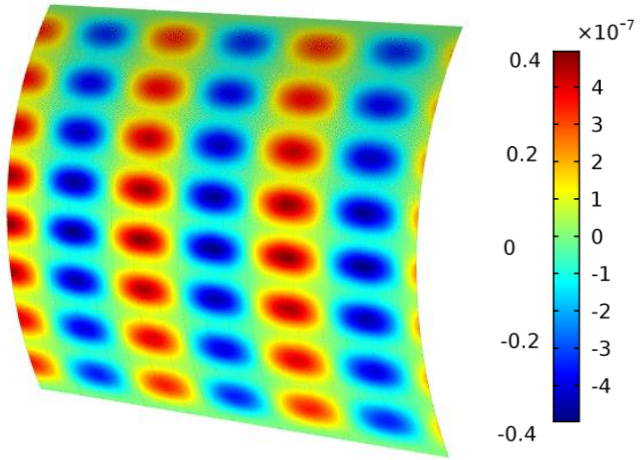
→ **Ring frequency effect**

Sound transmission through curved panels

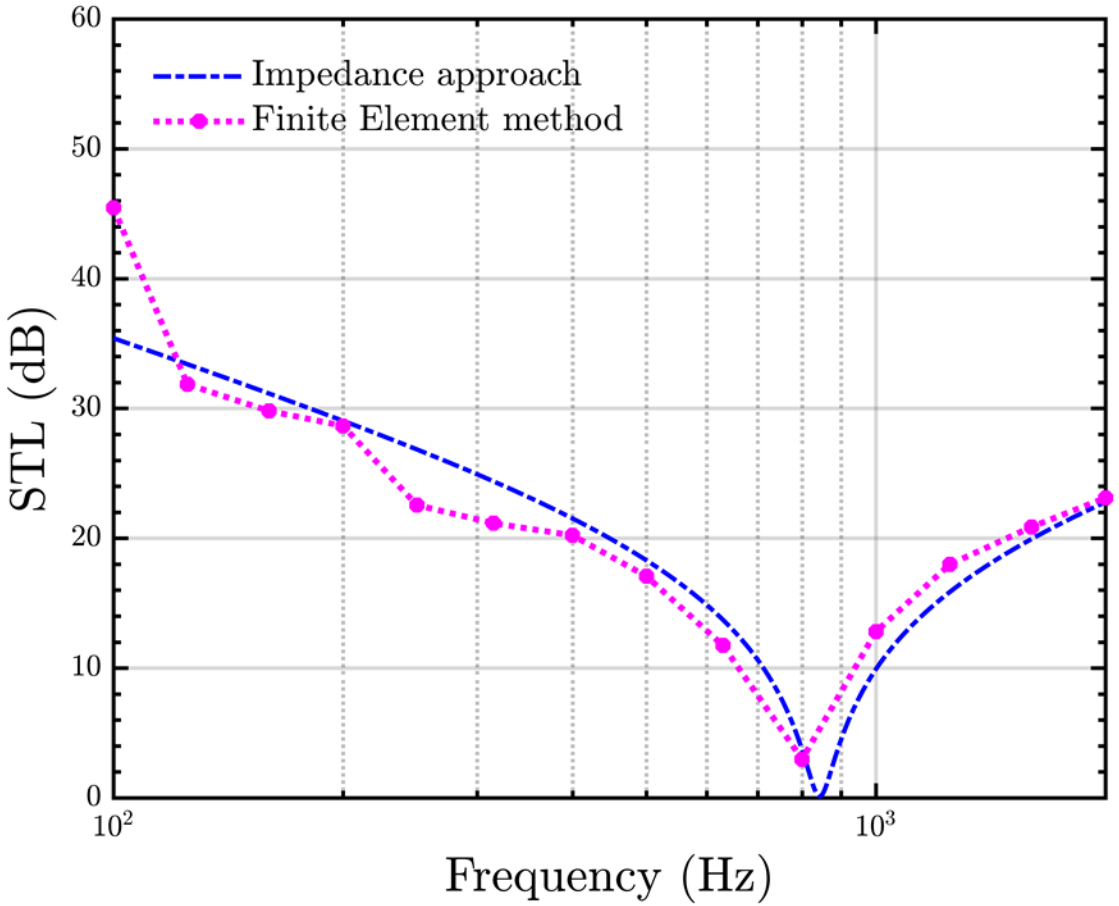
- *Impedance of the shell:*

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

- *Finite Element model: A section of the shell*



Multiple angle of incidence



Sound transmission through curved panels

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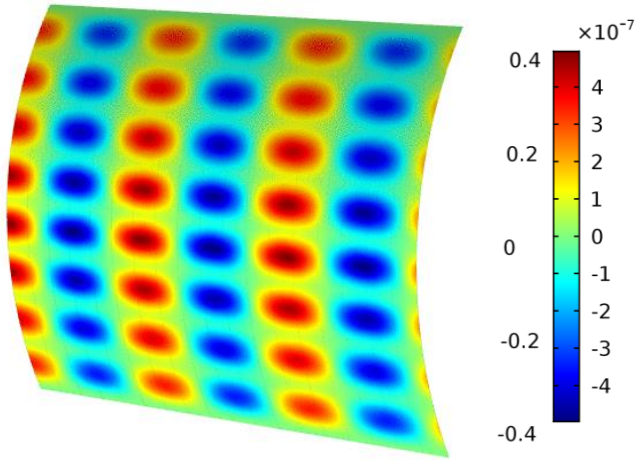
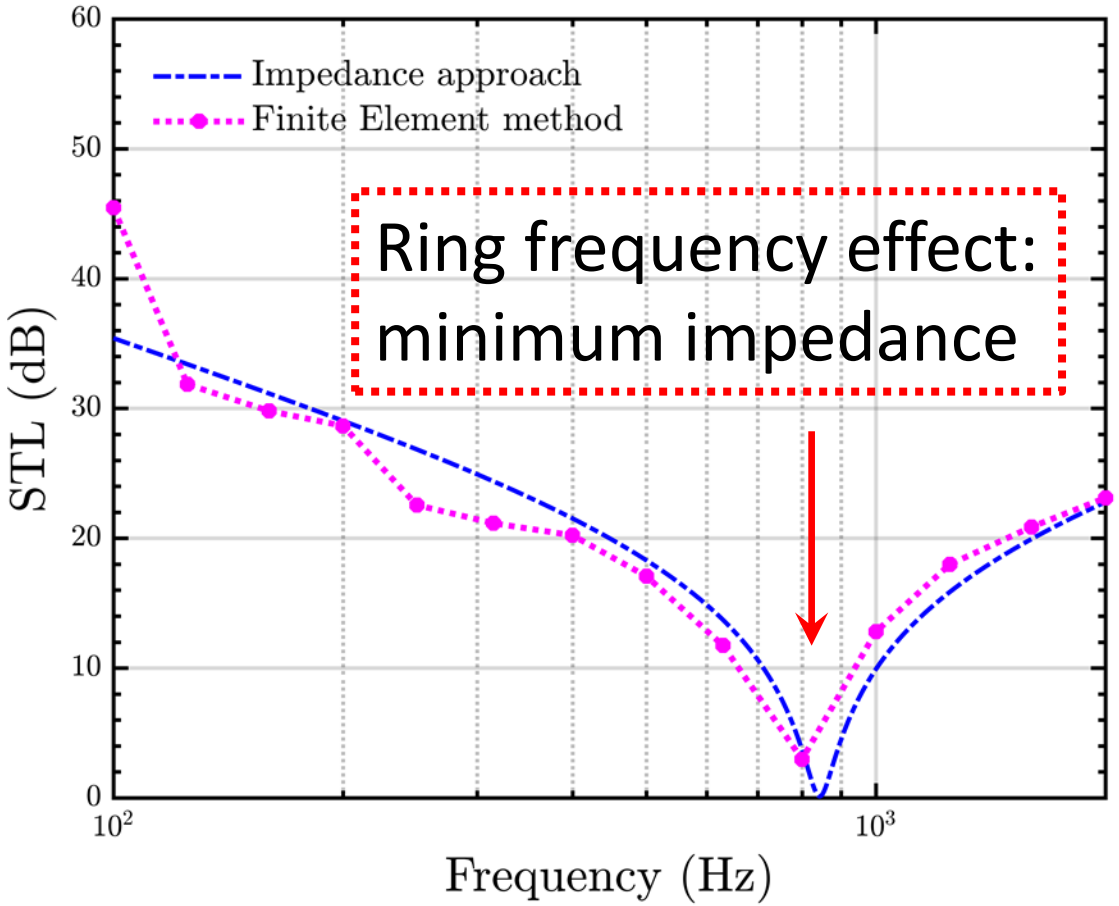
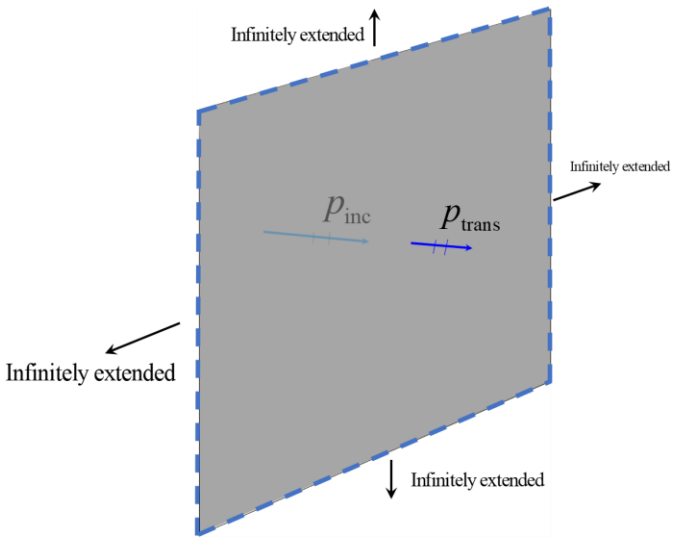


Multiple angle of incidence

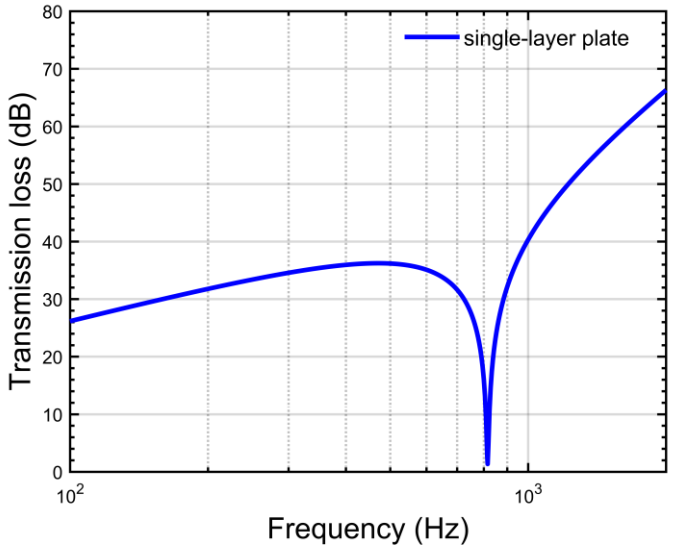


Sound transmission through curved panels

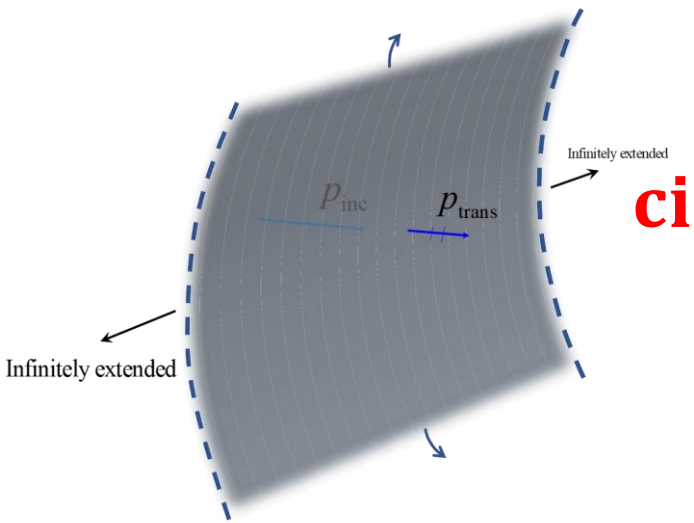


- **Coincidence:**

$$\lambda_{trace} = \lambda_{bending}$$

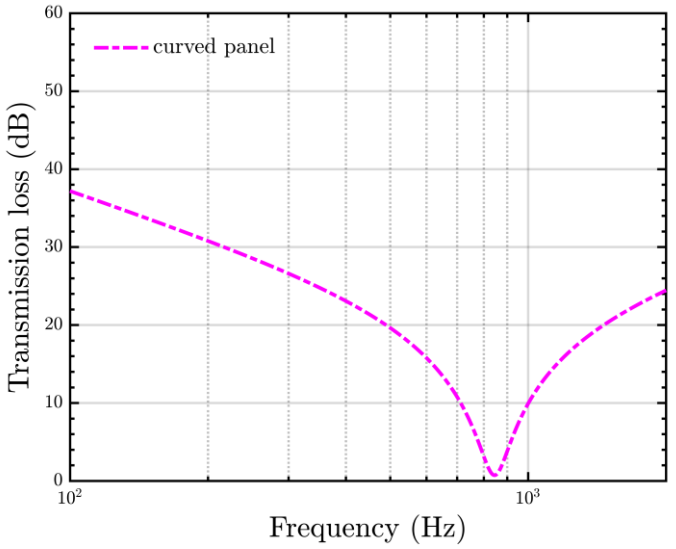


- **Ring:**

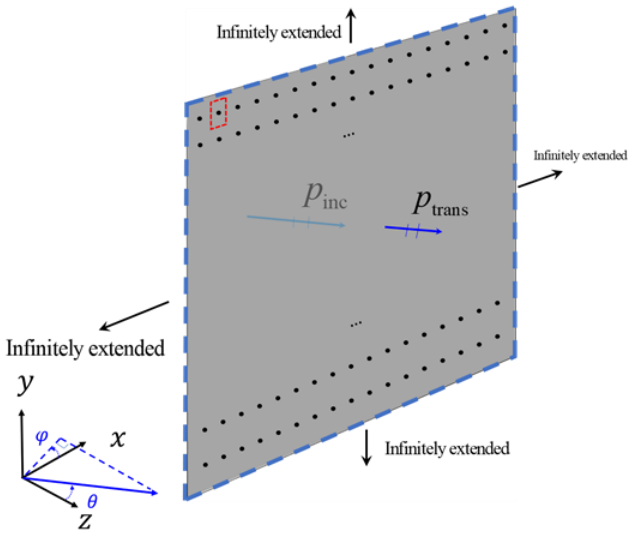


$$\text{circumference} = \lambda_{longitudinal}$$

→ **Resonators ?**



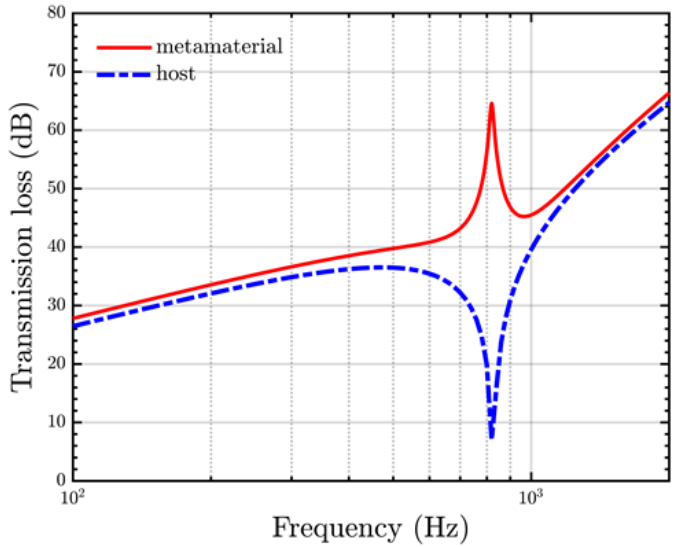
Coincidence effect vs. Ring frequency effect

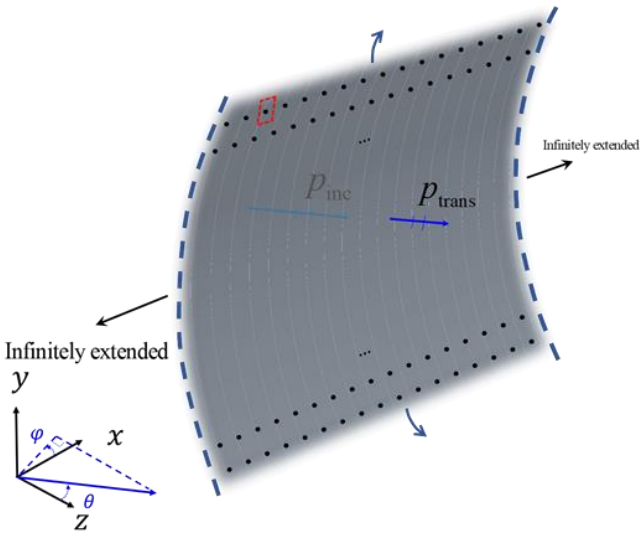


- **Coincidence:**

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

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

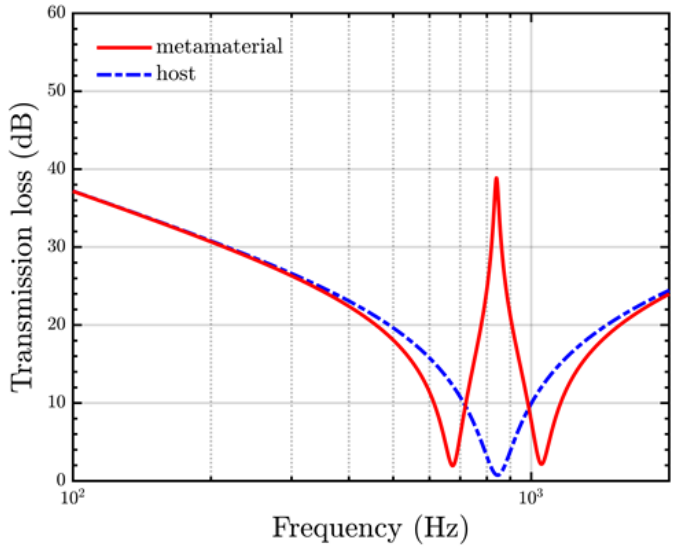




- **Ring:**

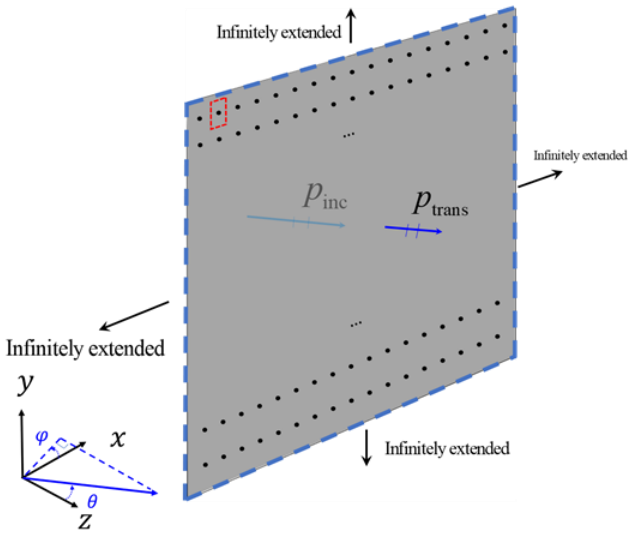
$$Z = \mathrm{j}\omega m\left(1-\frac{f^2}{f_{co}^{\ 2}}-\frac{f_{ri}^{\ 2}}{f^2}\right)$$

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



- ***'Side effects'***

Coincidence effect vs. Ring frequency effect



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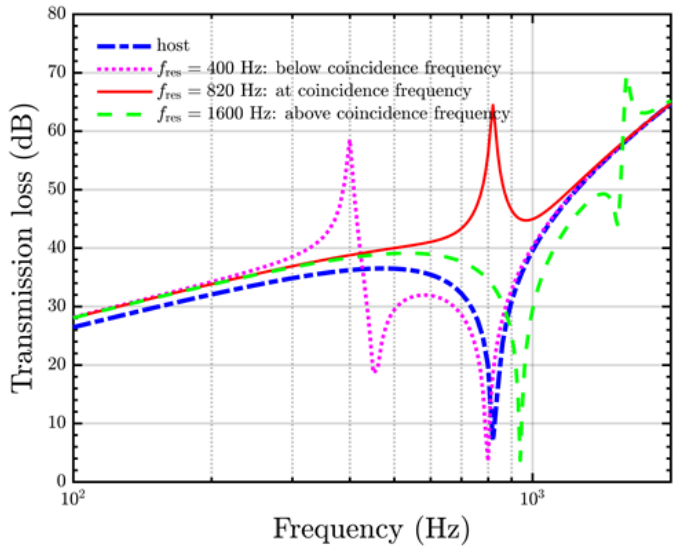

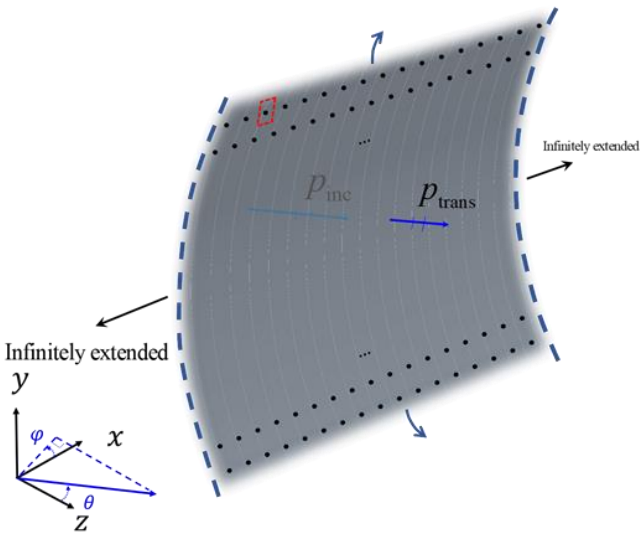

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$$Z = \mathrm{j}\omega m\left(1-\frac{f^2}{f_{co}^{\ 2}}-\frac{f_{ri}^{\ 2}}{f^2}\right)$$

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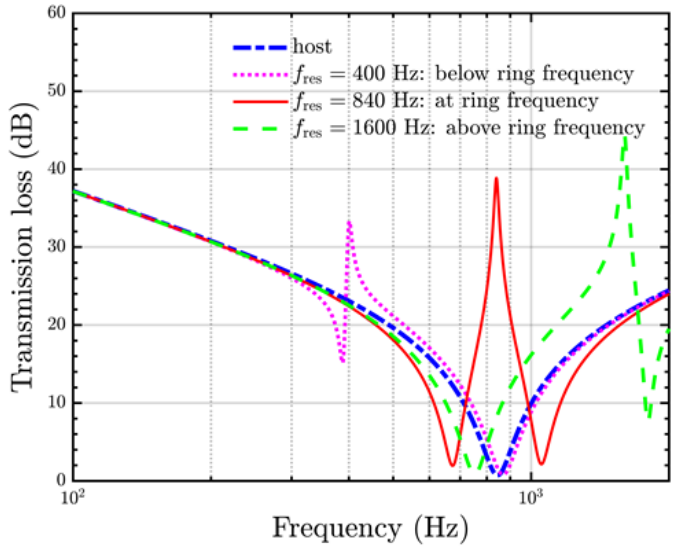
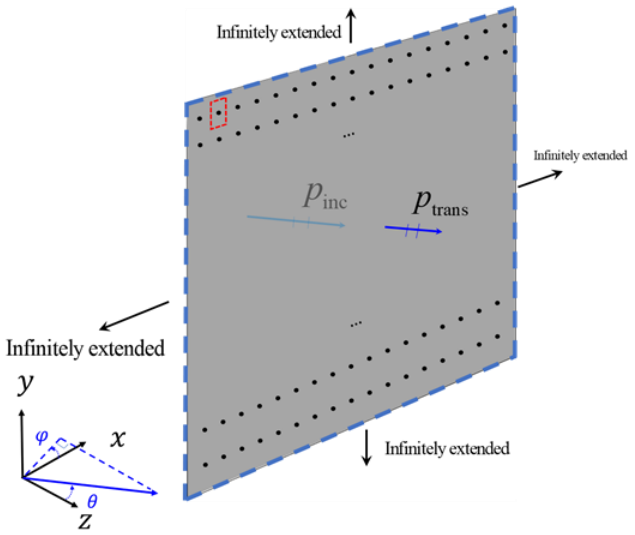
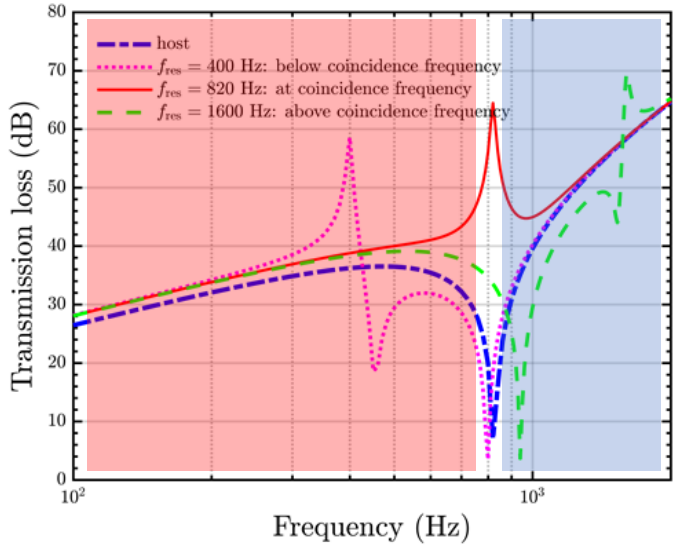


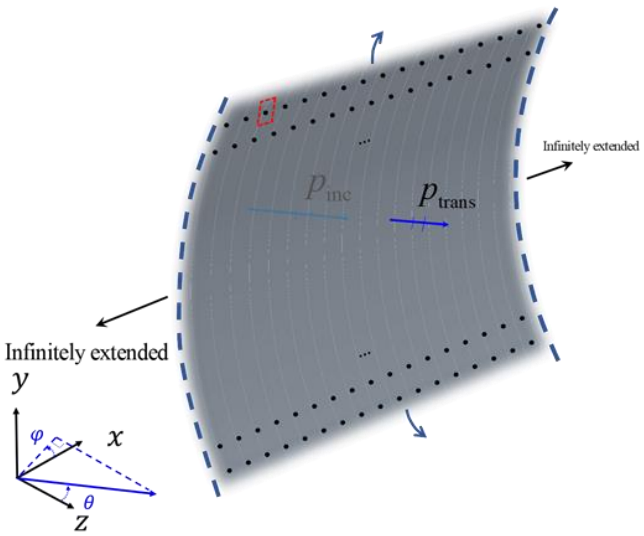
- ***'Side effects'***

Analysis from an impedance point of view

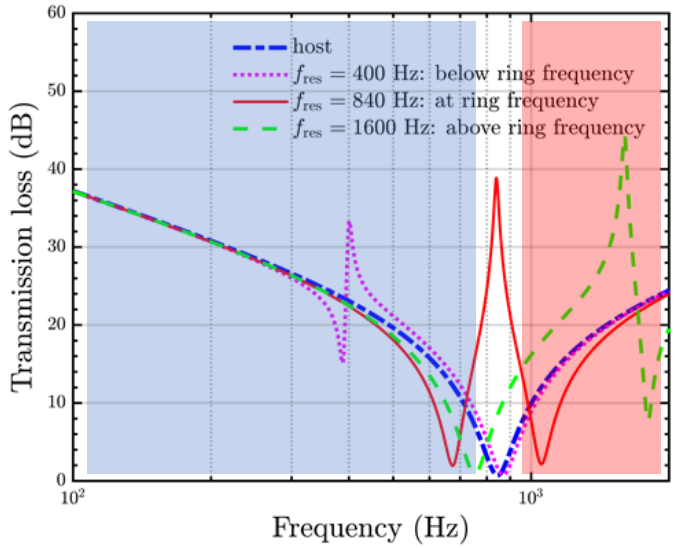


- **Coincidence:**
  - ***Mass-controlled* to *Stiffness-controlled***

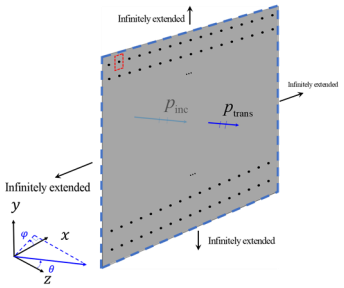




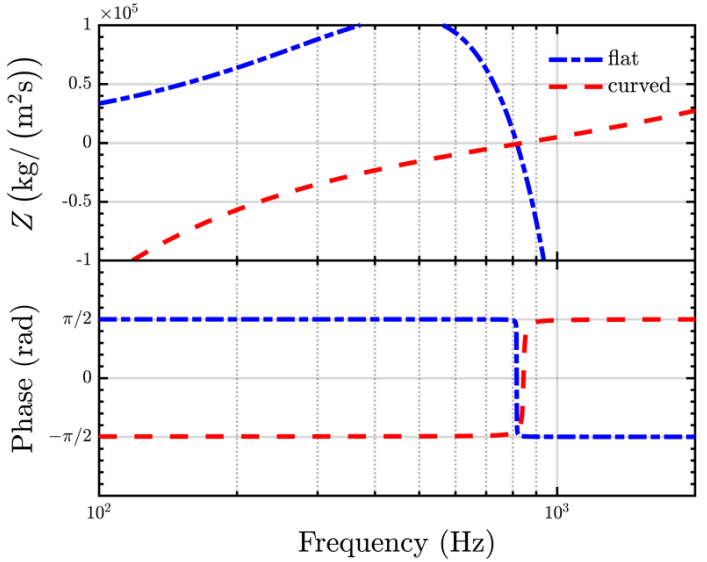
- **Ring:**
  - ***Stiffness-controlled* to *Mass-controlled***

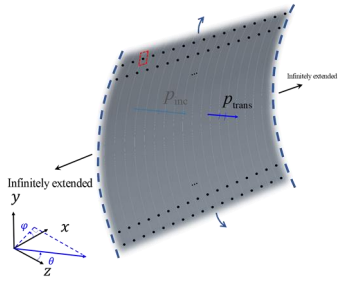


Analysis from an impedance point of view



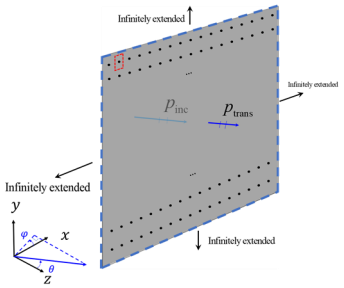
- ***Mass-controlled** to **Stiffness-controlled***





- ***Stiffness-controlled** to **Mass-controlled***

Analysis from an impedance point of view



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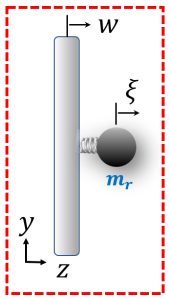
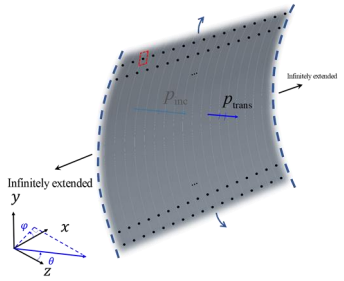
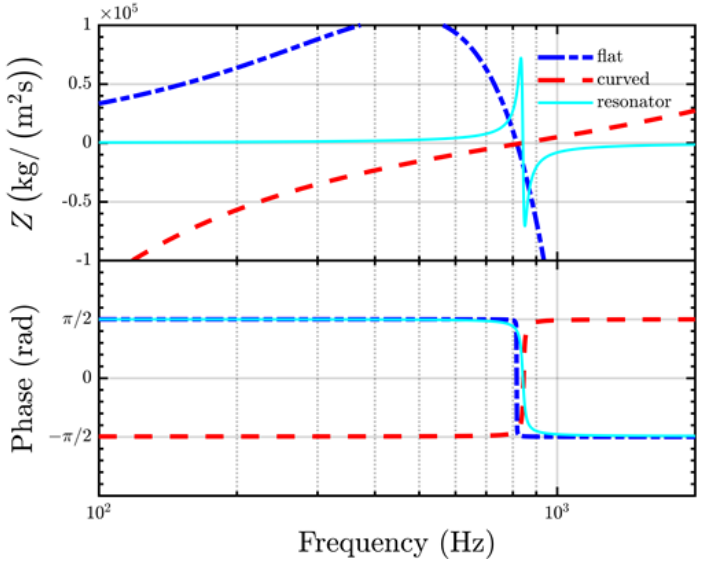


- ***Mass-controlled*** **to** ***Stiffness-controlled***



- ***Stiffness-controlled*** **to** ***Mass-controlled***



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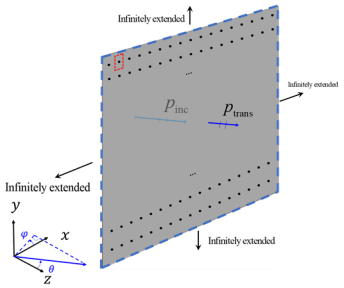

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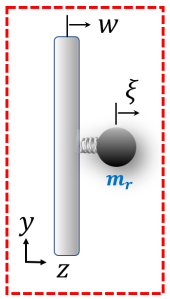

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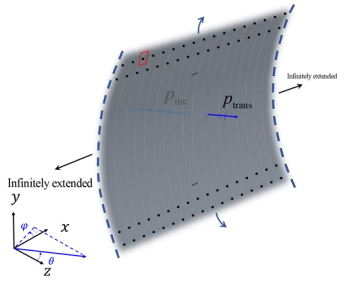
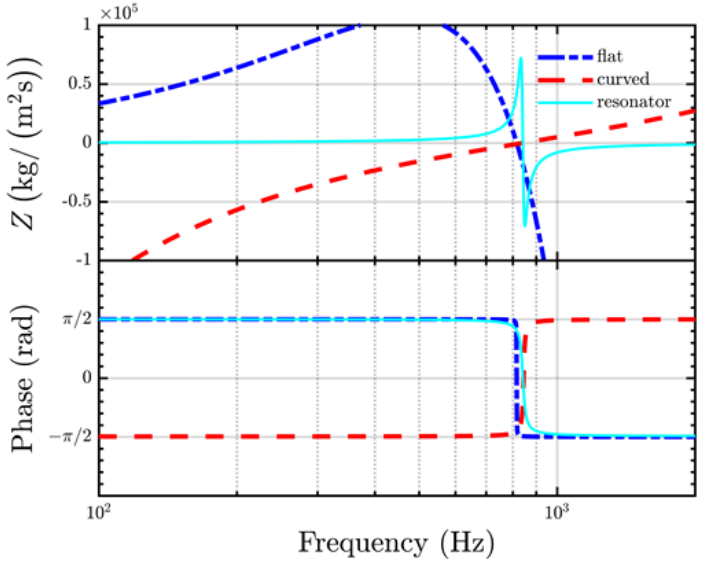
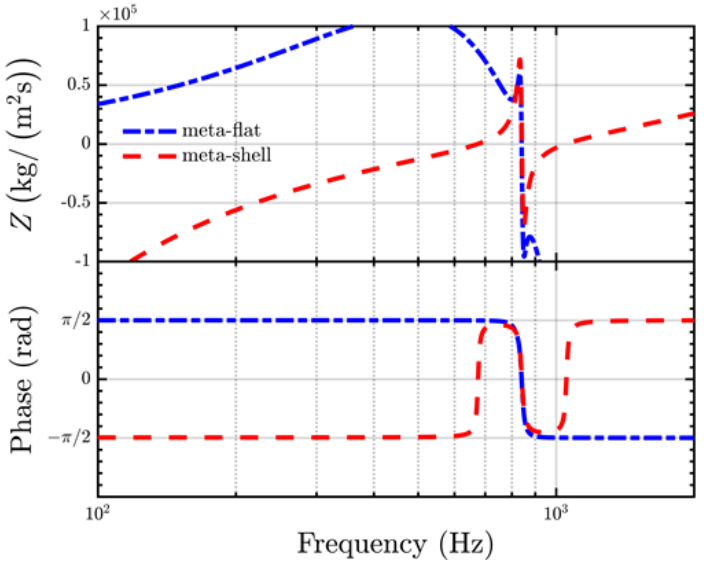


- ***Stiffness-controlled** to **Mass-controlled***

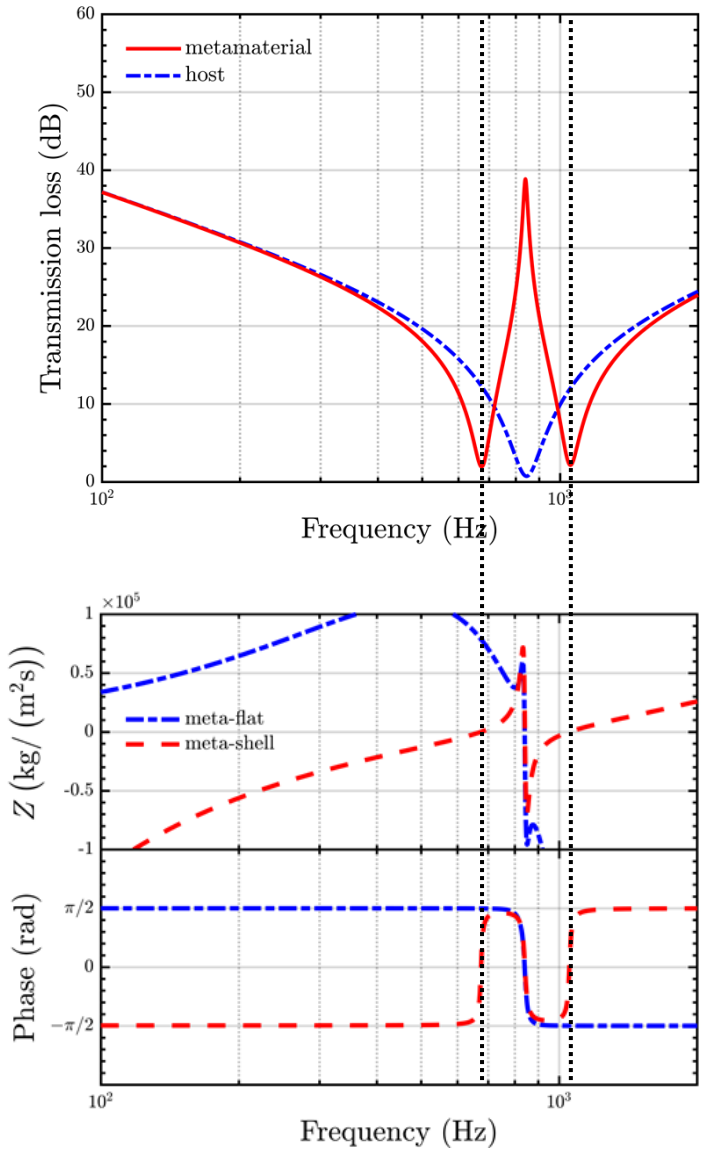




Analysis from an impedance point of view

Z	Resonators	Flat panel	Shell
Below freq. of interest	+	+	-
Above freq. of interest	-	-	+

- ***Conventional mass-spring resonators*** ☹
- ***Perspective resonators: phase change*** ☺



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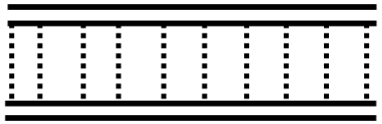
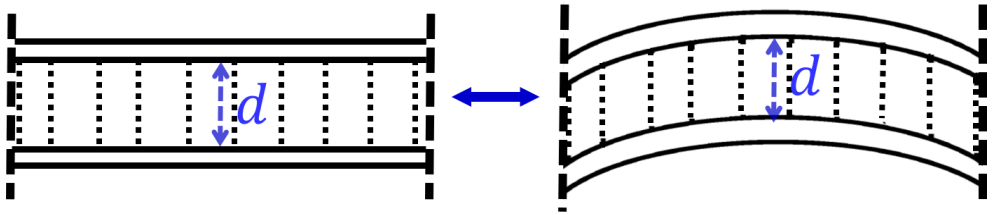
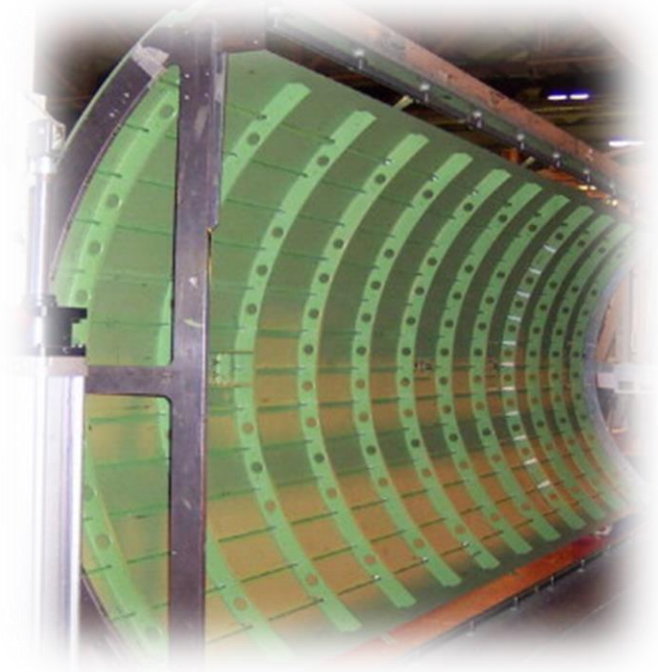
Motivation

- **Double wall:** 
  - Double-wall resonance
- **Curved double walls**



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

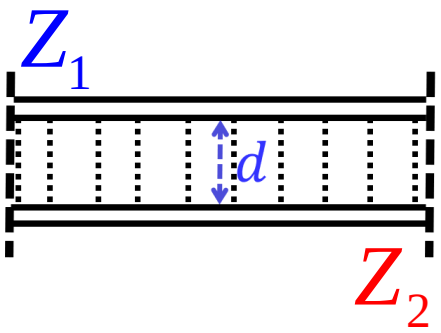
Side wall of an aircraft fuselage



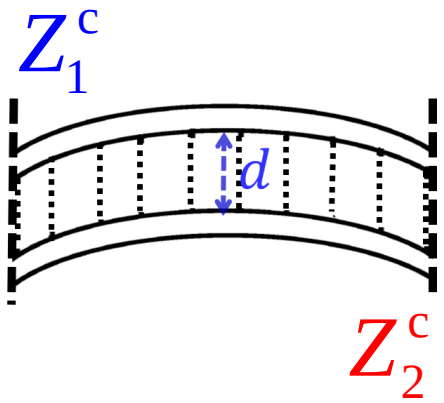
➡ *More Critical*

'Apparent' impedance approach

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



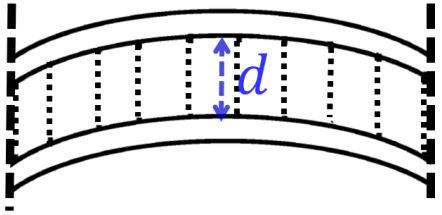
$$Z^{\mathrm{d}} = Z_1 + Z_2 + \frac{\mathrm{j}\omega}{s}\left(Z_1 + Z_a\right)\left(Z_2 + Z_a\right)$$



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

'Apparent' impedance approach

- **Estimation of characteristic frequencies:**



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

- **'Apparent' impedance → Minimum**

- ***Two curved panels, same ring frequency***

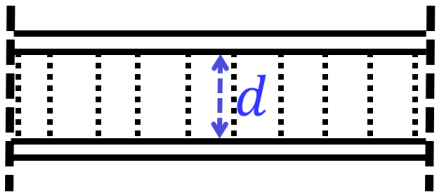
$$f_1^{\mathrm{cd}} = f_{\mathrm{ri}}$$

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

with

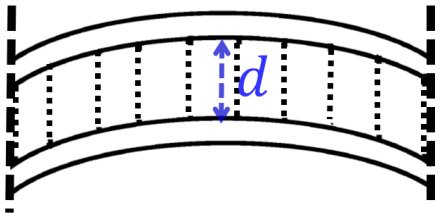
$$f_{\mathrm{msm}}^{\mathrm{d}} = \frac{1}{2\pi}\sqrt{s\left(\frac{1}{m_1} + \frac{1}{m_2}\right)}$$

→



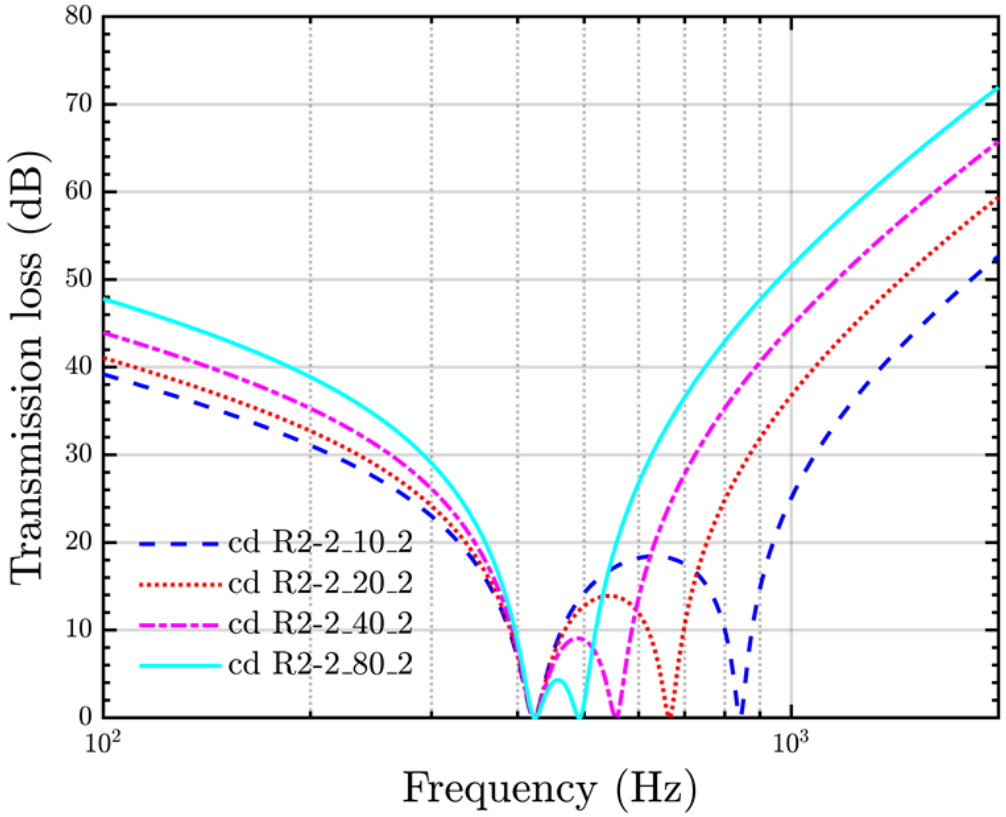
Characteristic frequencies

- **Estimation of characteristic frequencies:**



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

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



Design approach

- **Curved double walls → Broad 'valley' → can be narrowed**
- **Metamaterials → Limited working frequency range**
- ***Design method***

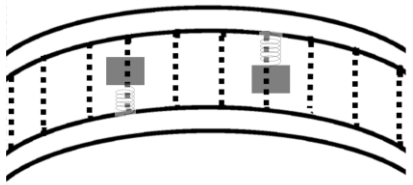
    1. *Narrow the 'valley'*
    2. *Mount tuned resonators*

Design approach

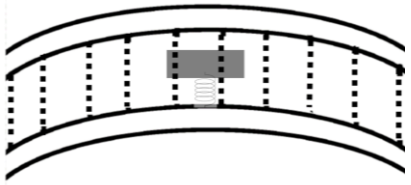
- ***Design approach***

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

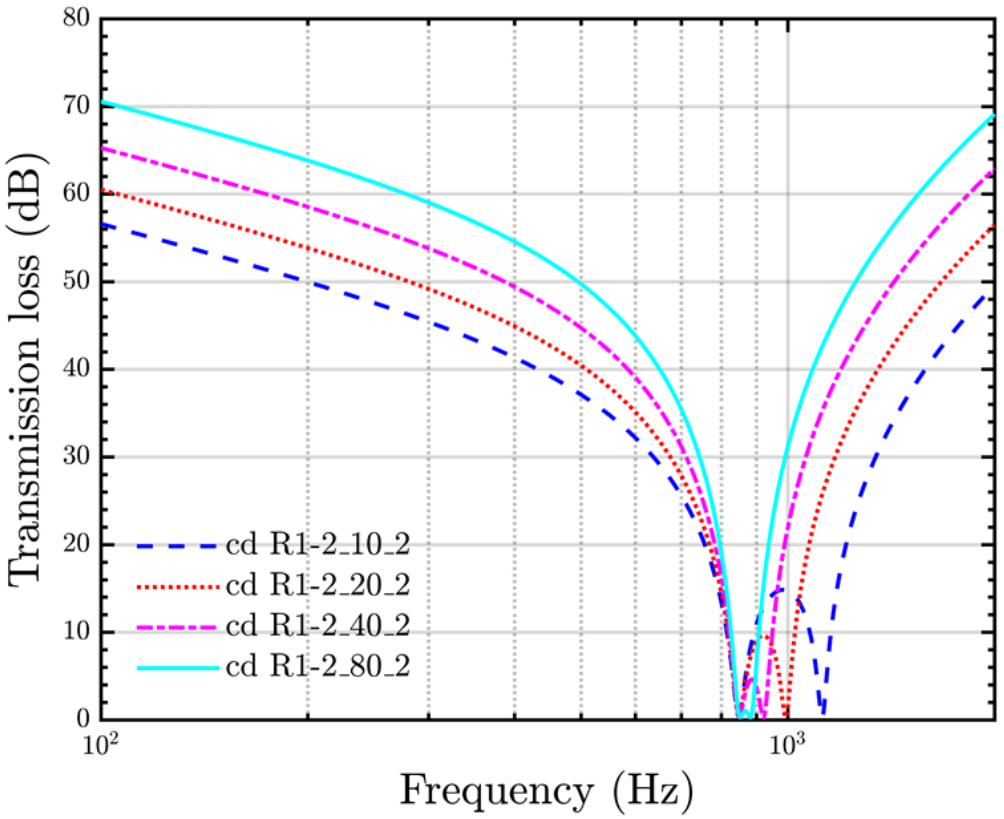
1. ***Resonators on both panels***



2. ***Resonators on one panel***

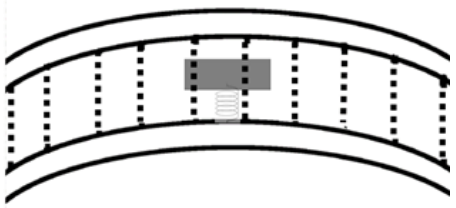


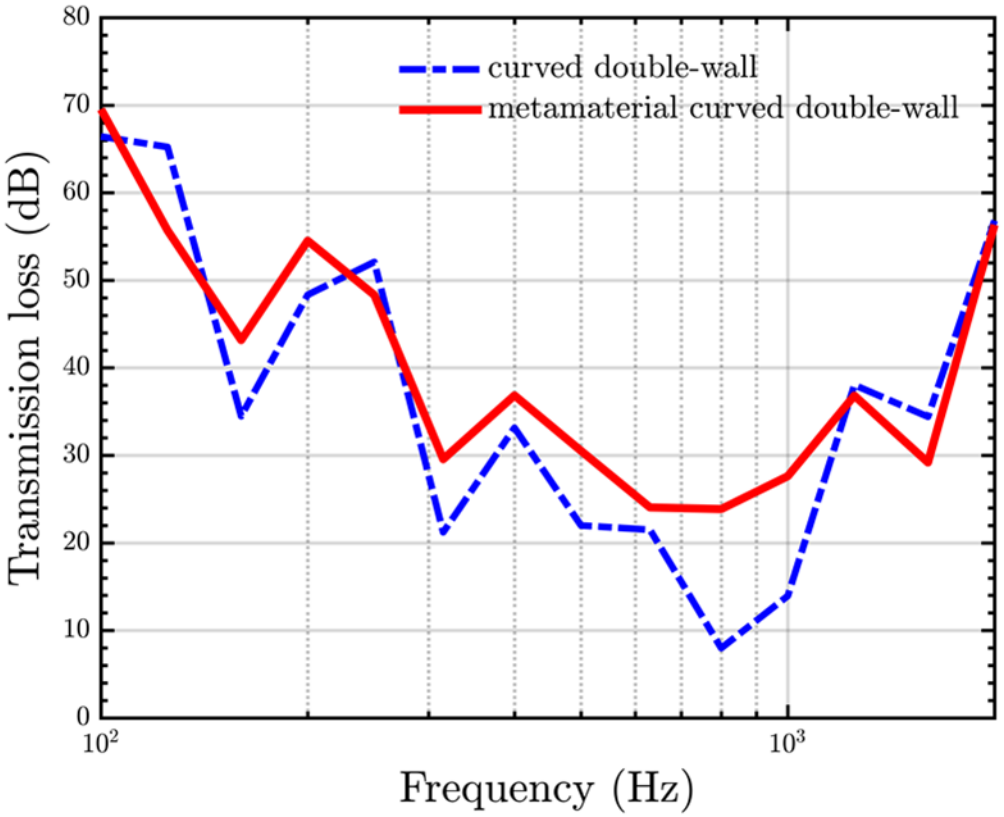
The total added mass is kept constant



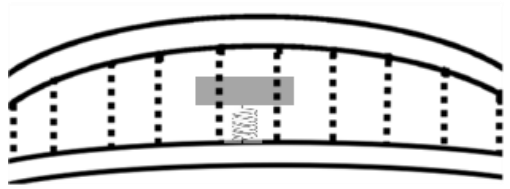
Metamaterial curved double wall

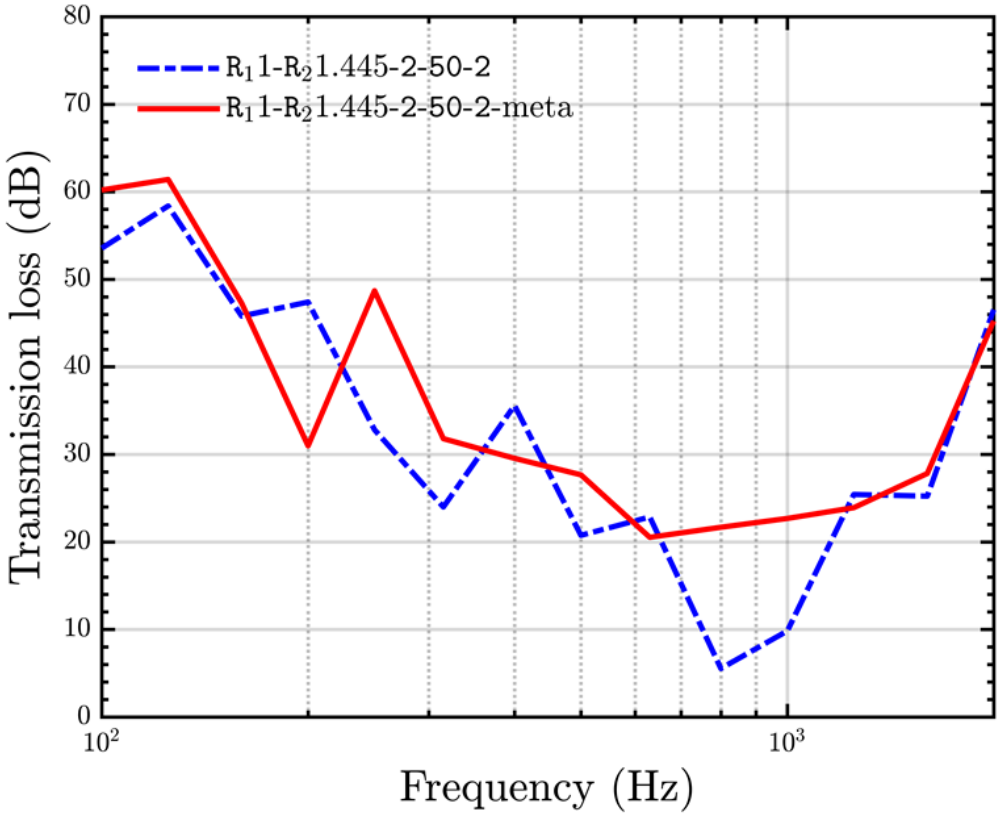
Identical:



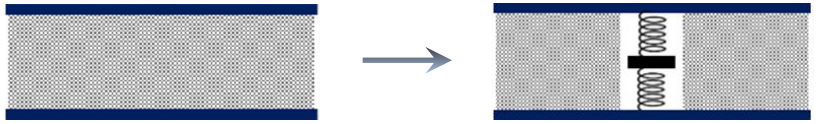
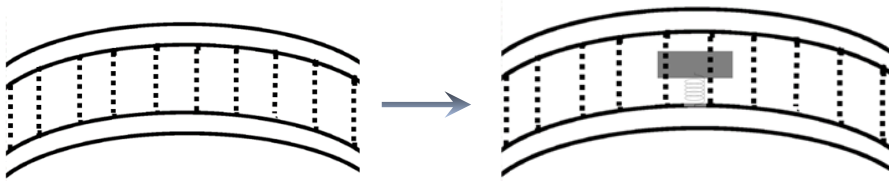


Non-identical:





Concluding remarks

- Sandwich: 
- Curved:  → Explanation
- Curved double wall: 

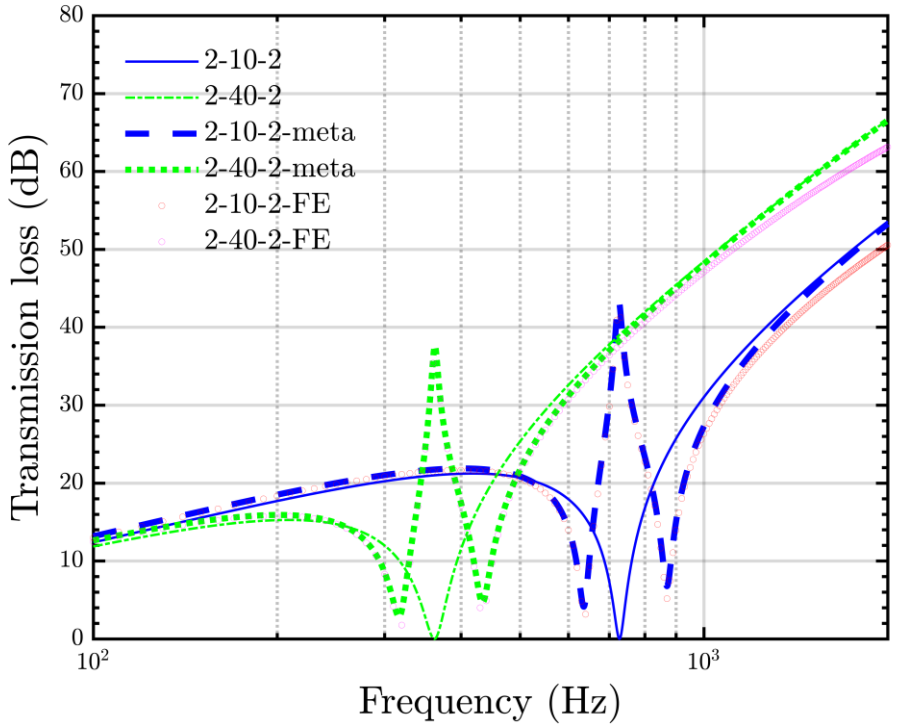
Coincidence

Ring frequency

Double-wall resonance

Future work

- Ring frequency
- Double wall resonance
- Experimental validation



Thank you for your attention!