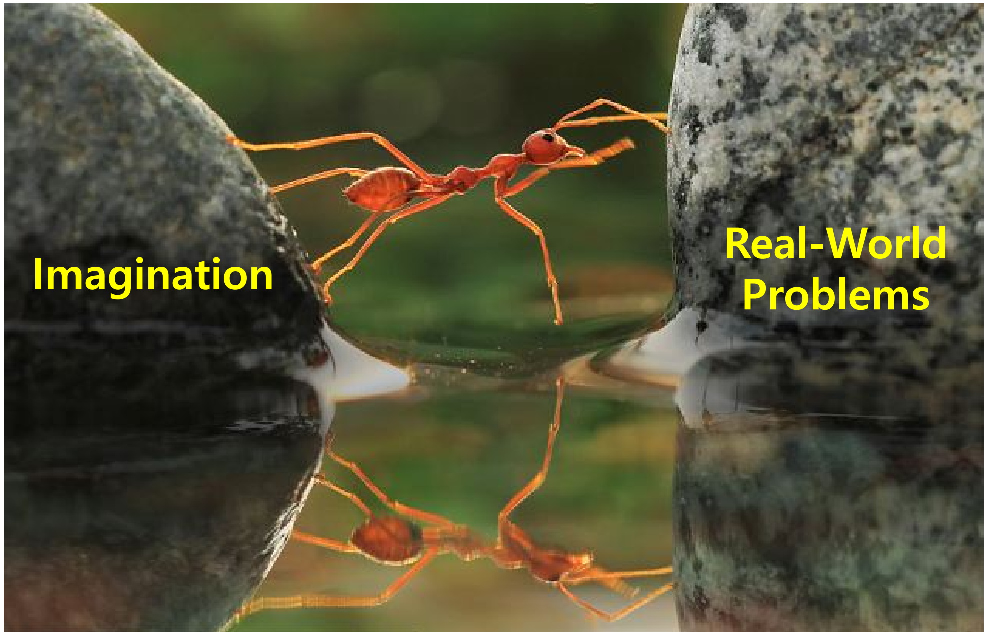
Acoustic Metamaterials and Metasurfaces: Effect of Flow and Visco-thermal Losses



23rd CEAS-ASC Workshop

(26 Sep 2019 / Roma Tre University, Italy)

Wonju Jeon

WAVE LAB, Department of Mechanical Engineering,

Korea Advanced Institute of Science and Technology (KAIST)

Ice Breaking

7 min

(1) Where I come from

(2) Who I am

(3) Research in WAVE LAB

Main Talk

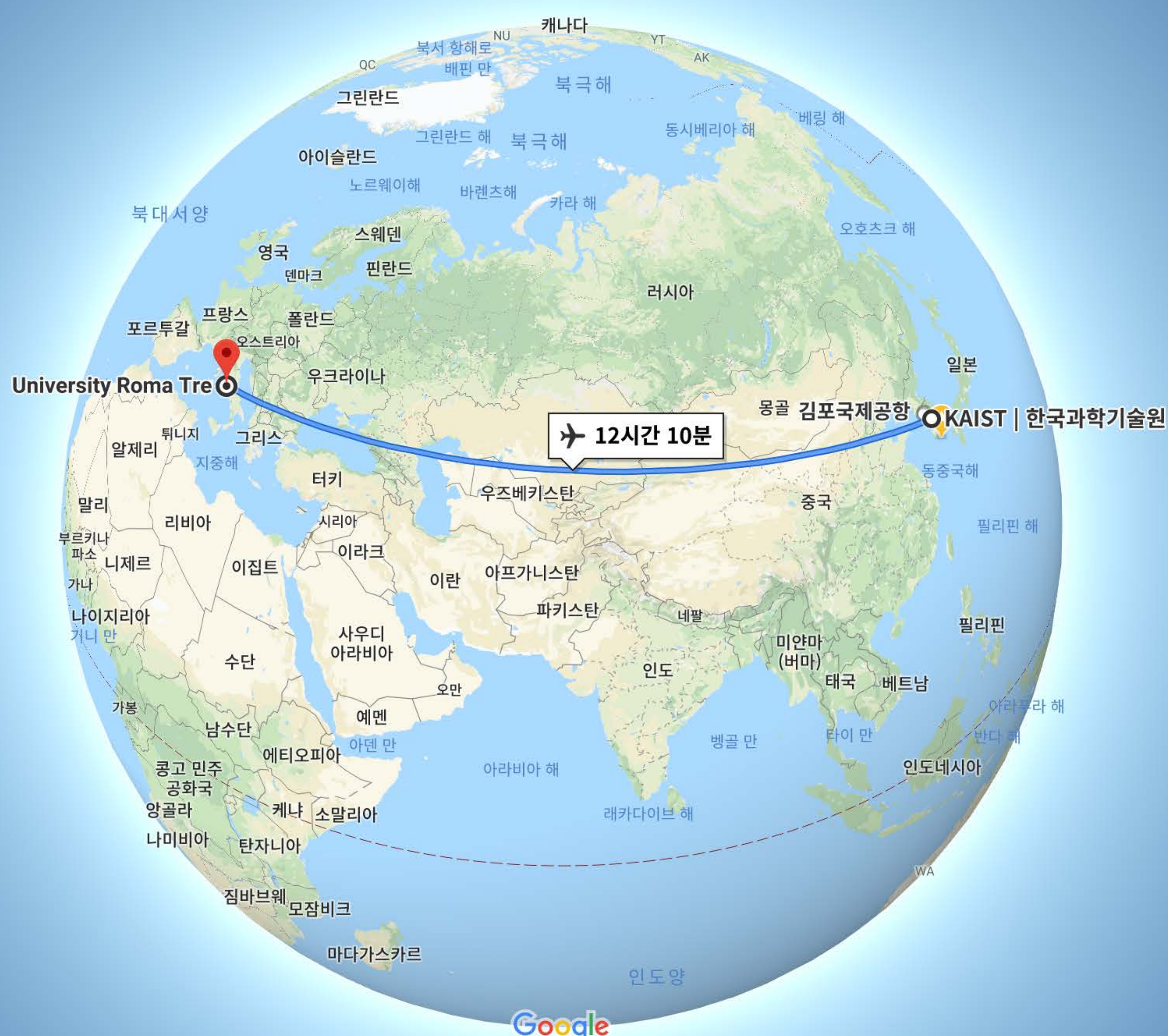
33 min

(1) Acoustic Cloak in Compressible Non-uniform Flow

(2) Perfectly Sound-Absorbing Metasurfaces

(3) A Few Words on Acoustic Black Holes

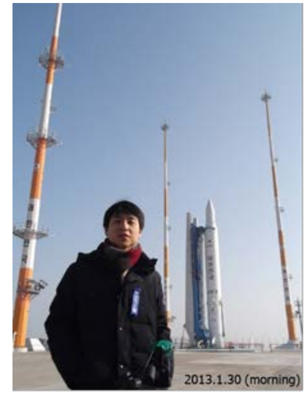
Ice-Breaking (Where I come from & Who I am)

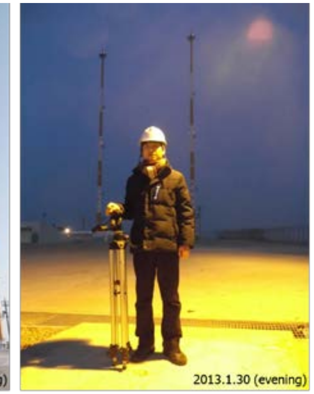


Ice-Breaking (Where I come from & Who I am)

BS, MS, PhD ('06)

AE KAIST



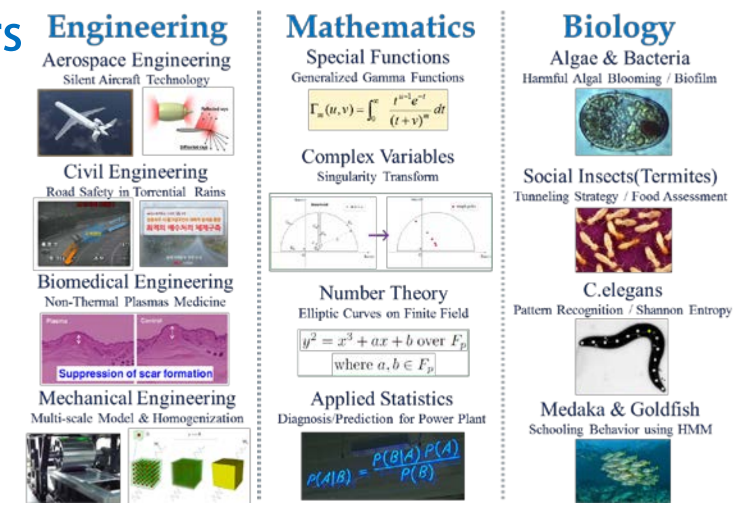


~2014: Multiple-Edge Diffraction in Flow & Others

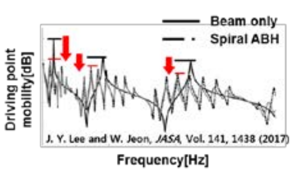
NIMS
National Institute
for Mathematical Sciences

H. Poincaré
(paper in 1895)

A. Sommerfeld
(paper in 1896)

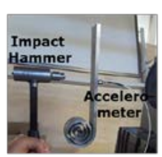


2014~present: KAIST Department of Mechanical Engineering

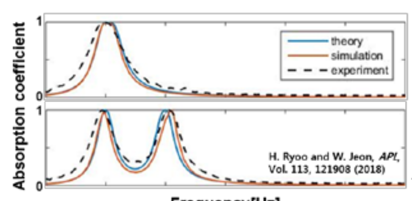


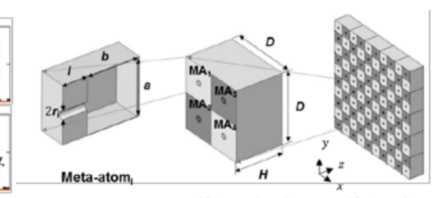
Vibration suppression by spiral ABH

Manufactured spiral ABH



Experimental setup
(impact hammer test)



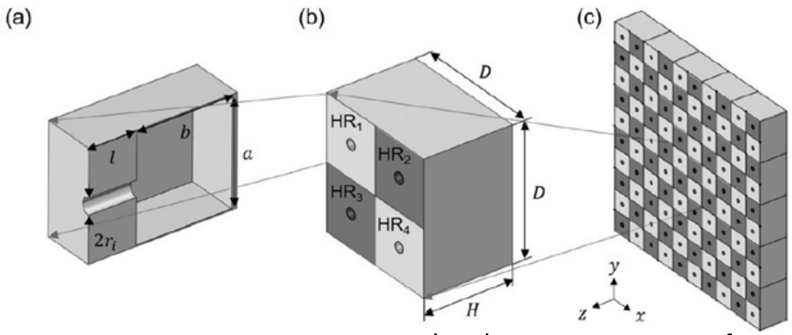


Waves are everywhere. Thanks to waves, we can **see**, we can **hear**, and we can **feel**.

Mechanical Meta-Structure Research in WAVE LAB

1. Acoustic Meta-Surfaces

(1) Perfect absorption of multi-frequency sound
(2) Hybrid resonance with visco-thermal losses

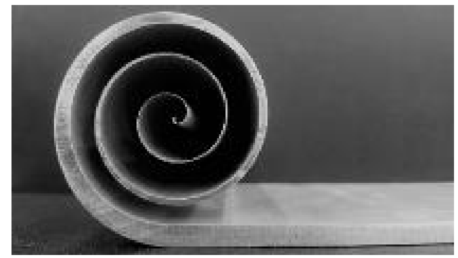


meta-atom meta-molecule meta-surface

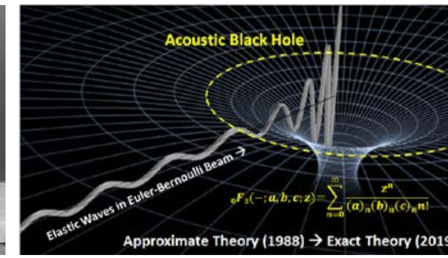
H. Ryoo and W. Jeon*, *J. Appl. Phys.*, **123**, 115110 (2018)
H. Ryoo and W. Jeon*, *Appl. Phys. Lett.*, **113**, 121903 (2018)

2. Acoustic Black Holes

(1) Spiral acoustic black hole for wave absorption
(2) Mathematical theory for acoustic black hole



Spiral Acoustic Black Hole

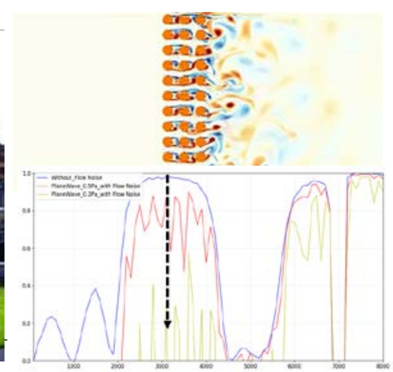


Exact Theory for ABH

J.Y. Lee and W. Jeon*, *JASA*, **141**, 1437-1445 (2017)
J.Y. Lee and W. Jeon*, *JSV*, **452**, 191-204 (2019)
S. Park, M. Kim and W. Jeon*, *JSV*, online published (2019)

3. Acoustic Cloak & Phononic Crystals

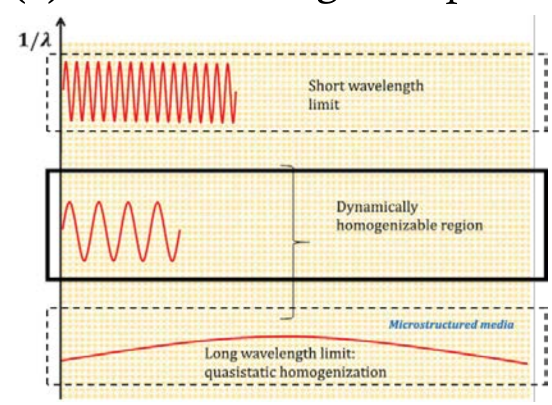
(1) Cloak within compressible non-uniform flow
(2) Theoretical explanation on bandgap quenching

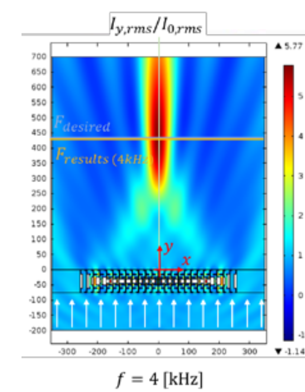


H. Ryoo and W. Jeon*, *Sci. Rep.*, **7**, 2125 (2017)

4. Dynamic Homogenization & Meta-lens

(1) Homogenization beyond the long-λ limit
(2) Sub-λ focusing & Impedance matching





K.Y. Lee and W. Jeon*, *J Appl. Phys.*, **124**, 175103 (2018)

Ice Melted

7 min

(1) Where I come from

(2) Who I am

(3) Research in WAVE LAB

Main Talk

33 min

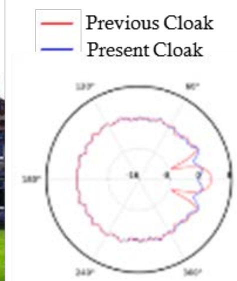
(1) Acoustic Cloak in Compressible Non-uniform Flow

(2) Perfectly Sound-Absorbing Metasurfaces

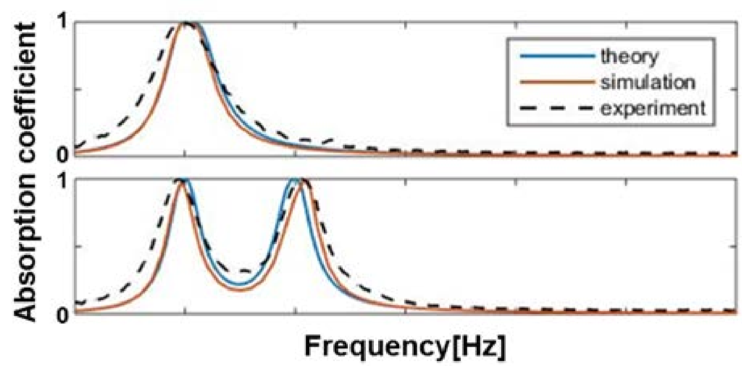
(3) A Few Words on Acoustic Black Holes

Contents

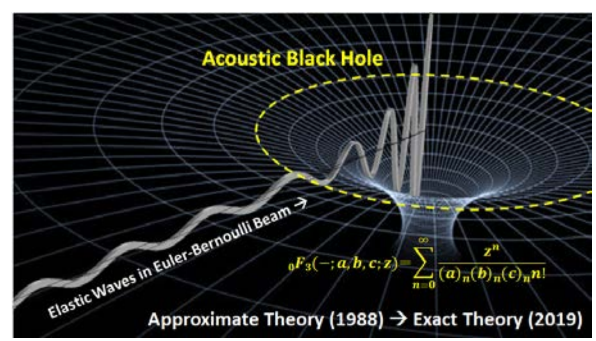
1. Acoustic Cloak in Compressible Flow



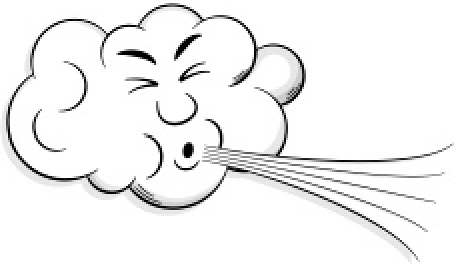
2. Hybrid-Resonant-Type Metasurface



3. A Few Words on Acoustic Black Holes



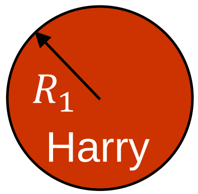
What Happens when Wind Blows…



in case that Harry wears an *acoustically* invisible cloak..

Substitutions

=



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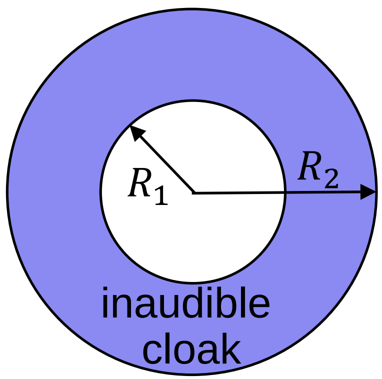
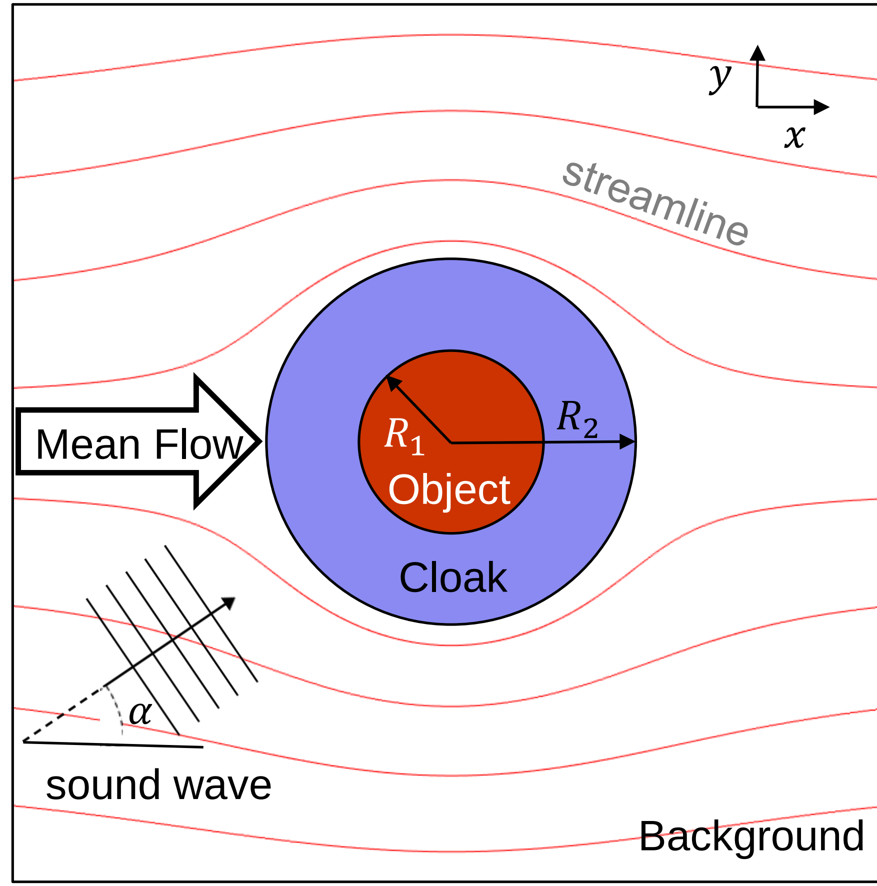
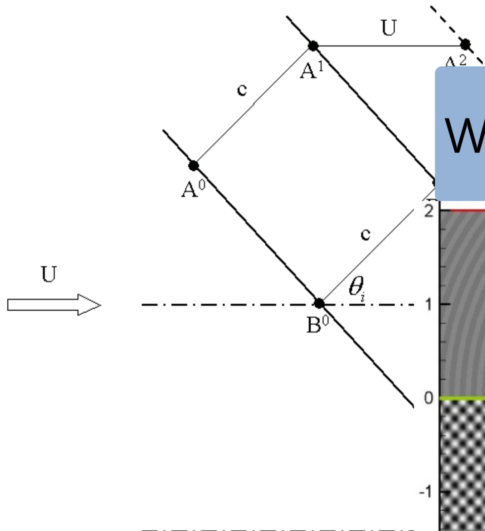




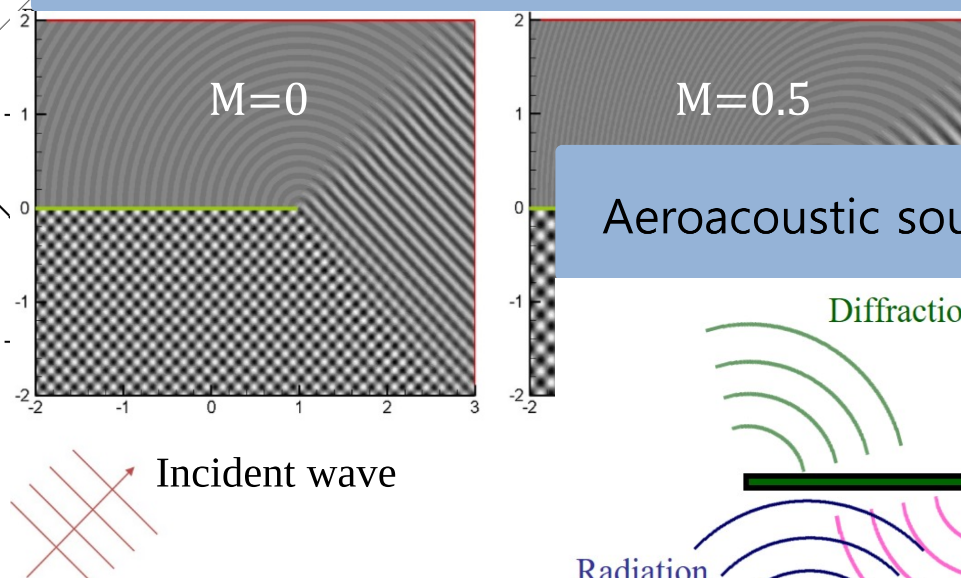
→ **Acoustic Cloak in the presence of Compressible Non-uniform Flow**

Basic Phenomena in Waves when Wind blows

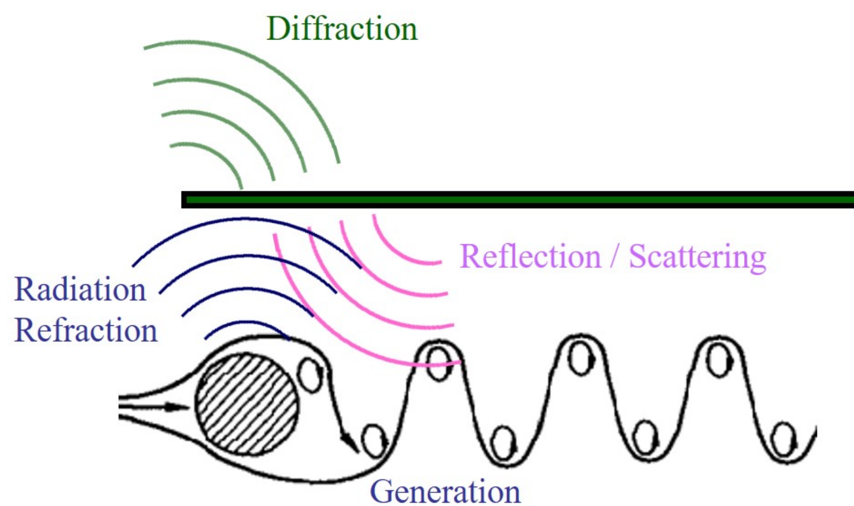
Speed of propagation is changed.



Wavelengths and amplitudes are changed.

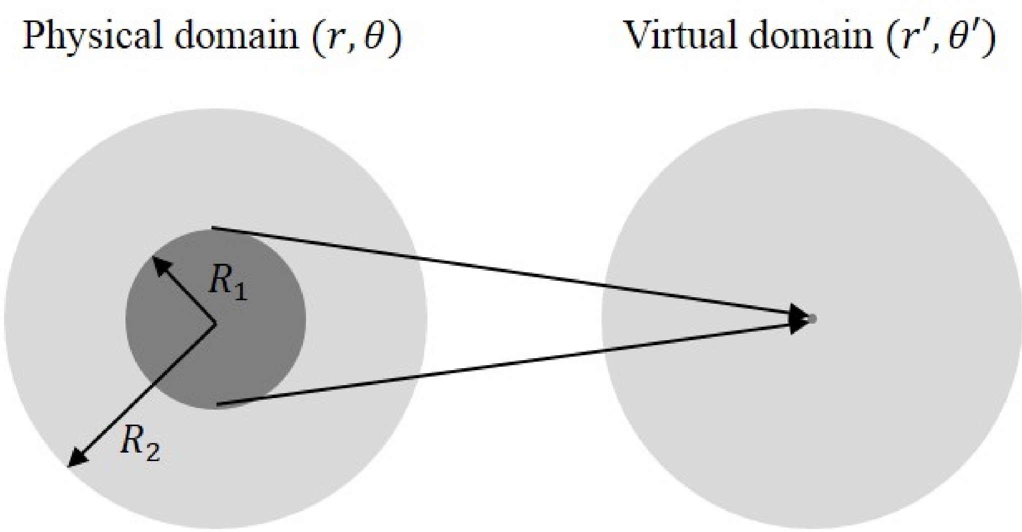


Aeroacoustic sources are generated.



Optical cloak makes the object "invisible"

Keyword: Coordinate Transform & Diffeomorphism



$$r = R_1 + r' \frac{R_1 - R_1}{R_2},$$

$$\theta = \theta'.$$

Pendry *et al.*, *Science*, 2006.

Original Idea (Math. Res. Lett., 2003)

On nonuniqueness for Calderon's inverse problem

Allan Greenleaf, Matti Lassas and Gunther Uhlmann *

Abstract. We construct anisotropic conductivities with the same Dirichlet-to-Neumann map as a homogeneous isotropic conductivity. These conductivities are singular close to a surface inside the body.

$$F_1 : B(0,2) \setminus \{0\} \to B(0,2) \setminus \overline{B}(0,1),$$
$$F_1(x) = (\frac{|x|}{2} + 1)\frac{x}{|x|}, \quad 0 < |x| < 2.$$

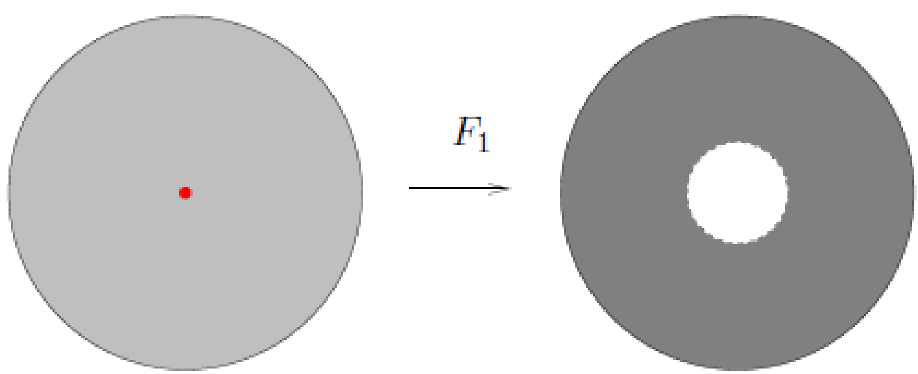


Figure 1: Map $F_1 : B(0,2) \setminus \{0\} \to B(0,2) \setminus \overline{B}(0,1)$

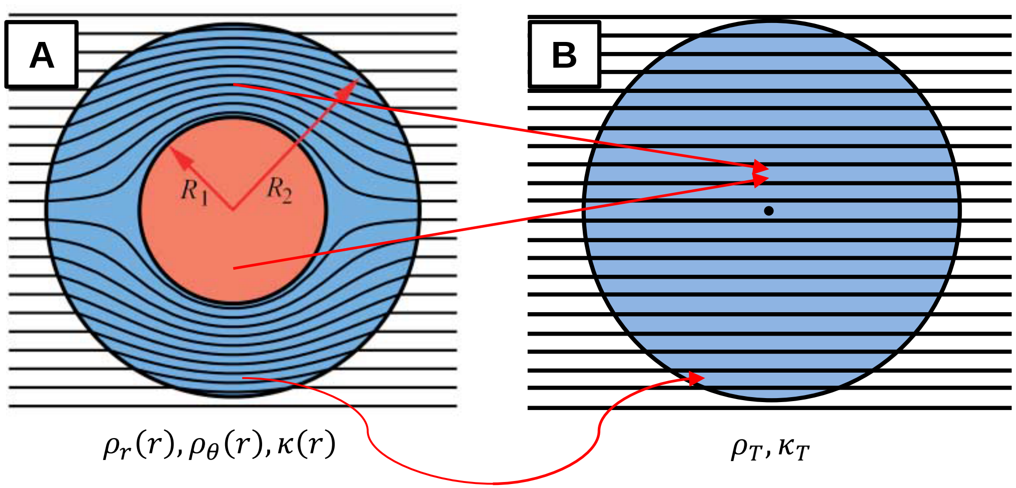
Transformation Acoustics (2007) in Stationary Medium

Acoustic cloak makes an object "acoustically invisible"

Cummer & Schurig used an analogy between Optics and Acoustics.

Maxwell's equation in cylindrical coordinate	Analogy in two dimension	Acoustic equation in cylindrical coordinate
$j\omega\mu_r(-H_r) = -\frac{1}{r}\frac{\partial(-E_z)}{\partial\theta}$ $j\omega\mu_\theta = -\frac{\partial(-E_z)}{\partial r}$ $j\omega\epsilon_z(-E_z) = -\frac{1}{r}\frac{\partial(rH_\theta)}{\partial r} - \frac{1}{r}\frac{\partial(-H_r)}{\partial\theta}$	$[p, v_r, v_\theta, \rho_r, \rho_\theta, \kappa^{-1}]$ $\leftrightarrow [-E_z, H_\theta, -H_r, \mu_\theta, \mu_r, \epsilon_z]$	$j\omega\rho_\theta v_\theta = -\frac{1}{r}\frac{\partial p}{\partial\theta}$ $j\omega\rho_r v_r = -\frac{\partial p}{\partial r}$ $j\omega\frac{1}{\kappa}p = -\frac{1}{r}\frac{\partial(rv_r)}{\partial r} - \frac{1}{r}\frac{\partial v_\theta}{\partial\theta}$

Cummer *et al.*, *New J. Phys.*, 2007.



Coordinate transform

A

$$\rho_r(r) = \frac{r}{r - R_1}\rho_0$$

$$\rho_\theta(r) = \frac{r - R_1}{r}\rho_0$$

$$\kappa(r) = \left(\frac{R_2}{R_2 - R_1}\right)^2 \frac{r - R_1}{r}\kappa_0$$

Coordinate ⟷ transform

B

$$\rho_T = \rho_0$$

(Property of air)

$$\kappa_T = \kappa_0$$

Anisotropic Material Properties

Multi-layered Structure for an Acoustic Cloak

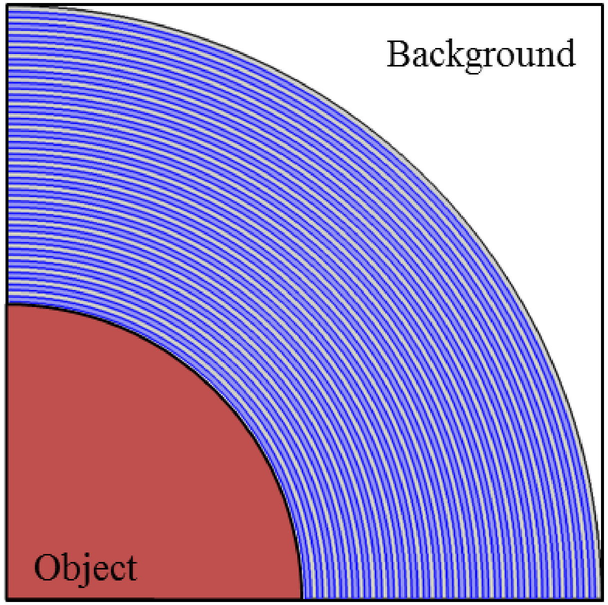
A Anisotropic material property

- Acoustic cloak requires an **anisotropic** density.
- In real world, **there is no such a material**.

B Multi-layered structure with **homogenization**

- Multi-layered structure of sub-wavelength scales shows an **effective anisotropic property** using homogenization

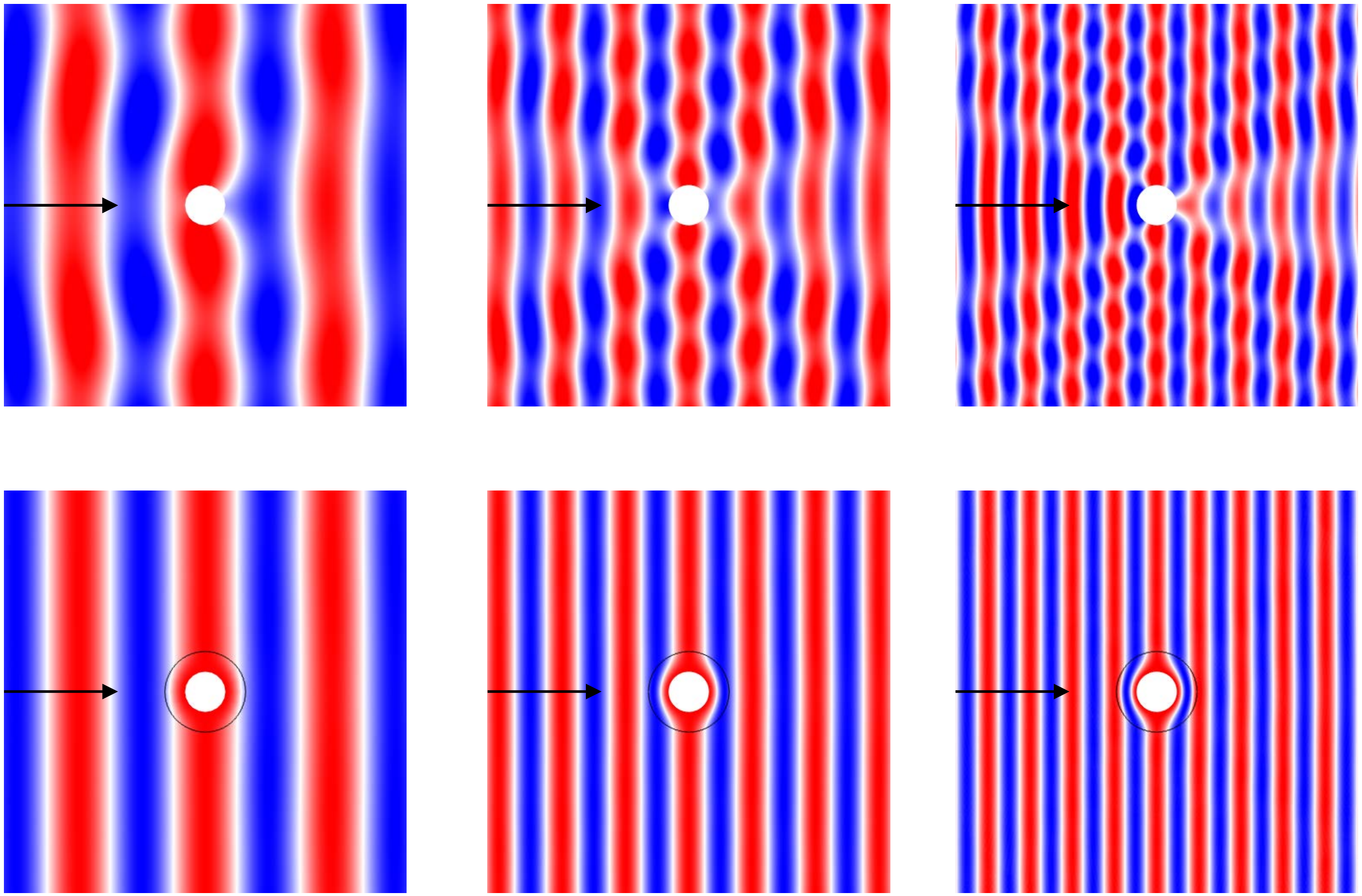
(A) Effective anisotropic material properties	(B) Multi-layered structure with homogeneous isotropic materials (2N-layered structure)
$\frac{\rho_r(r)}{\rho_0} = \frac{r}{r - R_1}$ $\frac{\rho_\theta(r)}{\rho_0} = \frac{r - R_1}{r}$ $\frac{\kappa(r)}{\kappa_0} = \left(\frac{R_2 - R_1}{R_2}\right)^2 \frac{r}{r - R_1}$	$\frac{\rho_{2i-1}(r)}{\rho_0} = \frac{r}{r - R_1} - \sqrt{\left(\frac{r}{r - R_1}\right)^2 - 1}$, $i = 1, 2, 3, \cdots, N$ $\frac{\rho_{2i}(r)}{\rho_0} = \frac{r}{r - R_1} + \sqrt{\left(\frac{r}{r - R_1}\right)^2 - 1}$, $i = 1, 2, 3, \cdots, N$ $\frac{\kappa_i(r)}{\kappa_0} = \left(\frac{R_2 - R_1}{R_2}\right)^2 \frac{r}{r - R_1}$, $i = 1, 2, 3, \cdots, 2N$



Homogenization Limit
d_A *and* $d_B \ll \lambda$

Torrent *et al.*, *New J. Phys.*, 2008 & Cheng *et al.*, *Appl. Phys. Lett.*, 2008.

Scattering without/with Acoustic Cloak



Without cloak
(Disc only)

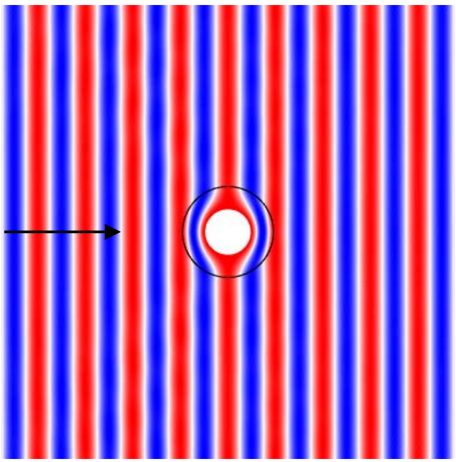
Multi-layered cloak
(Annulus region)

$kR_1 = 1$ $kR_1 = 2$ $kR_1 = 3$

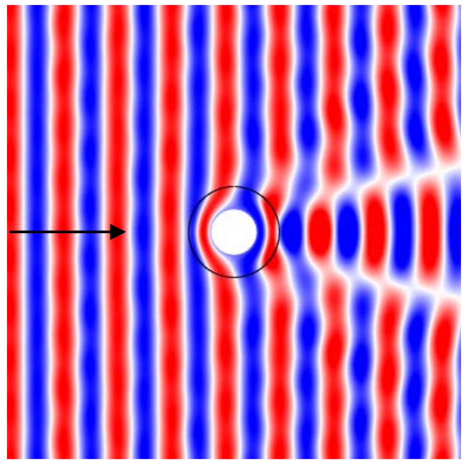
20 layers of sub-wavelength structures showed the "Acoustically Invisible Property" in stationary medium for different Helmholtz numbers.

What happens when wind blows

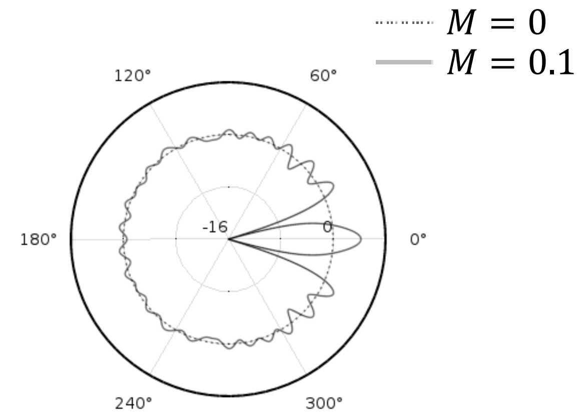
- Stationary to Moving Media



$kR_1 = 3,\ M = 0$



$kR_1 = 3, M = 0.1$



Directivity pattern @ $r = 10R_1$

Acoustic cloak fails in the presence of FLOW!

Ultimate Goal:
New Design of **Convective Cloak**

Intermediate Goals:
Investigating the **Scattering Pattern of Acoustic Cloak**
due to **Compressibility & Non-uniformity in Flow**
based on **A New Theoretical Framework**

Convective wave equation

$$\frac{D_0^2 p'}{D_0 t^2} - c_0^2 \nabla^2 p' = S_{eq}(\mathbf{x},t) = S_{non}(\mathbf{x},t) + S_{comp}(\mathbf{x},t),$$

where $\frac{D_0}{D_0 t} = \frac{\partial}{\partial t} + \mathbf{u}_0(\mathbf{x}) \cdot \nabla$

Equivalent Sources

$$S_{non}(\mathbf{x},t) = \rho_0 c_0^2 \nabla \cdot \left[2(\mathbf{u}' \cdot \nabla)\mathbf{u}_0 + \frac{\rho'}{\rho_0}(\mathbf{u}_0 \cdot \nabla)\mathbf{u}_0 \right]$$

$$S_{comp}(\mathbf{x},t) = -\rho_0 c_0^2 \left[\mathbf{u}' \cdot \nabla + \frac{D_0}{D_0 t}\left(\frac{\gamma p'}{\rho_0 c^2}\right) + \frac{\gamma p'}{\rho_0 c^2}\frac{D_0}{D_0 t} \right](\nabla \cdot \mathbf{u}_0)$$

$$-\rho_0 c_0^2 \frac{D_0}{D_0 t}\left[\frac{1}{\gamma \rho_0}(\mathbf{u}' \cdot \nabla)\rho_0 + \frac{1}{\gamma c_0^2}(\mathbf{u}' \cdot \nabla)c_0^2 \right]$$

$$-\rho_0 \left[\frac{D_0 p'}{D_0 t}(\mathbf{u_0} \cdot \nabla) - c_0^2 \nabla p' \cdot \nabla \right]\left(\frac{1}{\rho_0}\right)$$

$$-c_0^2 \frac{D_0 p'}{D_0 t}(\mathbf{u_0} \cdot \nabla)\left(\frac{1}{c_0^2}\right)$$

← **due to density inhomogeneity**

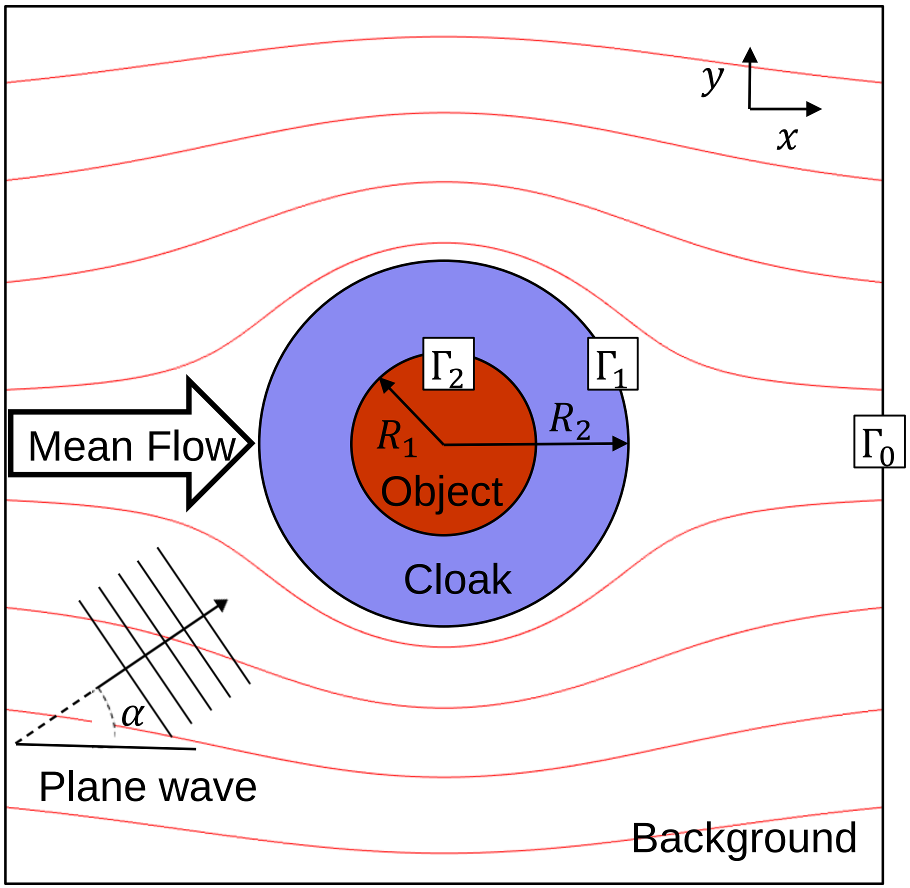
← **due to spatially varying speed of sound**

※ Note

In case of uniform flow,
$\mathbf{u}_0 = const \rightarrow S_{non} = 0$

In case of incompressible flow,
$\nabla \rho_0 = \mathbf{0}$ and $\nabla \cdot \mathbf{u}_0 = 0$
$\rightarrow S_{comp} = 0$

Summary of Problem Definition



1. Governing Equations

1.1 Background Flow

$$(\mathbf{u}_0 \cdot \nabla)\rho_0 + \rho_0 \nabla \cdot \mathbf{u}_0 = 0$$

$$\frac{1}{2}\nabla|\mathbf{u}_0|^2 + \frac{\gamma}{\gamma - 1}\frac{p_{ref}}{\rho_{ref}^{\gamma}}\nabla\left(\rho_0^{\gamma-1}\right) = \mathbf{0}$$

1.2 Acoustic Wave (outside the cloaking shell)

$$\frac{D_0^2 p'}{D_0 t^2} - c_0^2 \nabla^2 p' = S_{eq} = S_{non} + S_{comp}$$

1.3 Acoustic Wave in cloaking shell

$$\frac{\partial^2 p'}{\partial t^2} - c^2\, \nabla^2 p' = 0$$

2. Boundary Conditions

2.1 Boundary Condition on Γ_1

For acoustic wave: continuity in acoustic pressure and velocity

For background flow: impermeability

2.2 Boundary Condition on Γ_2

For acoustic wave: acoustically rigid

2.3 Boundary Condition on Γ_0

For acoustic wave: non-reflecting (buffer zone)

For background flow: inflow and outflow toward +x direction

Comparison of Previous & Present Frameworks

Previous Framework (X. Huang *et al.*, *JASA*, 2014)	Present Framework
Governing Equation	
$\left[\left(\frac{\partial}{\partial t} + \mathbf{u}_\infty \cdot \nabla\right)^2 - c_\infty^2 \nabla^2\right] p'(\mathbf{x},t) = s_0(\mathbf{x},t)$ (uniform flow velocity and constant speed of sound)	$\left[\left(\frac{\partial}{\partial t} + \mathbf{u_0}(\mathbf{x}) \cdot \nabla\right)^2 - c_0^2(\mathbf{x})^2 \nabla^2\right] p'(\mathbf{x},t) = S_{eq}(\mathbf{x},t)$ (non-uniform flow velocity and spatially varying speed of sound)
Equivalent Source	
$s_0(\mathbf{x},t) = s_1(\mathbf{x},t) + s_2(\mathbf{x},t)$ $s_1(\mathbf{x},t) = -(\partial_t + \mathbf{u}_\infty \cdot \nabla)(\mathbf{v} \cdot \nabla p')$ $s_2(\mathbf{x},t) = c_\infty^2 \nabla \cdot \left(\rho_\infty \mathbf{v} \cdot \nabla \mathbf{u}' + \rho_\infty \mathbf{u}' \cdot \nabla \mathbf{v} + \frac{p'}{c_\infty^2} \mathbf{u}_0 \cdot \nabla \mathbf{u}_0\right)$ where $\mathbf{v} = \mathbf{u}_0(\mathbf{x}) - \mathbf{u}_\infty$	$S_{eq}(\mathbf{x},t) = S_{comp}(\mathbf{x},t) + S_{non}(\mathbf{x},t)$ **(with physical meanings)**

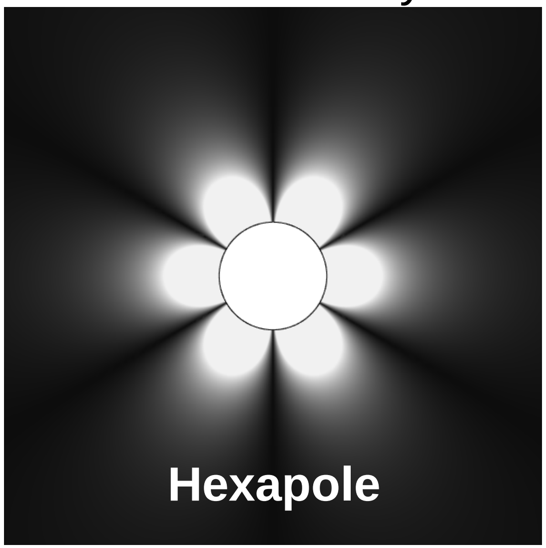
As pointed out by Phillips (1960), Lilley (1971), and Goldstein (1976),

more of the real fluid effect should be included in the wave operator part

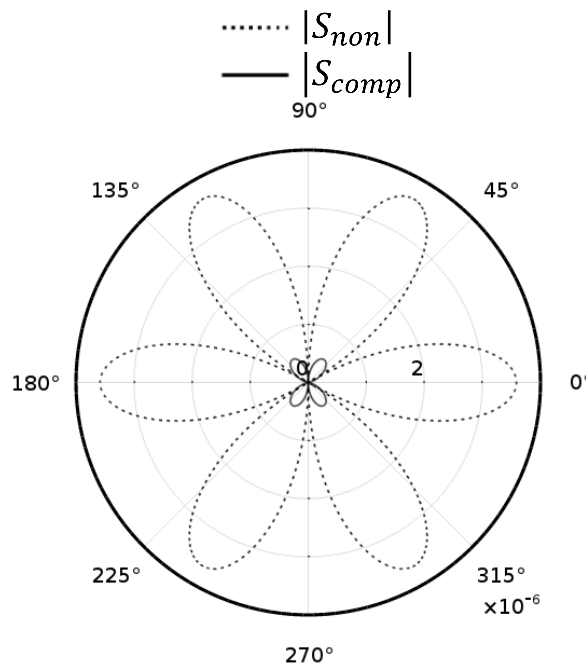
rather than in the equivalent source terms.

Non-uniformity & Compressibility Effects
- High Frequency and Low Mach number

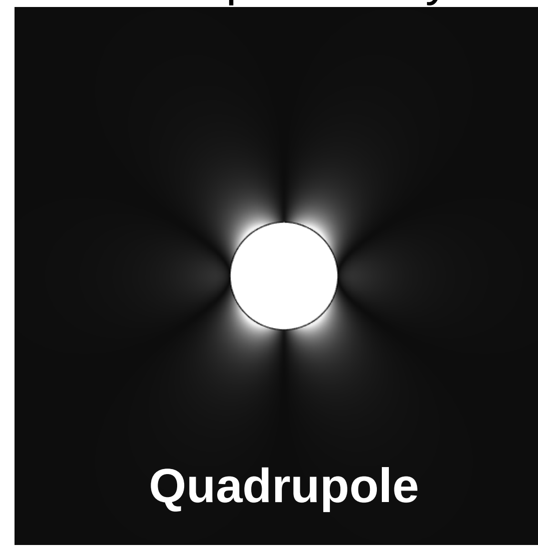
Non-uniformity



$kR_1 = 3,\ M = 0.1,\ \alpha = 0°$



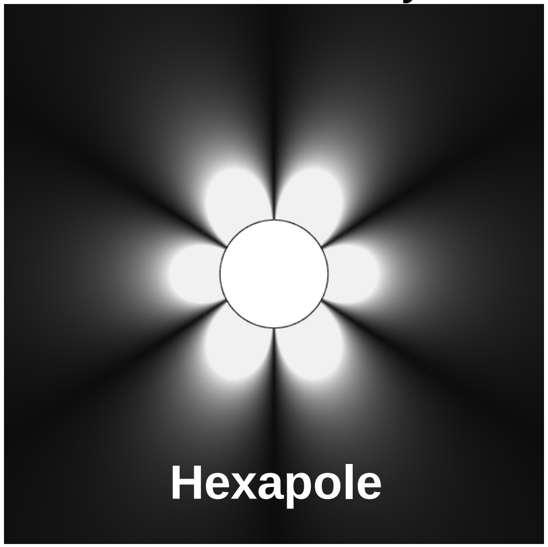
Compressibility



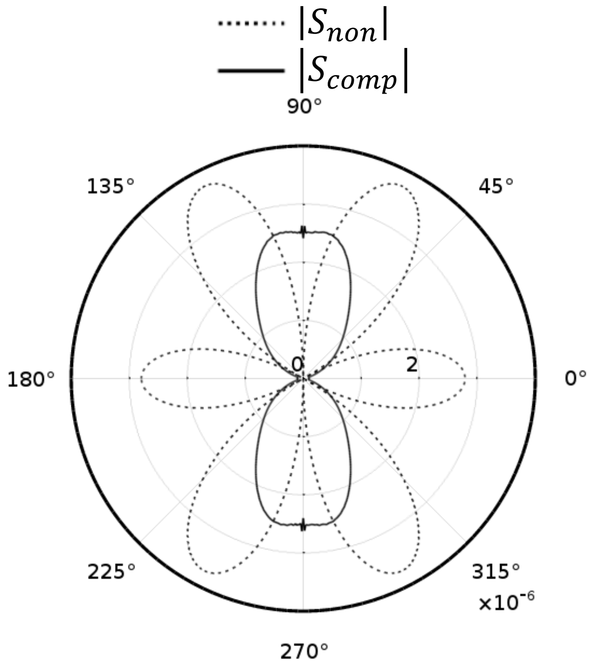
Compressibility effect is negligible compared to the non-uniformity effect in case of low Mach number and high frequency.

Non-uniformity & Compressibility Effects
- Low Frequency and High Mach number

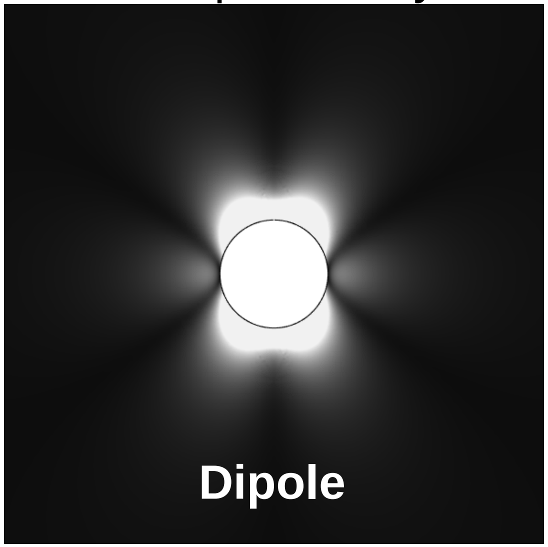
Non-uniformity



$kR_1 = 1$, $M = 0.35$, $\alpha = 0°$

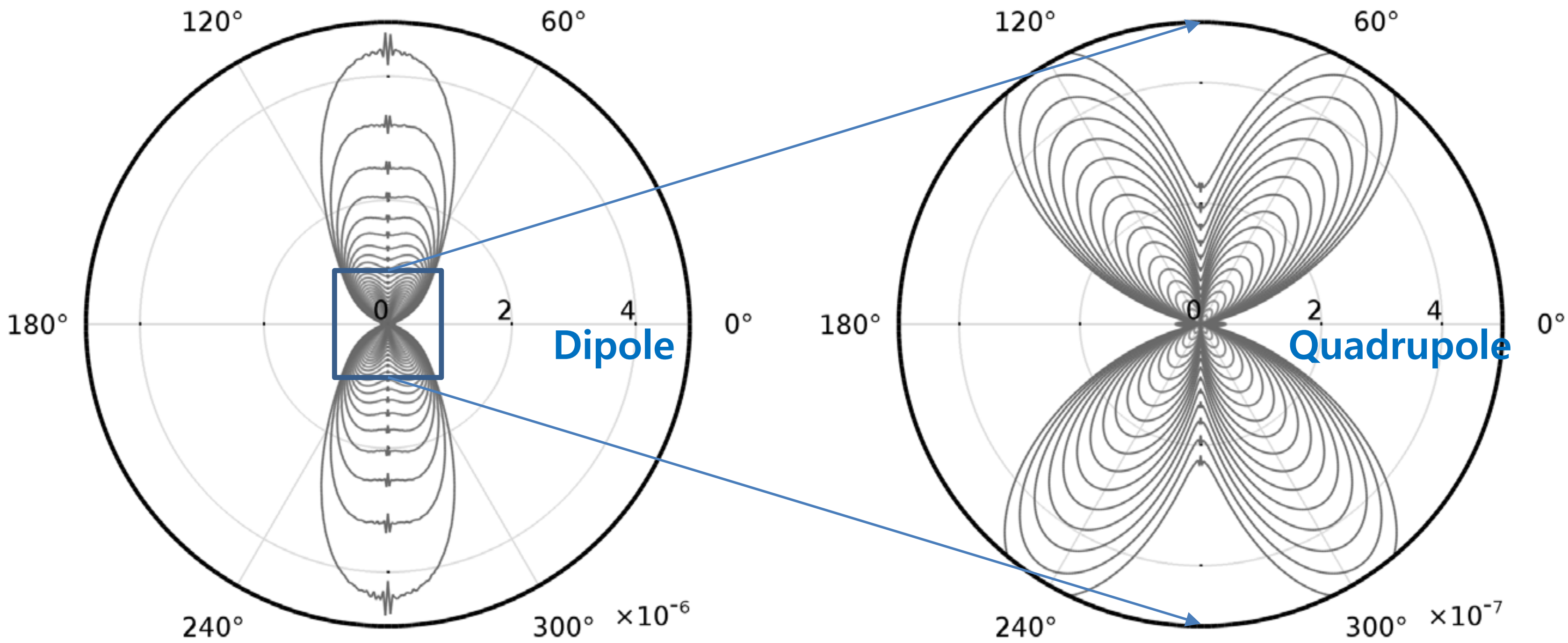


Compressibility



Compressibility effect is comparable to non-uniformity effect in case of high Mach number and low frequency.

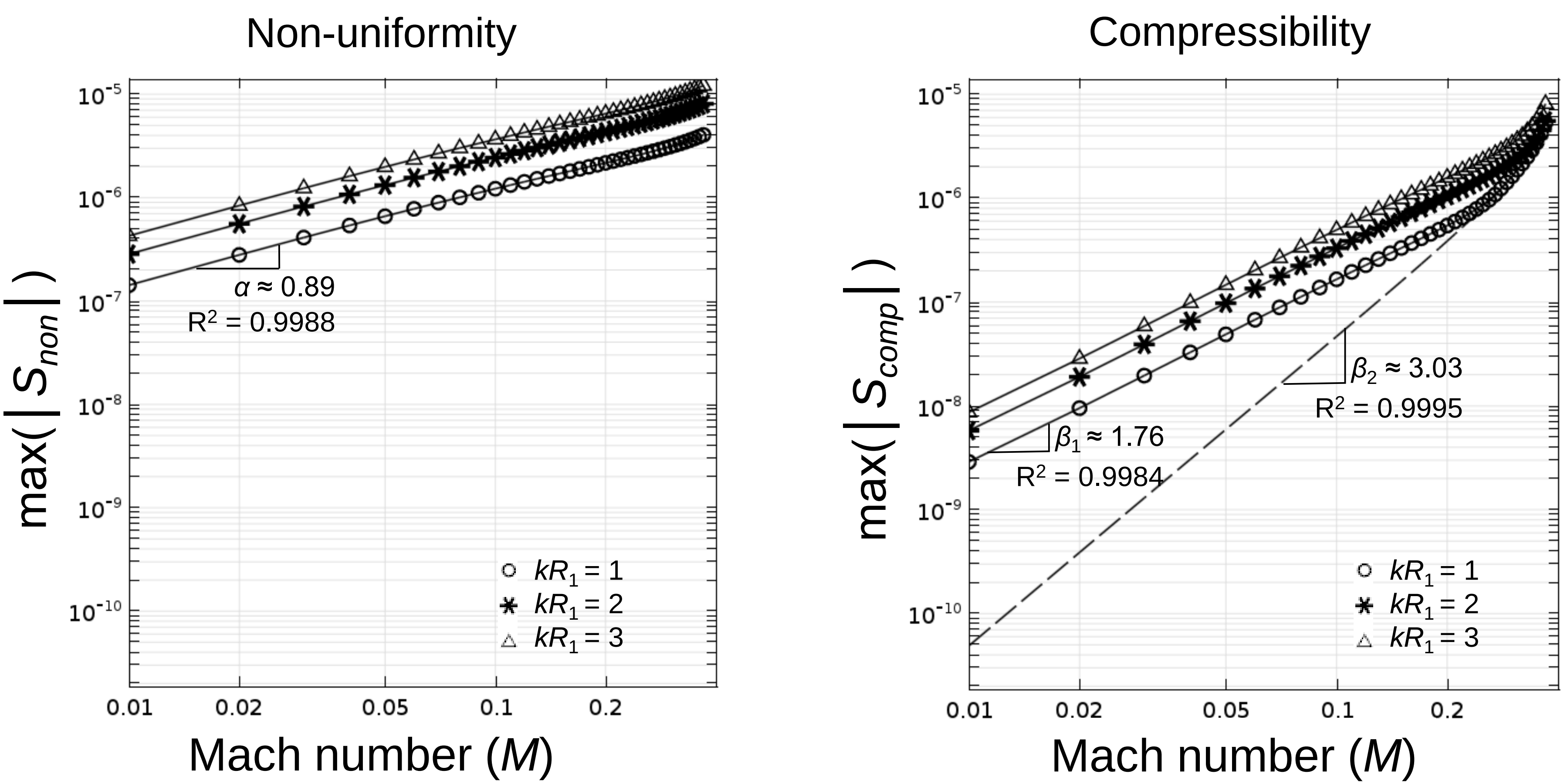
Compressibility Effect
- Transition of Polarity Type



$0 < M < 0.35$ $0 < M < 0.2$

The dominant polarity type of compressibility is shifted from the **quadrupole** to the **dipole.**

Power Laws for Non-uniformity and Compressibility Effects



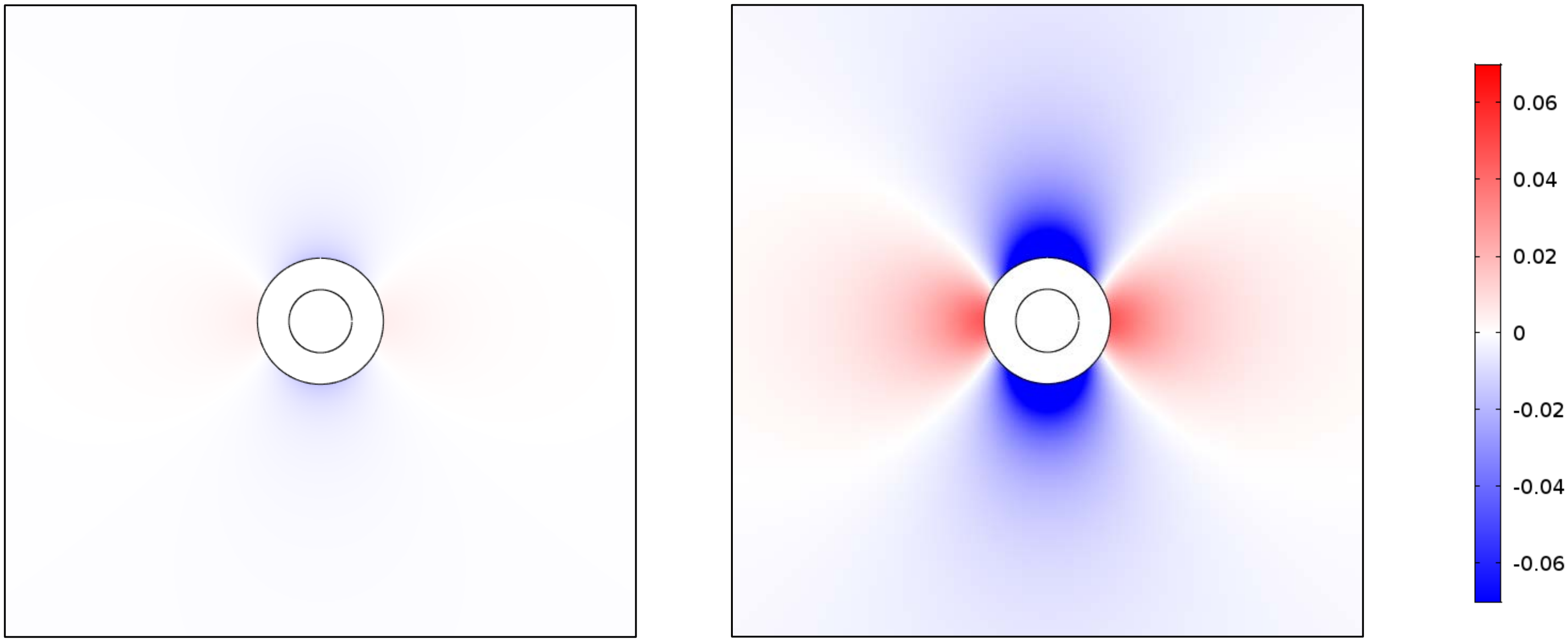
Power-law Relations

$\max(|S_{non}|) \propto M^{0.9}$, hexapole type

$$\max(|S_{comp}|) \propto \begin{cases} M^{1.8}, & \text{quadrupole type} \\ M^{3.0}, & \text{dipole type} \end{cases}$$

Compressibility Effect at Low Subsonic & High Subsonic Flows

Normalized Density Difference $(\rho_0 - \rho_\infty)/\rho_\infty$



M = 0.05 *M* = 0.35

Density Gradient → Refractive Index → Path of Acoustic Ray → Scattering Patterns

Newly Designed Convective Cloaks

The failure of acoustic cloak was mainly due to

(1) the **velocity gradient of background flow** and (2) **density inhomogeneity**

↓

Can we make use of our theoretical framework for a practical application?

or

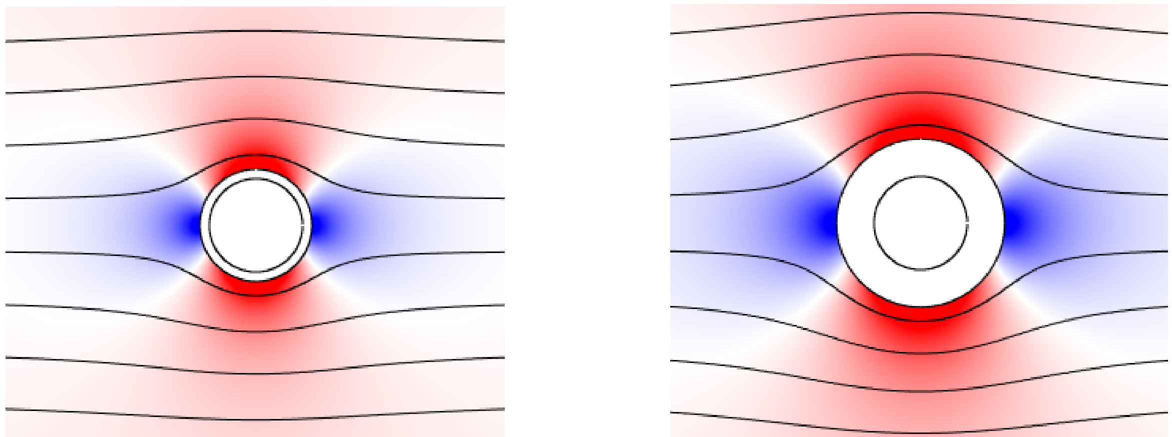
Can we design a new convective cloak?

By changing the shape (or size) of the Acoustic Cloak	**By changing the Material Properties of the Acoustic Cloak**

Controlling Thickness of Acoustic Cloak

Background Flow Velocity

$R_2 = 1.2R_1$ $\qquad$ $R_2 = 1.8R_1$



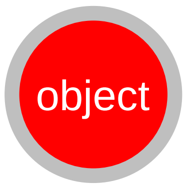
Equivalent Sources

$$S_{non}(\mathbf{x},t) = \rho_0 c_0^2 \nabla \cdot \left[2(\mathbf{u}' \cdot \nabla)\mathbf{u}_0 + \frac{\rho'}{\rho_0}(\mathbf{u}_0 \cdot \nabla)\mathbf{u}_0 \right]$$

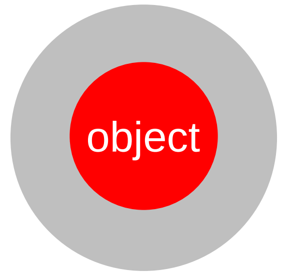
$$\begin{aligned} S_{comp}(\mathbf{x},t) = &-\rho_0 c_0^2 \left[\mathbf{u}' \cdot \nabla + \frac{D_0}{D_0 t}\left(\frac{\gamma p'}{\rho_0 c^2}\right) + \frac{\gamma p'}{\rho_0 c^2}\frac{D_0}{D_0 t} \right](\nabla \cdot \mathbf{u}_0) \\ &-\rho_0 c_0^2 \frac{D_0}{D_0 t}\left[\frac{1}{\gamma \rho_0}(\mathbf{u}' \cdot \nabla)\rho_0 + \frac{1}{\gamma c_0^2}(\mathbf{u}' \cdot \nabla)c_0^2 \right] \\ &-\rho_0 \left[\frac{D_0 p'}{D_0 t}(\mathbf{u_0} \cdot \nabla) - c_0^2 \nabla p' \cdot \nabla \right]\left(\frac{1}{\rho_0}\right) \\ &-c_0^2 \frac{D_0 p'}{D_0 t}(\mathbf{u_0} \cdot \nabla)\left(\frac{1}{c_0^2}\right) \end{aligned}$$

It is expected that
the thickness of acoustic cloak ↓
$\nabla \mathbf{u}_0$, ∇p_0, $\nabla \rho_0$ and ∇c_0 ↓

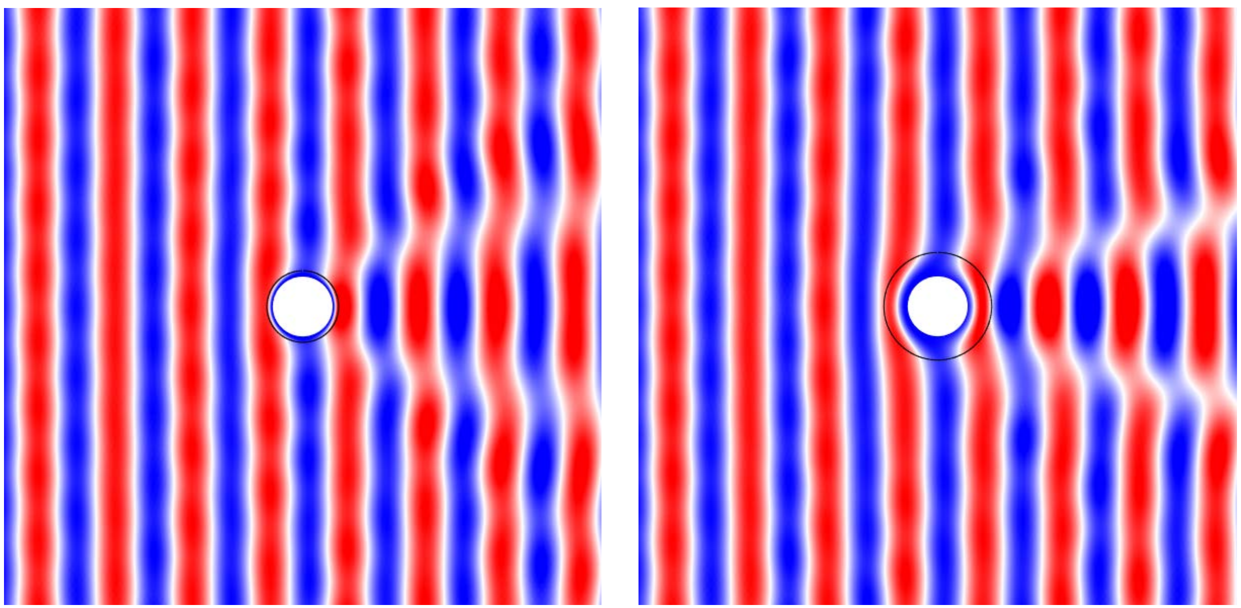
Effect of Thickness of in Moving Medium (M = 0.2)



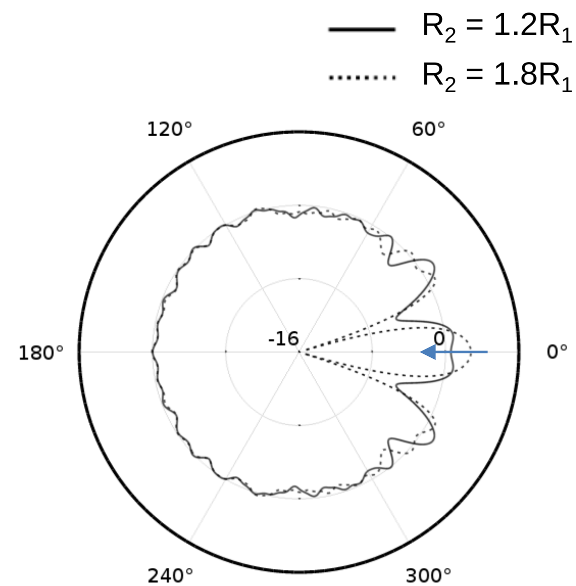
$R_2 = 1.2R_1$



$R_2 = 1.8R_1$



Acoustic pressure



Directivity pattern

Modified Anisotropic Material Properties in the Cloak

Design Parameters (β_i)

$$\frac{\rho_i^r(r)}{\rho_0} = \frac{r}{r - R_1}\frac{1}{1 + \beta_i M \cos\alpha},$$

$$\frac{\rho_i^\theta(r)}{\rho_0} = \frac{r - R_1}{r}\frac{1}{1 + \beta_i M \cos\alpha},$$

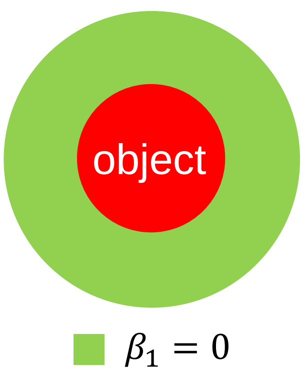
$$\frac{\kappa_i(r)}{\kappa_0} = \left(\frac{R_2 - R_1}{R_2}\right)^2 \frac{r}{r - R_1}(1 + \beta_i M \cos\alpha),$$

$$for\ i = 1, 2, \ldots, N,$$

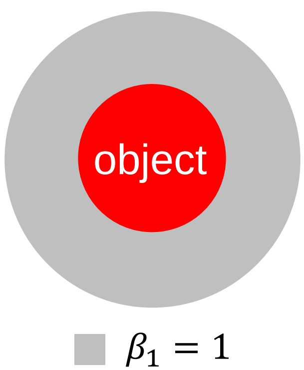
Objective Function to Minimize

$$e_{max} = \max_{0 \le \theta < 2\pi} \left| 10 \log_{10} \frac{p'^2}{p'^2_{inc}} \right| \text{ at } r = 10R_1$$

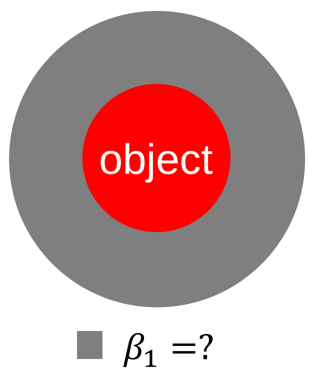
Single Zone Modification (N=1)



Acoustic Cloak
(*NJP*, 2007)

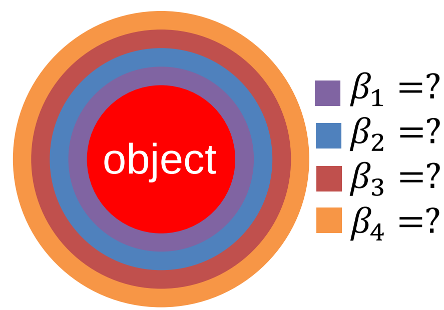


Convective Cloak
(*JASA*, 2014)



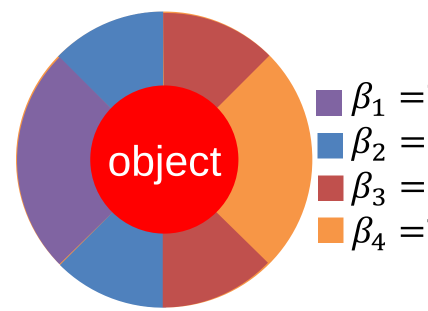
Type A

Multiple Zone Modification (N=4)



radial variation of β_i

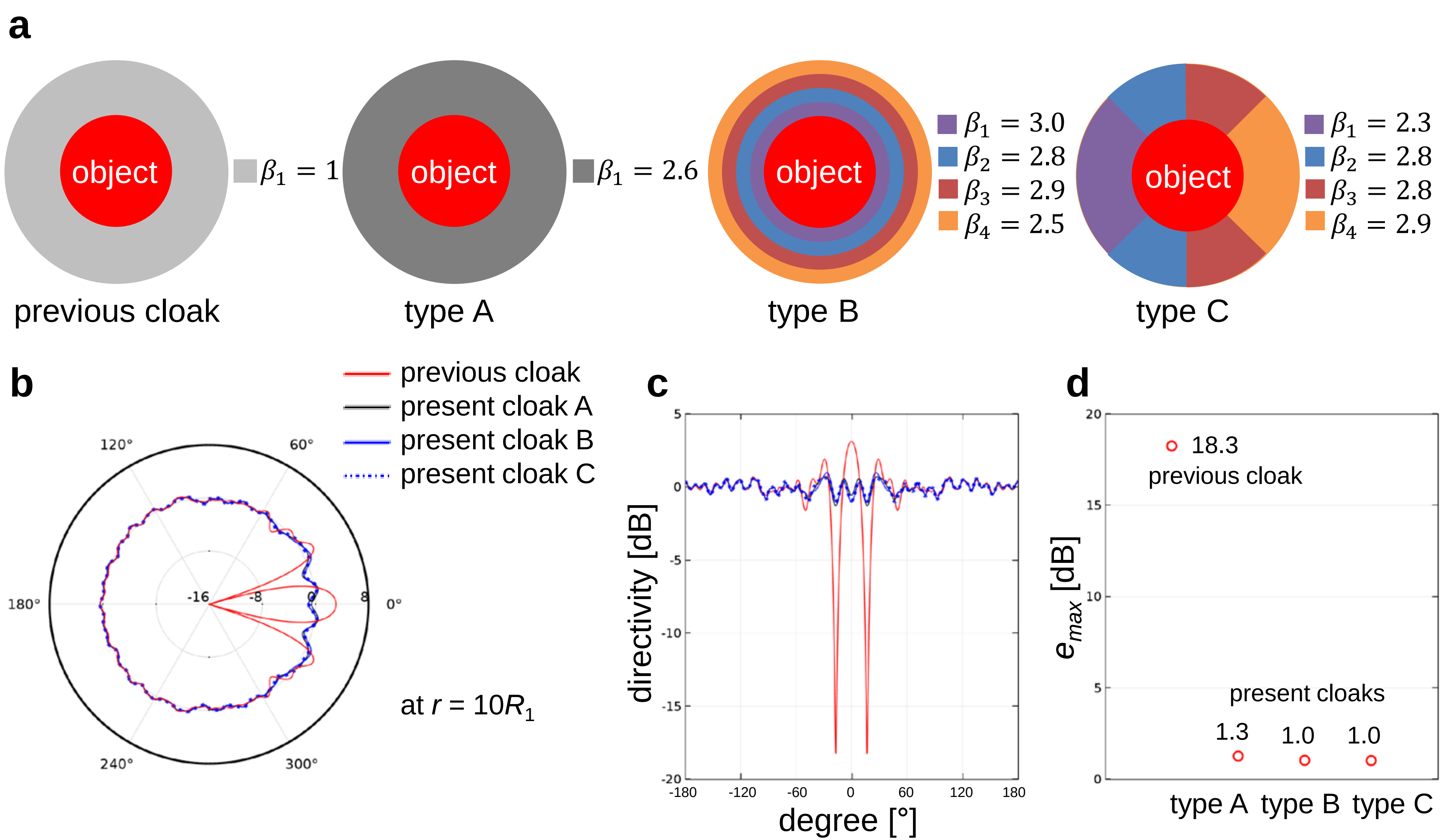
Type B



circumferential variation of β_i

Type C

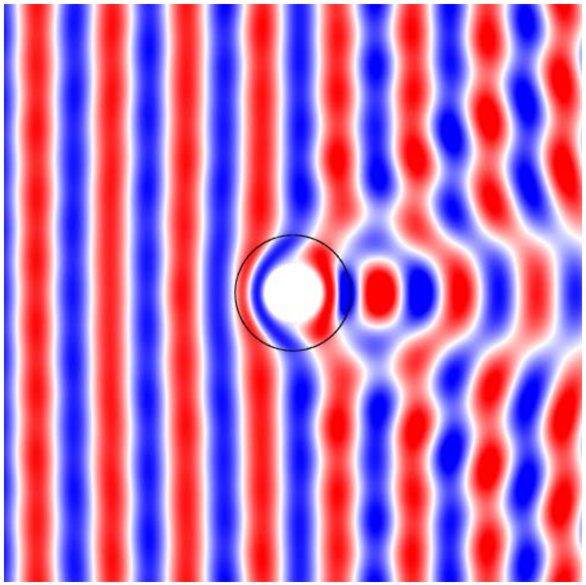
Results of Parametric Optimization



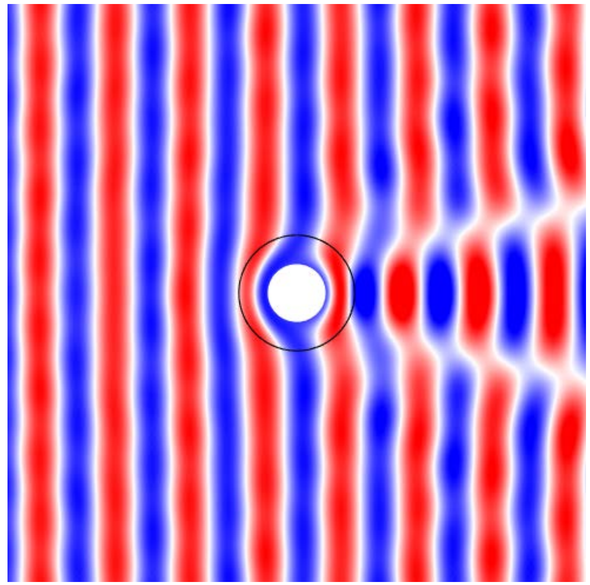
The lighter and stiffer material can be a good candidate for NEW convective cloak.

Comparison of Acoustic Scattering from Three Cloaks

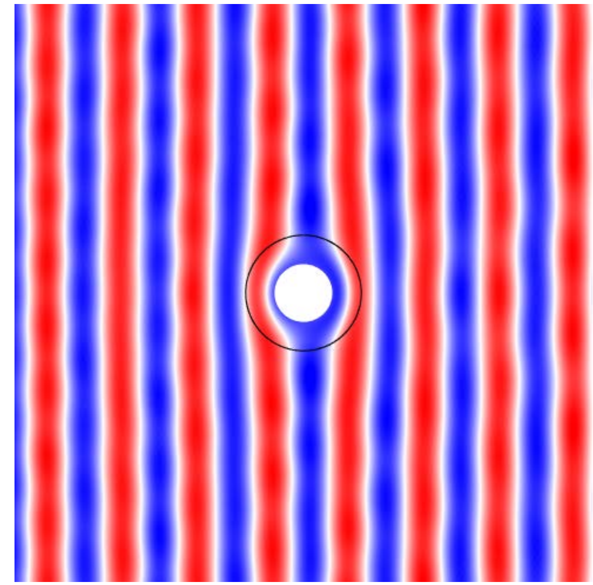
Total Acoustic Pressure Field ($\boldsymbol{M = 0.2}$, $kR_1 = 3$, $\alpha = 0°$)



Stationary Cloak
(*New J. Phys.*, 2007)



Convective Cloak
(*JASA*, 2014)



Present Cloak
(*Sci. Rep.*, 2017)

Existing Acoustic Cloaks

Almost All about Acoustic Cloak within Flow

- Acoustic cloak in stationary media $(M = 0)$ — since 2007
  - ⬍
- **Acoustic cloak in moving media** $(0 < M < 1)$ — since 2013
  - **Viscous**
    - **Turbulent**
  - **Inviscid**
    - **Irrotational**
      - **Incompressible**
      - **Compressible**

X. Huang , S. Zhong and X. Liu, J. Fluid Mech. (2014):
‘Cloak design in turbulent flow using **classical wave operator**’

Y. He, S. Zhong and X. Huang, J. Acoust. Soc. Am. (2019):
‘**Airfoil-shaped** cloak design in turbulent flow
using wave operator with **uniform mean flow velocity**’

C. Garcia-Meca *et al*. Sci. Rep. (2013)
‘analogue transformation approach’

X. Huang , S. Zhong and X. Liu, J. Acoust. Soc. Am. (2014):
‘Convective cloak design in potential flow
using wave operator with **uniform mean flow velocity**’

U. Iemma, Aerospace (2016):
‘Convective correction of the cloak design in potential flow
using integral form of wave equation with **uniform flow mean velocity**’

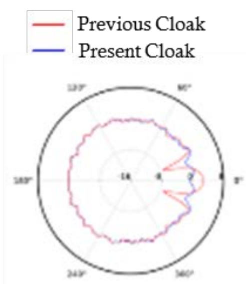
U. Iemma and G. Palma, Math. Probl. Eng. (2017):
‘Cloak design in potential flow using **analogue transformation acoustics**’

D. Eggler, M. Karimi and N. Kessissoglow, J. Acoust. Soc. Am. (2019):
‘**Active acoustic cloak** design in potential flow’

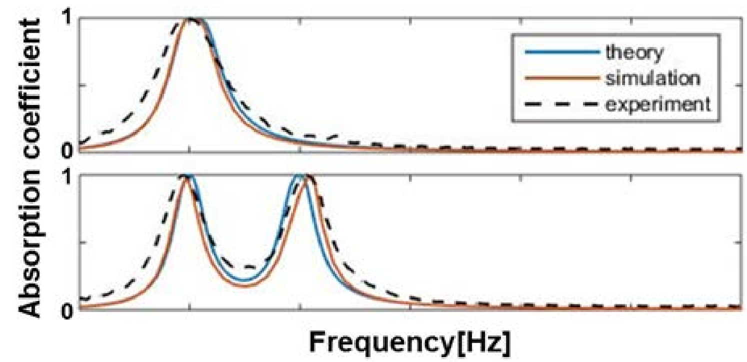
H. Ryoo and W. Jeon, Sci. Rep. (2017):
‘Cloak design in compressible potential flow
using wave operator with **non-uniform mean flow velocity**’

Contents

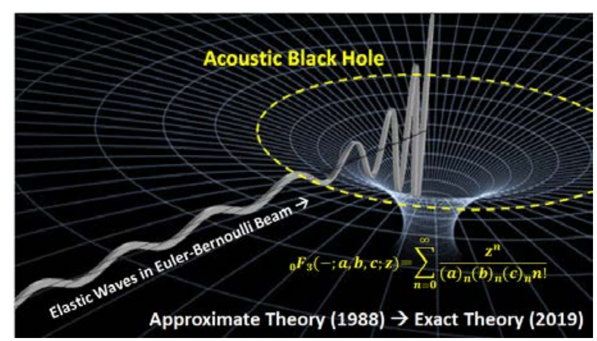
1. Acoustic Cloak in Compressible Flow



2. Hybrid-Resonant-Type Metasurface



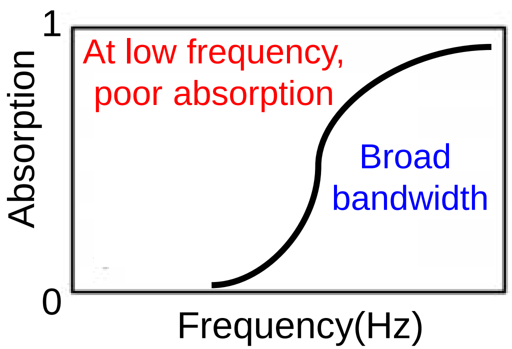
3. A Few Words on Acoustic Black Holes

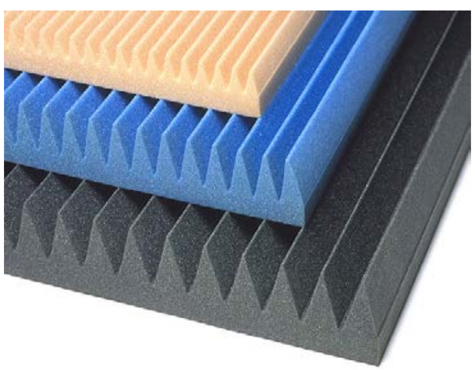


Conventional Sound Absorbing Materials

Porous/Fibrous Materials

Polyurethane Foam,
Cellular Melamine,
Fiberglass, Fluffy Fabrics

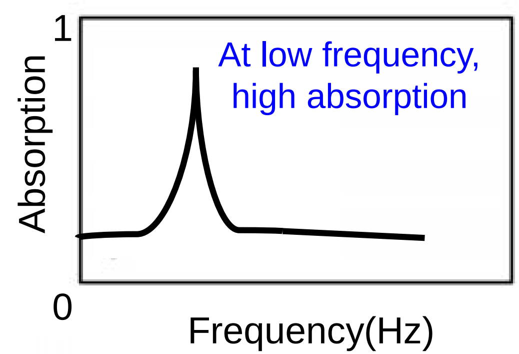


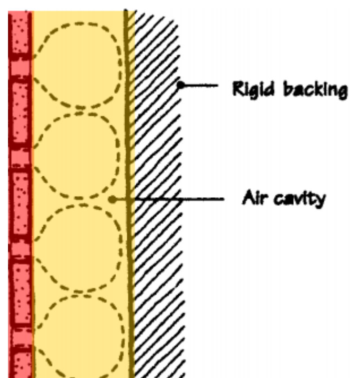


<Polyurethane Foam>

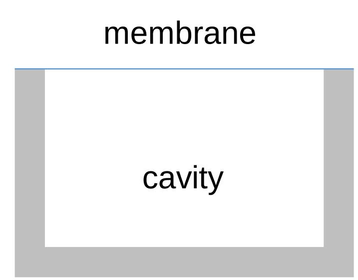
Resonant Absorbers

Helmholtz Resonators (HRs), Membrane Resonators (MRs),
Micro-Perforated Panels (MPPs)

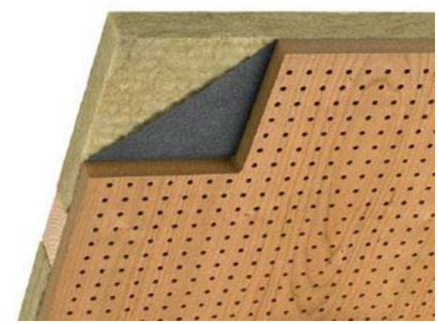




<Helmholtz Resonators>



<Membrane Resonators>



<Micro-Perforated Panel>

Helmholtz Resonator (HR)

Helmholtz Resonator	Sound Absorber using Helmholtz Resonators	Acoustic Metasurface using Hybrid Resonance

Helmholtz Resonator

An apparatus to pick out specific frequencies from a complex sound

resonance frequency

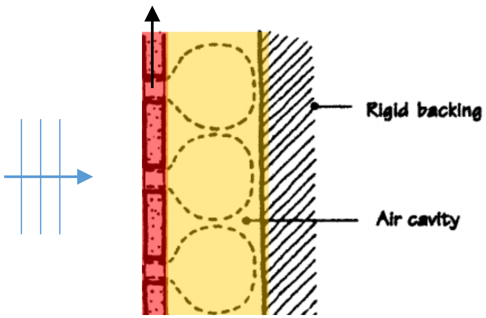
$$f_r = \frac{c}{2\pi}\sqrt{\frac{A}{V_0 L_{eq}}}$$

since 1885

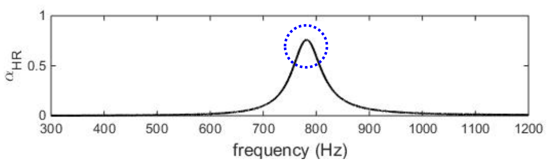
Sound Absorber using Helmholtz Resonators

Sound absorption using **visco-thermal loss** in the narrow necks of Helmholtz resonators

visco-thermal loss in narrow necks



absorption spectrum

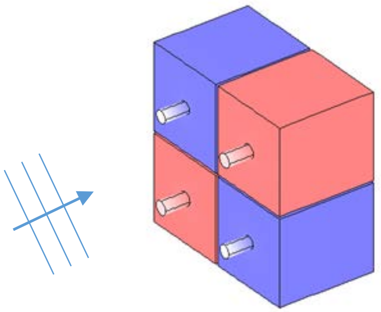


since 1940

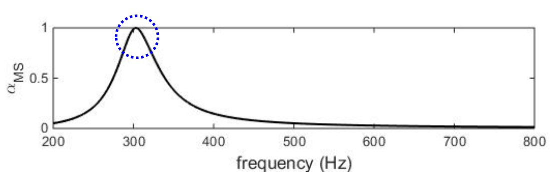
Acoustic Metasurface using Hybrid Resonance

Sound absorption using **hybrid resonance** between different Helmholtz resonators

π-phase difference between sub-λ resonators

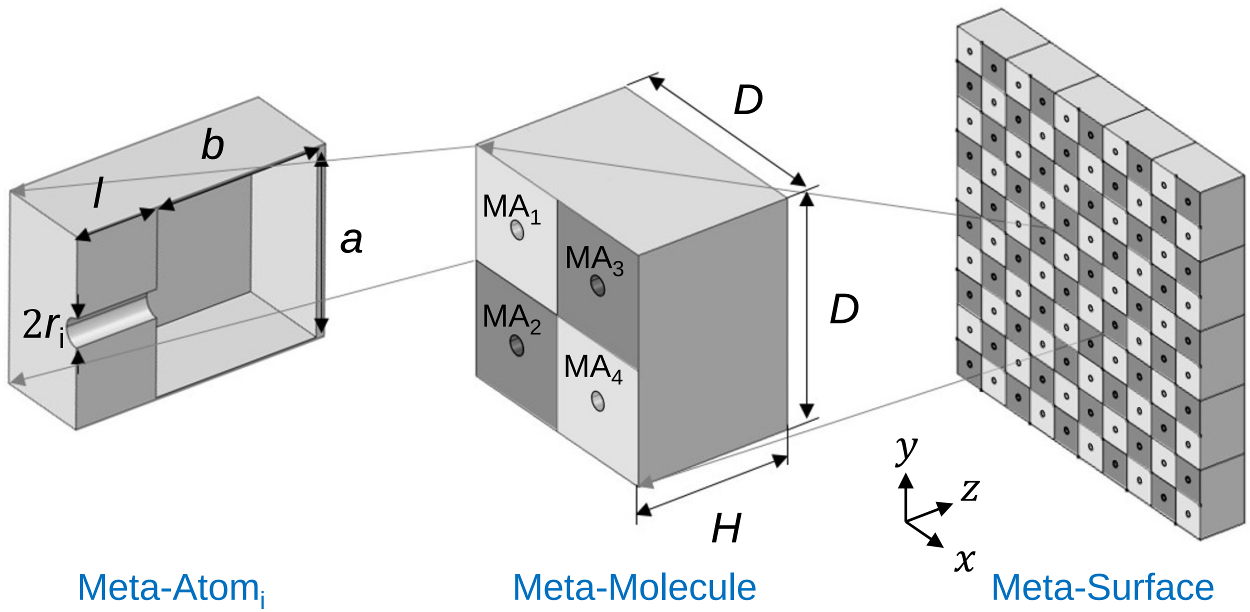


absorption spectrum



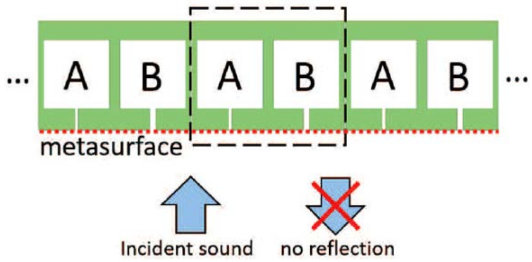
since 2016

Geometry of Metasurface



Perfect Absorption for Single and Multiple Frequencies

Previous Work



1D array of slit-type HRs

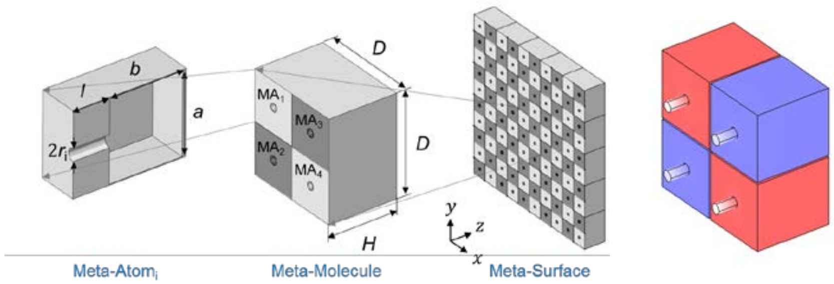
- Li et al. (Applied Physics Letters, 2016)

proposed a **conceptual idea** (1D array)

numerical model for a **specific frequency**
→ speed of sound = c(1+0.01i) for 1.3kHz

experimental validation of perfect absorption at the **single target frequency**

Present Work



2D array of checkerboard-type HRs

- Ryoo and Jeon (Journal of Applied Physics, 2018)
- Ryoo and Jeon (Applied Physics Letters, 2018)

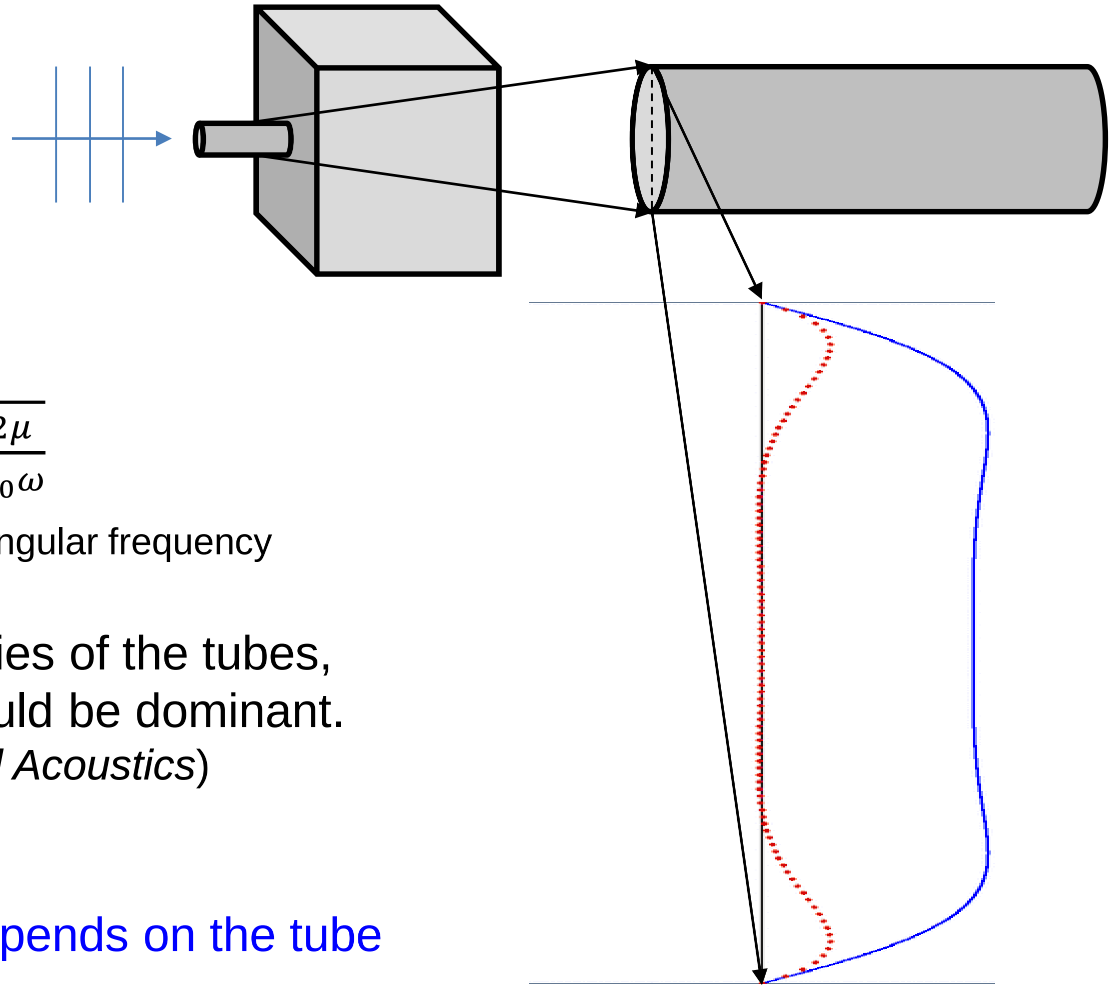
proposed a logical & systematic procedure to **analyze & design** metasurface (2D)

theoretical model by considering **frequency-dependent** visco-themal losses
→ generalization in frequency & geometry

experimental validation of perfect absorption at **dual (or multiple)** target frequencies

Visco-Thermal Loss in the Narrow Neck of HR

Helmholtz resonator (HR)



boundary layer thickness: $d_\nu = \sqrt{\frac{2\mu}{\rho_0 \omega}}$

where μ is the dynamic viscosity and ω is angular frequency

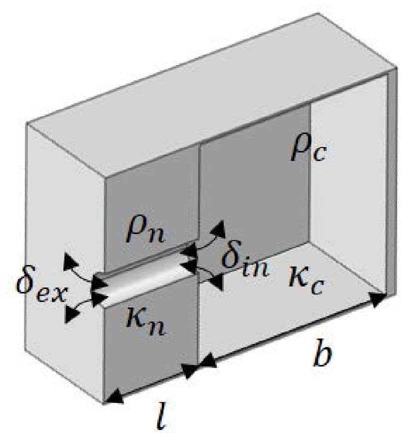
If d_ν is comparable to the geometries of the tubes, the effect of visco-thermal loss would be dominant.

(Morse & Ingard, *Theoretical Acoustics*)

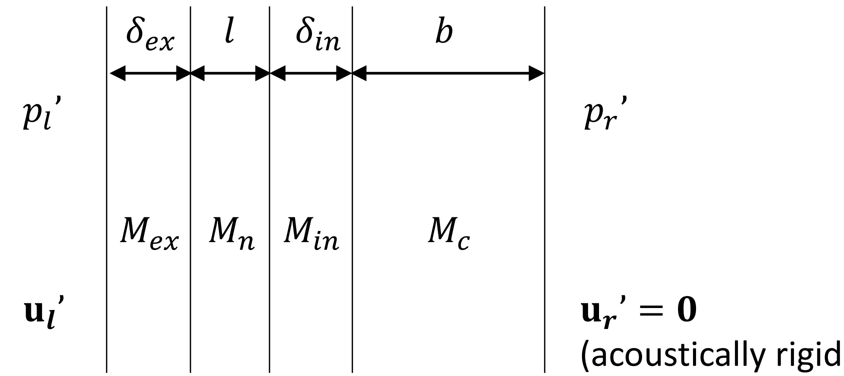
The effect of visco-thermal loss depends on the tube geometry and the frequency.

Acoustic Boundary Layer in Narrow Tubes (Stokes boundary layer, Wikipedia)

Effective Impedance of a Meta-Atom



Effective properties & end corrections



Equivalent four-layer model

Acoustic Impedances & Wavenumbers

$$Z_n = \sqrt{\rho_n \kappa_n}/\pi r^2$$

$$k_n = \omega\sqrt{\rho_n/\kappa_n}$$

$$Z_c = \sqrt{\rho_c \kappa_c}/a^2$$

$$k_c = \omega\sqrt{\rho_c/\kappa_c}$$

(Stinson, JASA, 1991)

External/Internal End Correction

$$\delta = 4r\sum_{p=1}^{\infty}\frac{J_1^2(x_p r/r_o)}{(x_p r/r_o)\left[x_p J_0(x_p)\right]^2}$$

r_o: Equivalent radius of the cavity or outer duct ($= a\sqrt{\pi}$ or $D/\sqrt{\pi}$)

x_p: p-th root of the equation $J_1(x_p) = 0$

(Karal, JASA, 1953)

Transfer Matrices

$$M_{ex} = \begin{pmatrix} 1 & ik_n\delta_{ex}Z_n \\ 0 & 1 \end{pmatrix}$$

$$M_n = \begin{pmatrix} \cos(k_n l) & iZ_n\sin(k_n l) \\ i\sin(k_n l)/Z_n & \cos(k_n l) \end{pmatrix}$$

$$M_{in} = \begin{pmatrix} 1 & ik_n\delta_{in}Z_n \\ 0 & 1 \end{pmatrix}$$

$$M_c = \begin{pmatrix} \cos(k_c b) & iZ_c\sin(k_c b) \\ i\sin(k_c b)/Z_c & \cos(k_c b) \end{pmatrix}$$

Transfer Matrix Method (TMM)

$$\begin{pmatrix} p_l' \\ |\mathbf{u}_l'| \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix}\begin{pmatrix} p_r' \\ \mathbf{0} \end{pmatrix} = M_{ex}M_n M_{in}M_c\begin{pmatrix} p_r' \\ \mathbf{0} \end{pmatrix}$$

Effective Impedance of a Meta-atom

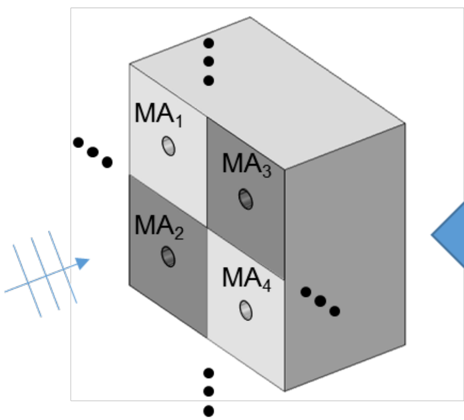
$$Z_{MA} = \frac{p_l'}{|\mathbf{u}_l'|} = \frac{T_{11}}{T_{21}}$$

Effective Impedance of a Meta-Molecule (four HRs)

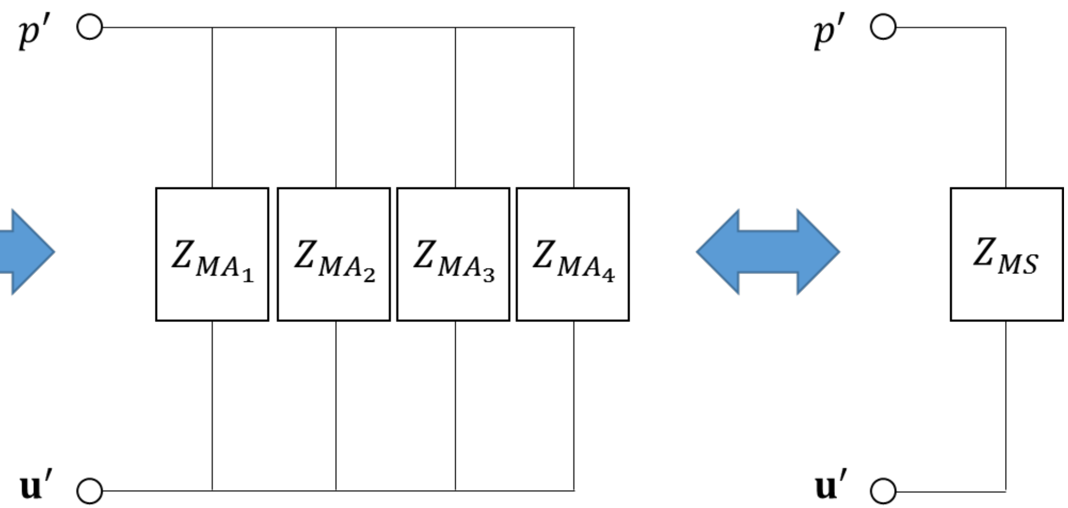
Effective Acoustic Impedance of each Meta-Atom

end corrections

$$Z_{MA} = -i\frac{\cos(k_n l)\cos(k_c b) - \sin(k_n l)\sin(k_c b)\,Z_n/Z_c - k_n(\delta_{in}+\delta_{ex})\cos(k_n l)\sin(k_c b)\,Z_n/Z_c + k_n\delta_{ex}\sin(k_n l)\cos(k_c b)}{\cos(k_n l)\sin(k_c b)/Z_c + \sin(k_n l)\cos(k_c b)/Z_n - k_n\delta_{in}\sin(k_n l)\sin(k_c b)/Z_c}$$



2-D Diagonally Arranged



Circuit Connected in Parallel

Acoustic impedance of the Metasurface consisting of N MAs (when $kD \ll \pi/2$)

$$Z_{MS} = \frac{1}{\sum_{i=1}^{N} 1/Z_{MA_i}}$$

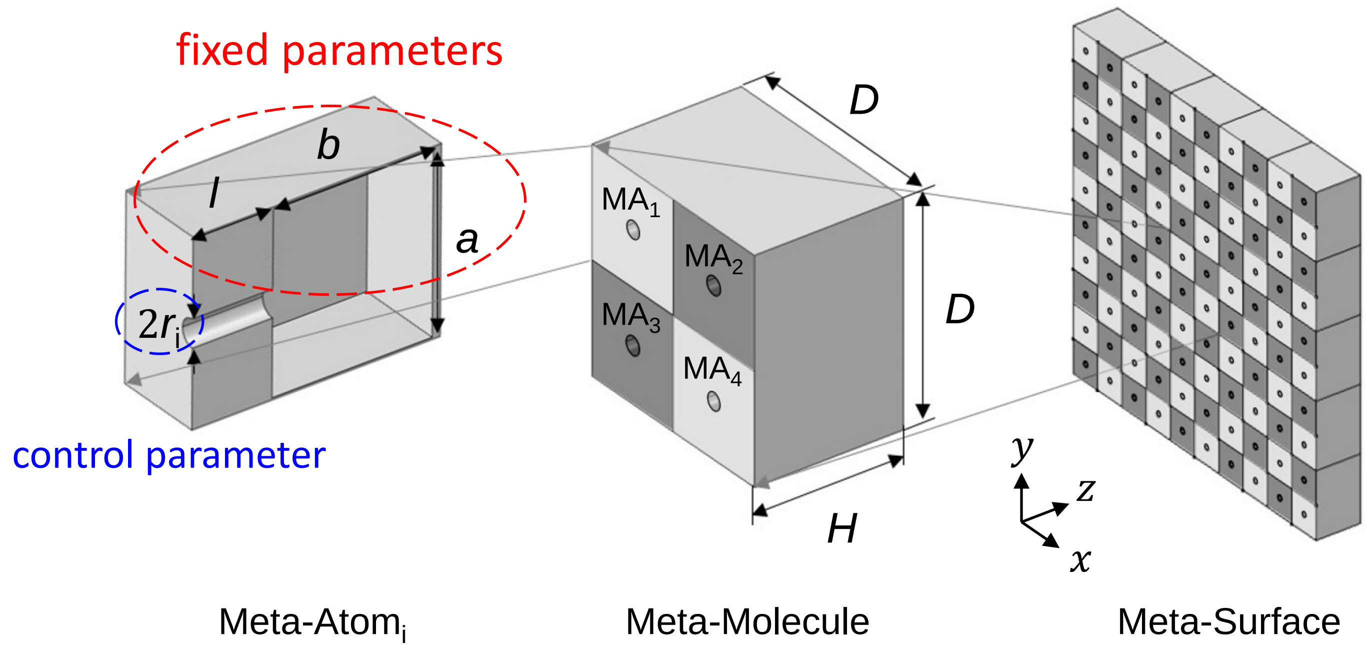
reciprocal of the sum of the admittances.

Then, the absorption coefficient of the Metasurface can be analytically obtained as $\alpha_{MS} = 1 - |(Z_{MS} - Z_0)/(Z_0 - Z_{MS})|^2$ where Z_0 is the acoustic impedance of air.

Ryoo and Jeon, *J. Appl. Phys.* 123(11), 115110 (Mar. 2018)

Geometrical Parameters of Each Resonator (A_i, l_i, V_i)

Forward Analysis



How to design a perfectly sound-absorbing meta-surface at desired frequencies by controlling *only neck radii*?

Inverse Design

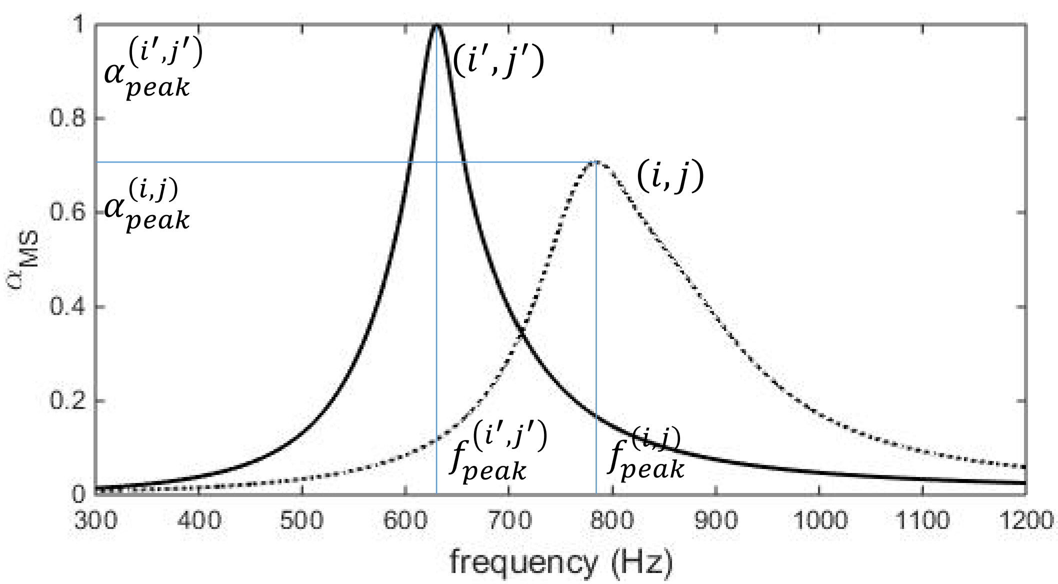
Peak Frequency of the Meta-Surface (f_{peak})

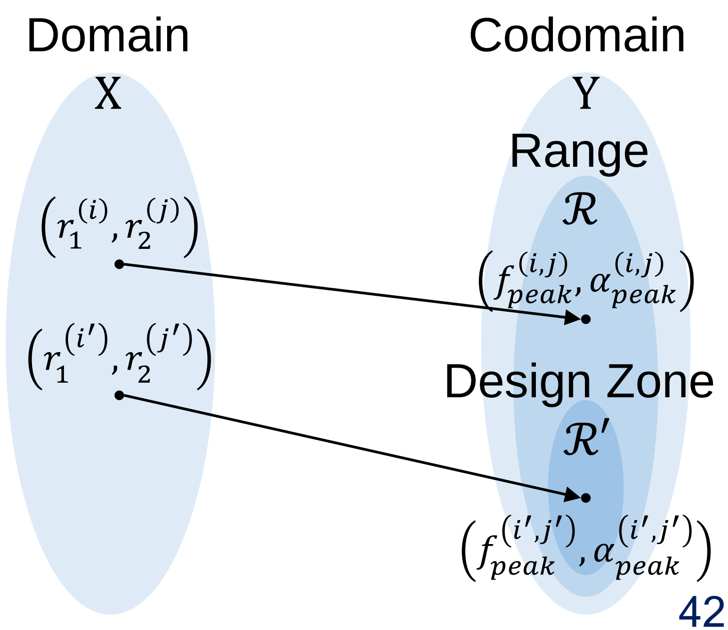
Existence of pre-image for any elements in codomain

We calculate the absorption coefficient spectra by changing r_1 and r_2
Frequency range: $300 \leq f \leq 1200$

	fixed parameters			control parameter	
Geometrical Parameter	$a\ [mm]$	$b\ [mm]$	$l\ [mm]$	$r_1\ [mm]$	$r_2\ [mm]$
	19	25	14	from 2 to 5.5 with $\Delta r = 0.01$	from 2 to 5.5 with $\Delta r = 0.01$

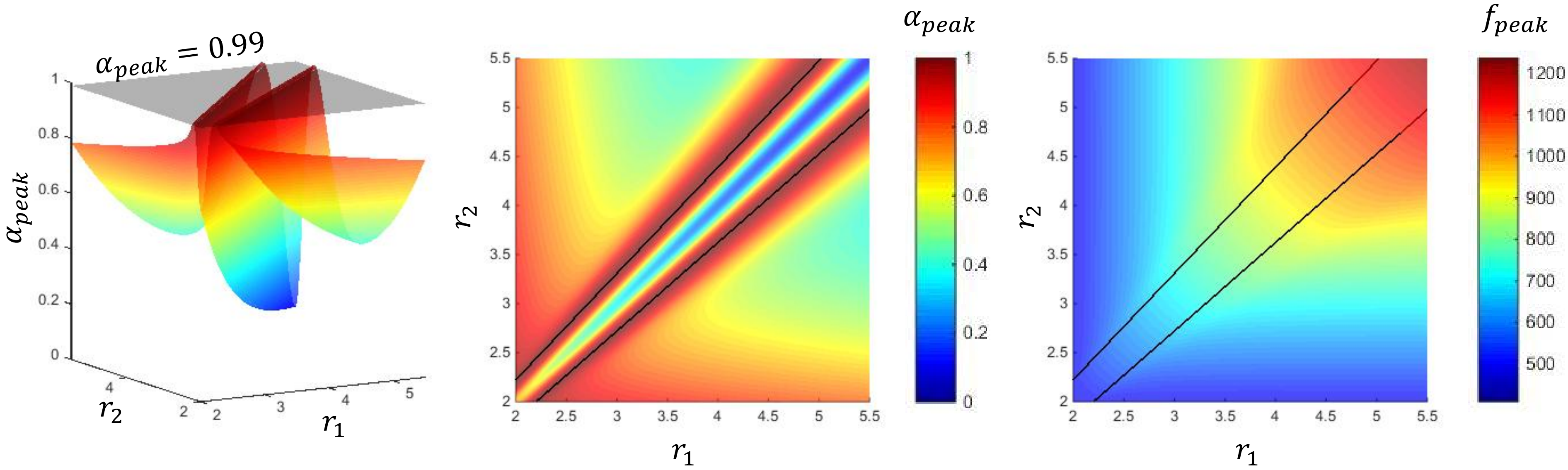
$\alpha_{\text{peak}}^{(i,j)}$: peak absorption coefficient for $r_1 = r_1^{(i)}$ and $r_2 = r_2^{(j)}$
$f_{\text{peak}}^{(i,j)}$: corresponding peak frequency for $r_1 = r_1^{(i)}$ and $r_2 = r_2^{(j)}$





Computational Proof on the Existence & Design Formula

Surface plots in r_1-r_2 plane



※ Relation between neck radii: r_2 in terms of r_1

$$r_2^{(j)} = 1.100 \times r_1^{(i)} + 0.024[mm], \qquad R^2 = 0.9996$$

※ Target frequency of perfect absorption: $f_{peak}^{(i,j)}$ in terms of r_1 and r_2

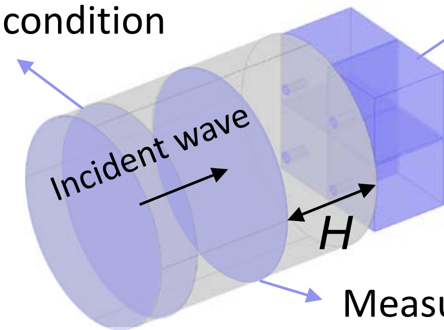
$$f_{peak}^{(i,j)} = 9473\left[\frac{Hz}{mm}\right] \times r_1^{(i)} - 8370\left[\frac{Hz}{mm}\right] \times r_2^{(j)} + 57.35\,[Hz], \qquad R^2 = 0.9995$$

Numerical/Experimental Setup

Numerical simulation setup

- Governing equation: Helmholtz equation
- Boundary condition: acoustically hard boundary at the walls

Perfectly matched layer:
non-reflecting condition

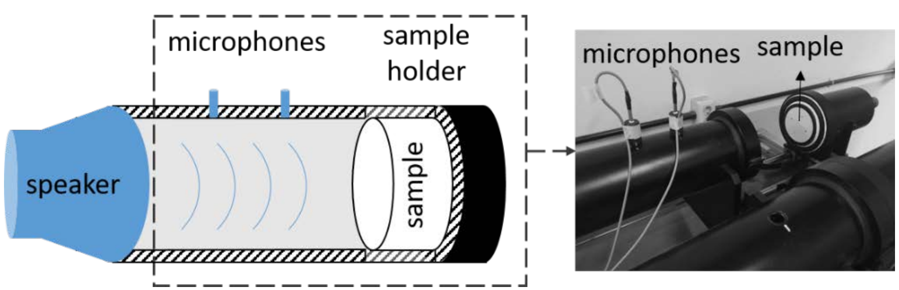


Stinson's visco-thermal loss model (Stinson, *JASA*, 1991) is used.
The effective material properties (ρ_{eff} & κ_{eff})
regarding **visco-thermal losses**
depending on the **frequencies** and **geometries**
for 'infinite' square tubes and 'infinite' circular tubes

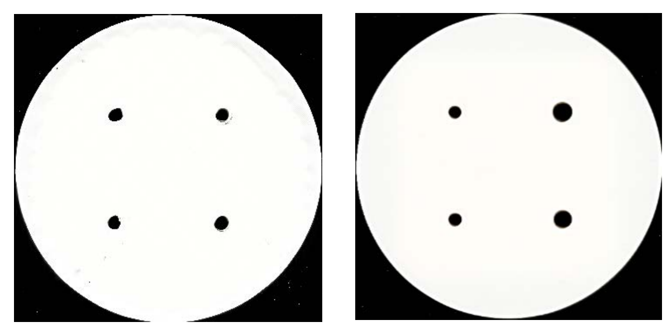
Measurement of absorption coefficient

Experimental setup

- Tested in Impedance tube (cylindrical shape)
- International standard: ISO 10534-2

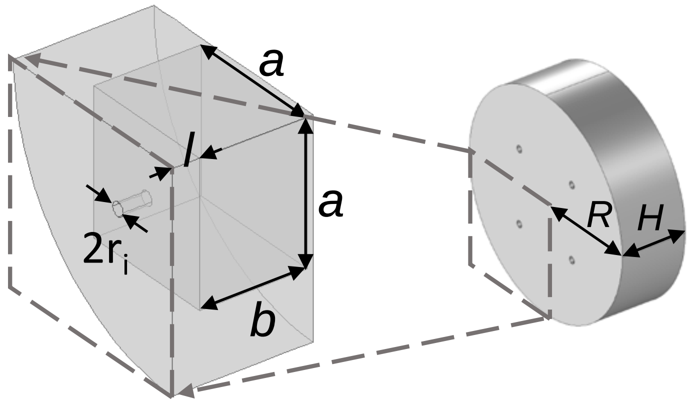


Photographs of the samples



Fabrication of Samples (single- & dual-target frequencies)

Geometry & Dimensions for Experiment

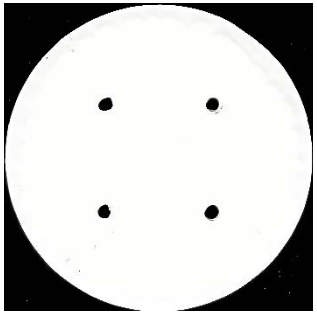


We fabricated meta-molecules in cylindrical shapes for impedance tube test.

Fabrication using 3D Printing Technology

Single-Frequency Metasurface (Sample A)

- Target frequencies: 300 Hz
- Thickness Optimization X

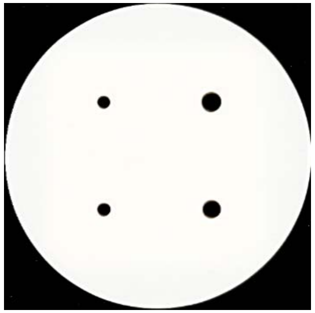


Geometrical parameters

a [mm]	b [mm]	l [mm]	r_1 [mm]	r_2 [mm]	r_3 [mm]	r_4 [mm]	R [mm]	H [mm]
33.4	39	10	2.45	2.67	2.67	2.45	50	50

Dual-Frequency Metasurface (Sample B)

- Target frequencies: 300 & 400 Hz
- Thickness Optimization X



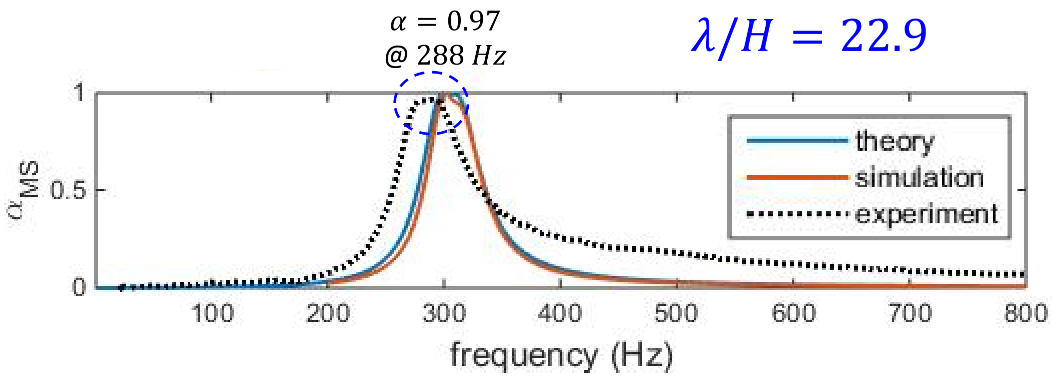
Geometrical parameters

a [mm]	b [mm]	l [mm]	r_1 [mm]	r_2 [mm]	r_3 [mm]	r_4 [mm]	R [mm]	H [mm]
33.4	39	10	2.46	2.52	3.39	3.56	50	50

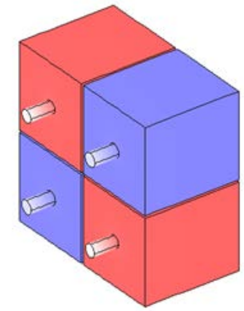
Method: Stereo lithography apparatus (SLA)
Material: UV cured acrylic polymer

Numerical/Experimental Validation

Absorptions spectrum (Sample A)

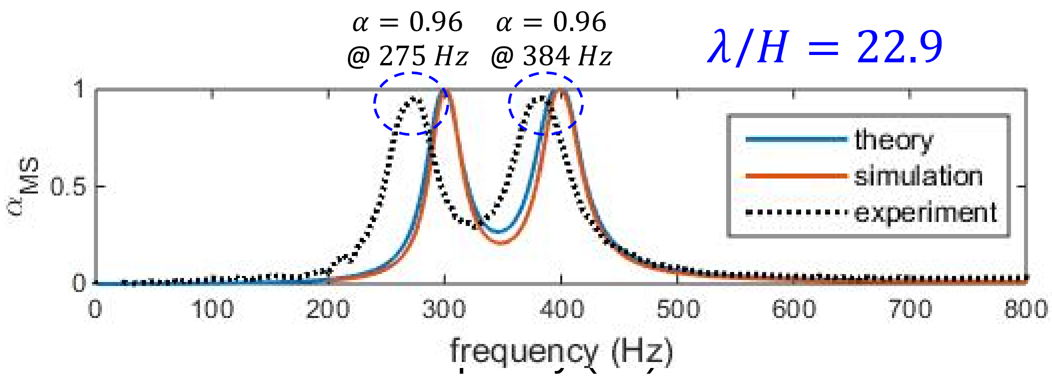


Simulated scattered pressure $(p_s' = p_t' - p_{inc}')$

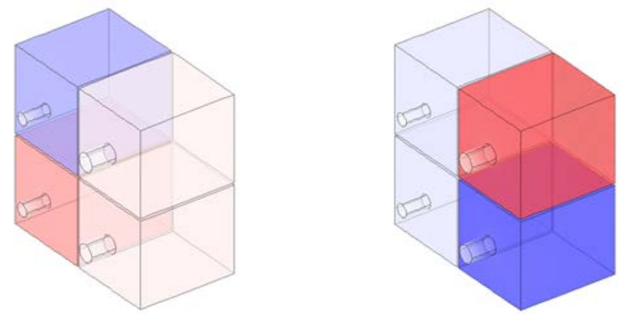


Hybrid resonance @ 300 Hz

Absorptions spectrum (Sample B)



Simulated scattered pressure $(p_s' = p_t' - p_{inc}')$



Hybrid resonances @ 300 Hz & 400 Hz

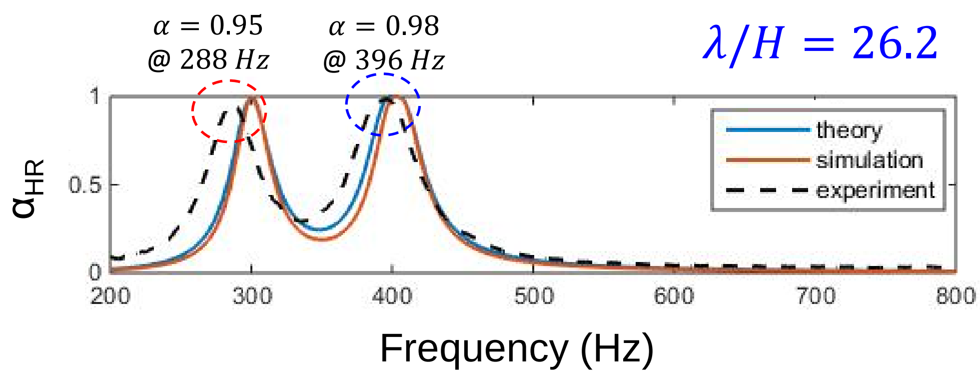
- Theoretical & numerical results have a good agreement.
- Experimental result shows nearly perfect absorption ($\alpha > 0.95$) at lower frequency than theoretical and numerical results.
  → Discrepancies between simulation and experiment are due to fabrication errors.

Thickness Optimization of Metasurface with Validation

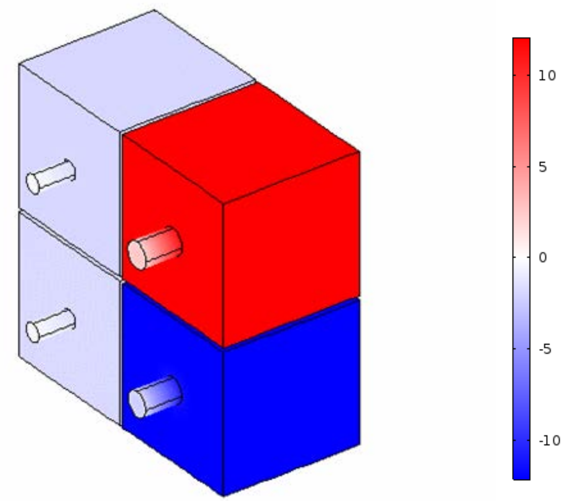
Geometrical parameters

a [mm]	b [mm]	l [mm]	r_1 [mm]	r_2 [mm]	r_3 [mm]	r_4 [mm]	R [mm]	H [mm]
33.36	33.64	8.97	2.14	2.14	2.94	3.06	50	43.6

Absorptions spectrum



Simulated scattered pressure ($p_s' = p_t' - p_{inc}'$)

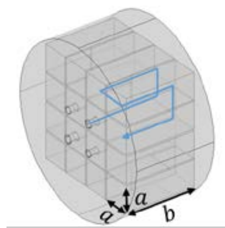


Hybrid resonance @ 400 Hz

- Theoretical & numerical results have a good agreement.
- Hybrid resonance is characterized at 400 Hz.
- Shapes of experimental curves are well matched with theory and simulation.
- Experimental result shows nearly perfect absorption ($\alpha > 0.95$) at lower frequency than theoretical and numerical results.
  → Discrepancies between simulation and experiment are due to fabrication errors.

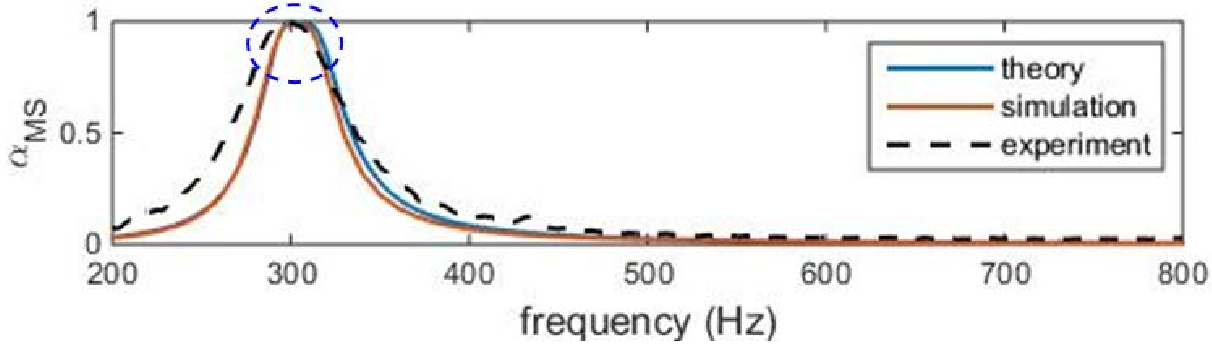
Toward Ultra-Thin Metasurface with Space Coiling

Sample C

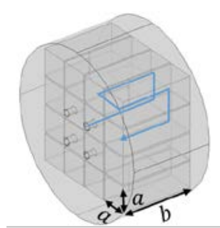


$\alpha = 0.99$
@ $297\ Hz$

$\lambda / H = 26.2$



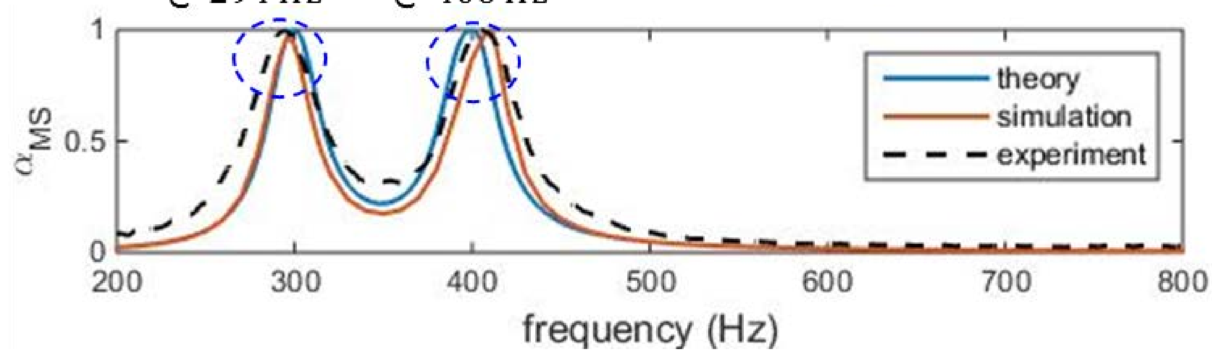
Sample D



$\alpha = 0.99$
@ $294\ Hz$

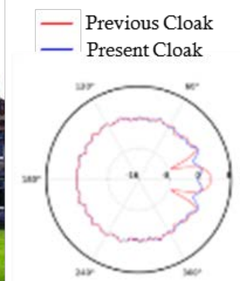
$\alpha = 0.99$
@ $406\ Hz$

$\lambda / H = 29.85$

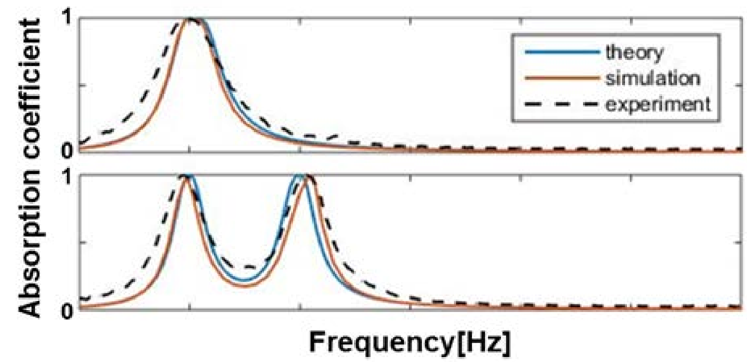


Contents

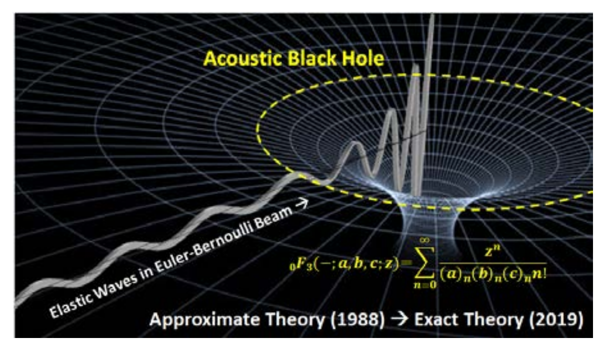
1. Acoustic Cloak in Compressible Flow



2. Hybrid-Resonant-Type Metasurface



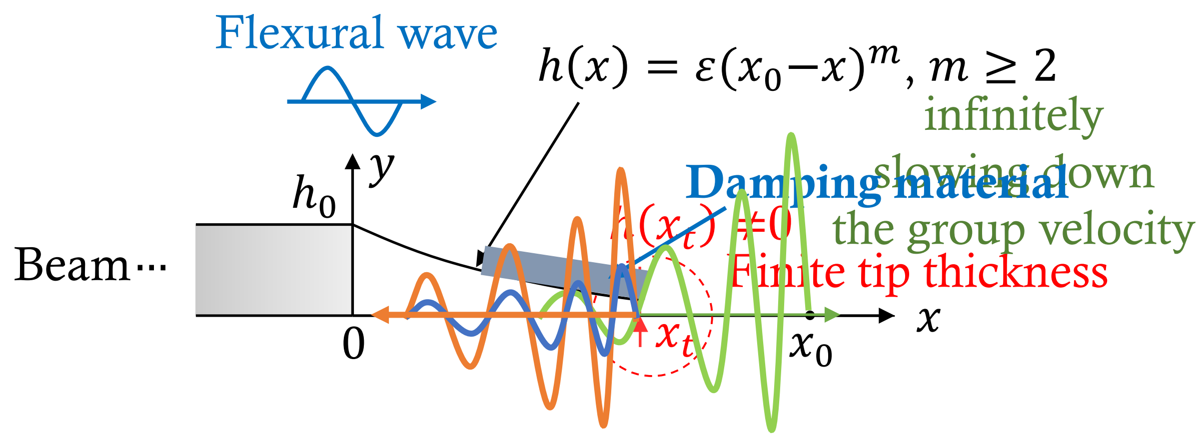
3. A Few Words on Acoustic Black Holes



Acoustic Black Hole

What is an Acoustic Black Hole (ABH) ?

ABH is a wedge-type structure with a power-law profile connected to vibrating structures such as beams or plates.

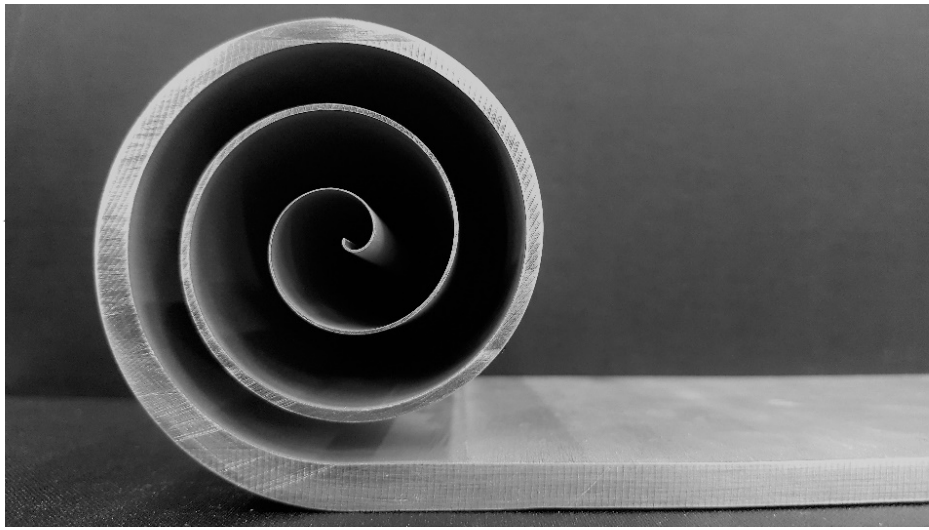


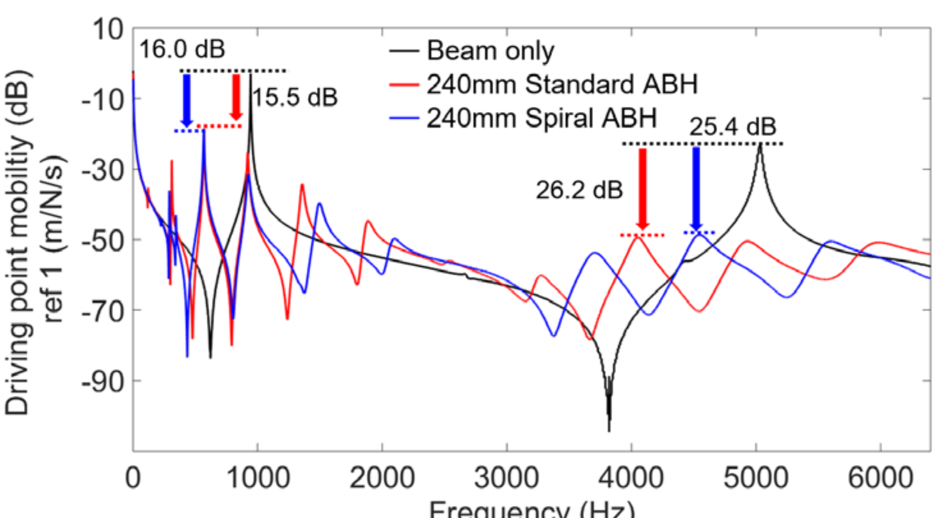
ABH is an elastic wave absorber used for vibration damper.

Practical & Theoretical Advances in Acoustic Black Hole

1. Archimedean Spiral ABH

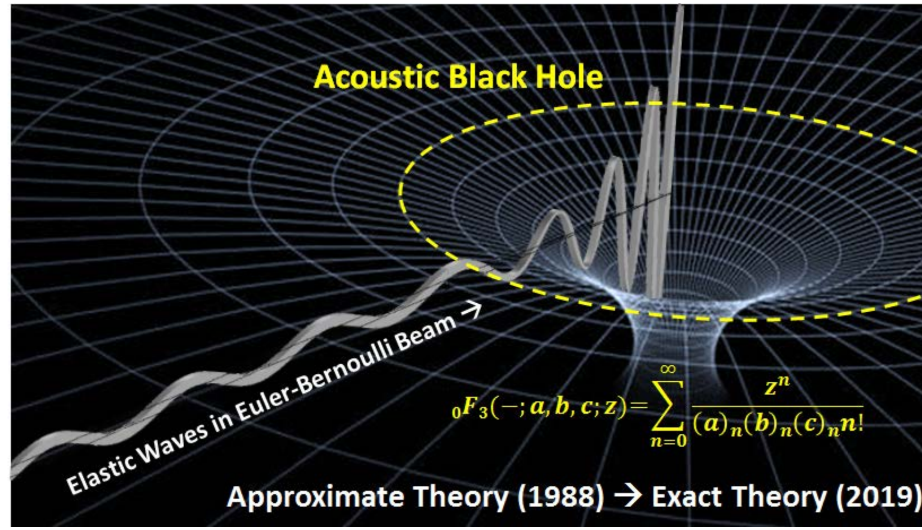
Geometrical generalization to 'non-zero' curvature using Arcs or Archimedean Spirals





2. Exact Mathematical Theory of ABH

Approximate theory based on geometrical acoustics (1988) → Exact Theory (2019)



$$_pF_q(a_1,\dots,a_p;b_1,\dots,b_q;z)=\sum_{n=0}^{\infty}\frac{(a_1)_n(a_2)_n\cdots(a_p)_n}{(b_1)_n(b_2)_n\cdots(b_q)_n}\frac{z^n}{n!}$$

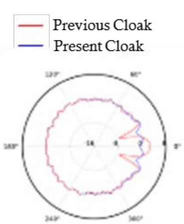
Acoustic Black Hole with Hypergeometric Functions($_pF_q$)

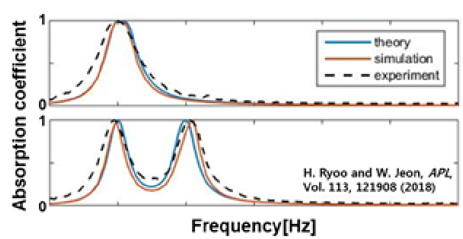
Leonhard Euler (1707-1783) | Friedrich Gauss (1777-1855) | Ernst Kummer (1810-1893) | Bernhard Riemann (1826-1866)

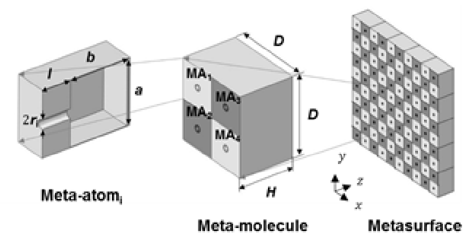
Summary

Ice Breaking with an Introduction to WAVE LAB

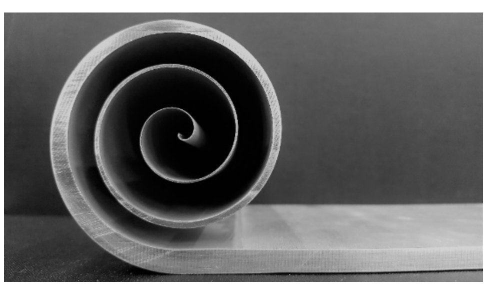
Acoustic Cloak in Flow & Sound Absorbing Metasurfaces

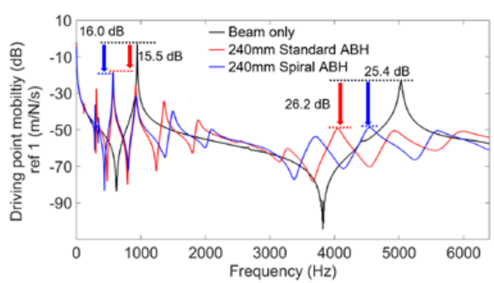


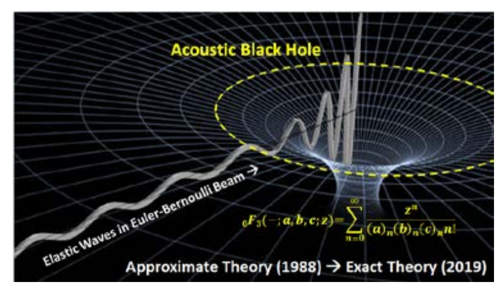




A Few Words on Recent Advances in Acoustic Black Holes








Thank You!
Imagination
Real-World
Problems