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Lightweight Absorption and Barrier Systems Comprising N-Layer Microperforates

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LIGHTWEIGHT ABSORPTION AND BARRIER SYSTEMS COMPRISING *N*-LAYER MICROPERFORATED PANELS

J. Stuart Bolton and Nicholas N. Kim

Purdue University

Ray W. Herrick Laboratories

2017/06/28

PURDUE MECHANICAL ENGINEERING

RAY W. HERRICK LABORATORIES

Paper 4pEA3 - 173rd meeting of The Acoustic Society of America

Boston MA

The Effect of Flexibility on the Acoustical Performance of Microperforated Materials

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Ray W. Herrick Laboratories
School of Mechanical Engineering
Purdue University

With thanks to: Jinho Song (Otis Elevator), Taewook Yoo (3M/EAR), Ryan Schultz (Sandia) and Yangfan Liu (Purdue)

Herrick Laboratories
PURDUE UNIVERSITY

ASA Fall meeting, Kansas City, 10/22/12

Joint ASA/ASJ meeting
Honolulu December 2016

Computational Investigation of Microperforated Materials: End Corrections, Thermal Effects and Fluid-Structure Interaction

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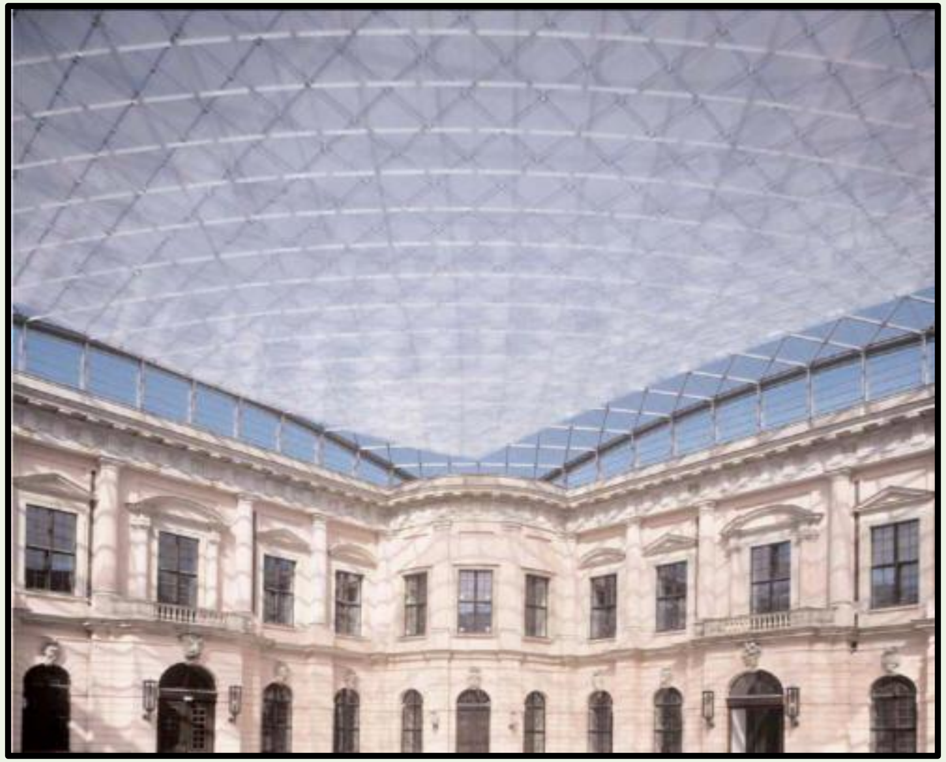
INTRODUCTION

- Traditional Uses of MPP's
  - Absorptive surface treatments



Deutsche Museum of History
Berlin

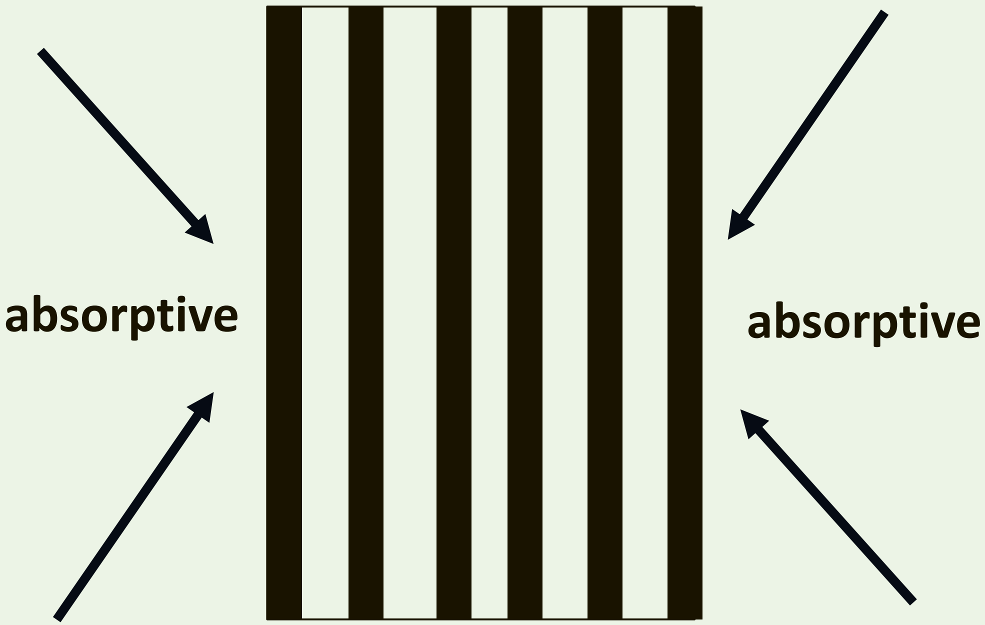
Great Ape House – National Zoo
Washington DC

OBJECTIVES

- Proposed Alternative Uses

  (i) Functional Absorbers

  →Lightweight, multi-layer, highly dissipative systems

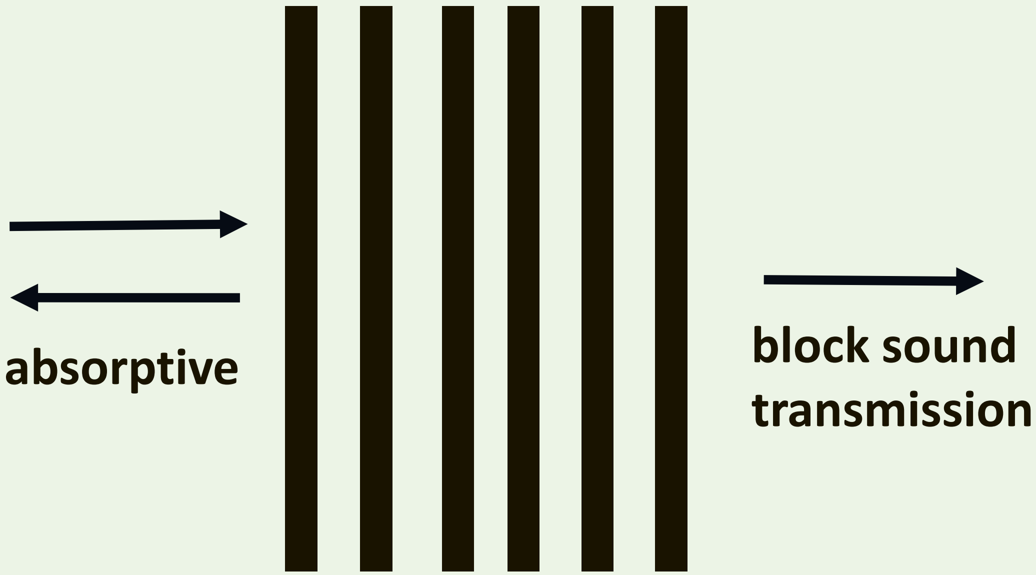


OBJECTIVES

- Proposed Alternative Uses

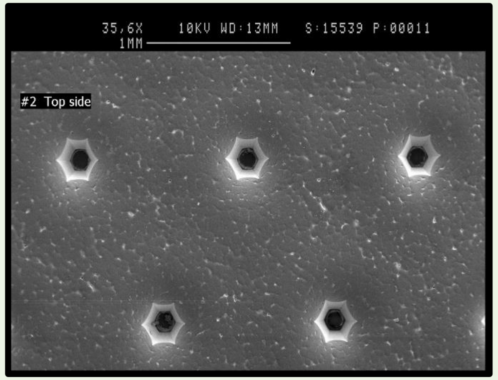
(ii) Absorbing barriers

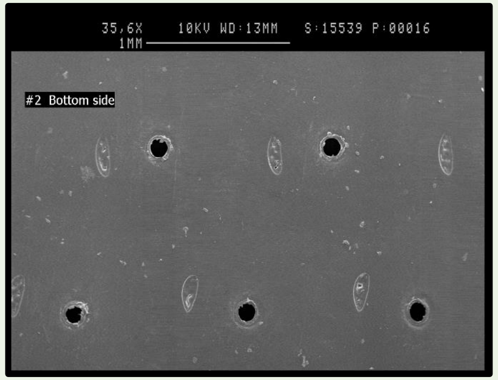
→Lightweight, multi-layer, repositionable highly dissipative barrier

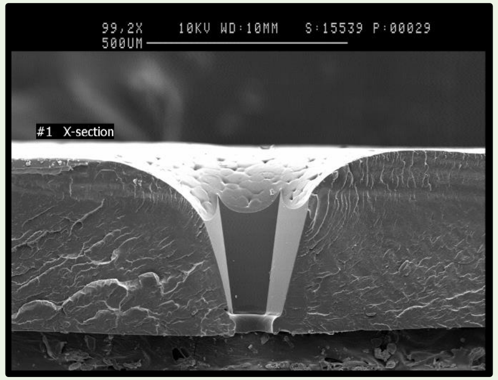


INTRODUCTION

- **Microperforated material**
  - Thin film with 100 microns scale holes
  - Clean, light → one alternative to fibrous sound absorbing materials

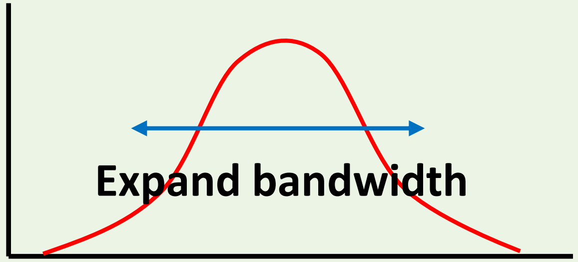






- **Viscous Dissipation**
  - In hole
  - Within shearing fluid exterior to the hole

- **Objective**
  - Multilayer panels to control sound level in speech interference range (500 Hz to 4 KHz)

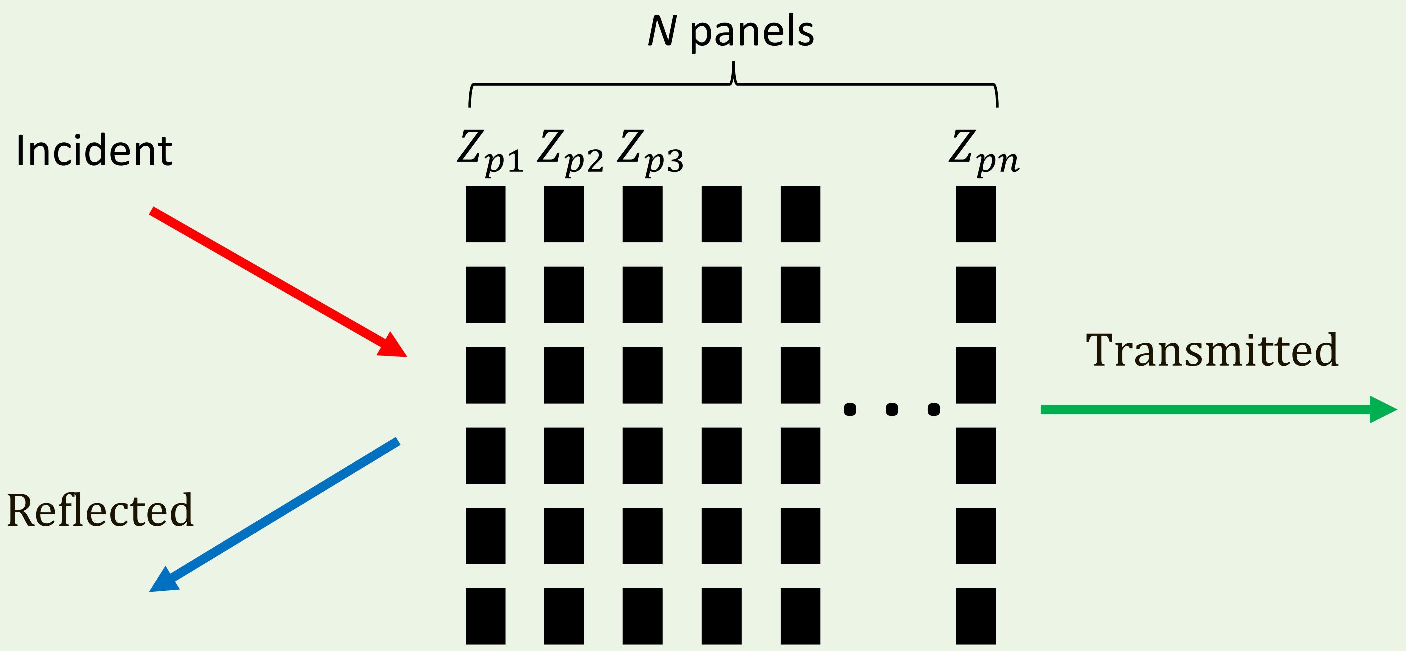


PROCEDURE

- Procedure

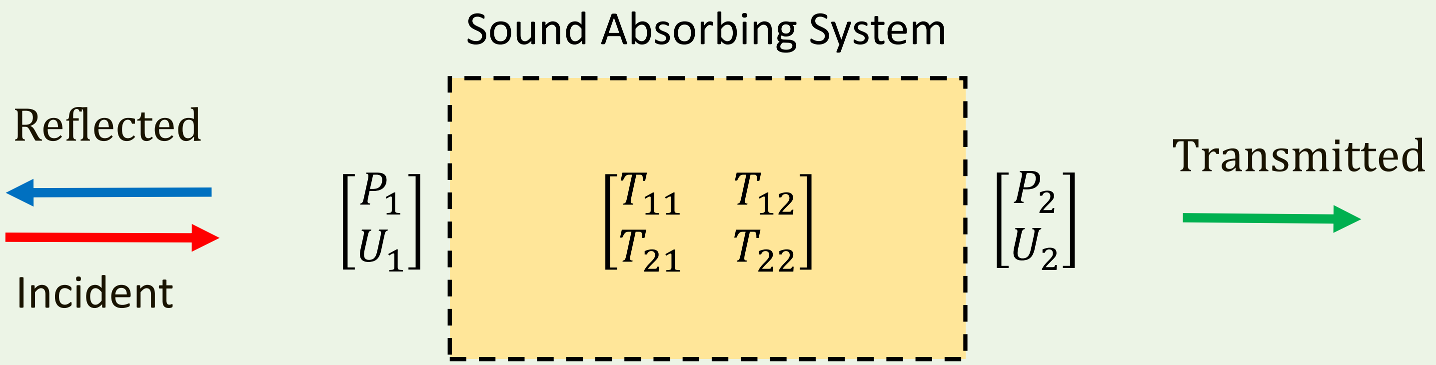
  - ✓MPP's modeled as flexible
  - ✓Locally reacting
  - ✓Bounded properties
  - ✓Arbitrary number of layers up to 10
  - ✓Arbitrary spacing of layers
  - ✓Genetic Algorithm used to optimize properties over the Speech Inteference Range (500 Hz to 4 kHz)
  - ✓Objective function depends on application

MULTI-LAYER OF MICROPERFORATED PANELS



- **Assumptions**
  - Hole in the MPP are cylindrical and sharp edged
  - Flexural stiffness of the panel can be ignored
  - Only locally reacting case considered
  - Infinite panels

TRANSFER MATRIX METHOD



- Transfer Matrix

$$\begin{bmatrix} P_1 \\ U_1 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} P_2 \\ U_2 \end{bmatrix}$$

- Reflection Coefficient

$$R = \frac{T_{11} + T_{11} \cos\theta/(\rho c) - T_{21}\,(\rho c)/\cos\theta - T_{22}}{T_{11} + T_{11} \cos\theta/(\rho c) + T_{21}\,(\rho c)/\cos\theta + T_{22}}$$

- Transmission Coefficient

$$\tau = \frac{2e^{jk \cos\theta L}}{T_{11} + T_{11} \cos\theta/(\rho c) + T_{21}\,(\rho c)/\cos\theta + T_{22}}$$

- Dissipation Coefficient

$$\alpha_d = 1 - |R|^2 - |\tau|^2$$

TRANSFER MATRIX METHOD

- Random Incidence
  - **Absorption Coefficient**

$$\bar{\alpha} = \frac{\int_0^{\pi/2} \alpha(\theta)\sin(\theta)\cos(\theta)\,d\theta}{\int_0^{\pi/2} sin(\theta)\,cos(\theta)\,d\theta}$$

  - **Dissipation Coefficient**

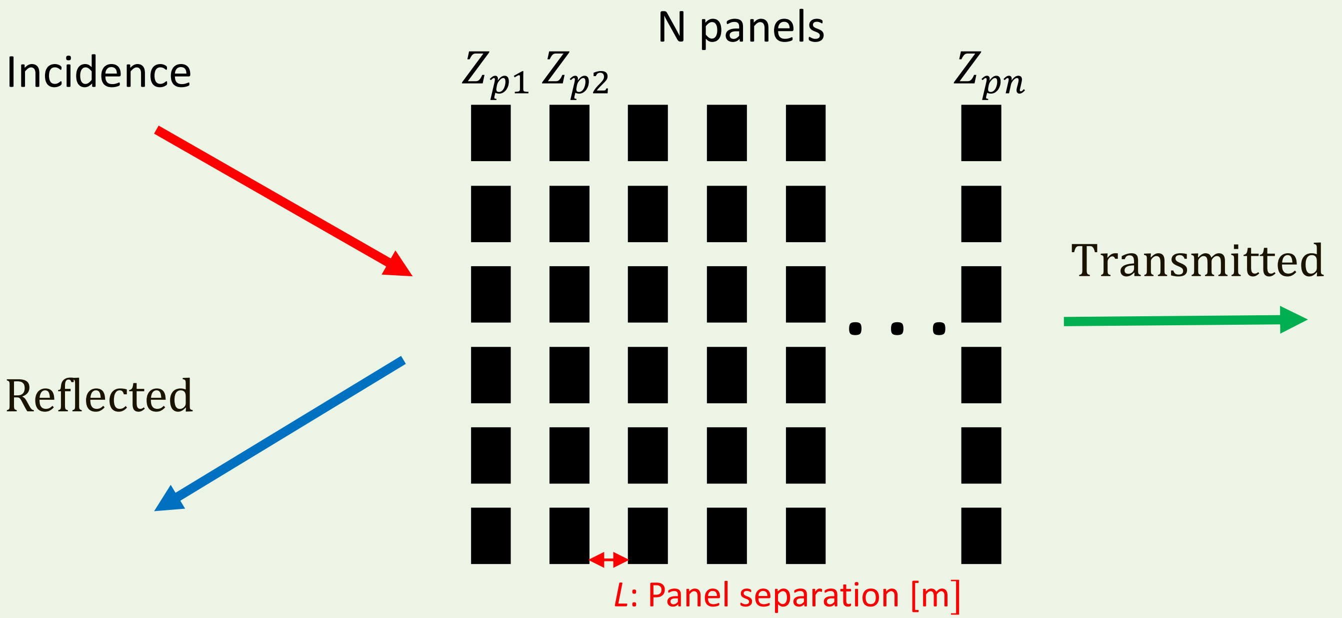
$$\bar{\alpha}_d = \frac{\int_0^{\pi/2} \alpha_d\,(\theta)\sin(\theta)\cos(\theta)\,d\theta}{\int_0^{\pi/2} sin(\theta)\,cos(\theta)\,d\theta}$$

  - **Transmission Loss**

$$\bar{\tau} = \frac{\int_0^{\pi/2} |\tau(\theta)|^2 \sin(\theta)\cos(\theta)\,d\theta}{\int_0^{\pi/2} sin(\theta)\,cos(\theta)\,d\theta}$$

$$TL = 10\log_{10}\frac{1}{\bar{\tau}}$$

TRANSFER MATRIX METHOD



TOTAL

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}_{Total} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}_{MPP1} \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}_{Air1} \cdots \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}_{MPP\,n}$$

AIR

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}_{Air} = \begin{bmatrix} \cos(kL) & j\rho c \sin(kL) \\ j\sin(kL)/\rho c & \cos(kL) \end{bmatrix}$$

(Local Reaction) $k = \frac{\omega}{c}$

MPP

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}_{MPP} = \begin{bmatrix} 1 & Z_{MPP} \\ 0 & 1 \end{bmatrix}$$

Z_{MPP} : **Transfer Impedance of each MPP**

MICROPERFORATED PANEL

- Guo et al. Model

$$R = \left(Re\left\{ \frac{j\omega t}{\sigma c}\left[1 - \frac{2}{k\sqrt{-j}}\frac{J_1(k\sqrt{-j})}{J_0(k\sqrt{-j})}\right]^{-1} \right\} + \frac{\alpha 2R_s}{\sigma \rho c} \right) \times \rho c$$

Symbol	
t	Time [sec]
σ	Surface Porosity
d	MPP hole diameter [m]

$$k = d\sqrt{\frac{\omega\rho_0}{4\eta}} \qquad R_s = \frac{\sqrt{2\omega\rho_0\eta}}{2}$$

$\alpha = 4$ when sharp end

- Previous work
  - adjusted α by CFD calculation

$$\alpha = (16.9\frac{t}{d} + 152.8)f^{-0.5}$$

  - Note that this equation was formulated in specific range of hole diameter, thickness of the panel, and porosity

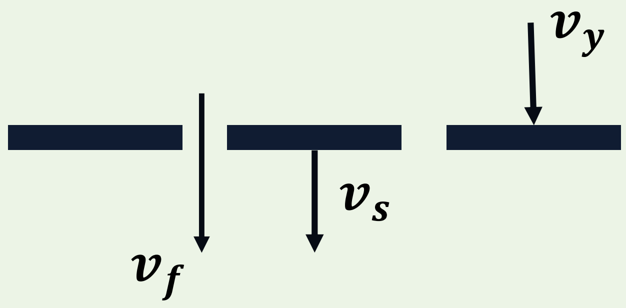
MICROPERFORATED PANEL

- Continuity and Force equilibrium – fully coupled

$$v_y = (1-\sigma)v_s + \sigma v_f$$

$$P_1 - P_2 + (v_f - v_s)R\frac{\sigma^2}{1-\sigma} = j\omega m v_s$$

$$P_1 - P_2 + (v_f - v_s)R\sigma = \rho h_p j\omega v_f$$



where $h_p = t + 2\delta\,, \quad \delta = 8d/3\pi$

- Fully coupled transfer impedance of MPP*

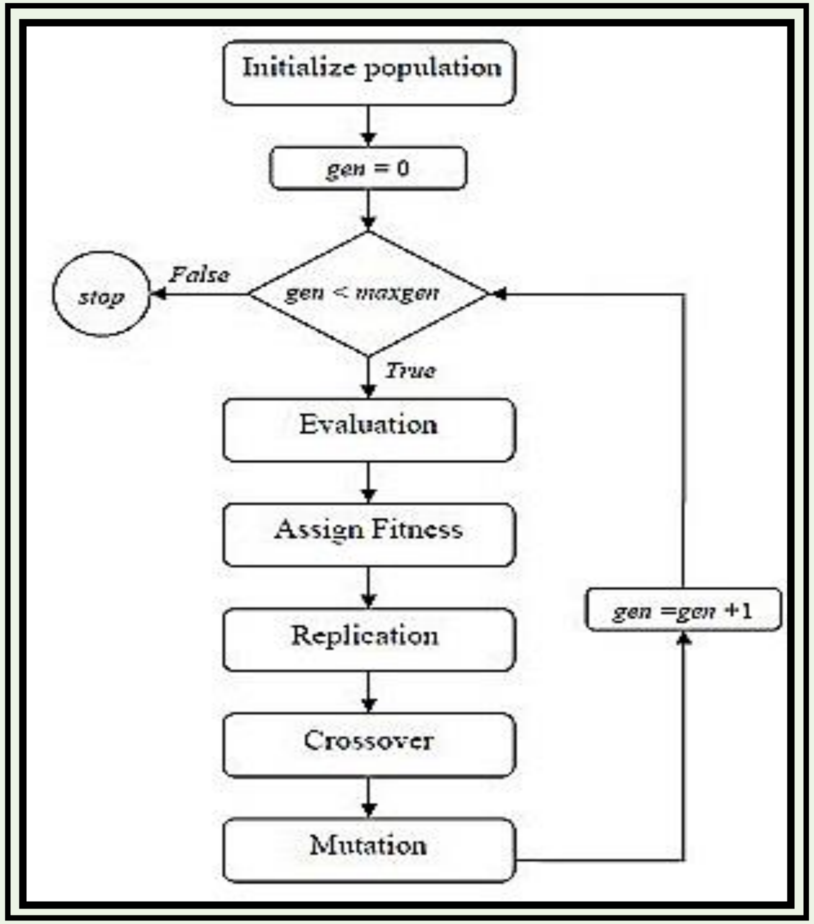
m: Panel Mass [kg/m^2]

$$Z_{MPP} = \frac{R\sigma(1-\sigma)\big(j\omega m - j\omega\rho(t+2\delta)\big) + j\omega\rho(t+2\delta)\big(j\omega m(1-\sigma) + R\sigma\big)}{\sigma(1-\sigma)(R + j\omega m) + (1-\sigma)^2\rho(t+2\delta)j\omega + \sigma^2 R}$$

* Taewook Yoo, Ph.D Thesis, Purdue University (2008)

OPTIMIZATION ALGORITHM

- GA [GENETIC ALGORITHM]

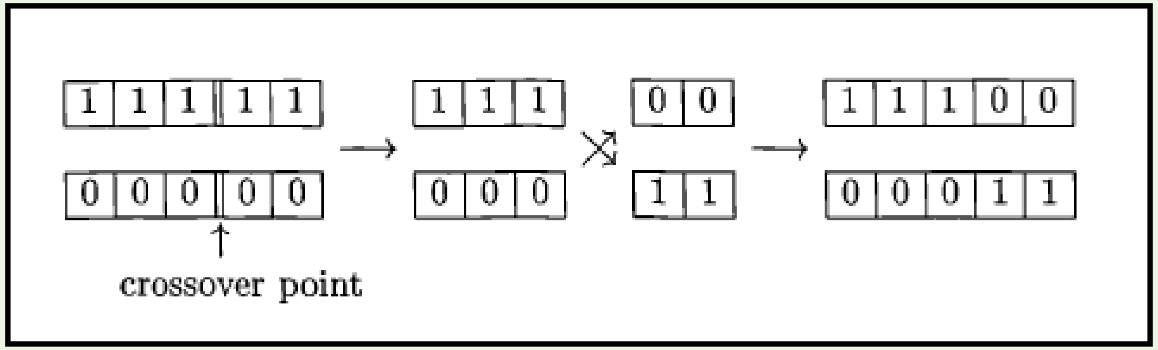


Initial population (initial point) generated at random.

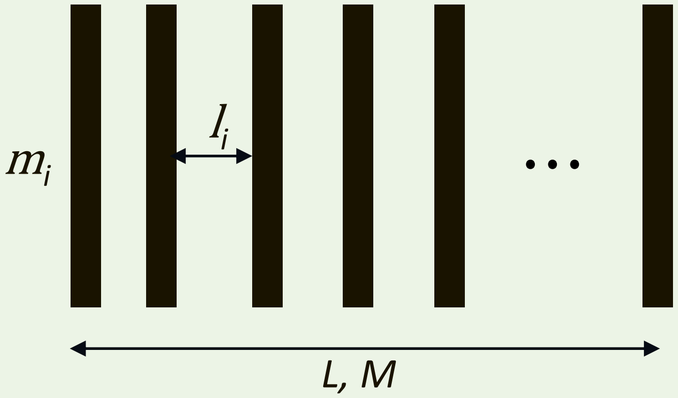
Replication is the process of choosing the best individuals to participate in the production of offspring.

Crossover is to reconstruct points by mixing from the pool. Each solution is split in two by the crossover point, which is chosen at random.

Mutation is a random change of some individuals.



OPTIMIZATION



- Constraints

	Minimum	Maximum
N	2	10
Thickness of MPP: t [mm]	0.2	0.8
MPP hole diameter: d [mm]	0.1	0.3
Surface porosity: σ	0.01	0.2
Panel mass: m [kg/m^2]	0.1	0.8
Panel separation: l [m]	0.001	0.2
Total mass: M [kg/m^2]		3
Total depth: L [m]		0.5

Varied in optimization process

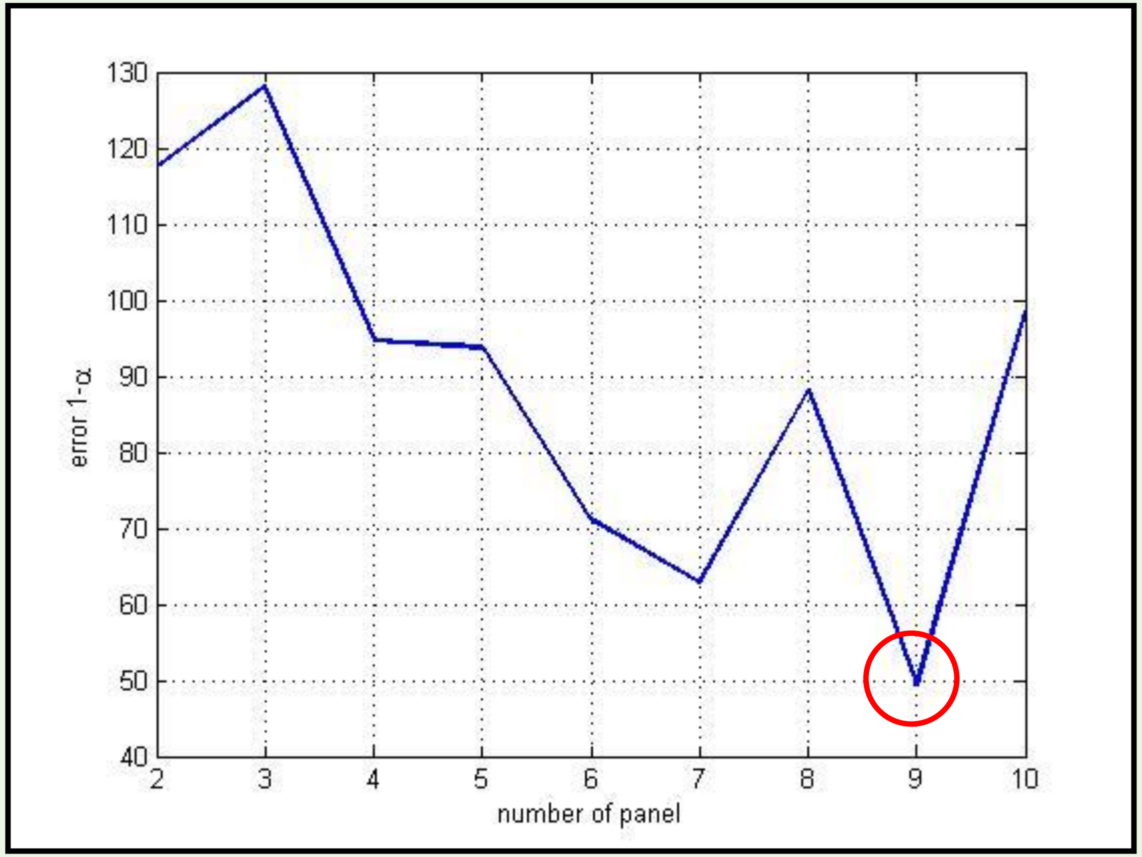
- **Genetic Algorithm was used for optimization: function for optimization is not differentiable and also is not continuous at some points**

FUNCTIONAL ABSORBER

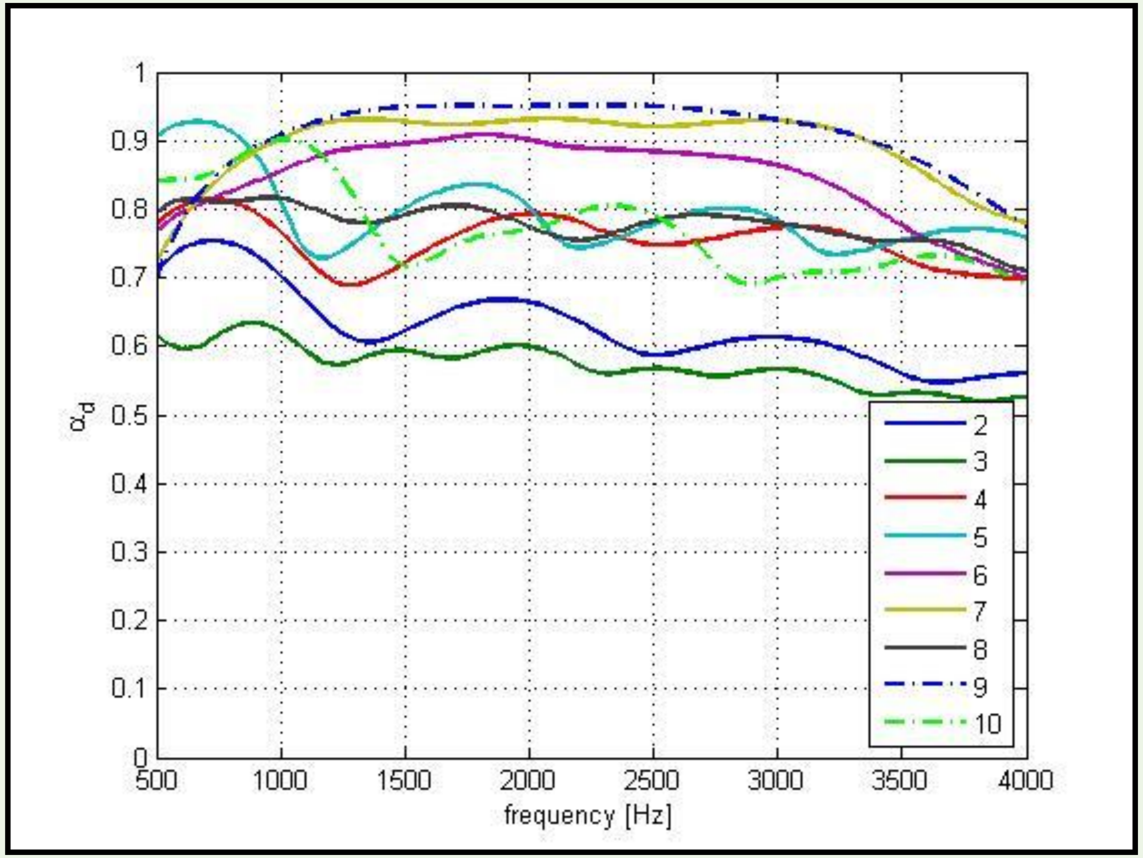
- Used for dissipating energy
- Both directions were considered
- Maximize dissipation coefficient, $\overline{\alpha}_d$

- **Optimization for Dissipation Coefficient**

Result by number of panel (error function: Σ(1-$\overline{\alpha}_d$))



Result by number of panels ($\overline{\alpha}_d$)



RANDOM INCIDENCE CASE

- **Optimization for Dissipation coefficient**

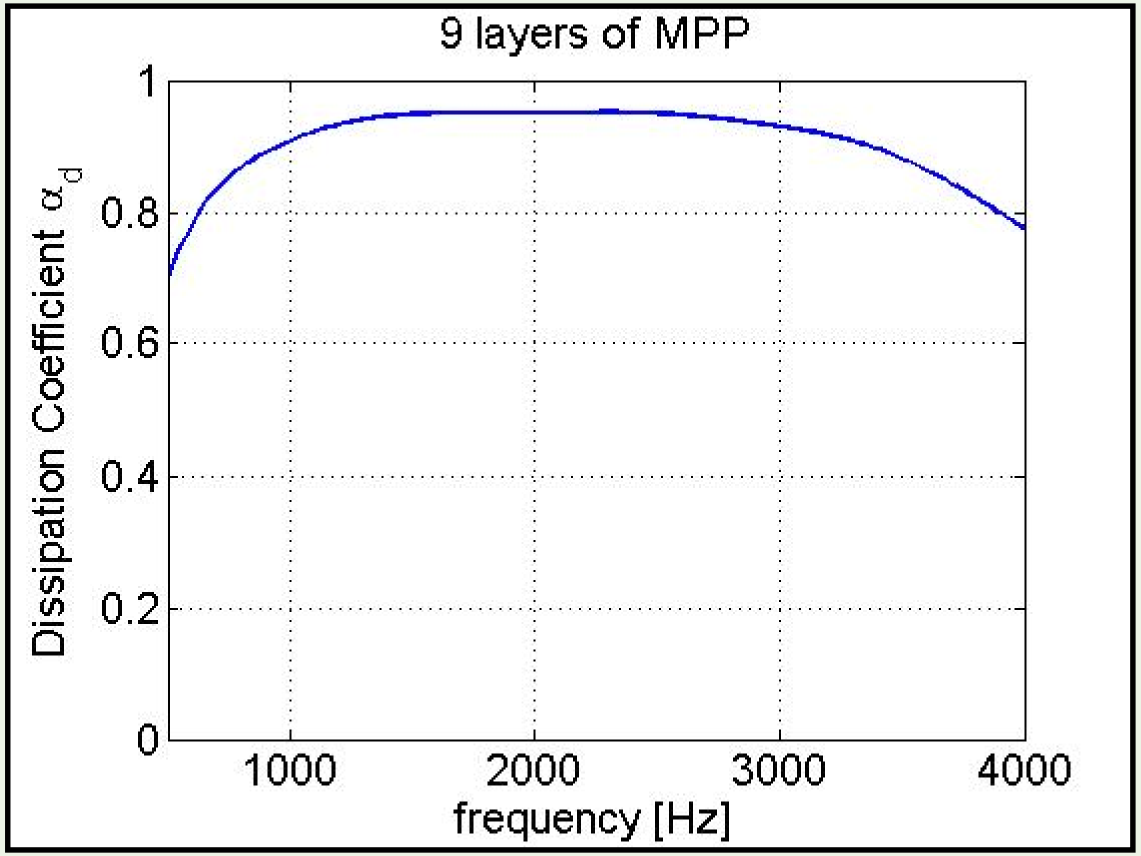
Parameters for 9 panels

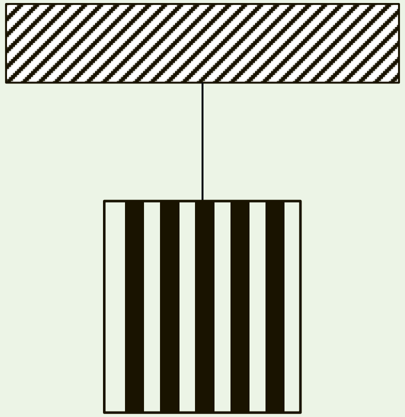
	t Thickness [mm]	*d* Diameter [mm]	*σ* Porosity	*m* Mass per unit area [kg/m²]	*l* Distance to next panel [m]
Panel 1	0.3411	0.2831	0.0635	0.6974	0.0368
Panel 2	0.7350	0.1191	0.0614	0.1181	0.0401
Panel 3	0.7531	0.1000	0.0648	0.2289	0.0372
Panel 4	0.6777	0.1000	0.0240	0.7085	0.0053
Panel 5	0.7493	0.3000	0.0438	0.7308	0.0368
Panel 6	0.7960	0.1000	0.0437	0.1880	0.0176
Panel 7	0.4441	0.3000	0.0125	0.1115	0.0395
Panel 8	0.7960	0.1610	0.1219	0.1051	0.0286
Panel 9	0.7493	0.3000	0.0725	0.1000	-

M = 2.9883 kg/m², L = 0.2479 m

RANDOM INCIDENCE CASE

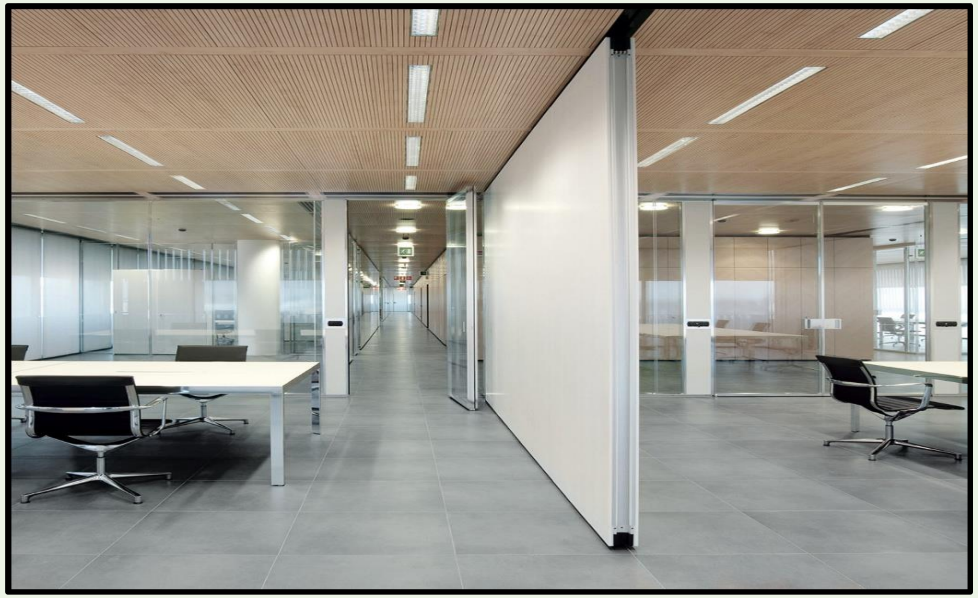
- **Optimization for Dissipation coefficient**
  - Finite size wall alter performance (*L* = 0.25 m, *M* = 3 kg/m*m)





- **Suspended multilayer systems can dissipate almost all incident acoustic energy**
- **Finite size will impact performance**

ABSORPTIVE BARRIER (I): Maximize TL

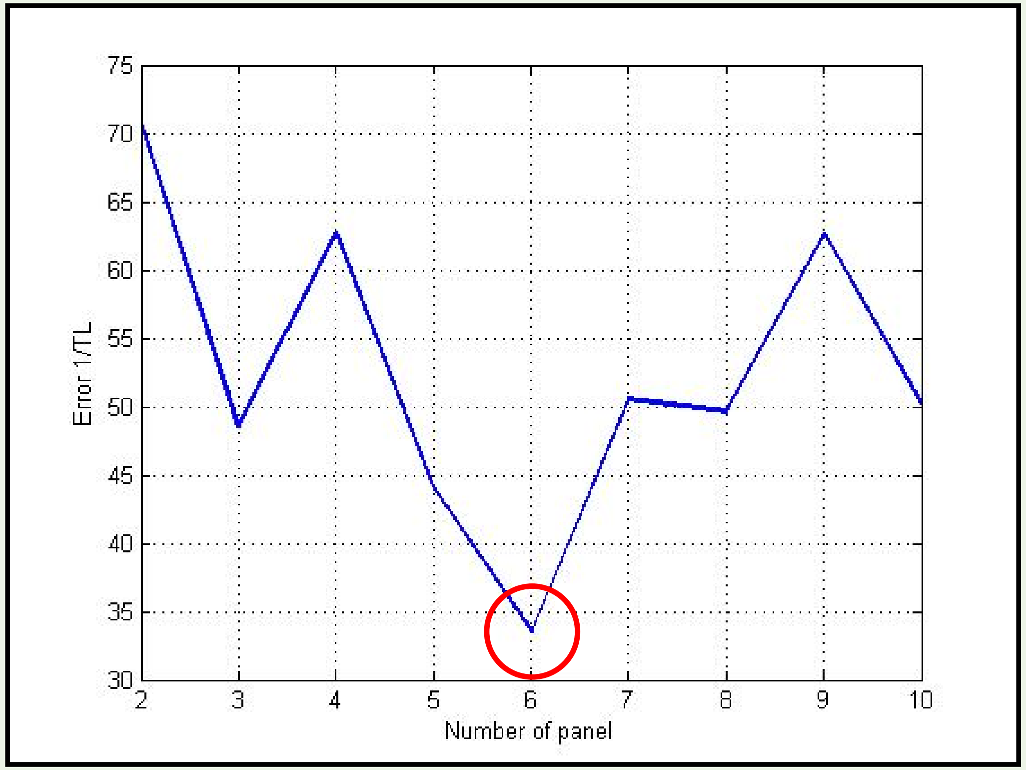


- Use for blocking noise propagating from one side to other
- One direction was considered
- Maximizing transmission loss
- Remove the valley point (eliminate minima in TL, which does not guarantee high peak TL)

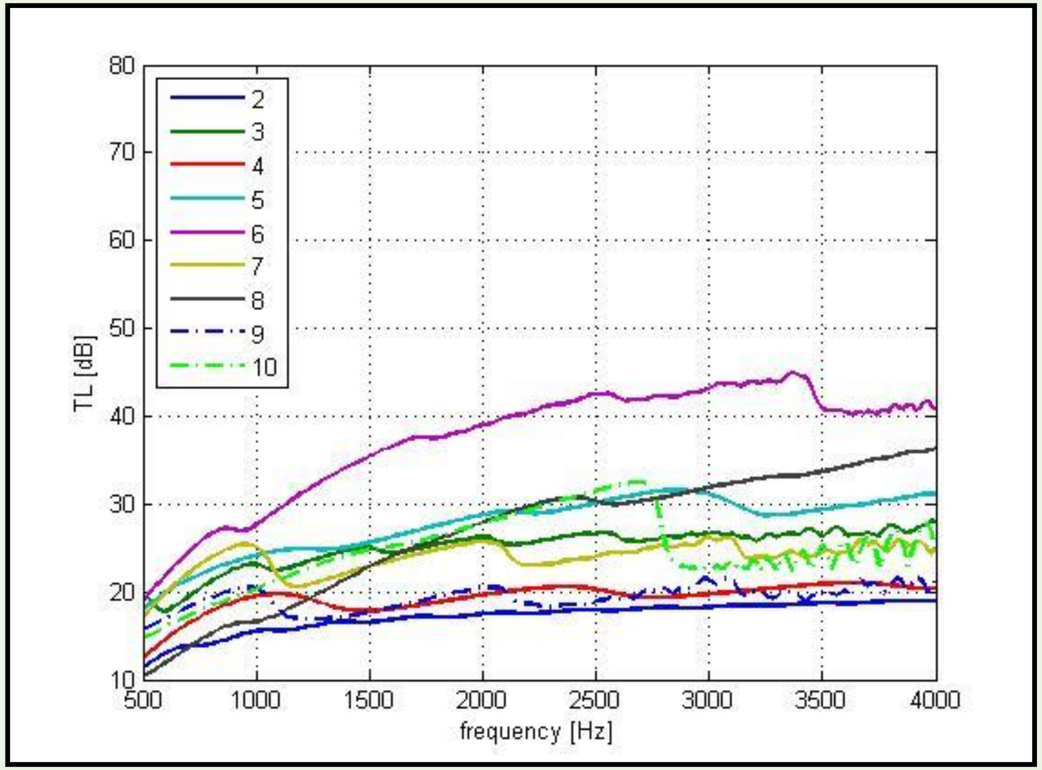
RANDOM INCIDENCE CASE

- **Optimization for Transmission Loss**

Result by number of panel (error function: Σ(1/*TL*))



Result by number of panels



RANDOM INCIDENCE CASE

- **Optimization for Transmission Loss**

Parameters for 6 panels

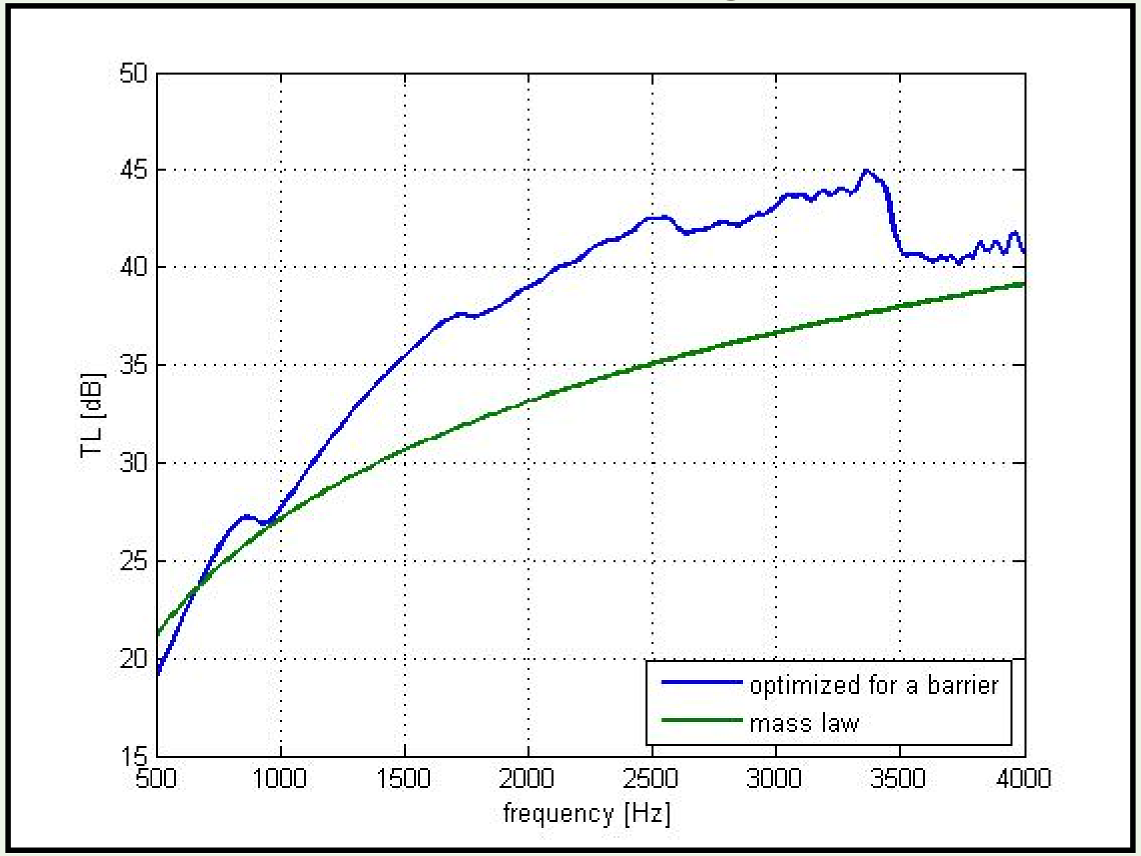
	t Thickness [mm]	*d* Diameter [mm]	*σ* Porosity	*m* Mass per unit area [kg/m²]	*l* Distance to next panel [m]
Panel 1	0.8000	0.3000	0.0725	0.3755	0.2000
Panel 2	0.7494	0.1000	0.0100	0.7000	0.2000
Panel 3	0.8000	0.1000	0.0101	0.7295	0.0363
Panel 4	0.8000	0.3000	0.2000	0.7014	0.0020
Panel 5	0.8000	0.3000	0.1375	0.1332	0.0049
Panel 6	0. 7646	0.1000	0.0100	0.3500	-

M = 2.9896 kg/m^2, L = 0.4475 m

RANDOM INCIDENCE CASE

- **Comparison of optimized set and mass law set (Number of panels: 6)**

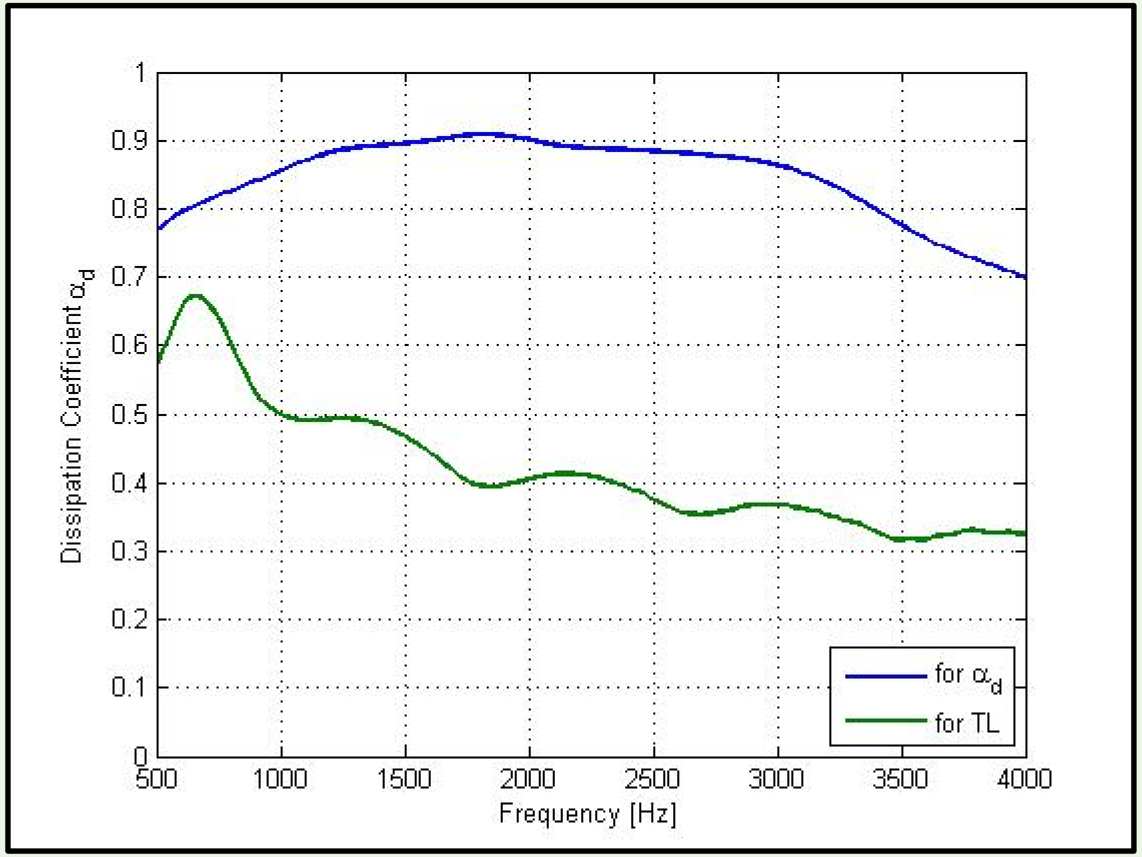
Mass Law: m = 3 kg/m²



- **Performance of multilayer system is better than mass law**
- **Has further advantage of being absorptive on incident side, so does not increase level on source side**

RANDOM INCIDENCE CASE

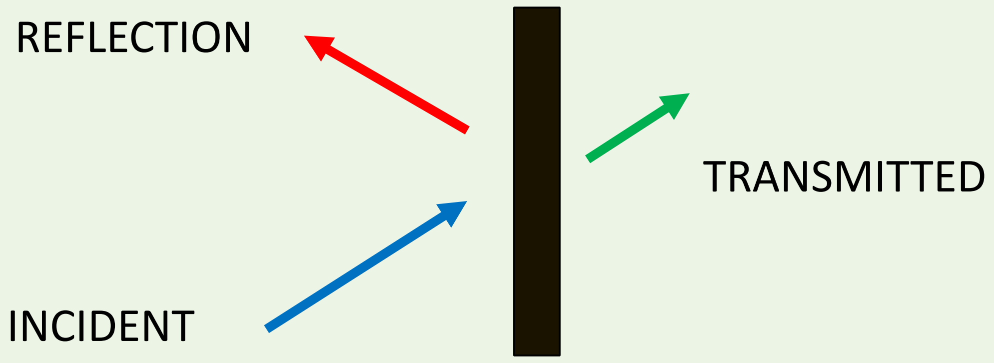
- **Comparison of optimized set for $\overline{\alpha}_d$ and for *TL* (*N* = 6)**



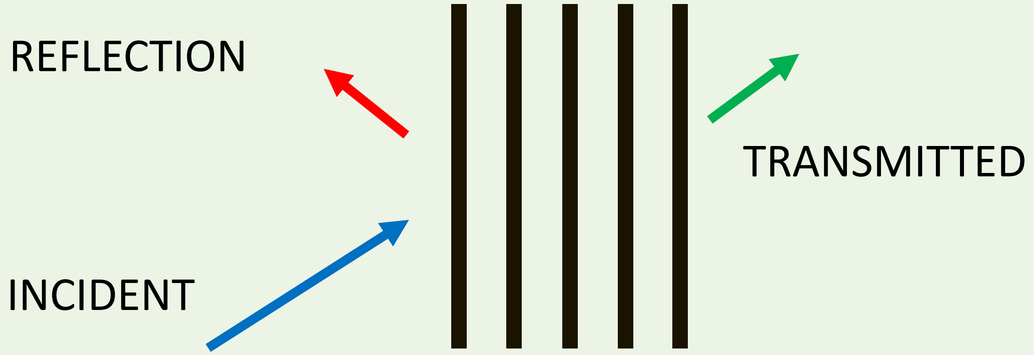
- **Still significant dissipation when optimized for transmission loss**

BARRIER TREATMENT

- **Impermeable Barrier**

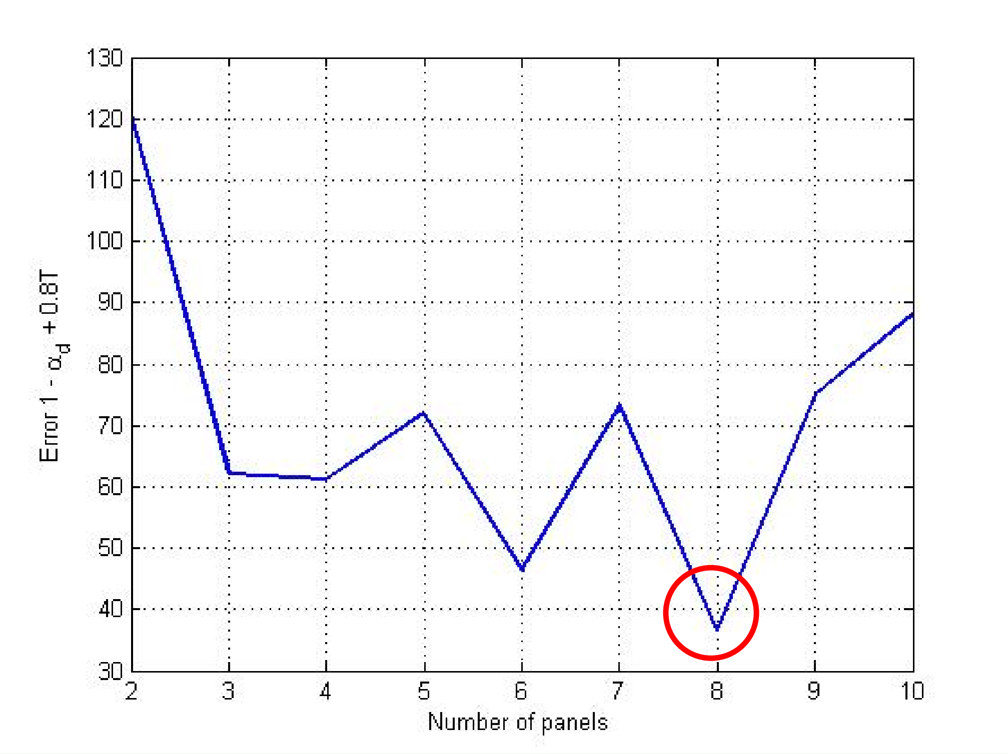


- **Dissipative Barrier**



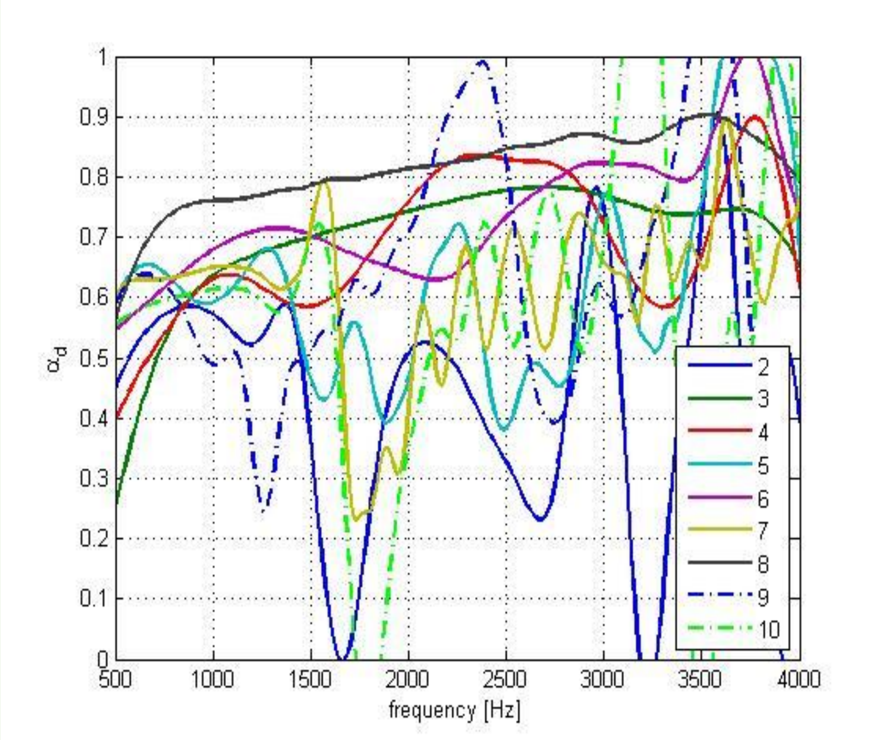
ABSORPTIVE BARRIER (II): TL and absorption

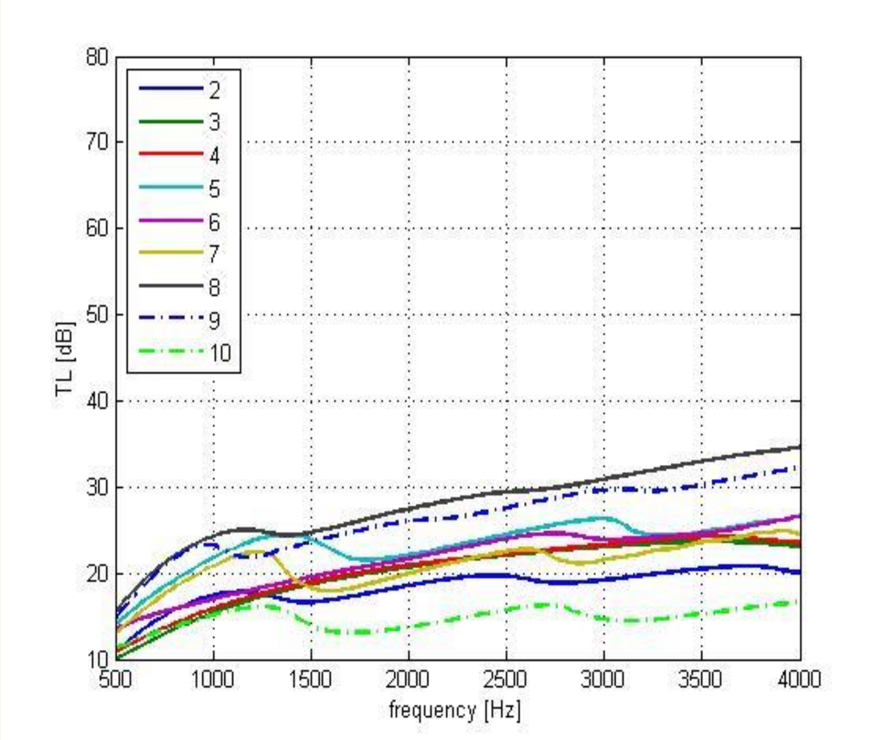
- **Optimization for Partition**
  - **Result by number of panels (error function: Σ(1-α_d-0.8T))**



RANDOM INCIDENCE CASE

- **Optimization for Partition**
  - **Result by number of panels**





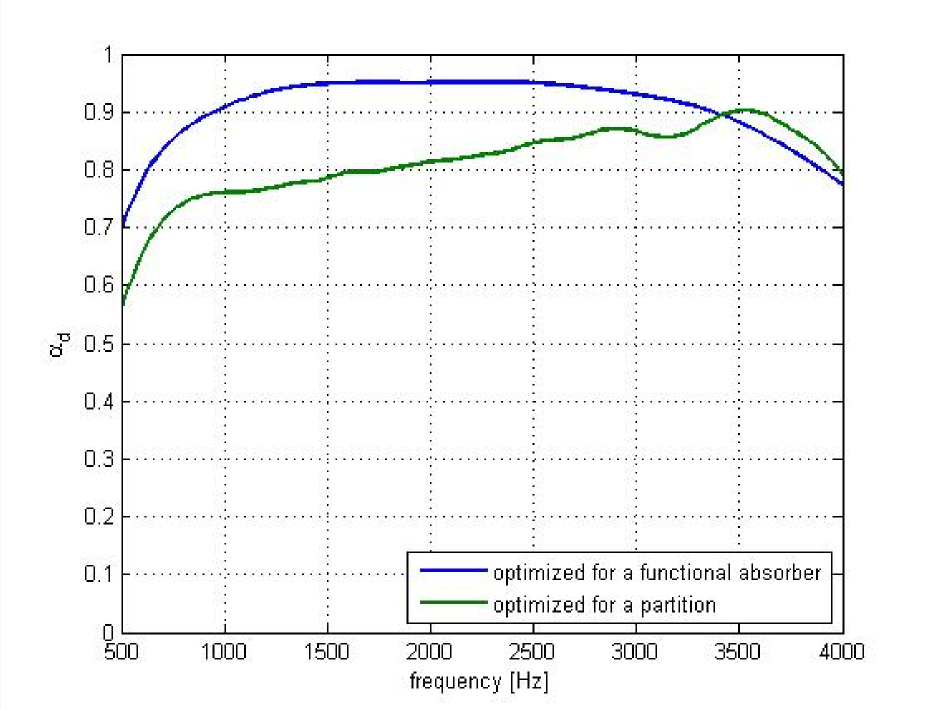
RANDOM INCIDENCE CASE

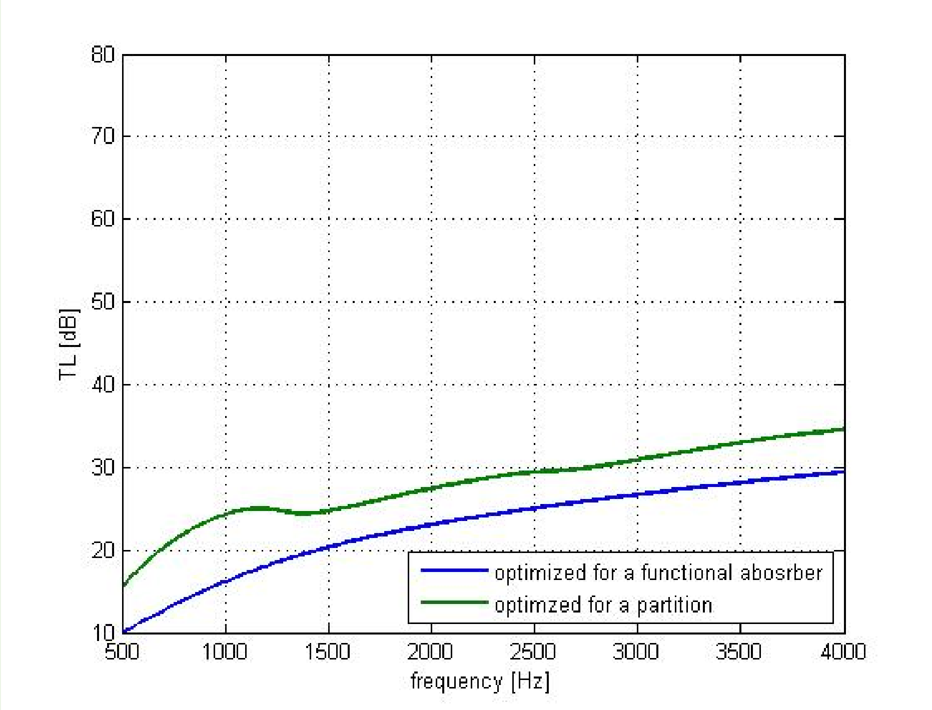
- **Optimization for Partition**
  - **Parameters for 8 panels**

	Thickness [mm]	Diameter [mm]	Porosity	Mass per unit area [kg/m²]	Distance to next panel [m]
Panel 1	0.800	0.300	0.113	0.100	0.030
Panel 2	0.800	0.300	0.105	0.140	0.023
Panel 3	0.800	0.300	0.183	0.382	0.017
Panel 4	0.800	0.176	0.042	0.100	0.024
Panel 5	0.780	0.300	0.076	0.112	0.004
Panel 6	0.234	0.193	0.015	0.631	0.031
Panel 7	0.800	0.100	0.035	0.644	0.136
Panel 8	0.800	0.100	0.010	0.618	-

RANDOM INCIDENCE CASE

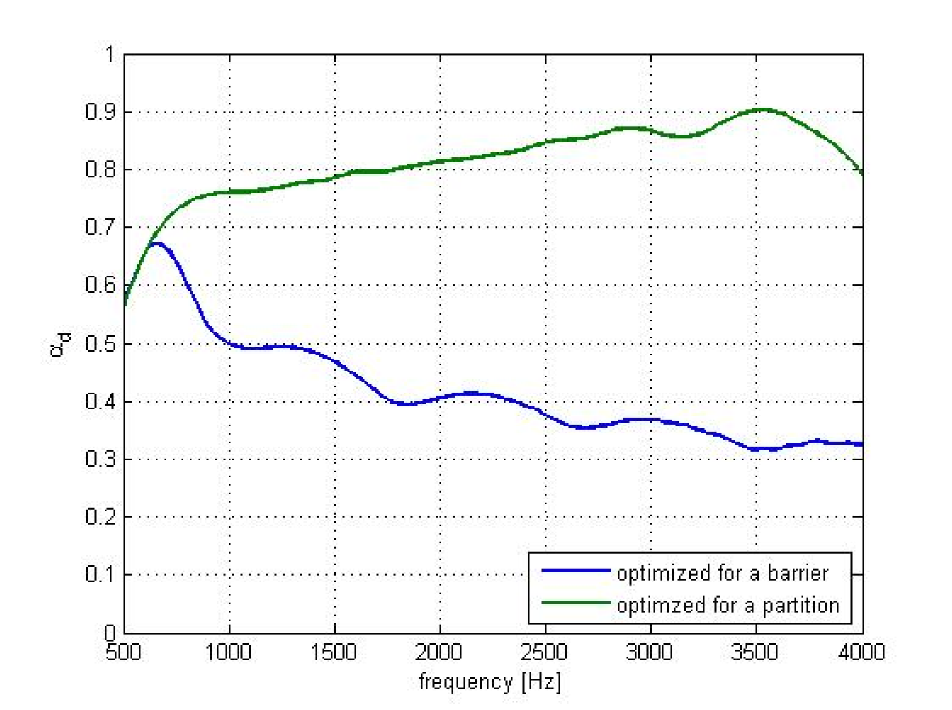
- **Comparison optimized result for a functional absorber and for a partition**

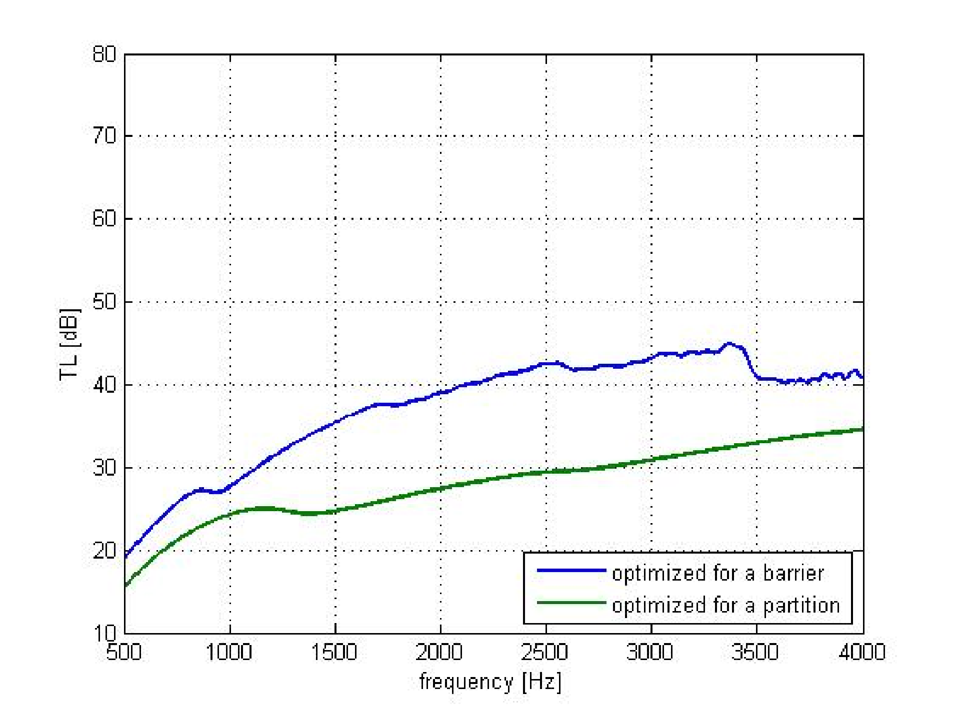




RANDOM INCIDENCE CASE

- **Comparison optimized result for a functional absorber and for a partition**





CONCLUSIONS

- **Optimization model for a functional absorber and a barrier cases were introduced**

- **Optimization result for multi-layer panels covers much broader frequency range than single panel**

- **Future work:**

  - **To decide number of segments, design optimization model for an extended reacting case**
  - **To decide size of the system, effects edge scattering and constraint when optimizing the system**

- **For presentations – search for "Herrick e-Pubs"**