8-26-2019

Poro-elastic Materials and the Control of Low Frequency Sound

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NOISE-CON 2019

August 26-28, 2019
San Diego, CA

PORO-ELASTIC MATERIALS AND THE CONTROL OF LOW FREQUENCY SOUND

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PURDUE MECHANICAL ENGINEERING

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LOW FREQUENCY ACOUSTIC PERFORMANCE

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ARTICLE

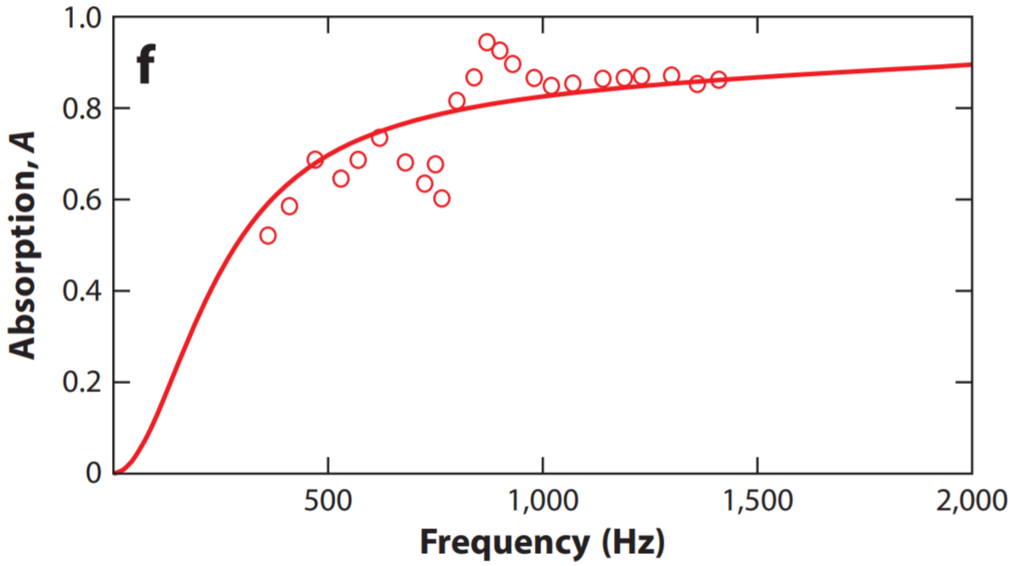
Received 25 Jul 2011 | Accepted 23 Feb 2012 | Published 27 Mar 2012

DOI: 10.1038/ncomms1758

Dark acoustic metamaterials as super absorbers for low-frequency sound

Jun Mei[1,*], Guancong Ma[1,*], Min Yang[1], Zhiyu Yang[1], Weijia Wen[1] & Ping Sheng[1]

The attenuation of low-frequency sound has been a challenging task because the intrinsic dissipation of materials is inherently weak in this regime. Here we present a thin-film acoustic metamaterial, comprising an elastic membrane decorated with asymmetric rigid platelets that aims to totally absorb low-frequency airborne sound at selective resonance frequencies ranging from 100–1,000 Hz. Our samples can reach almost unity absorption at frequencies where the relevant sound wavelength in air is three orders of magnitude larger than the membrane thickness. At resonances, the flapping motion of the rigid platelets leads naturally to large elastic curvature energy density at their perimeter regions. As the flapping motions couple only minimally to the radiation modes, the overall energy density in the membrane can be two-to-three orders of magnitude larger than the incident wave energy density at low frequencies, forming in essence an open cavity.



https://www.nature.com/articles/ncomms1758
https://doi.org/10.1146/annurev-matsci-070616-124032

INTRODUCTION

- Effect of front and rear surface boundary conditions on foam sound absorption
- Influence of edge constraints on transmission loss of poroelastic materials including effect of finite mass supports
- “Metamaterial” barrier

CEPSTRAL TECHNIQUES IN THE MEASUREMENT OF ACOUSTIC REFLECTION COEFFICIENTS, WITH APPLICATIONS TO THE DETERMINATION OF ACOUSTIC PROPERTIES OF ELASTIC POROUS MATERIALS

by

John Stuart Bolton

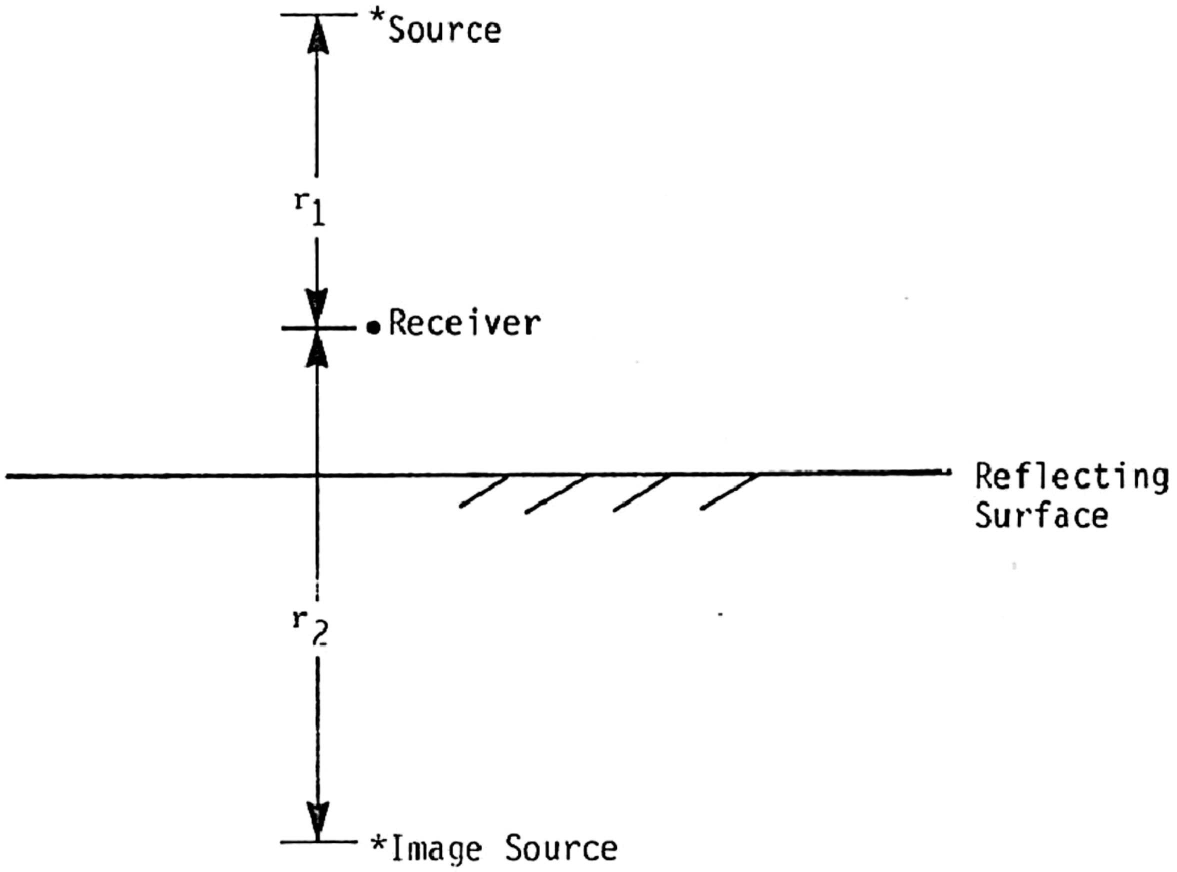
Institute of Sound and Vibration Research
Faculty of Engineering and Applied Science
University of Southampton

Thesis submitted for the degree of

Doctor of Philosophy

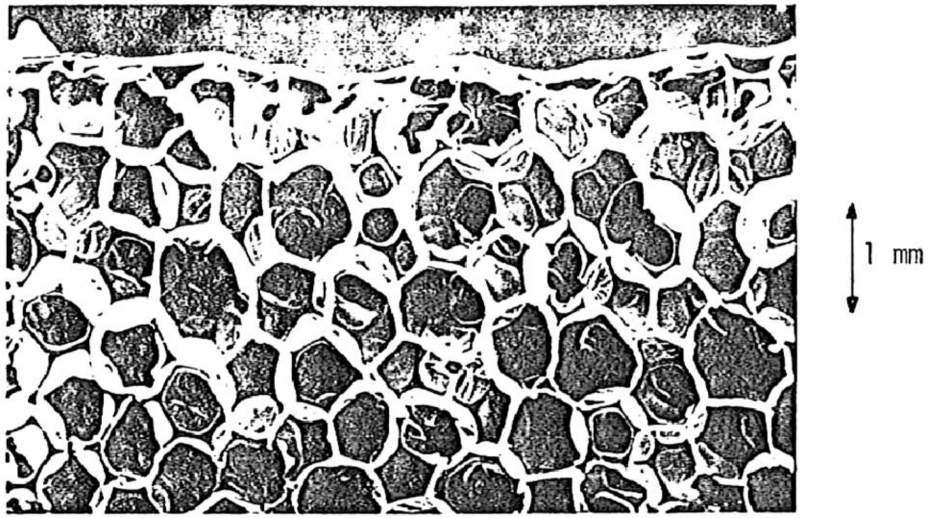
July 1984

Normal Incidence Measurement of Reflection

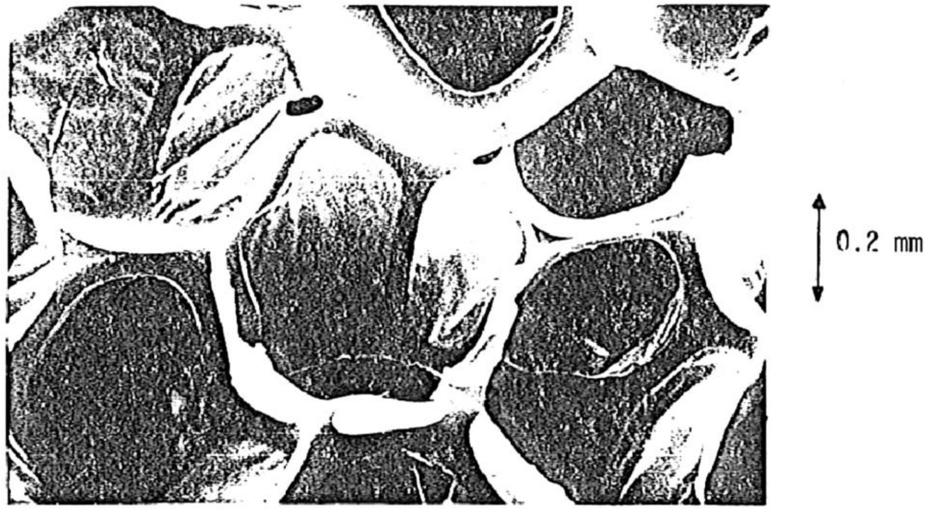


Experimental geometry.

Film-faced Polyurethane Foam



Side view of Film surface. Note: 40µ m thick polyurethane film and the fact that most cells are partially closed by thin membranes.

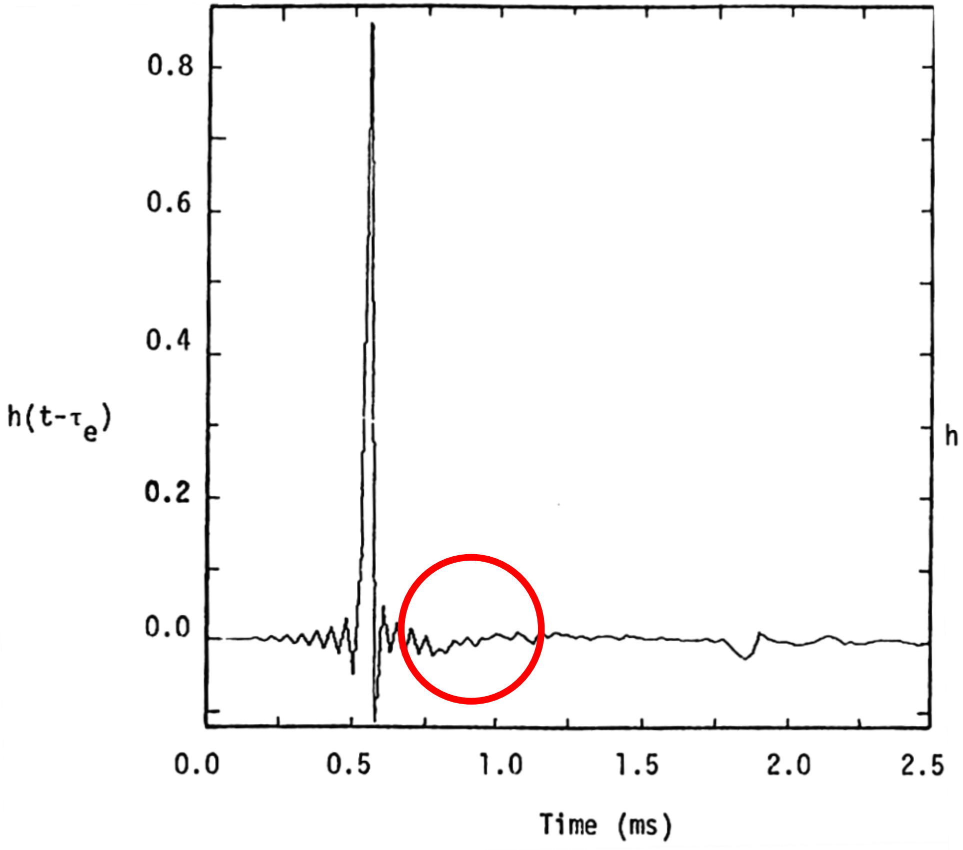


Detail of foam interior. Note: angular fibre shape and that the membranes do not appear to be under tension.

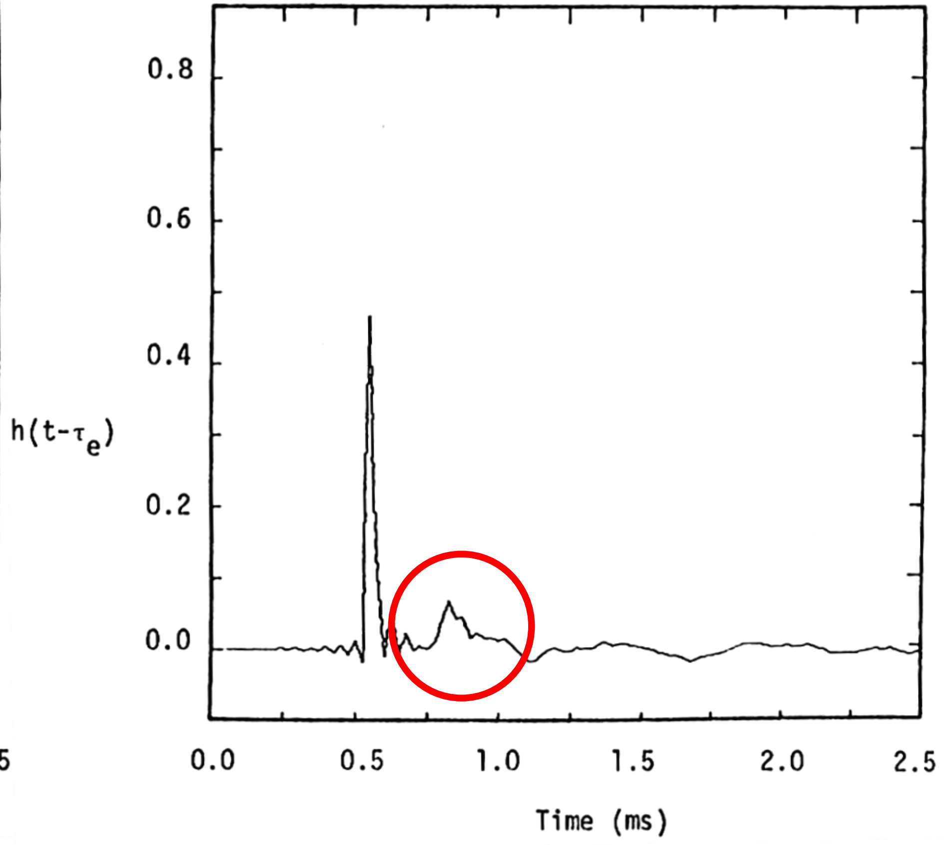
Scanning electron micrographs of the foam sample

- 25 mm layer of foam – one side covered with flame-bonded film, the other open.
- Many intact membranes

Reflection Impulse Response

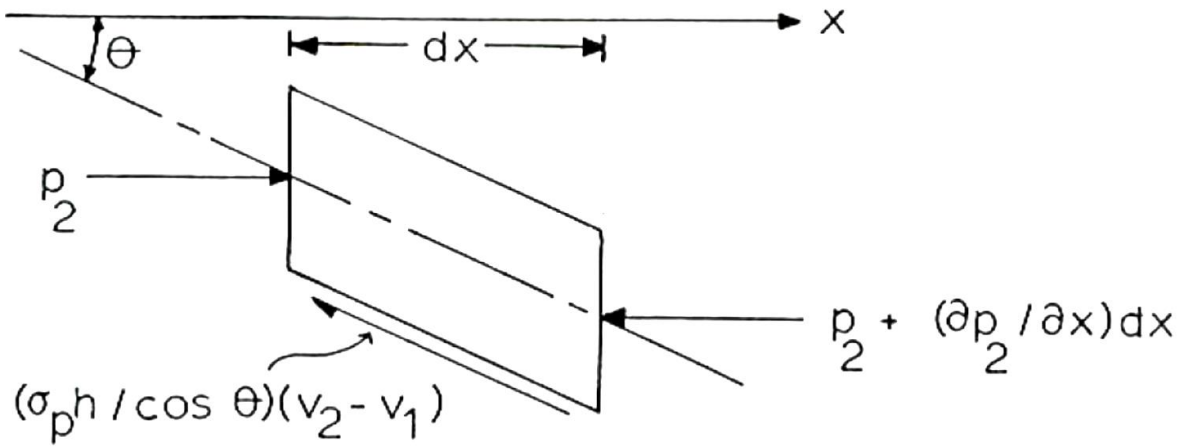


(Film-faced surface up)



(Foam-open surface up)

One-Dimensional Poroelastic Material Theory



External forces acting on the fluid component.

Equations of motion:

Fluid:

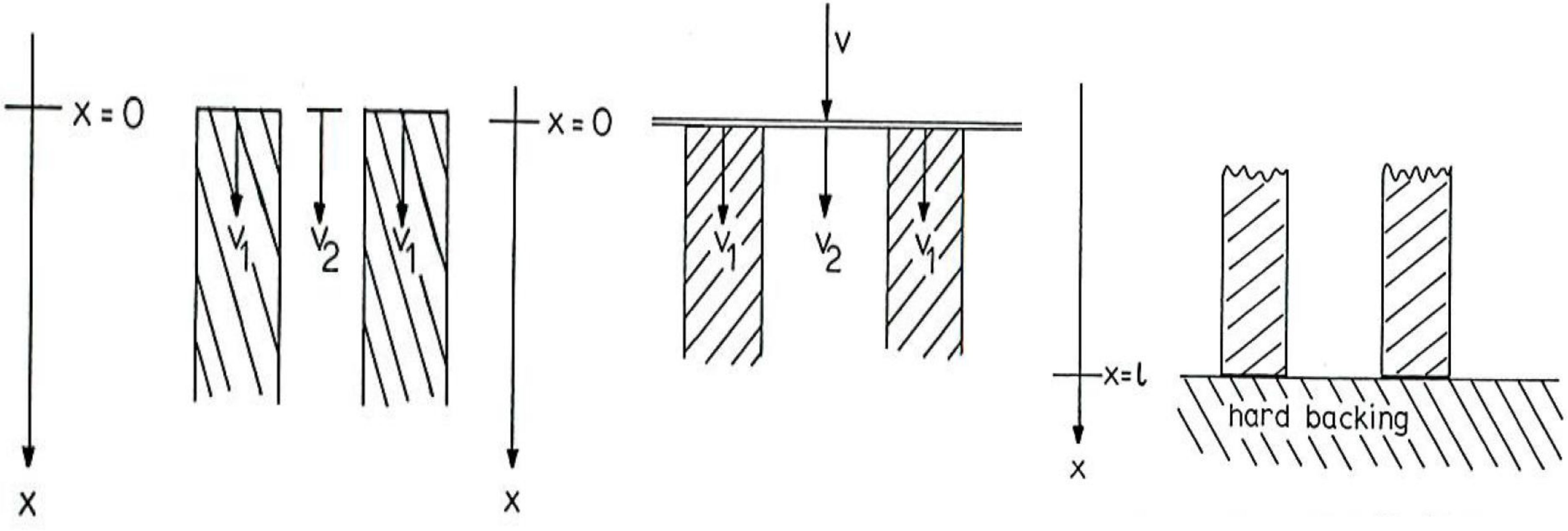
$$-\frac{\partial p_2}{\partial x} = \rho_2\frac{\partial v_2}{\partial t} + \rho_2(\epsilon - 1)\frac{\partial(v_2 - v_1)}{\partial t} + \sigma h^2(v_2 - v_1).$$

Solid:

$$-\frac{\partial p_1}{\partial x} = \rho_1\frac{\partial v_1}{\partial t} + \rho_2(\epsilon - 1)\frac{\partial(v_1 - v_2)}{\partial t} + \sigma h^2(v_1 - v_2).$$

- Based on Zwikker and Kosten, plus Rosin with complex density and air stiffness taken from Attenborough.

Boundary Conditions



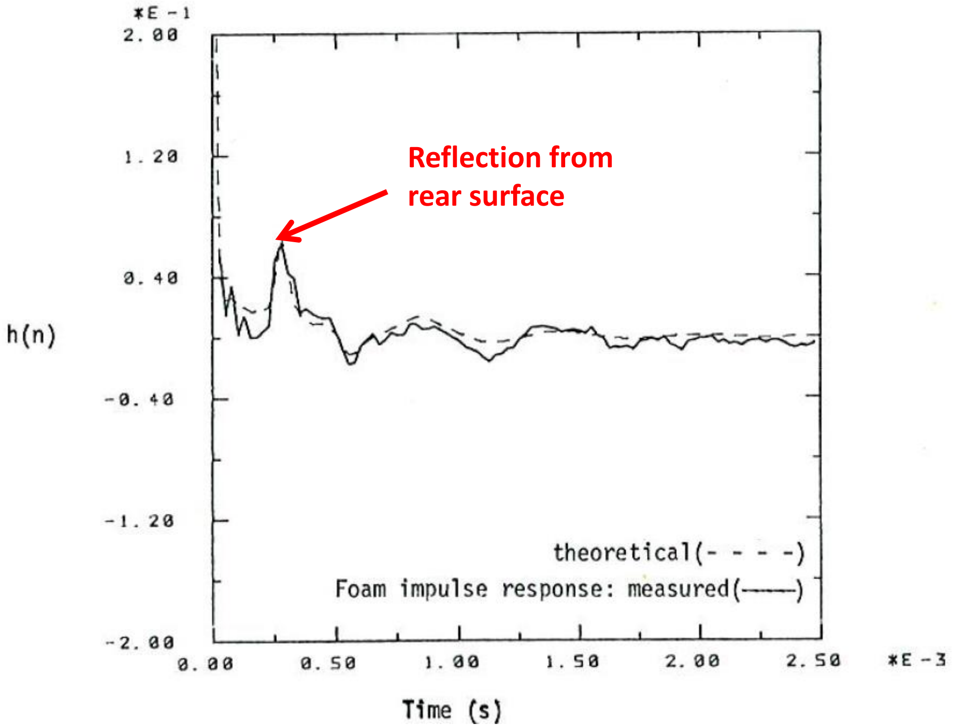
Open foam surface

Foam surface sealed with an impervious membrane

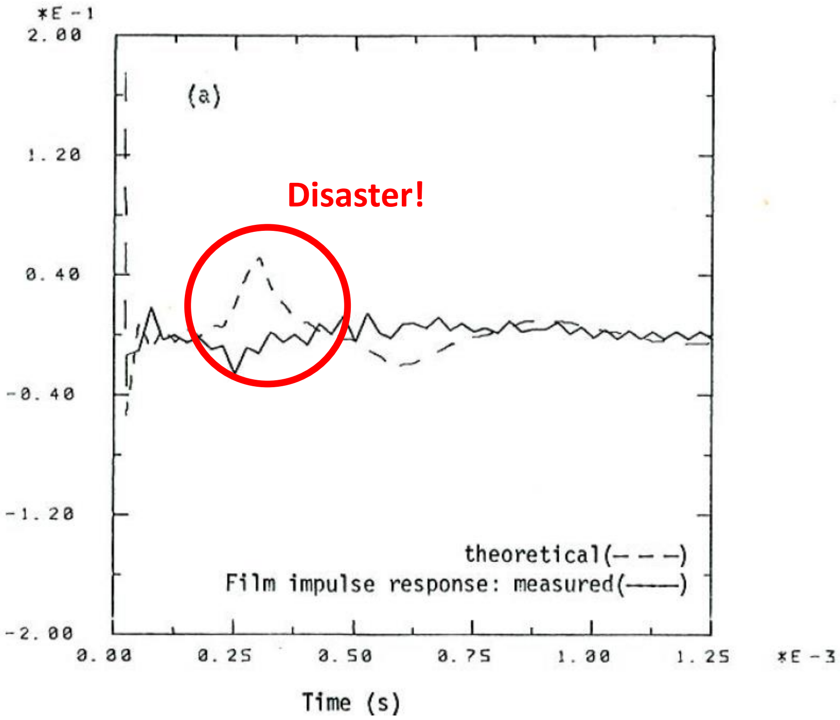
Foam fixed to a hard backing

Reflection Impulse Response - Predicted

Open Surface Foam



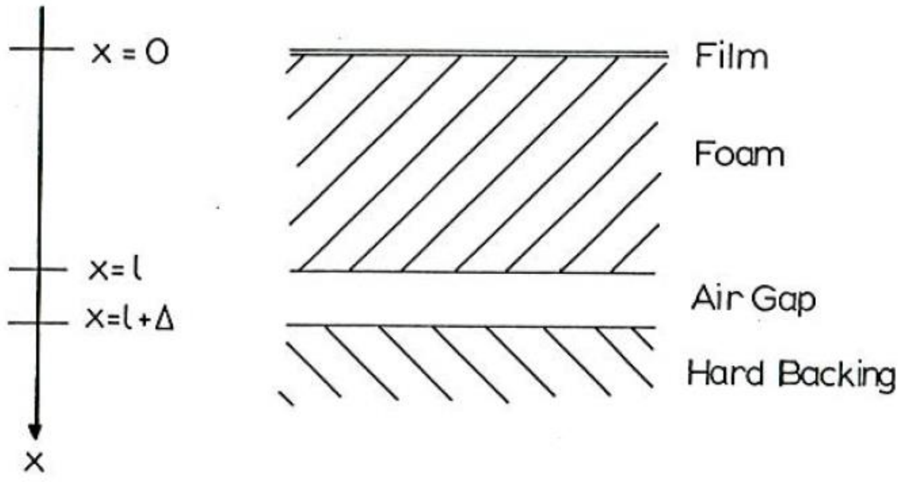
Film-faced Foam



$\rho_1 = 30\, kg/m^3\, l = 25\, mm, \varphi = 0.9, E_0 = 4 \times 10^5 Pa, \eta = 0.265,$

$\varepsilon = 6.025, \sigma = 130 \times 10^3\, mks\ Rayls/m\, , \upsilon = 0.39, m_s = 0.045\ kg/m^2$

Film-forced Foam / Thin Air Gap



A finite depth layer of film-faced foam separated from a hard backing surface by an air layer of depth Δ.

at $x = l + \Delta$, $\quad v_a = 0;$

at $x = l$, $\quad P_1 = P_a(1-h), P_1 = P_a h,$
$v_a = v_1(1-h) + v_2 h;$

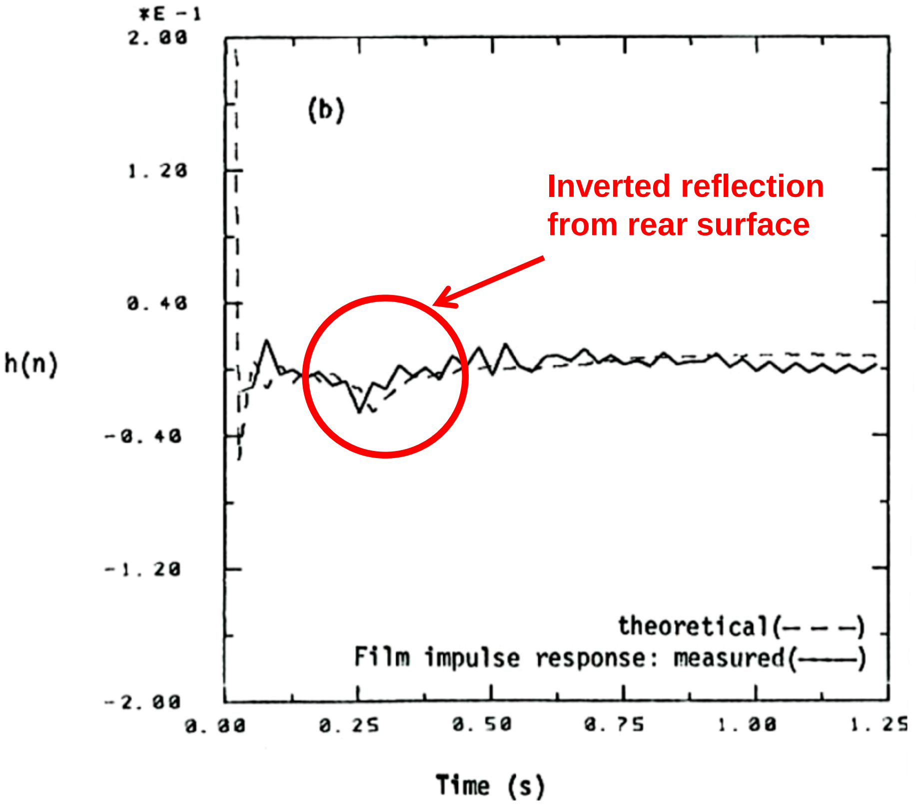
at $x = 0$, $\quad v_1 = v, v_2 = v,$
$p - p_1 - p_2 = m_s\, dv/dt$

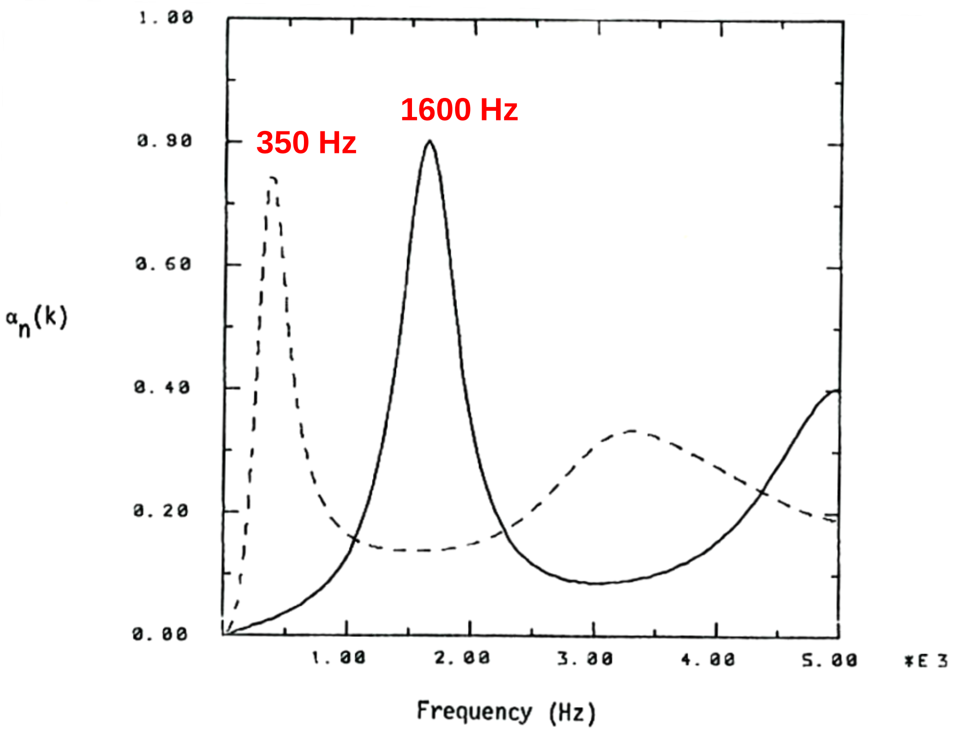
Impedance: $\quad j\omega z = -\omega^2 m_s - N'/D'$

The solution of this set of seven equations presents no difficulties in principle, but is algebraically tedious. The complete solution is outlined in Appendix 6.2; only the result is given here. The impedance takes the form

$$j\omega Z = -\omega^2 m_s - N'/D'$$

Film-forced Foam / Thin Air Gap

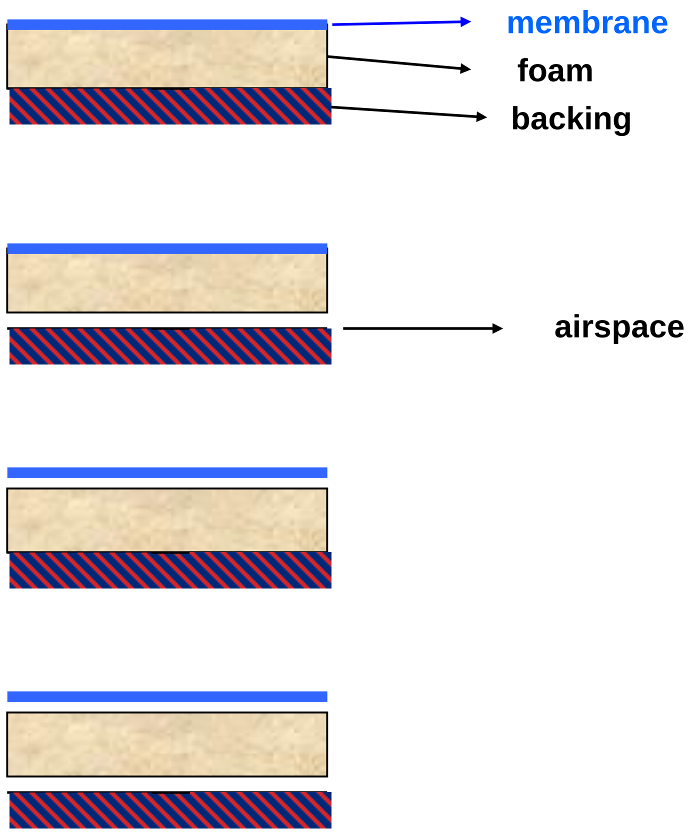




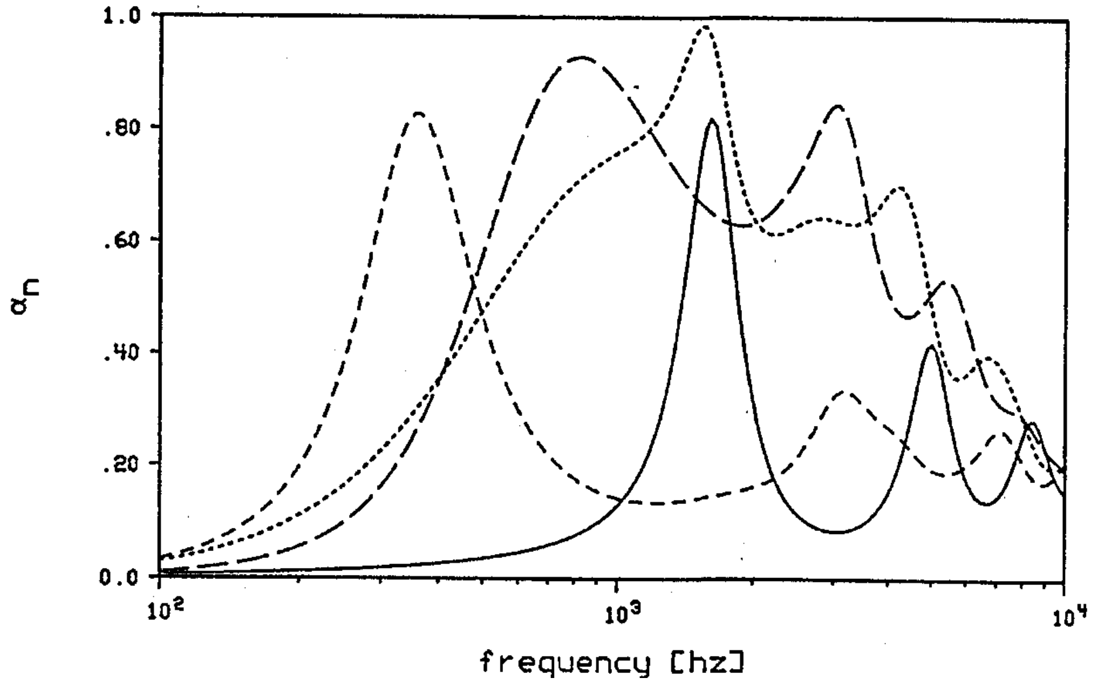
Effect of rear surface boundary condition on Film normal incidence absorption coefficient: model of section 6.4.3.2(——); model of section 6.4.3.3, air layer depth 0.001m(– –).

Absorption treatments

- Bonded/Bonded
- Bonded/Unbonded
- Unbonded/Bonded
- Unbonded/Unbonded



Normal Incidence Absorption



- **Foam** – 25 mm, 30kg/m^3
- **Membrane** – 0.045 kg/m^2
- **Airspaces** – 1 mm

Effects of Airspace at front and rear

1. Film/Foam/Backing
2. Film/Space/Foam/Backing
3. Film/Foam/Space/Backing
4. Film/Space/Foam/Space/Backing

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Sound absorption of elastic framed porous materials in combination with impervious films: effect of bonding

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[b]*D.G. Latimer and Associates Ltd, P O Box 12-032, Christchurch, New Zealand*

Received 3 May 2001; received in revised form 20 January 2002; accepted 14 February 2002

Abstract

The absorption characteristics of elastic framed absorbers in combination with impervious films has been investigated. The effect of bonding the film to the absorber and the absorbers to their rear surface was examined. The results have been modelled using established methods for predicting the absorption of elastic framed porous materials. The absorption of a foam with a film bonded to its top surface was most sensitive to the rear surface bonding condition. Plain foams and foams with loose-laid surface films were less sensitive to the rear surface bonding condition. The results demonstrate that test data used to predict absorption performance need to reflect the absorber mounting conditions.

Table 1
Parameters used for the modelled results in Fig. 1

Thickness	Tortuosity	Bulk density	Flow resistivity	Porosity	Complex shear modulus	Poison's ratio	Form factor
t (mm)	k_s	ρ_1 (kg/m^3)	r (mks rayls/m, or Ns/m^4)	h	N (N/cm^2)	ν	c
24	2.85	43	22000	0.98	20 + 10i	0.3	4

Resting on Floor

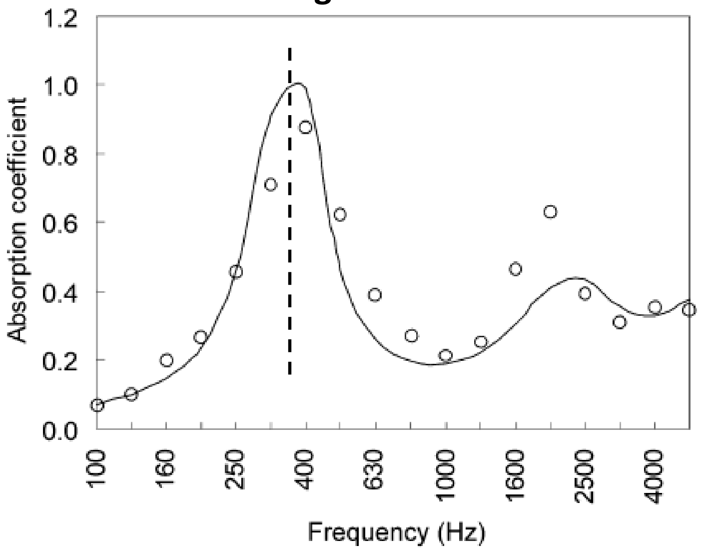


Fig. 1. Measured (○) and modelled (–) absorption of film faced foam at 24 mm thickness; foam was placed on rear surface (floor of reverberation room).

Bonded to Backing

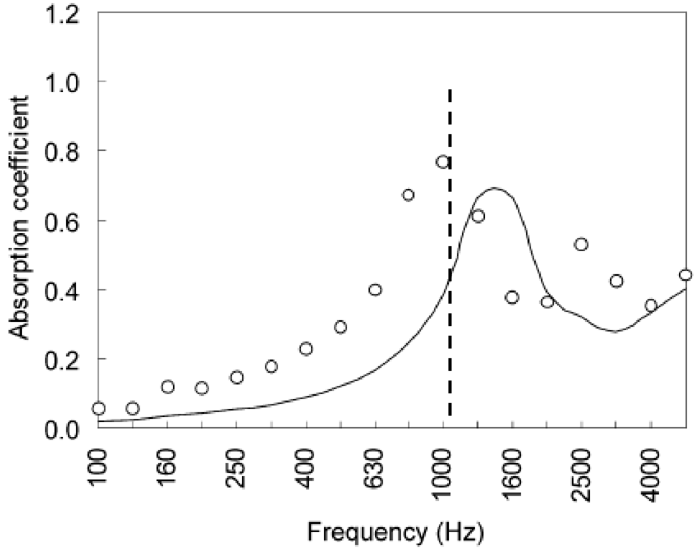
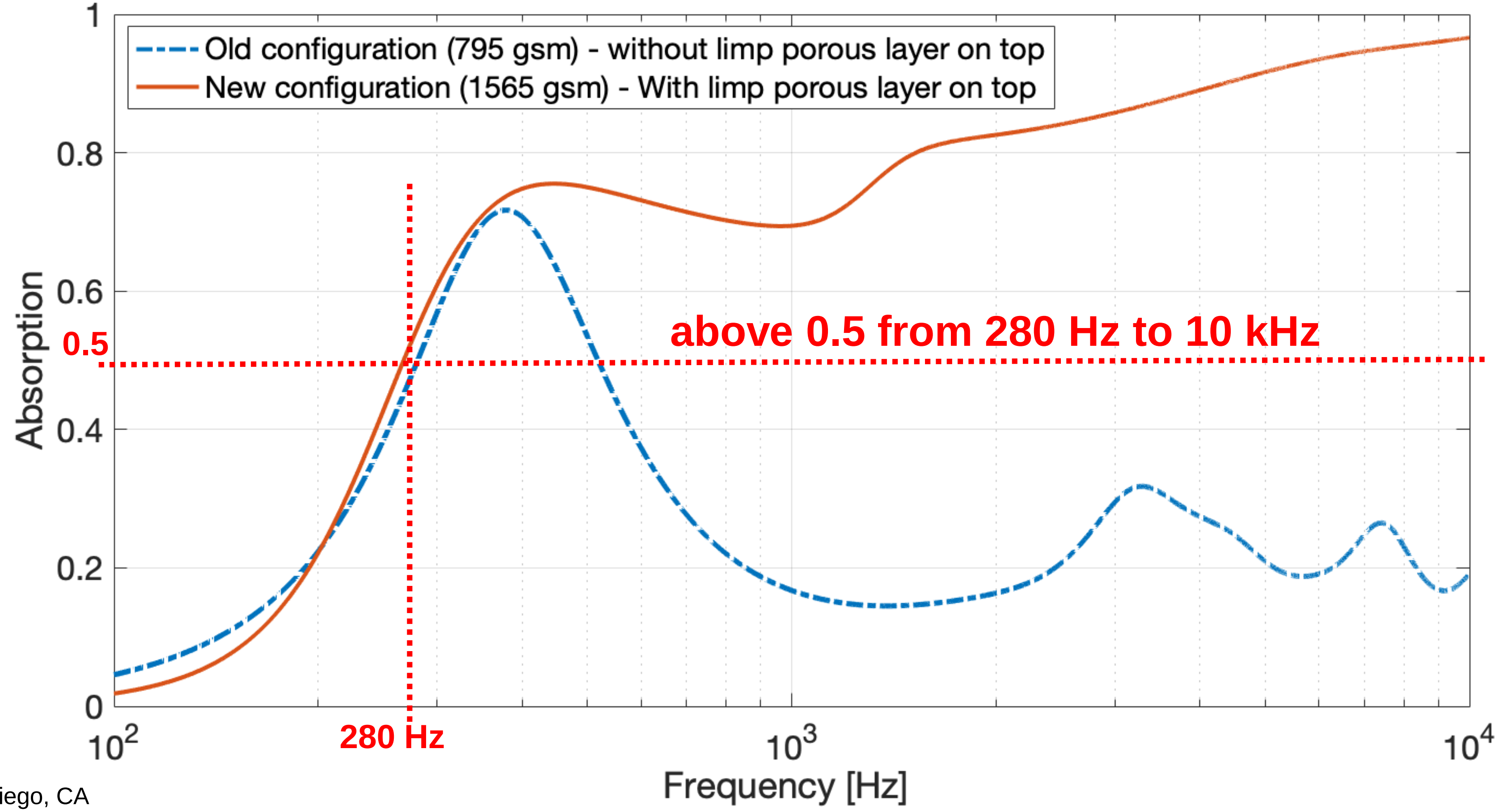


Fig. 2. Measured (○) and modelled (–) absorption of film faced foam at 24 mm thickness; foam was bonded to rear surface (gypsum board).

$$m_s = 35\, g/m^2$$

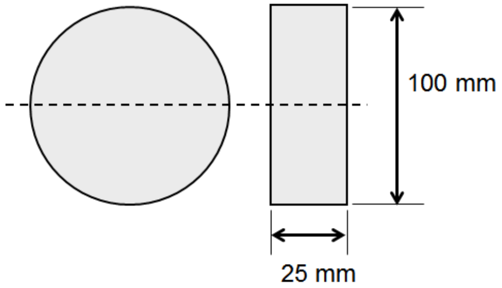
Normal Incidence Absorption

- Bonded/Unbonded



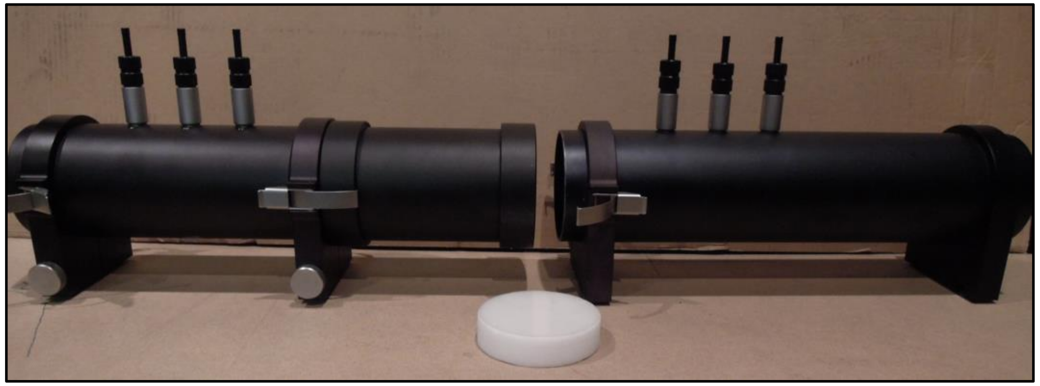
Impedance Tube Testing

- ❑ **Melamine Foam (8.6 kg/m³)**
  - ➢ 100 mm diameter
  - ➢ 25 mm thick



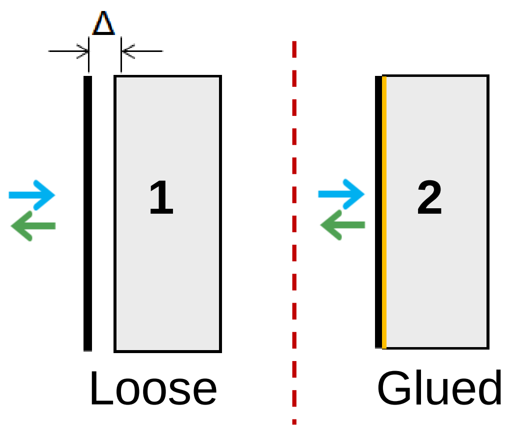
- ❑ **Each sample fit exactly by trimming the diameter & checking the fit with a TL measurement**

- ❑ **Two Facing & Two Rear Surface Boundary Conditions**
  - ➢ Multiple trials
  - ➢ Multiple samples



Surface Configurations

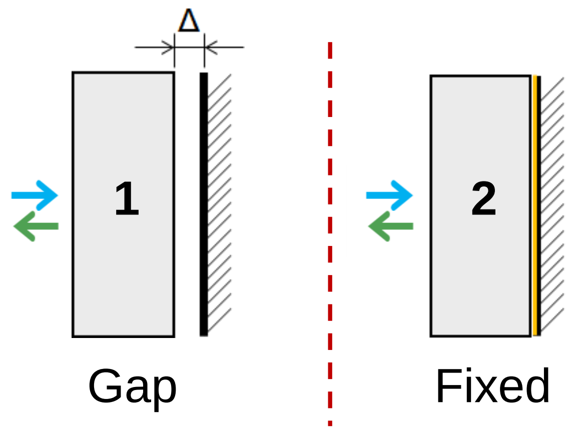
<u>*Front Surface:*</u>



1) *Plastic film near, but not adhered to foam*

2) *Plastic film glued to foam*

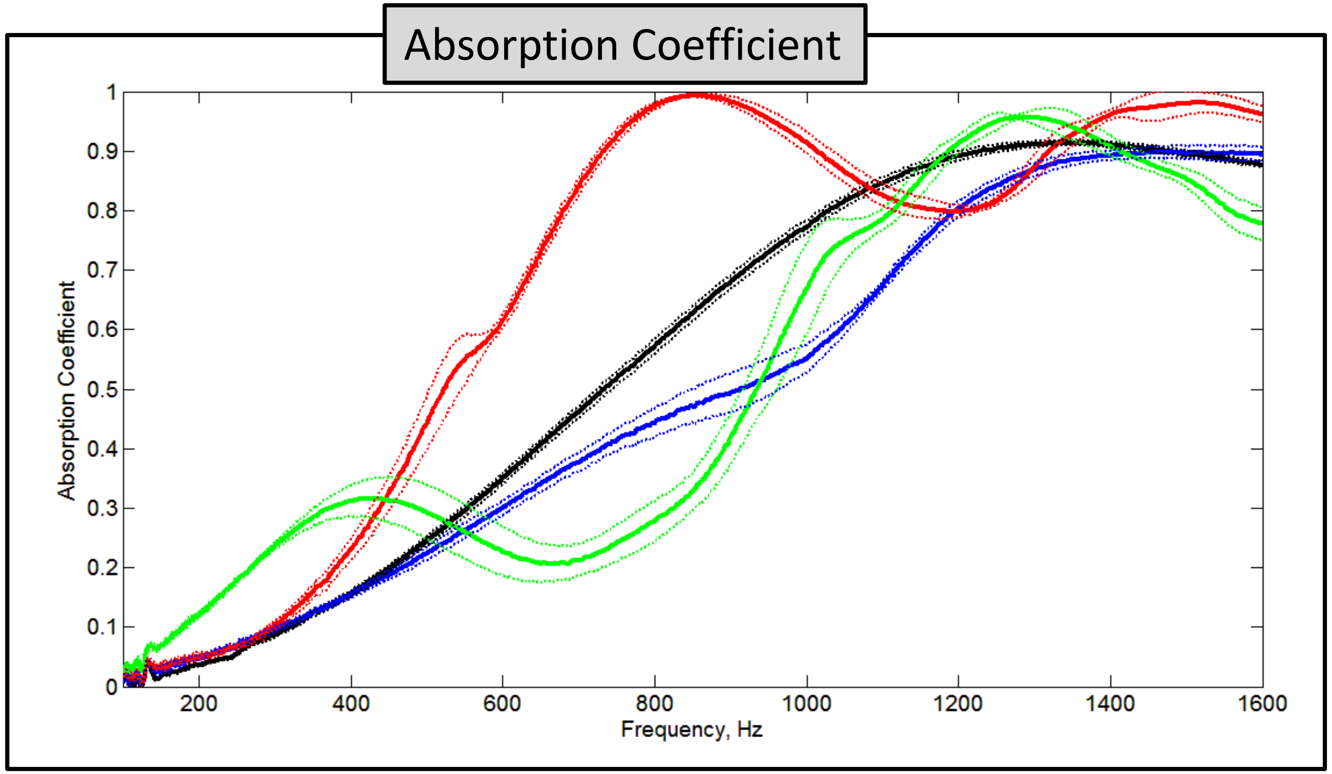
<u>*Rear Surface:*</u>

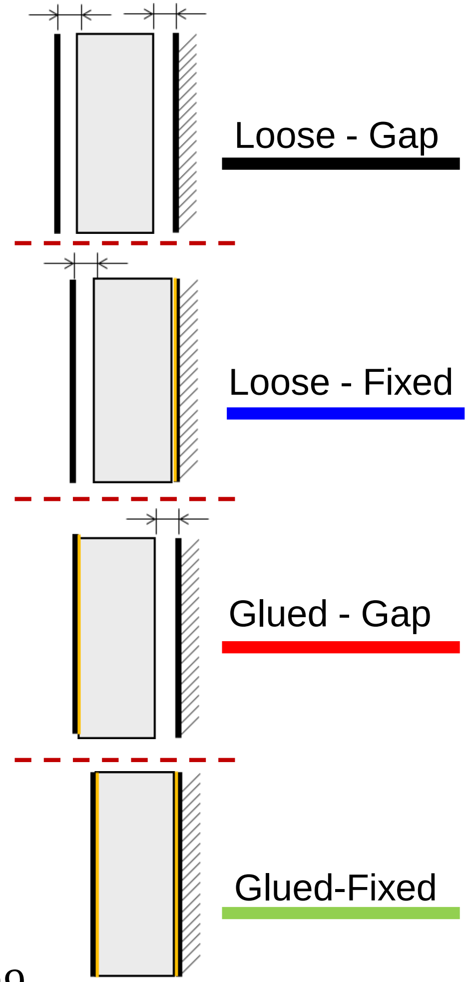


1) *Small gap between foam & rigid wall*

2) *Foam adhered to rigid wall*

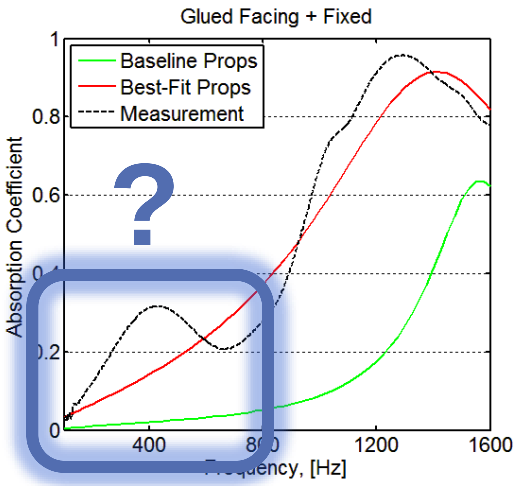
Absorption vs. Configuration - Test

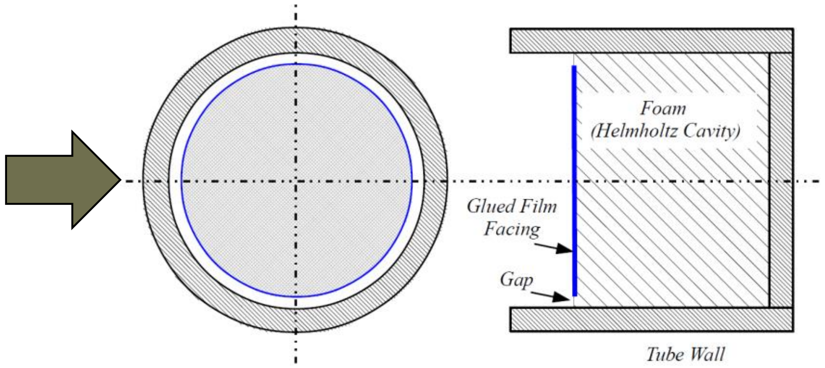




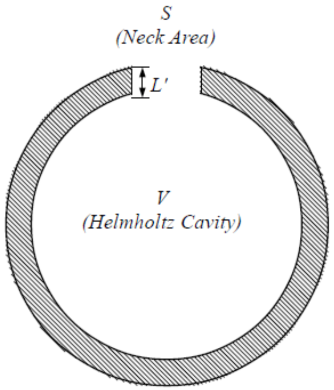
$l = 25mm, \Delta_1 = 4.5mm, \Delta_2 = 1mm, m_s = 50\ g/m^2, h = 0.99,$
$\sigma = 9.5 \times 10^3 mks\ \ Rayls/m, \qquad \varepsilon = 1.4,$
$P - wave\ modulus = 6.5 \times 10^5 Pa, \eta = 0.2$

Helmholtz Resonator Effect

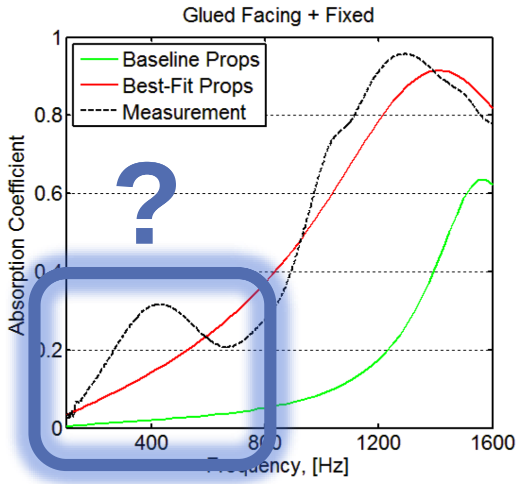


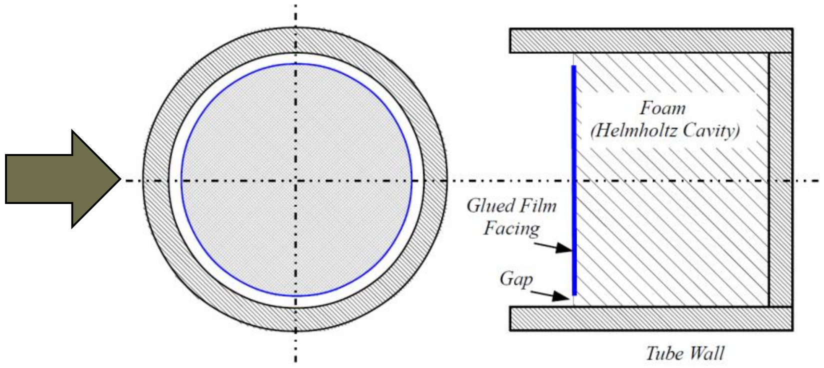


Mechanical Impedance	$z_m = R_r + j(\omega m - s/\omega)$
Mass	$m = \rho_0 S L'$
Stiffness	$s = \rho_0 c_0^2 S^2 / V$
Total Acoustic Impedance	$z = 1/(1/z_H + 1/z_f)$

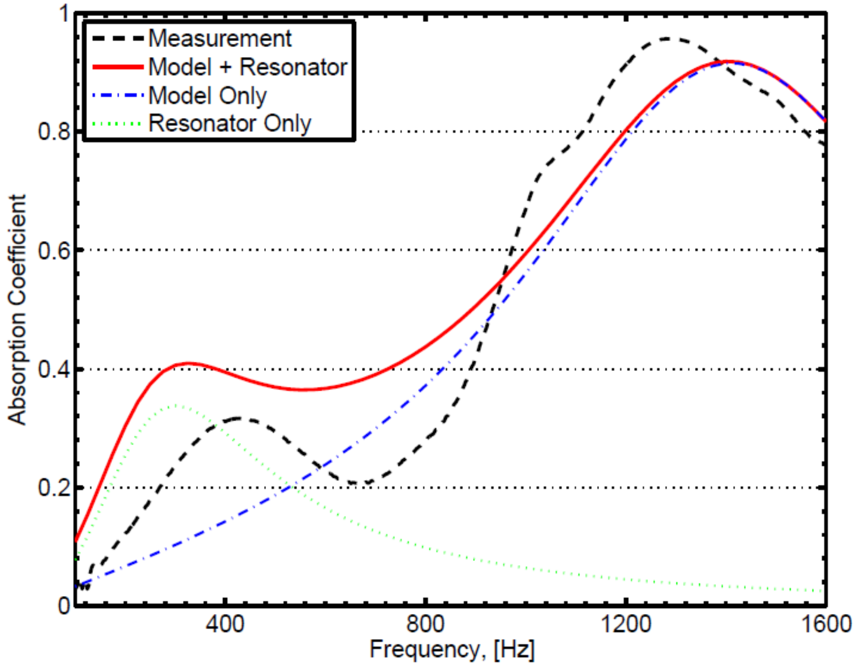


Helmholtz Resonator Effect

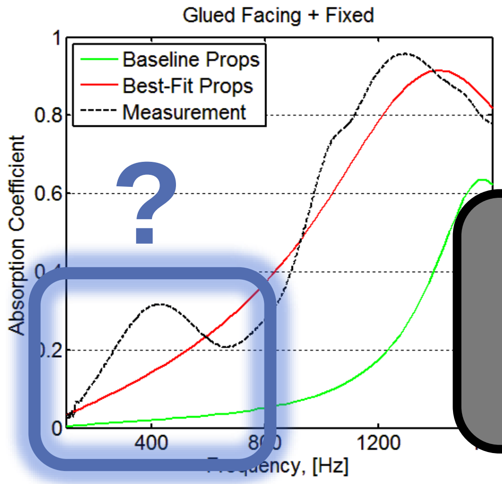


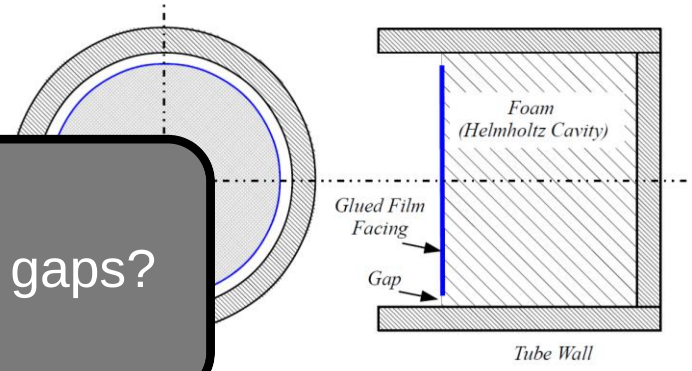


Combined Foam + Helmholtz Resonator System is Similar to Measured System



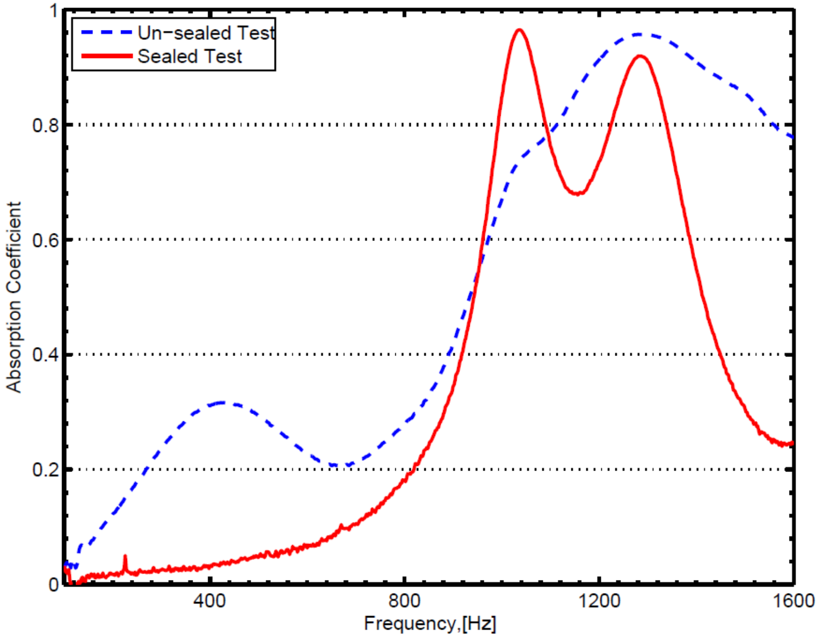
Helmholtz Resonator Effect





But is it really due to edge gaps?

Measured Glued Facing + Fixed with Edge Sealed



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Enhancement of the low frequency performance of thin, film-faced layers of foam by surface segmentation

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[2] LISMMA EA2336, SUPMECA, 3 Rue Fernand Hainaut, 93407 Saint-Ouen Cedex, France.
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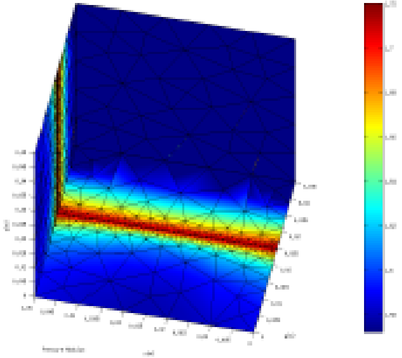
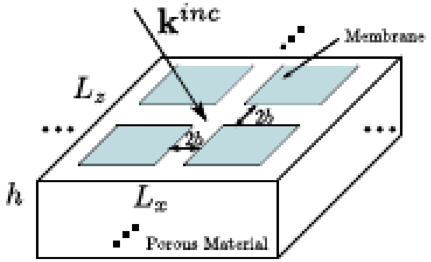
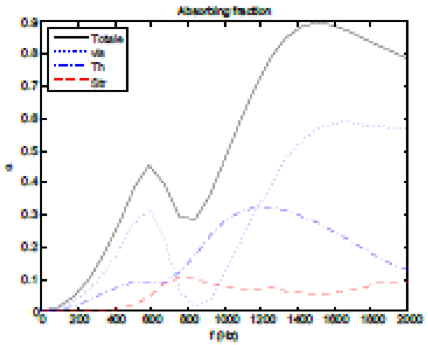
bolton@purdue.edu, benoit.nennig@supmeca.fr, nicolas.dauchez@utc.fr

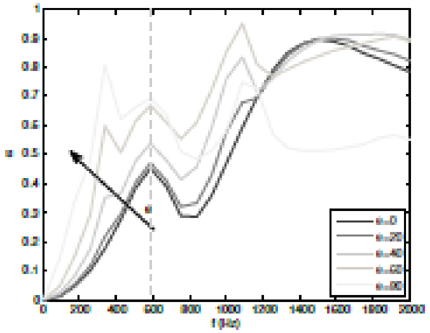
Periodic patch and oblique incidence effect : $L_x = 50$ mm, $L_z = 50$ mm, $b = 1$ mm, $h = 25$ mm







Normal incidence

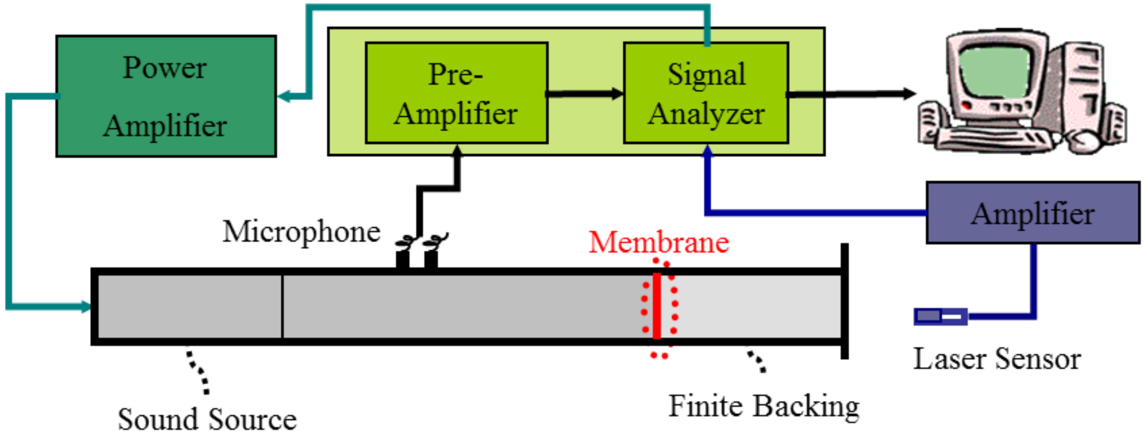


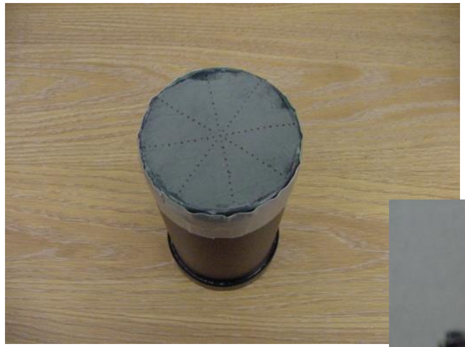
Other incidences

Prospects :

- Combination with double porosity material [5]
- Combination with Cuboid [6]

Tensioned Membranes
Model Verification – Velocity Measurement



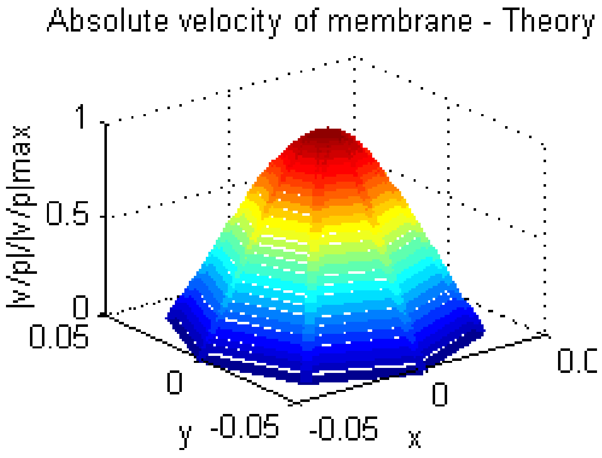


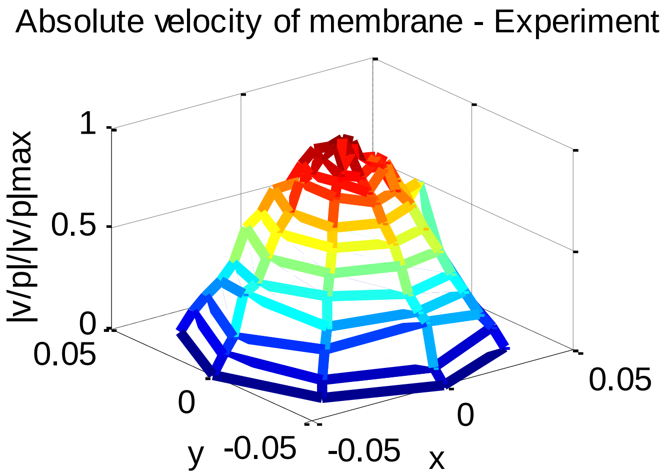
Model Verification – Vibrational Modes

Theory

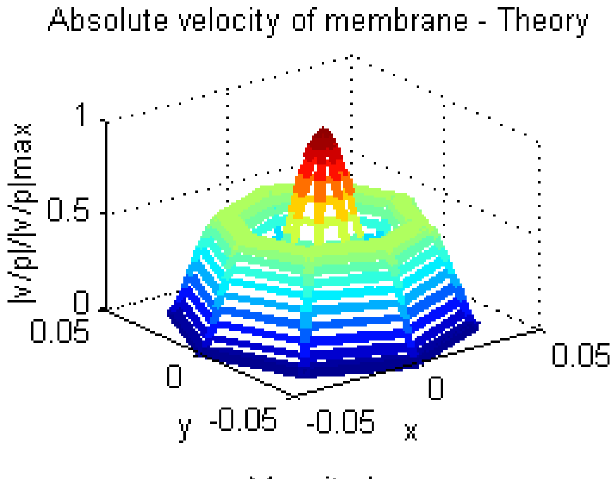
Experiment

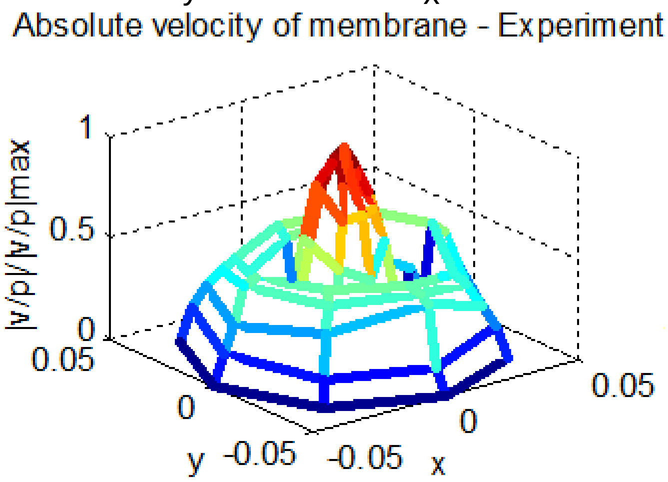
1st



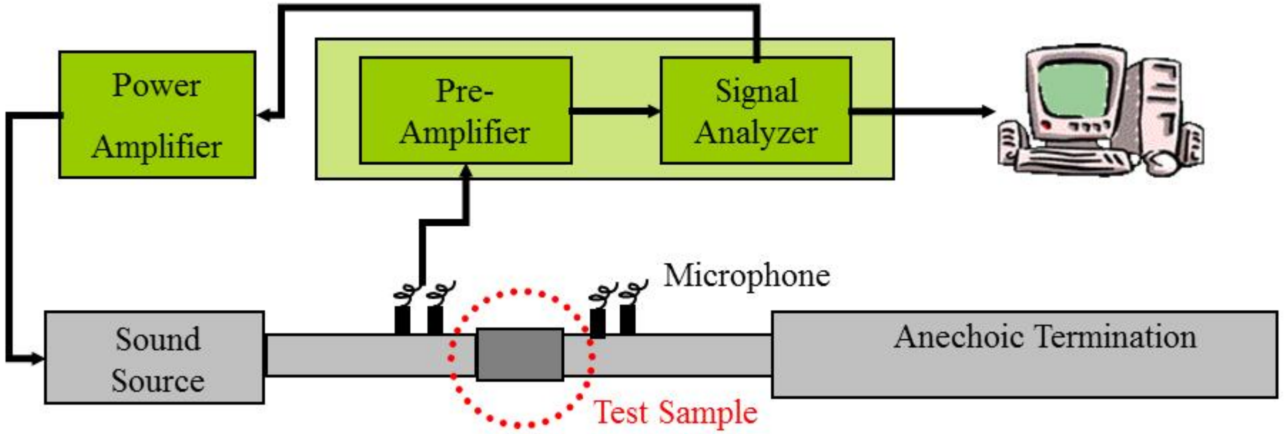


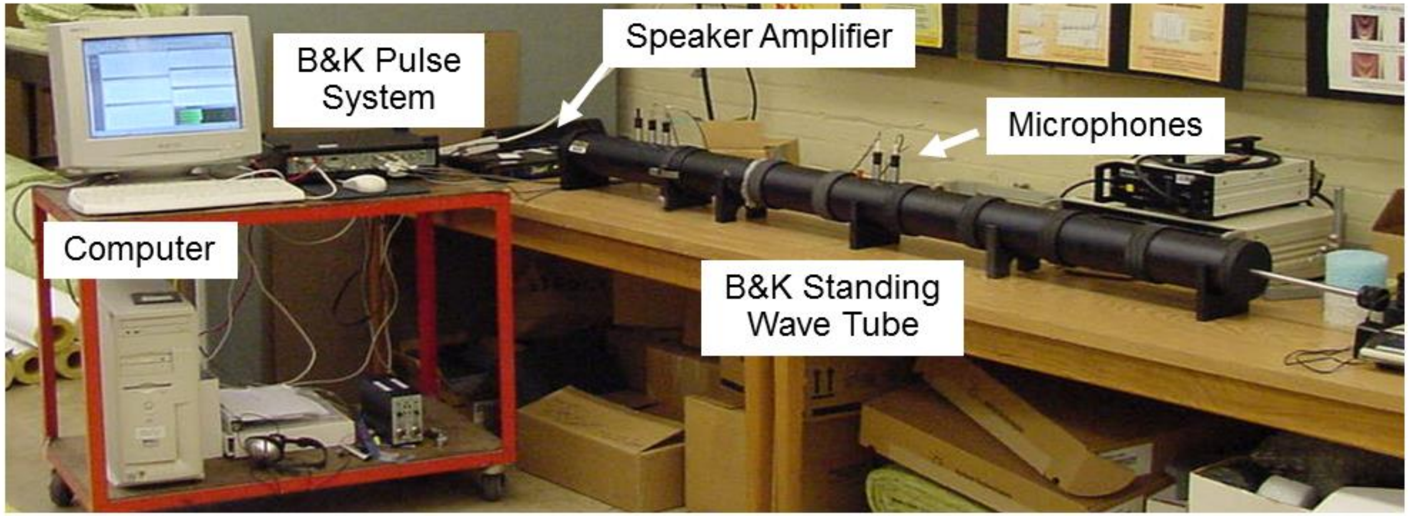
2nd





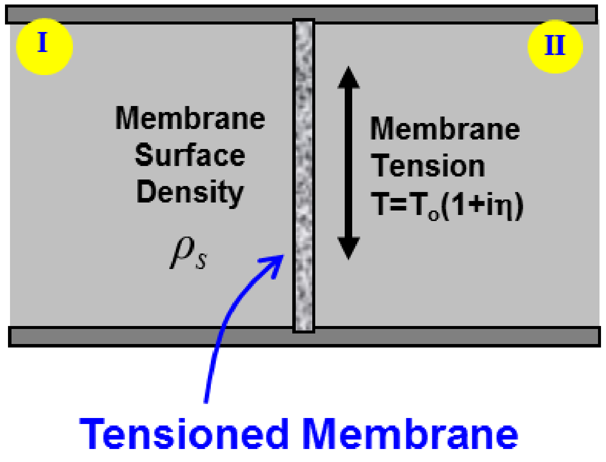
Model Verification – Experiment Set-up

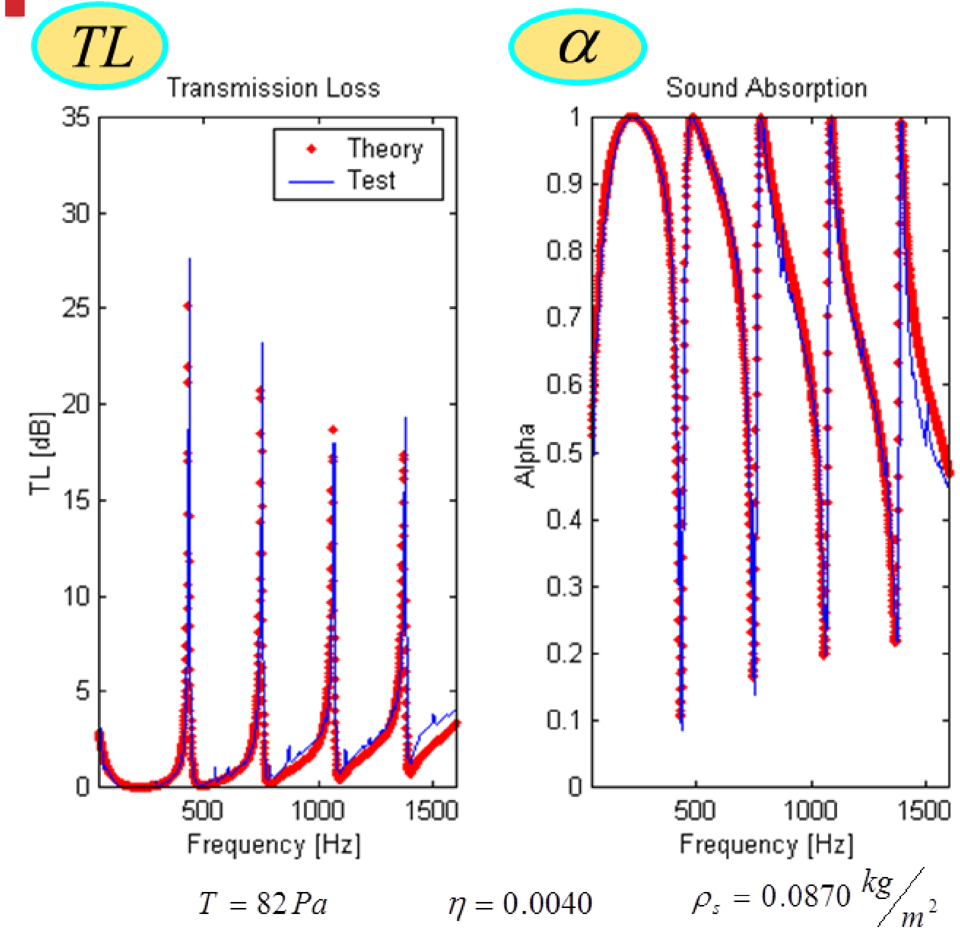




Model Verification – Model Optimization

- Given experimental results as input, Find appropriate material properties (T_o , ρ_s , η)





➢ Why this behavior? – Finite size, held at edge, finite stiffness.

- Volume velocity cancellation produced TL peaks

Glass Fiber Material Inside of Sample Holder

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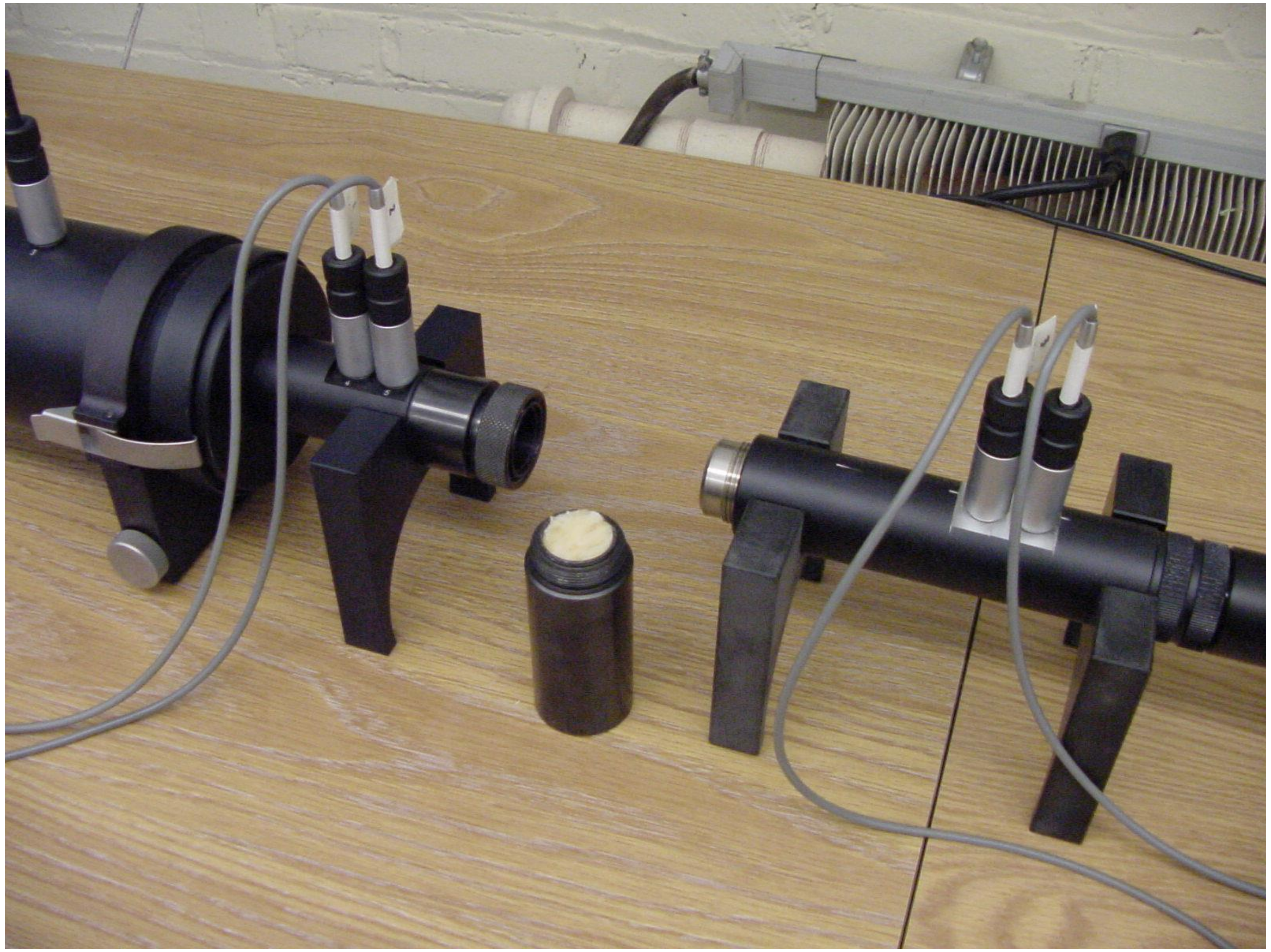
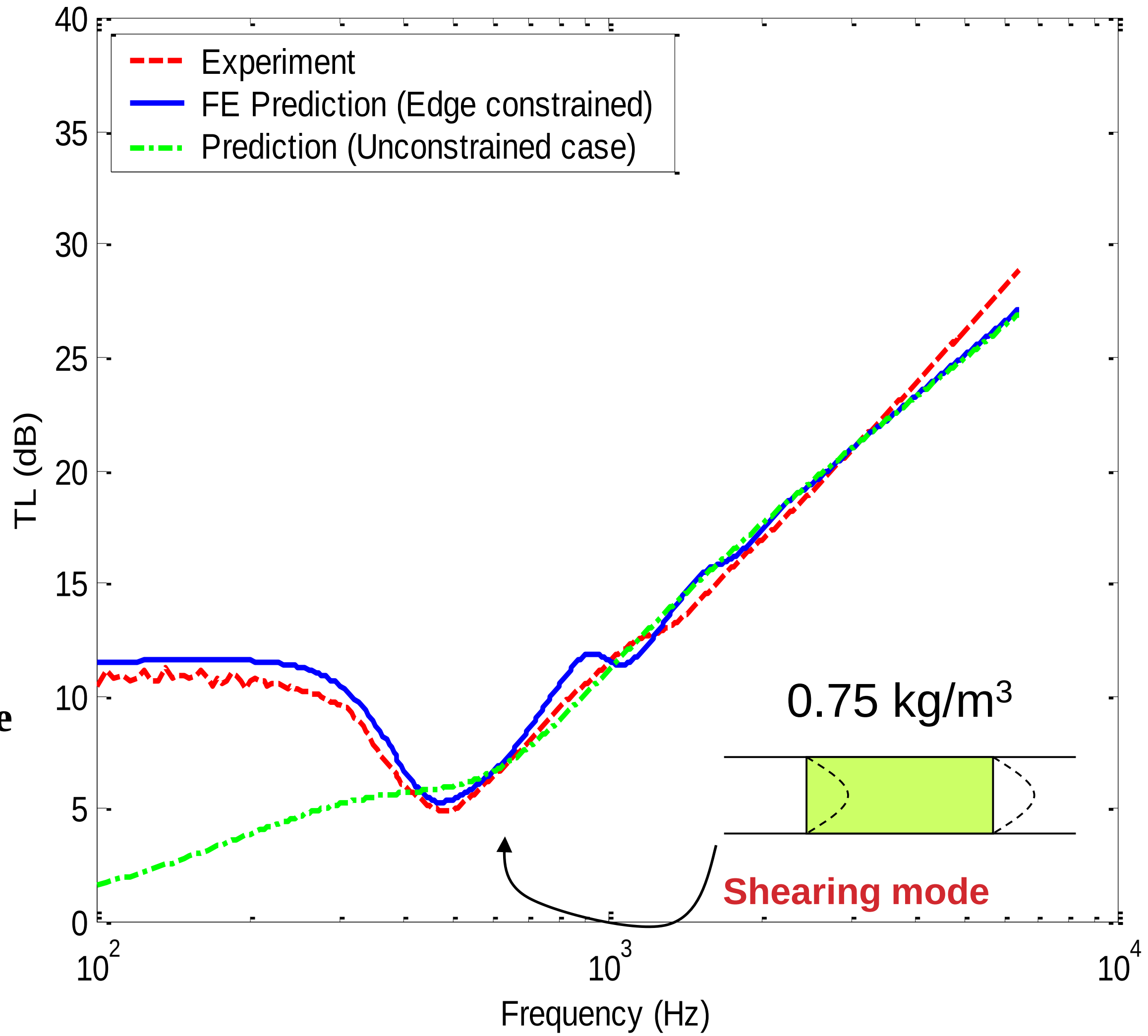


Anechoic Transmission Loss (Green)



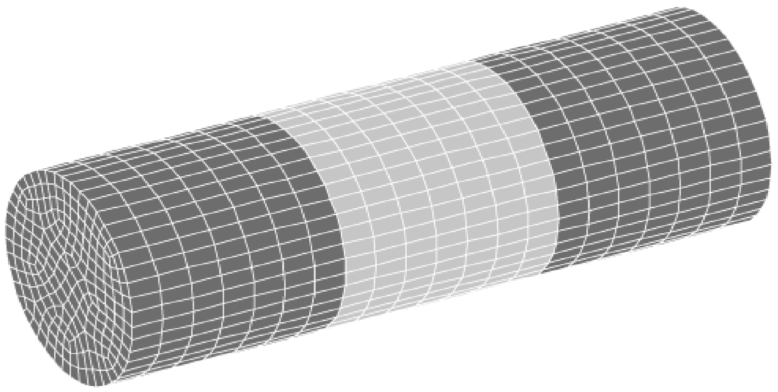
Increase in TL due to edge constraint

(10dB)

- Low frequency limit controlled by flow resistance

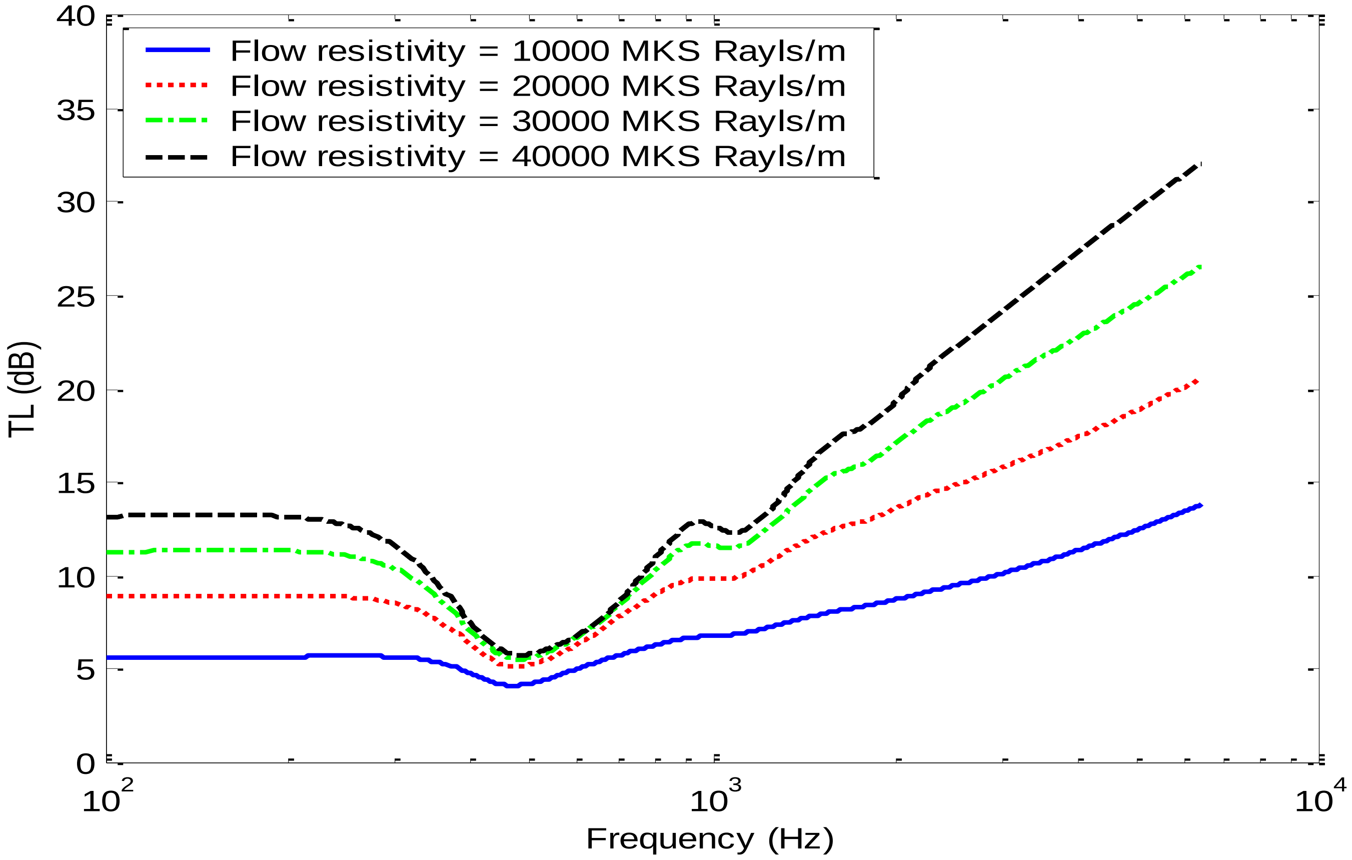
Poroelastic Material Properties Used in Calculations

Material	Bulk density (Kg/m^3)	Porosity	Tortuosity	Estimated flow resistivity (MKS Rayls/m)	Shear modulus (Pa)	Loss factor
Yellow	6.7	0.99	1.1	21000	1200	0.350
Green	9.6	0.99	1.1	31000	2800	0.275

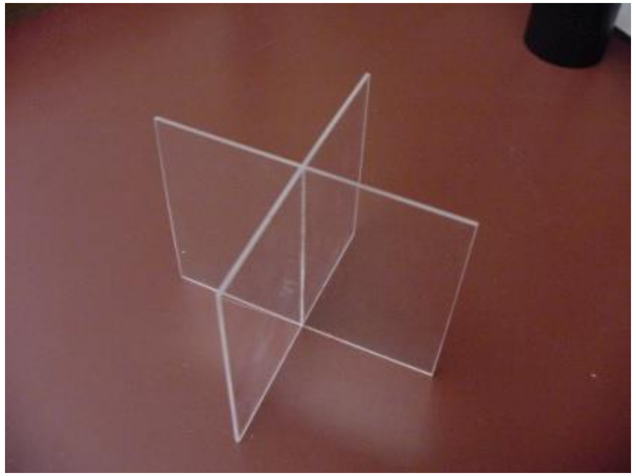


Variation of Flow Resistivity

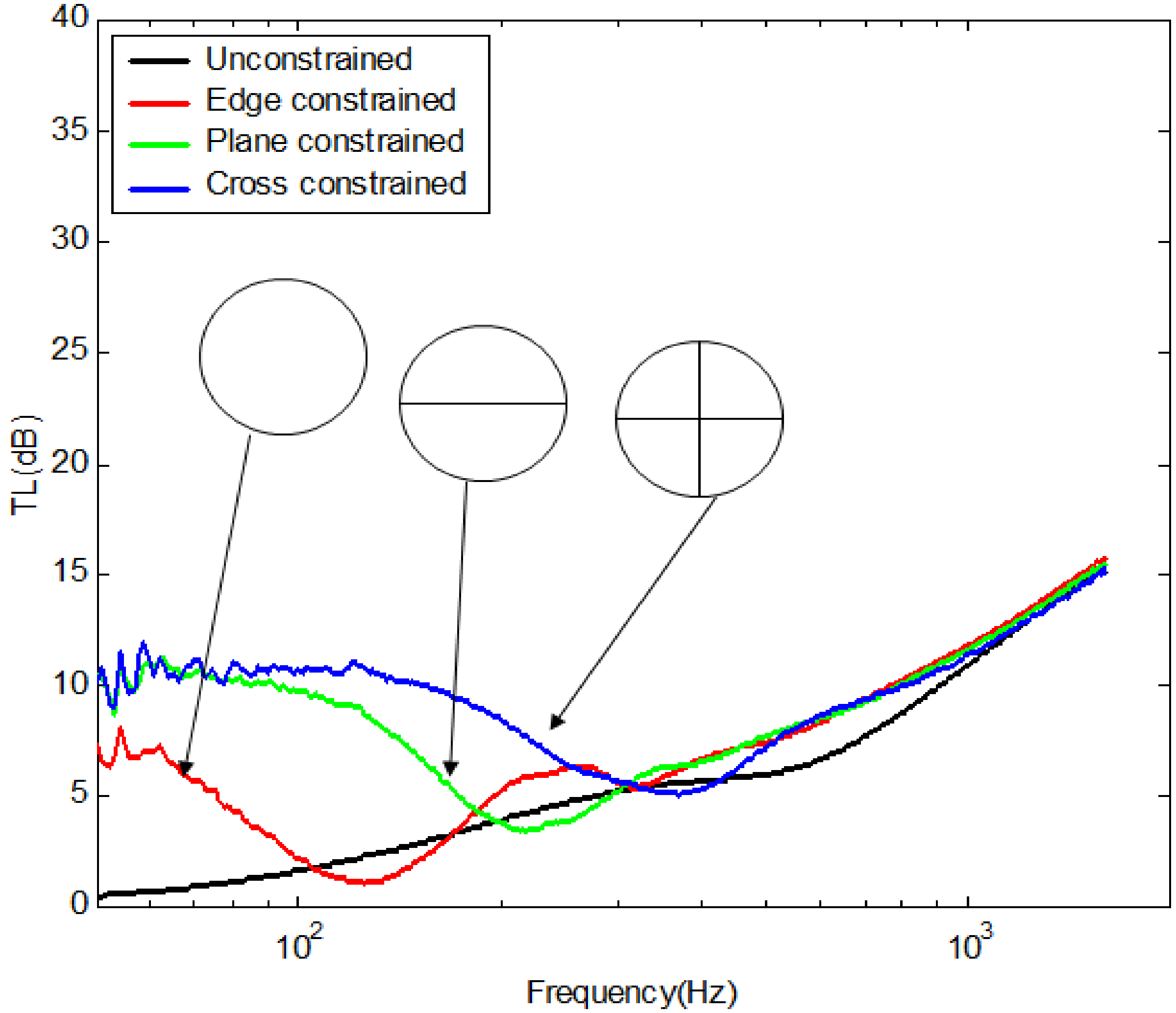
- Flow resistivity controls TL at low and high frequency limit



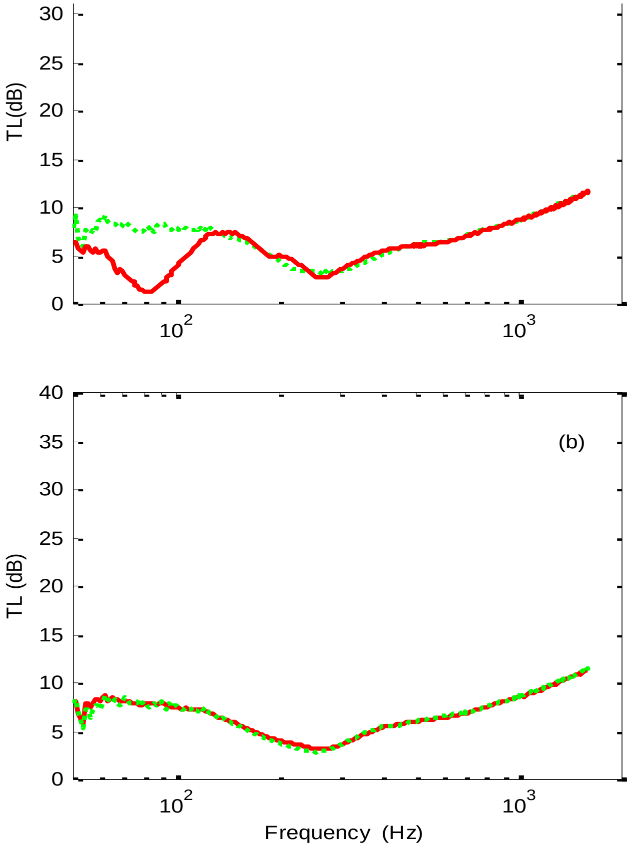
Internal Constraint to Enhance the Sound Transmission Loss

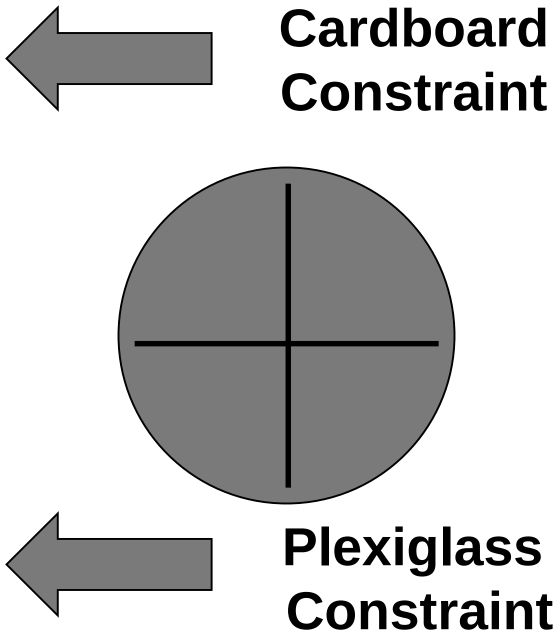


Sound Transmission Loss (Experiment, Green) [Density of Plexiglass: 1717 Kg/m3]



Effect of Releasing the Internal Cross- Constraint (Measurement)

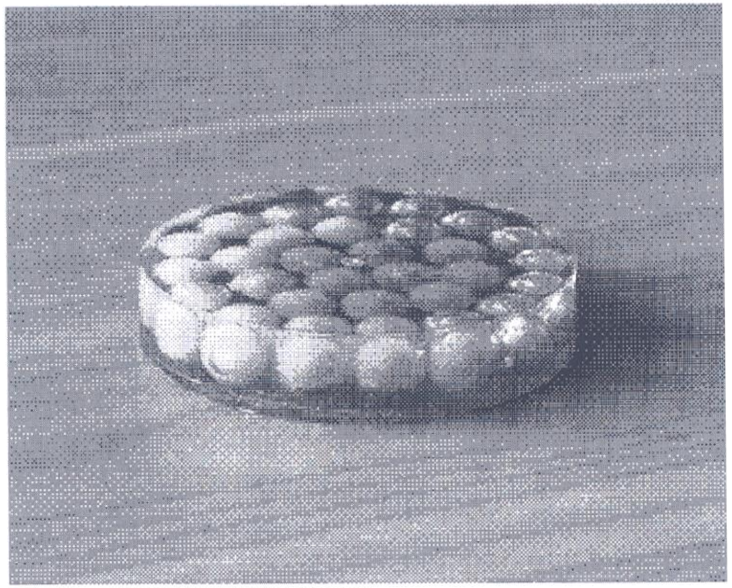




- Relatively heavy constraint required to realize low frequency benefit.

Metamaterials

- **Metamaterials** are artificial materials engineered to have properties that may not be found in nature. Metamaterials usually gain their properties from structure rather than composition, using small inhomogeneities to create effective macroscopic behavior.



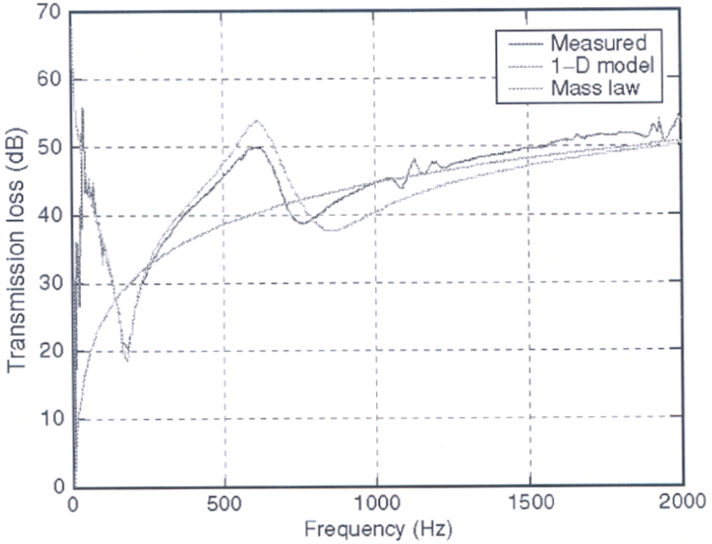


Figure 7. Measured and predicted normal incidence transmission loss for sample with 30 balls.

From : Meta-Material Sound Insulation by E. Wester, X. Bremaud and B. Smith, Building Acoustics, **16** (2009)

Membrane-type metamaterials: Transmission loss of multi-celled arrays

Christina J. Naify,[1,a)] Chia-Ming Chang,[2] Geoffrey McKnight,[2] Florian Scheulen,[2]
and Steven Nutt[1]
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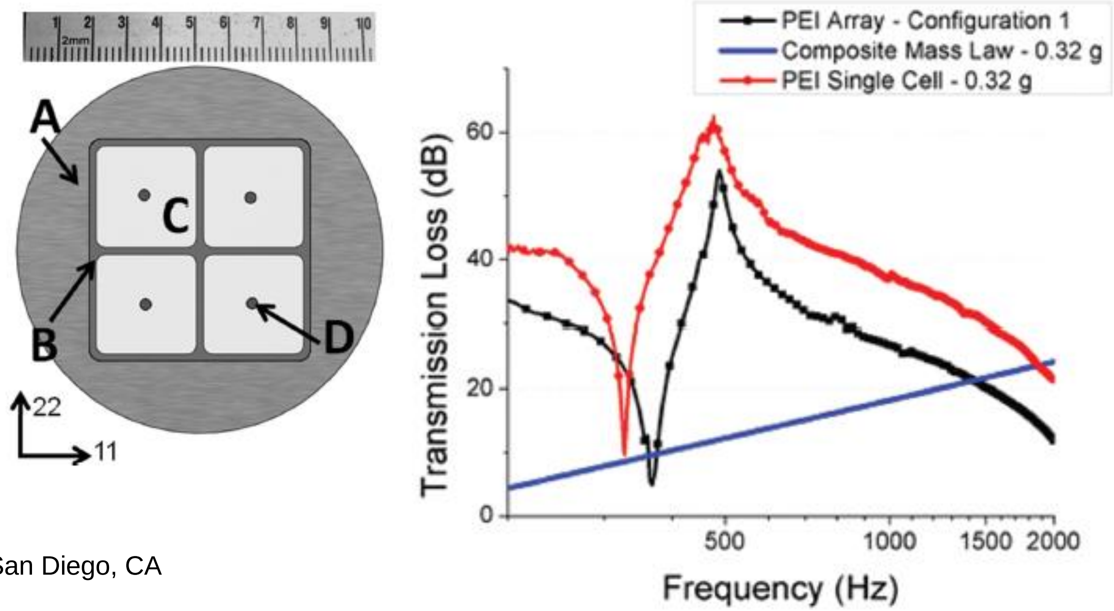
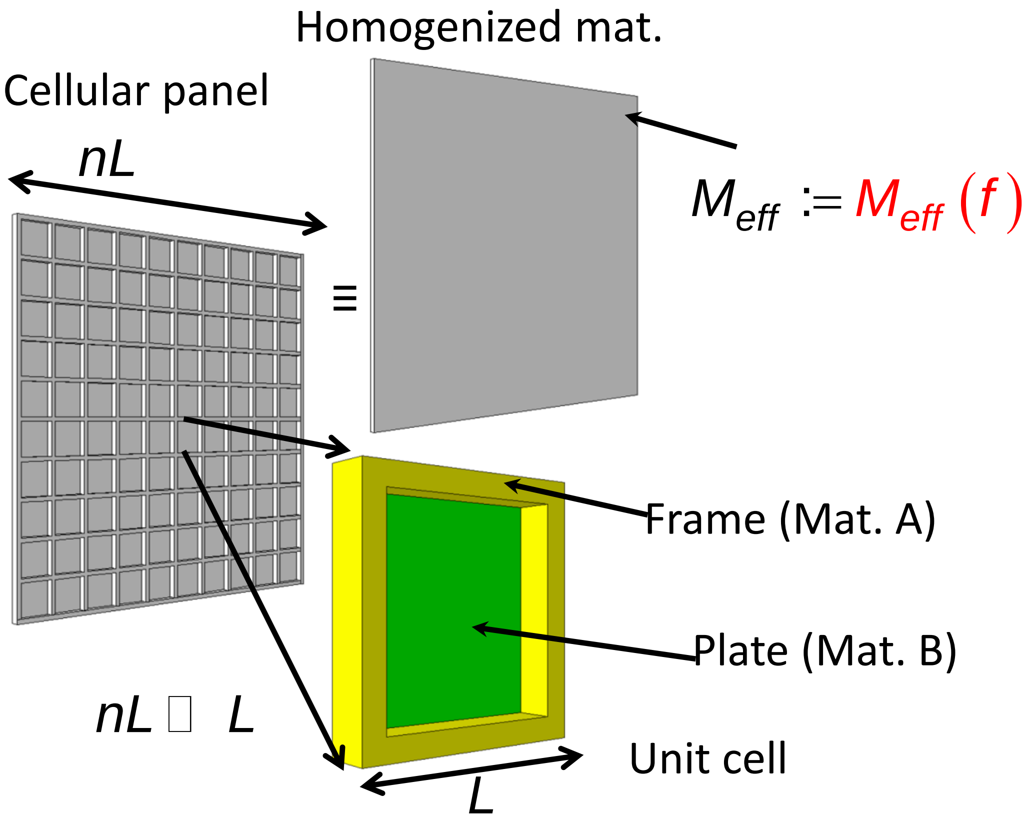
(Received 22 November 2010; accepted 28 March 2011; published online 17 May 2011)

Acoustic metamaterials with negative dynamic mass density have been shown to demonstrate a five-fold increase in transmission loss (TL) over mass law predictions for a narrowband (100 Hz) at low frequencies (100–1000 Hz). The present work focuses on the scale-up of this effect by examining the behavior of multiple elements arranged in arrays. Single membranes were stretched over rigid frame supports and masses were attached to the center of each divided cell. The TL behavior was measured for multiple configurations with different magnitudes of mass distributed across each of the cell membranes in the array resulting in a multipeak TL profile. To better understand scale-up issues, the effect of the frame structure compliance was evaluated, and more compliant frames resulted in a reduction in the TL peak frequency bandwidth. In addition, displacement measurements of frames and membranes were performed using a laser vibrometer. Finally, the measured TL of the multi-celled structure was compared with the TL behavior predicted by finite element analysis to understand the role of nonuniform mass distribution and frame compliance. © *2011 American Institute of Physics*. [doi:10.1063/1.3583656]



Proposed Mass-Neutral Material



$$T = \frac{2\rho_0 c}{2\rho_0 c + j2\pi f M_{eff}(f)}$$

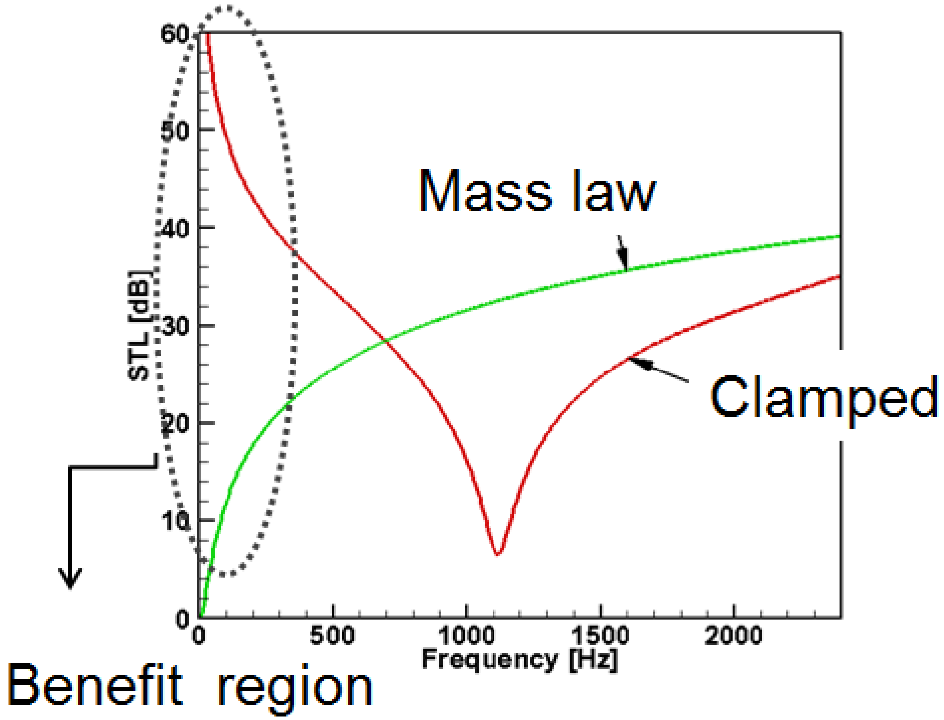
$$STL = -20\log|T|$$

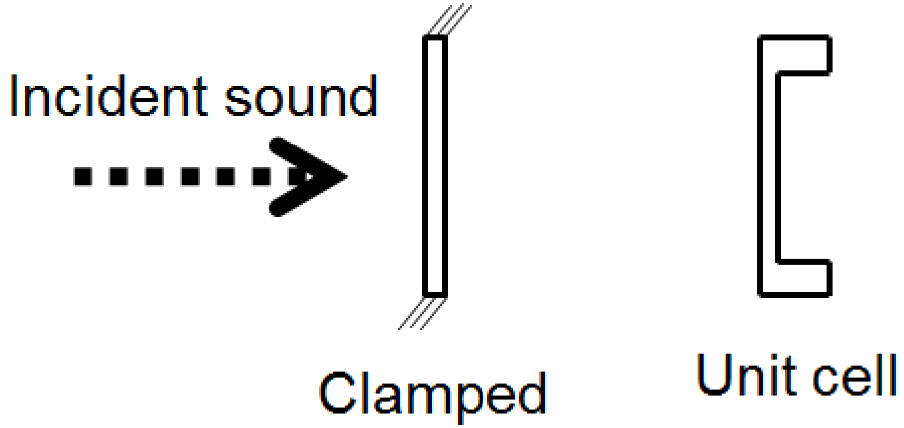
M_{eff} : Mass per unit area

STL : Sound Transmission Loss

- Cellular material with a periodic array of unit cells
- Unit cell has components with contrasting mass and moduli
- Characteristics of infinite, periodic panel are same as that of a unit cell for normally incident sound

Low Frequency Enhancement



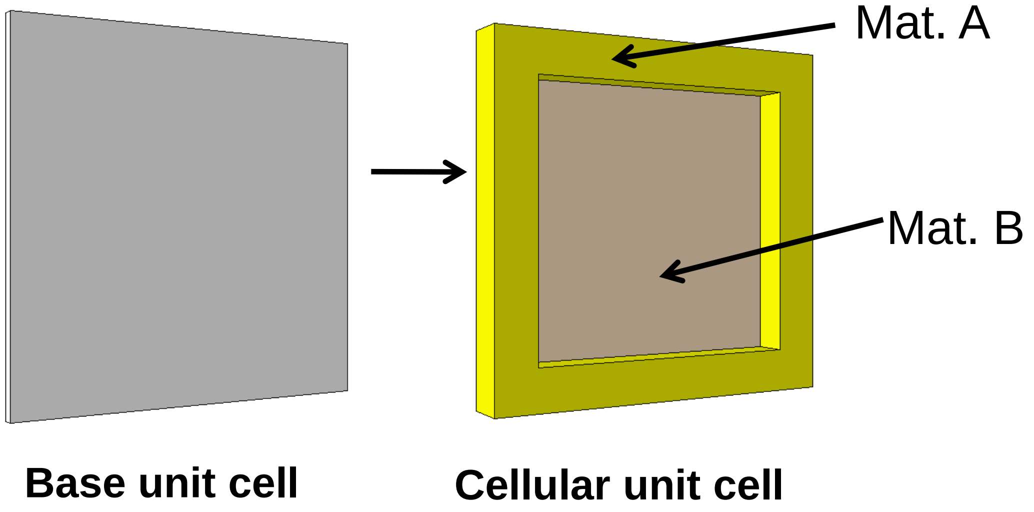


- ❑ **A clamped plate has high STL at very low frequencies due to the effect of boundary conditions and finite size and stiffness.**

Material-Based Mass Apportioning

- **Each unit cell**
  - Overall mass constant
  - Different materials for frame and plate

- **A series of cases for μ between 0.1 and 10000**
  - ρ_p and ρ_f varied
  - E_f varied keeping E_p constant so that $E_f / E_p = \rho_f / \rho_p$



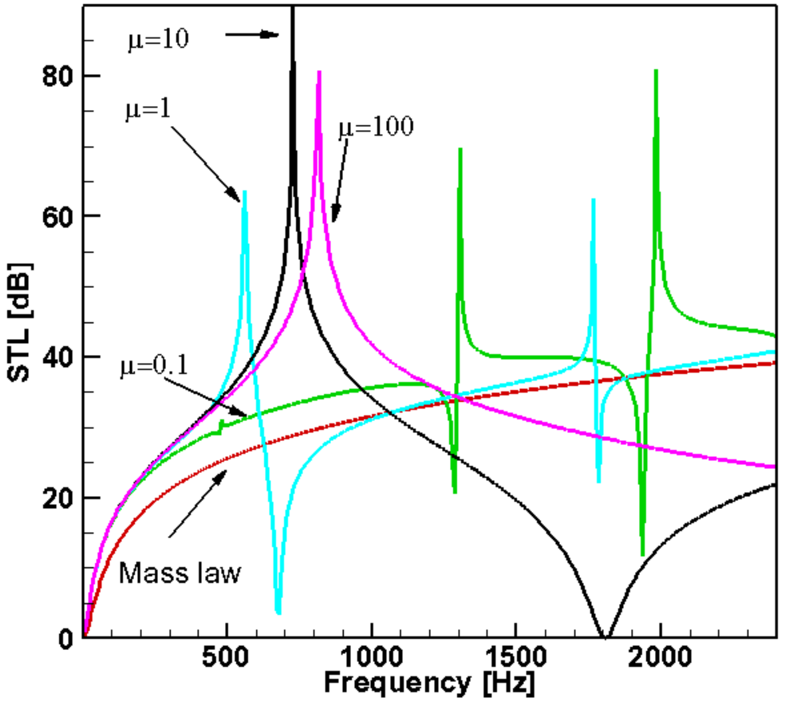
Material-Based Mass Apportioning

- As $\mu\uparrow$
  - High STL region broadens in the low frequency regime
  - Region between the first peak and dip is widening
  - The dip – being shifted to the right – desirable

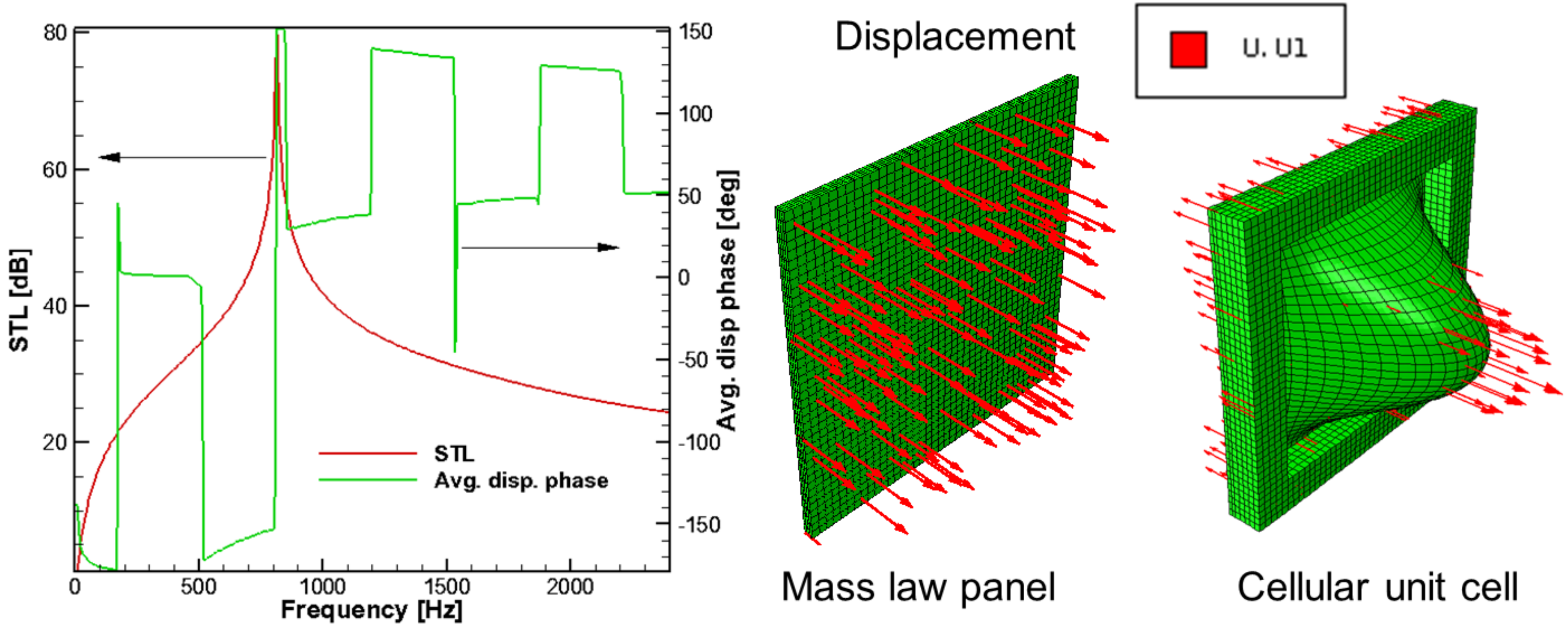
- $\mu \rightarrow O(100) \rightarrow$ saturates

μ	ρ [kg/m^3] Plate	Fr.	E_{fr} (GPa)
0.1	3910	107	0.055
0.5	2868	393	0.274
1	2151	590	0.549
10	391	1073	5.490
100	43	1168	54.900

$E_p = 2$ GPa



Mechanism Behind High STL



- Averaged displacement phase switches from negative to positive value at the STL peak
- Parts of the structure move in opposite directions—similar to observations in LRSMs—resulting in zero averaged displacement
- “Negative mass” observed without locally resonant elements

Hybrid Metamaterial

(12) **United States Patent**
Varanasi et al.

(10) **Patent No.: US 9,163,398 B2**
(45) **Date of Patent: Oct. 20, 2015**

(54) **SOUND BARRIER SYSTEMS**

(71) Applicant: **Purdue Research Foundation**, West Lafayette, IN (US)

(72) Inventors: **Satya Surya Srinivas Varanasi**, West Lafayette, IN (US); **Somesh Khandelwal**, Sunnyvale, CA (US); **Thomas Siegmund**, West Lafayette, IN (US); **John Stuart Bolton**, West Lafayette, IN (US); **Raymond J. Cipra**, West Lafayette, IN (US)

(73) Assignee: **PURDUE RESEARCH FOUNDATION**, West Lafayette, IN (US)

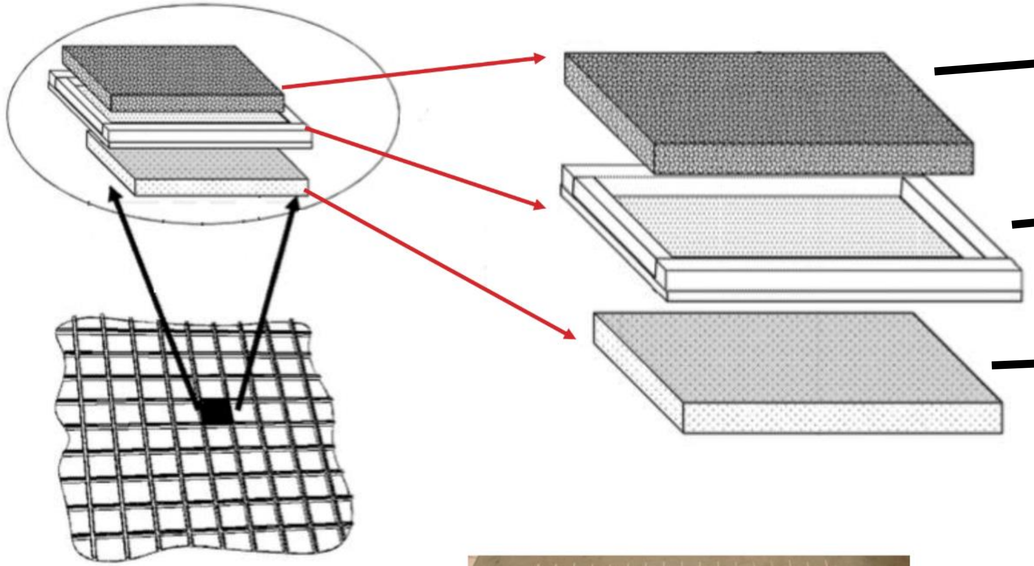
USPC 181/290, 284, 292
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,196,352	B1 *	3/2001	Goodchild	181/290
6,220,388	B1 *	4/2001	Sanborn	181/290
6,360,844	B2 *	3/2002	Hogeboom et al.	181/213
8,087,494	B2 *	1/2012	Palumbo et al.	181/290
8,573,358	B2 *	11/2013	Nonogi et al.	181/291
2005/0194209	A1 *	9/2005	Yang et al.	181/286
2006/0124388	A1 *	6/2006	Pompei	181/290
2009/0178882	A1 *	7/2009	Johnson	181/286
2011/0186380	A1 *	8/2011	Beauvilain et al.	181/292
2013/0209782	A1 *	8/2013	Kipp et al.	428/313.3
2014/0233781	A1 *	8/2014	Kawakami et al.	381/359

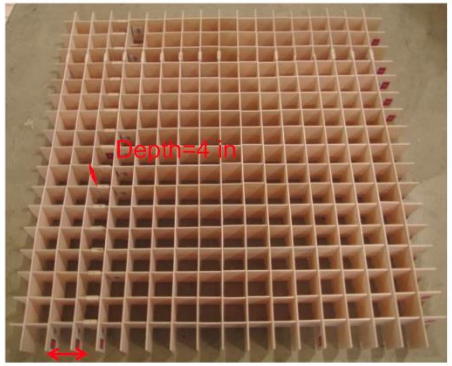
▪ Hybrid Metamaterial



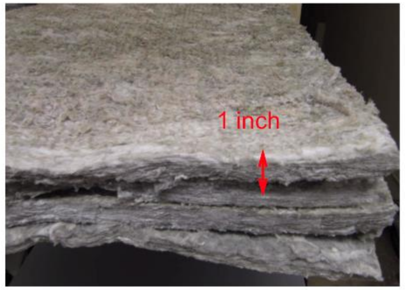
Normalizing layer

Cellular metamaterial

High performance fibrous layer



2.5 inches



CONCLUSIONS

- Poro-elastic materials can give excellent low frequency performance when designed property
- Front and rear boundary conditions have a profound effect on the sound absorption offered by poroelastic materials
- Those effects are predictable and measureable
- Internal constraint of poroelastic materials can increase their transmission loss, but finite weight of required supports should be accounted for
- Metamaterials for transmission loss typically depend on the presence of constraints, geometry and flexural stiffness for their performance
- A proposed mass-neutral “metamaterial” barrier featuring spatially-periodic internal constraints gives low frequency advantage with respect to the mass law, but would require supplementary material to mitigate performance loss at high frequencies

176th ASA & 2018 Acoustics Week
Victoria, BC, Canada
5–9 November 2018

2aNS1: FUTURE TRENDS IN NOISE CONTROL TECHNOLOGY

J. Stuart Bolton

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School of Mechanical Engineering, Purdue University
West Lafayette, IN, USA

Presentation available at Herrick E-Pubs: http://docs.lib.purdue.edu/herrick/
See also: https://www.youtube.com/watch?v=1voc1-2ZUYQ

FUTURE TRENDS

- **Noise Control ≠ Acoustics**
- **Noise Control = "Constrained" Acoustics**
- **Constraints:**
  - Cost
  - Weight
  - Volume
  - Robustness
  - Manufacturability
  - Recyclability

4. Noise Control Methods

- **Advanced Noise Control Materials**
  - MPP's – very attractive functional attributes – multilayer barriers & absorbers
  - Carbon fiber composites
  - Very thin absorbents (internal degrees of freedom)
  - Hybrid metamaterials →
  - 3D printing of acoustical materials
  - Multi-functional acoustic materials
    - – damping plus absorption
    - – absorption plus barrier
  - Custom manufacturing of noise control materials

4. Noise Control Methods

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

ACKNOWLEDGEMENTS

- **Former Students:**
  - Edward R. Green
  - Bryan H. Song
  - Jinho Song
  - Ryan Schultz
- **Current Students:**
  - Srinivas Varanasi
  - Yutong Xue

REFERENCES

•pp. 4–12: J. Stuart Bolton, Ph.D. Thesis, University of Southampton, 1984. Cepstral techniques in the measurement of acoustic reflection coefficients, with applications to the determination of acoustic properties of elastic porous materials.

•pp. 13-14: J. Stuart Bolton, Paper DD4 presented at 110th meeting of the Acoustical Society of America, Nashville TN, November 1985. Abstract published in the Journal of the *Acoustical Society of America* 78(S1) S60. Normal incidence absorption properties of single layers of elastic porous materials.

•pp. 18-23: Ryan Schultz and J. Stuart Bolton, Proceedings of INTER-NOISE 2012, New York City, 19-22 August, 2012. Effect of solid phase properties on the acoustic performance of poroelastic materials.

•P. 24: J. Stuart Bolton, Benoit Nennig and Nicolas Dauchez, "Enhancement of the low frequency performance of thin,film-faced layers of foam by surface segmentation," Proceedings of Symposium on the Acoustics of Poro-Elastic Materials (SAPEM) 2014, Stockholm, Sweden, 8 pages, 2014.

•pp. 26-29: Jinho Song and J. Stuart Bolton, Proceedings of INTER-NOISE 2002, paper N574, 6 pages, Dearborn, Michigan, August 2002. Modeling of membrane sound absorbers.

•pp. 30-33: Bryan H. Song, J. Stuart Bolton and Yeon June Kang, Journal of the Acoustical Society of America, Vol. 110, 2902-2916, 2001. Effect of circumferential edge constraint on the acoustical properties of glass fiber materials.

•pp. 34-36: Bryan H. Song and J. Stuart Bolton, *Noise Control Engineering Journal*, Vol. 51, 16-35, 2003. Enhancement of the barrier performance of porous linings by using internal constraints.

•pp. 39-43: Srinivas Varanasi, J. Stuart Bolton, Thomas Siegmund and Raymond J. Cipra, *Applied Acoustics*, Vol. 74, 485-495, 2013. The low frequency performance of metamaterial barriers based on cellular structures.

•pp. 44-45: Sound Barrier Systems (S. Varanasi, S. Khandelwal, T. Siegmund, J.S. Bolton and R.J. Cipra). US Patent No.: US 9,163,398 B2. October 2015.

•pp. 47-50: J. Stuart Bolton, "Future trends in noise control technology," 176th meeting of the Acoustical Society of America and 2018 Acoustics Week in Canada, Victoria, British Columbia, November 2018. Paper 2aNS1. Abstract published in the Journal of the Acoustical Society of America 144(3) Pt. 2, p. 1754, 2018.

•See also: J. Stuart Bolton and Edward R. Green, Paper E4 presented at 112th meeting of the Acoustical Society of America, Anaheim CA, December 1986. Abstract published in the *Journal of the Acoustical Society of America* 80(S1), p. S10. Acoustic energy propagation in noise control foams: approximate formulae for surface normal impedance.

•Presentations available at: http://docs.lib.purdue.edu/herrick/