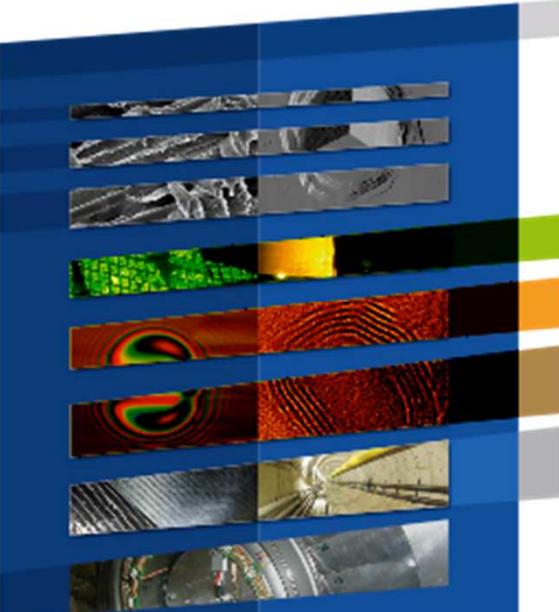


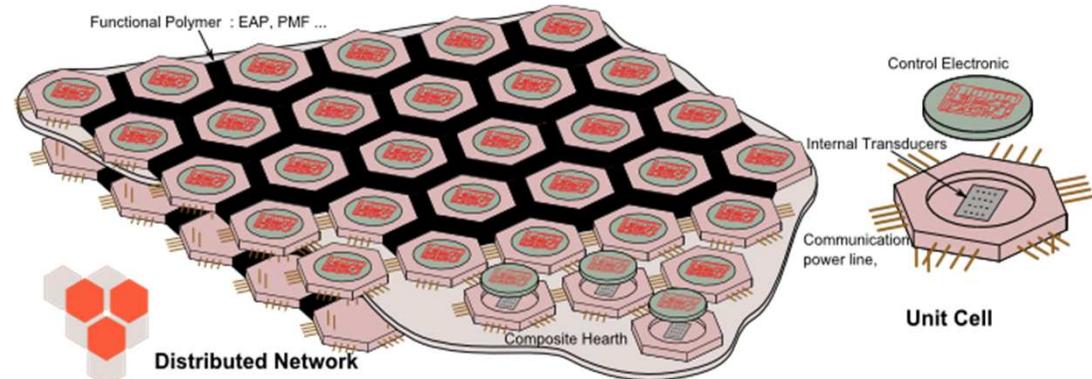
## Contrôle distribué appliqué à la vibroacoustique



Laboratoire de  
Tribologie et  
Dynamique des  
Systèmes

LTDS UMR 5513

<http://ltds.ec-lyon.fr>



Manuel COLLET (CNRS, LTDS)

With contributions from M. Ouisse (FEMTO), M. Ruzzene (GT), M. Ichchou , Fan Yu (LTDS), F. Tateo, K. Billon, A. Khelif, G. Matten (FEMTO-ST), B Beck, K. Cunefare (GT), F. Ablitzer & C. Pezerat (LAUM), H.Lissek (EPFL), S Karkar (EPFL)

## La rupture technologique en aéronautique :

- Enjeux pour l'industrie aéronautique civile portent sur le développement d'avions majoritairement composites, avec une perspective de production de près de **15000 nouveaux appareils d'ici 2020**
- Développement de nouvelles technologies aéronautiques 'vertes' (Wings Shaping,...) pour améliorer l'efficacité aérodynamique, diminuer les émissions de CO<sub>2</sub> (**5-15%**), réduire les bruits ....



Boeing 787 DreamLiner tout composite

Clean Sky , DREAM EU Project s, X-noise, AIAA's Emerging Technologies Committee (ETC)

## « Green » Aerospace technologies – structural weight reduction

(decrease CO<sub>2</sub> emission (5-15%), noise control....)

- Intensified dynamical environment
- Fatigue and damage : security
- Stability problem
- Adapted design methodologies

FR & EC research strategies, Clean Sky , DREAM EU Project s, AIAA's Emerging Technologies Committee (ETC) ...

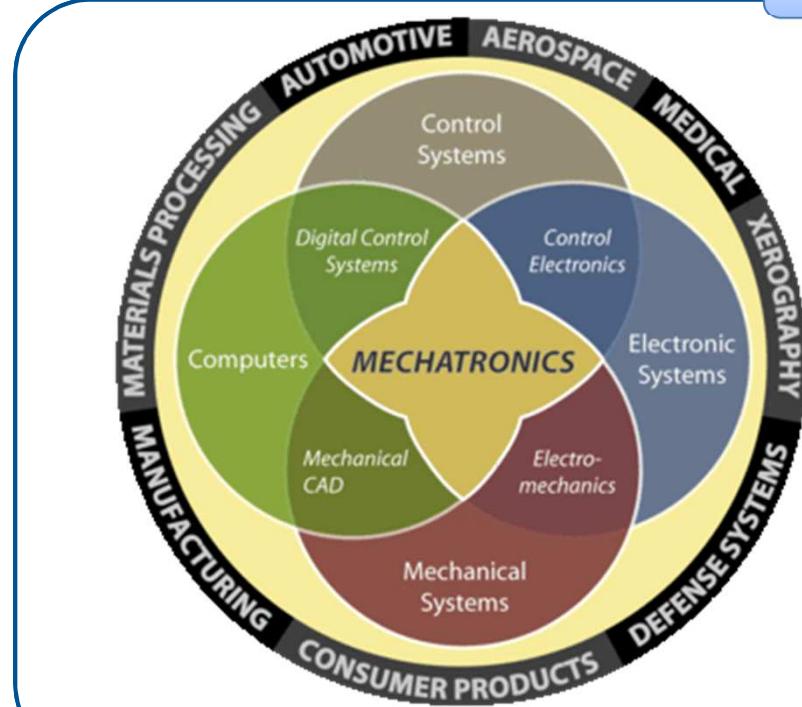




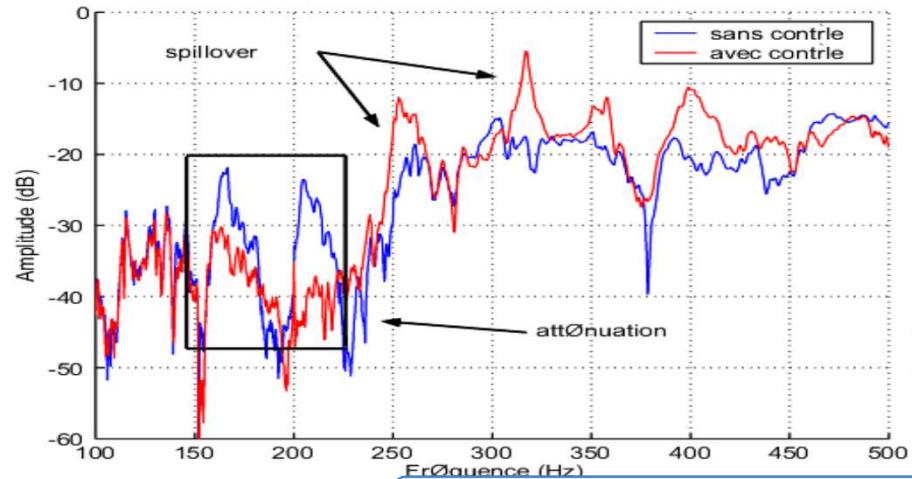
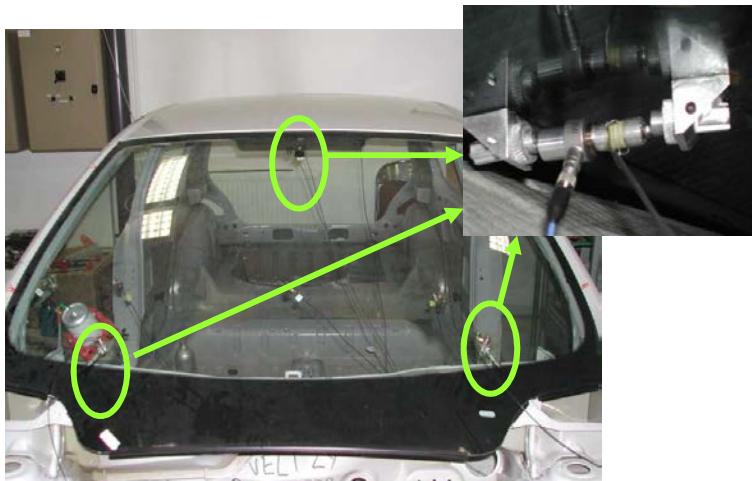
## New Integrated functionalities

- Active Vibration Control -AVC-
- Active Noise Control -ANC-
- Structural Health Monitoring -SHM-
- NDE, PHM
- Shape Control
- Mechatronic
- Energy harvesting/scavenging

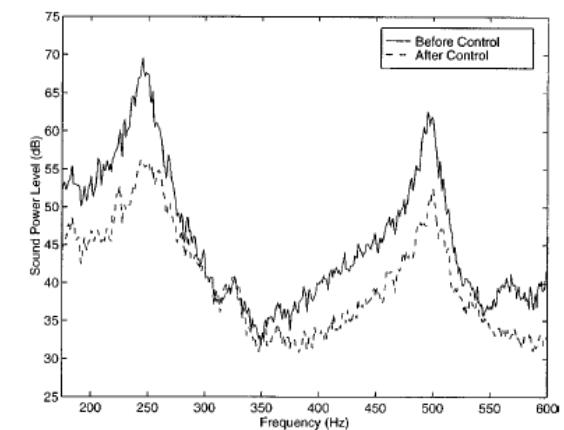
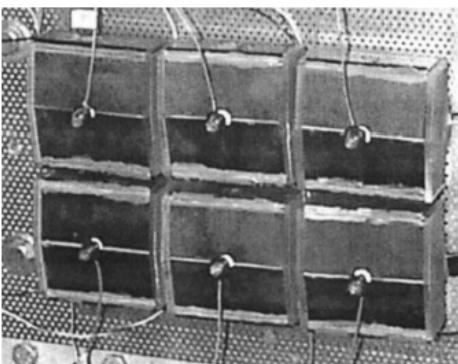
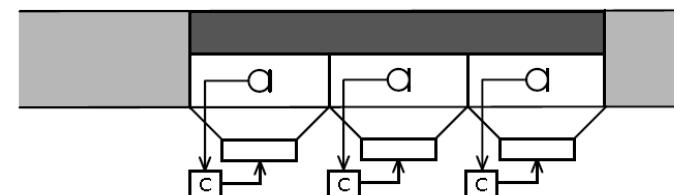
Meyer et al.: Advanced Microsystems for Automotive Applications 2009 - Smart Systems for Safety, Sustainability and Comfort, Springer 2009



Aerial Venn diagram from [RPI](#)'s website describes the various fields that make up Mechatronics



Collocated Active Damping [Monnier, JSCHM, 2001])



Broadband control using active-skin and structural acoustic sensing [Fuller, JASA, 2000]

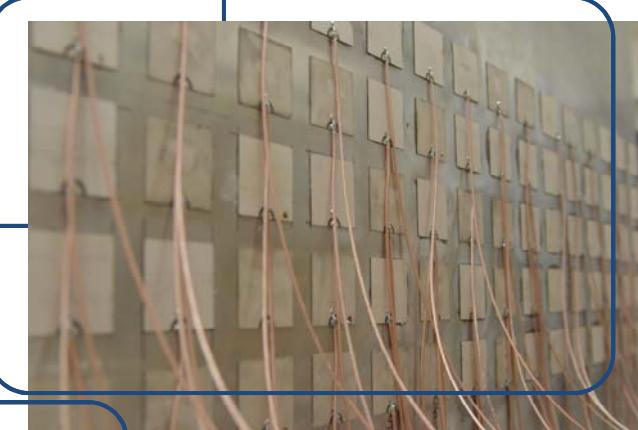
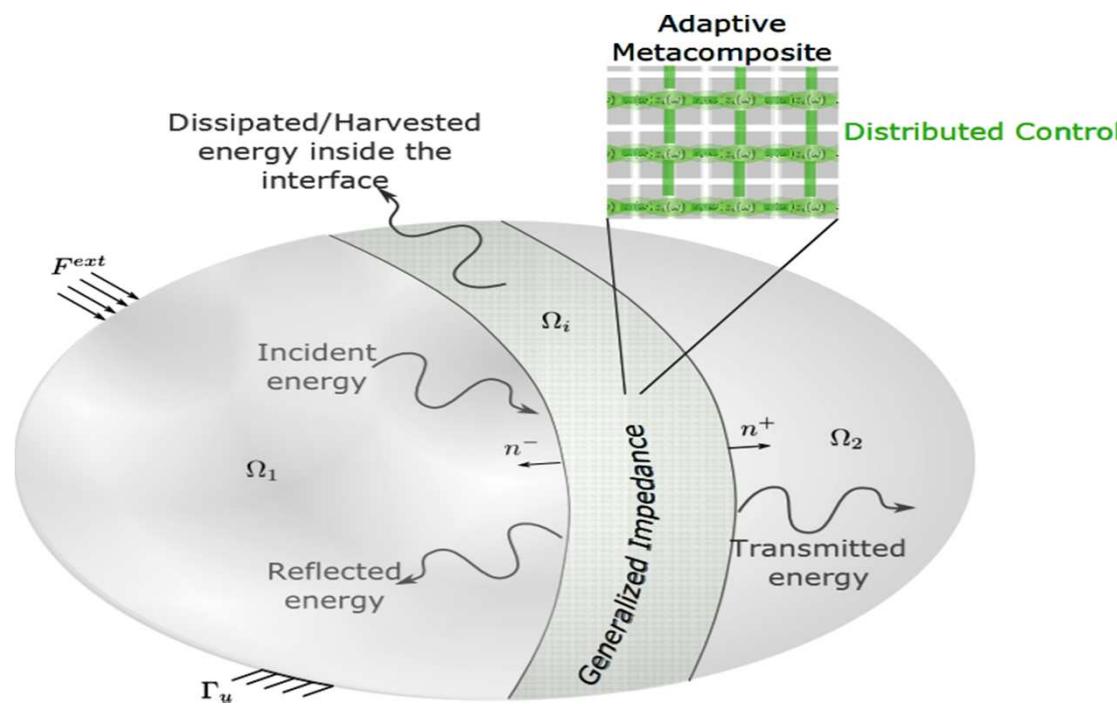
# From Structural Control to Material Programming

Classical approaches of ANC or AVC is difficult to apply into real fully distributed applications :

- Technological and Numerical **complexity**
- Difficulties for integrating such technology into the **Design Process** (**Robustness**/Performances)
- Energy Cost

Necessity to propose a new approach ....

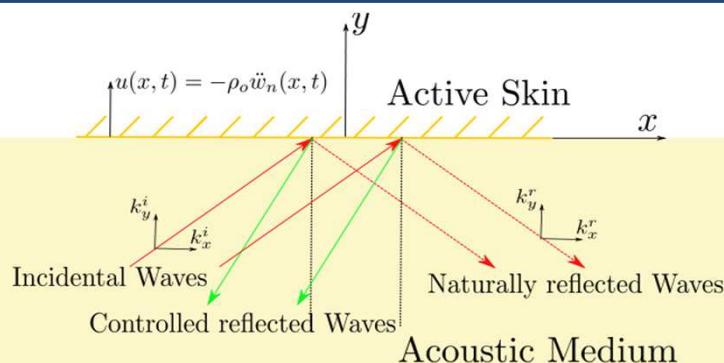
Synthesis of generalized Impedance operator using distributed (low cost, low energy) individual (communicating) cells



**Metacomposites:**  
Synthesis of functional constitutive laws inside hybrid composite material by using distributed sets of smart cells

Scale of interest:  
mm -> few cm

# Application: design of an active skin for acoustics



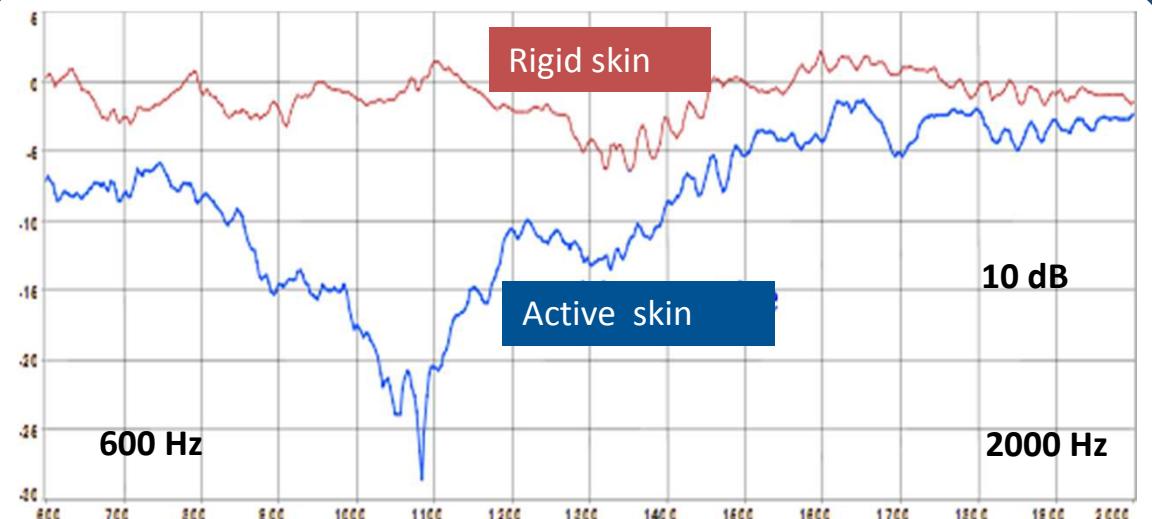
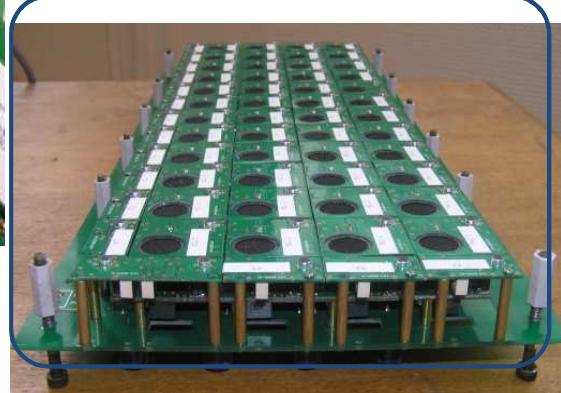
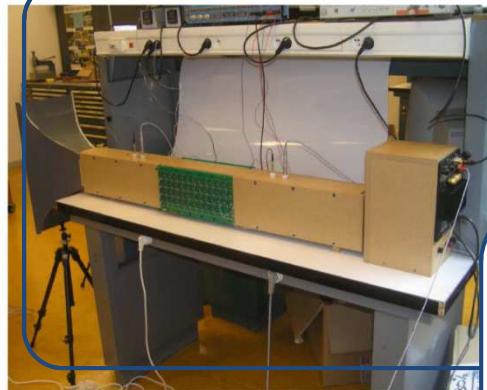
$$\begin{cases} \frac{1}{c_0^2} \frac{\partial^2 p}{\partial t^2} - \Delta p = 0 & \text{on } \mathfrak{R}_y^{-*} \times \mathfrak{R}_x \times \mathfrak{R}_t^{*+} \\ \frac{\partial p(x, 0, t)}{\partial y} = u(x, t) \\ y(x, t) = p(x, 0, t) \end{cases}$$

The physics

Control law that guarantees  $kx < 0$ :

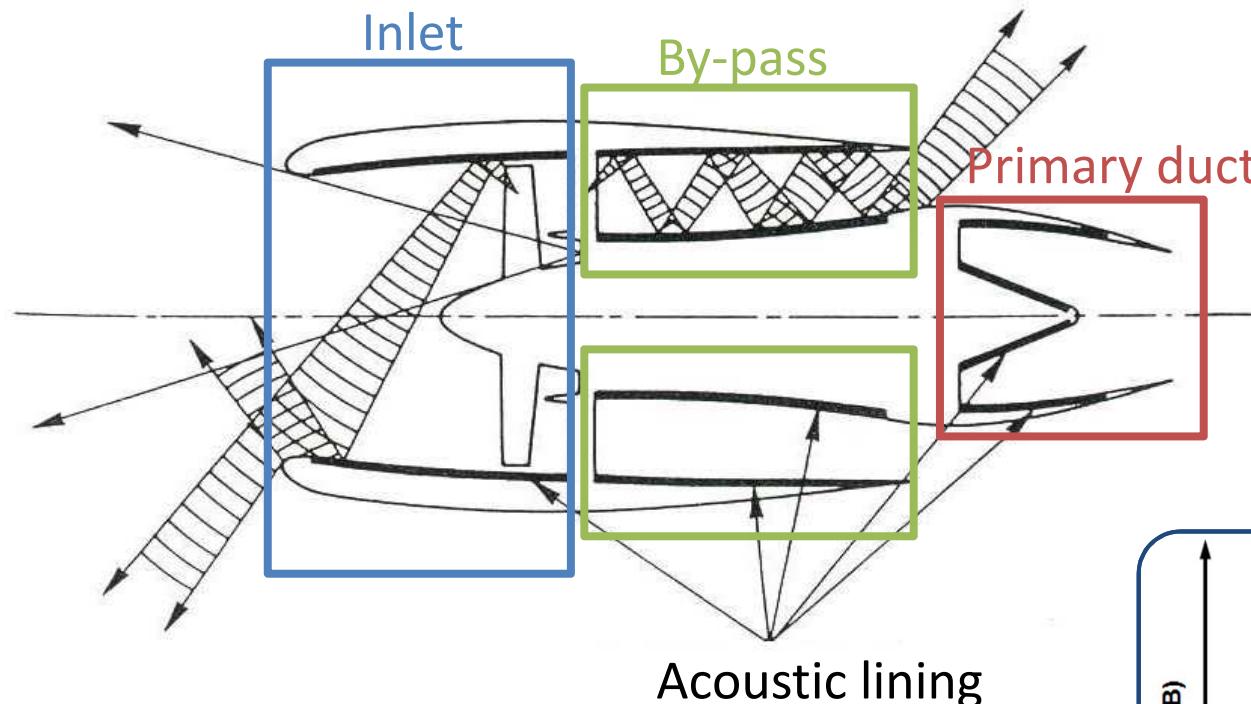
$$u(x, t) = - \left( \frac{1}{c_a} \frac{\partial p(x, 0, t)}{\partial t} - \frac{\partial p(x, 0, t)}{\partial x} \right)$$

Finite difference estimation of 1st-order derivatives

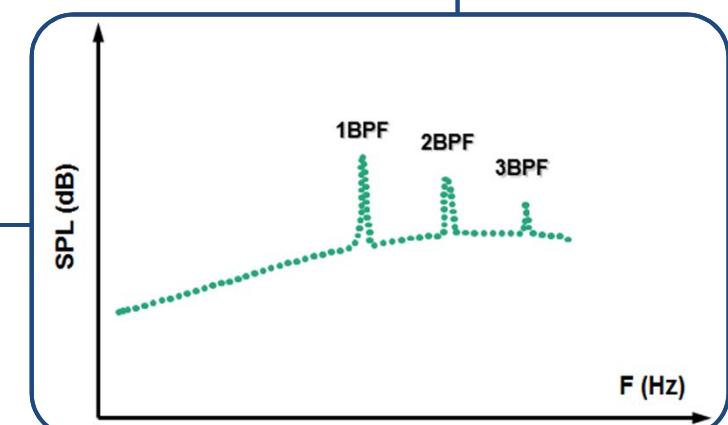
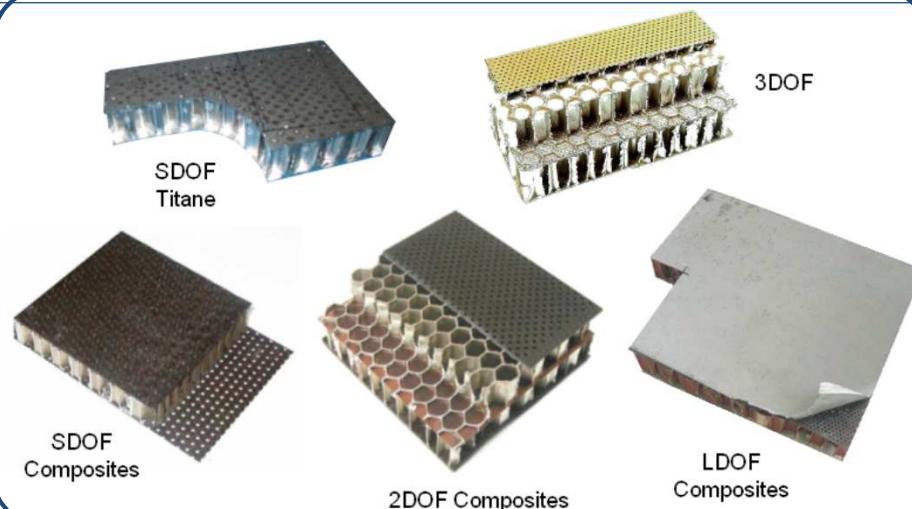


P. David, M Collet et al., SMS, 19(3), 2012

# Application: design of an active skin for acoustics

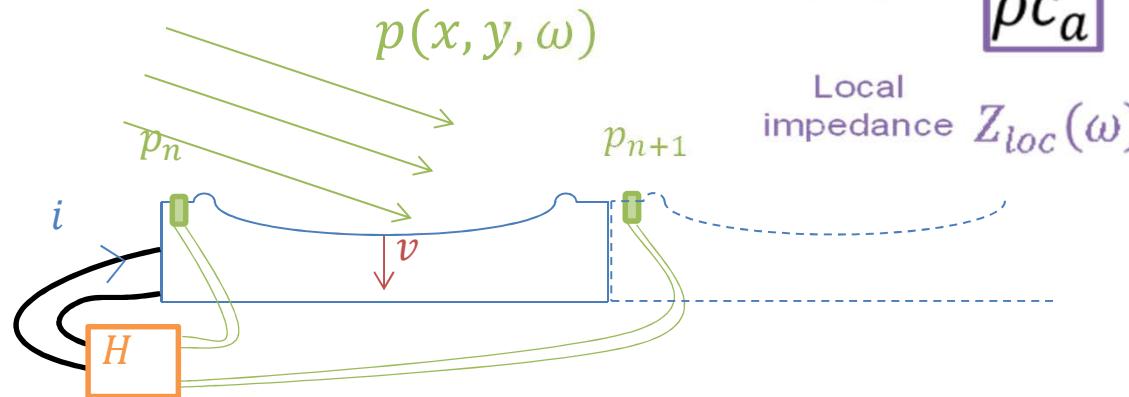


Acoustic lining



## B. Distributed control

Target “impedance”:



$$v(\omega) = \frac{1}{\rho c_a} p(\omega) - \frac{1}{j\omega\rho} \frac{\partial p}{\partial x} (\omega)$$

Distributed impedance  $Z_{dis}(\omega)$



Equation of control:

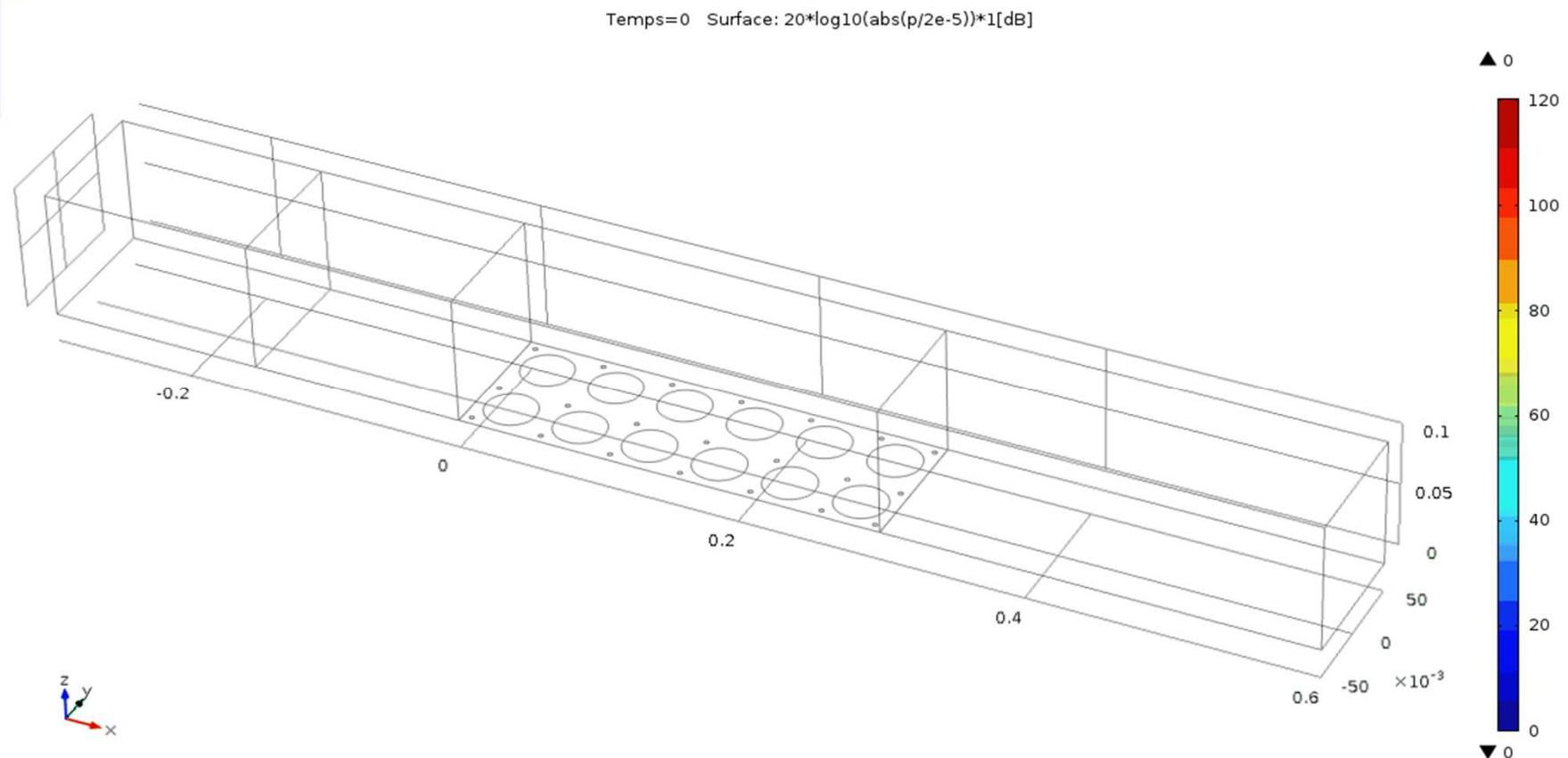
$$i(\omega) = H_{loc}(\omega) \frac{p_{n+1}(\omega) + p_n(\omega)}{2} + H_{dis}(\omega) \frac{p_{n+1}(\omega) - p_n(\omega)}{\Delta x}$$

$$H_{loc}(\omega) = \frac{1}{Bl} \left( S_d - \frac{Z_m(\omega)}{Z_{loc}(\omega)} \right)$$

$$p(x, y, \omega)$$

$$H_{dis}(\omega) = \frac{Z_m(\omega)}{Bl Z_{dis}(\omega)}$$

## B. Distributed control

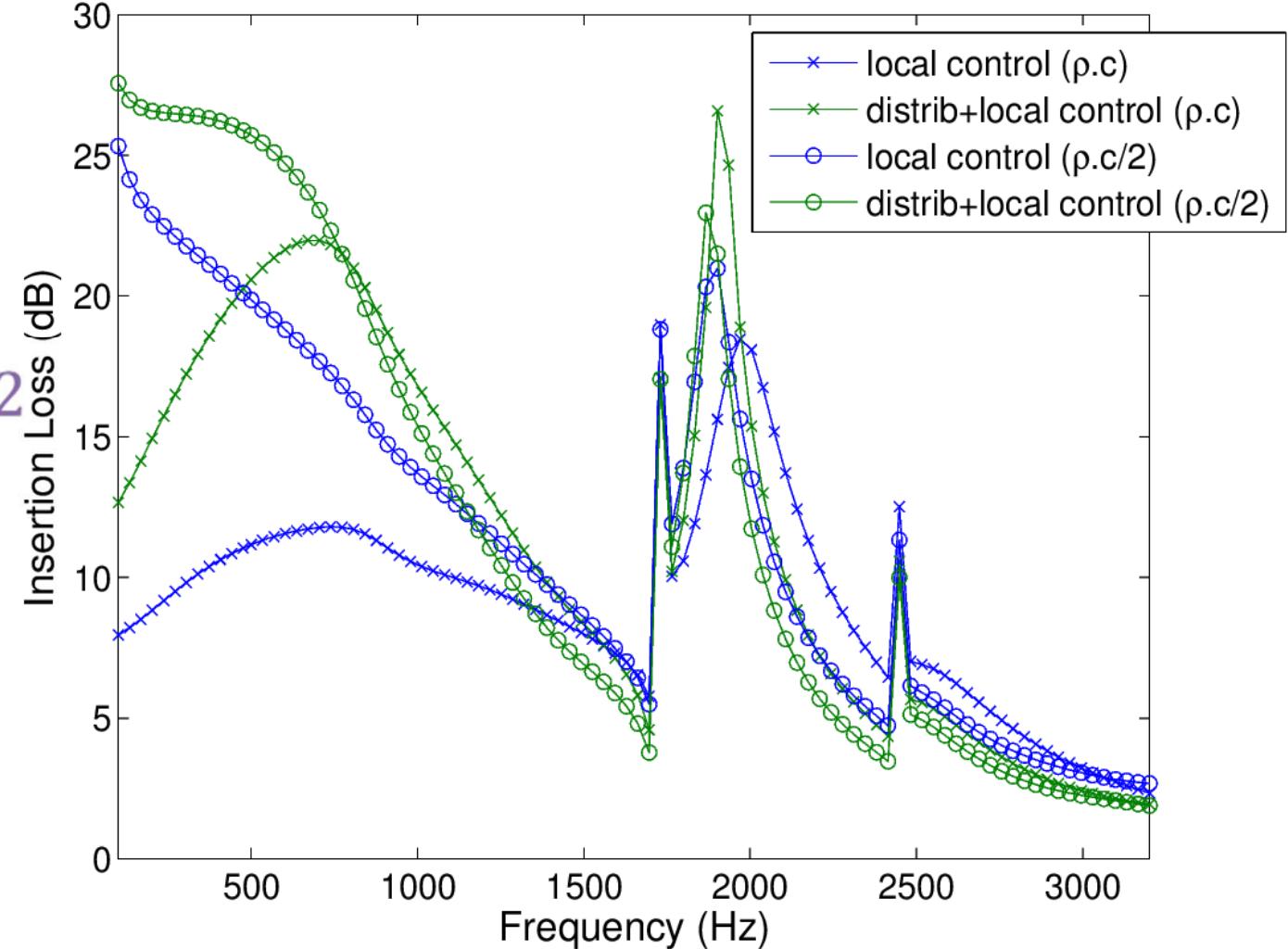


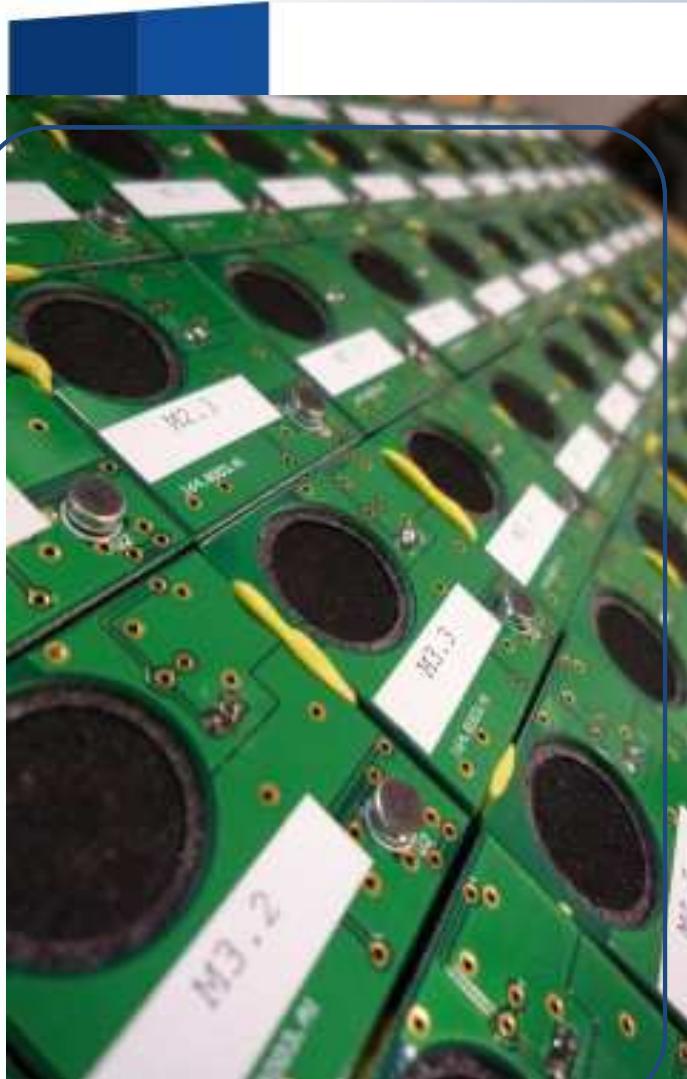
## B. Distributed control

### Local vs. distributed

$$Z_{loc}(\omega) = \rho c \text{ or } \rho c/2$$

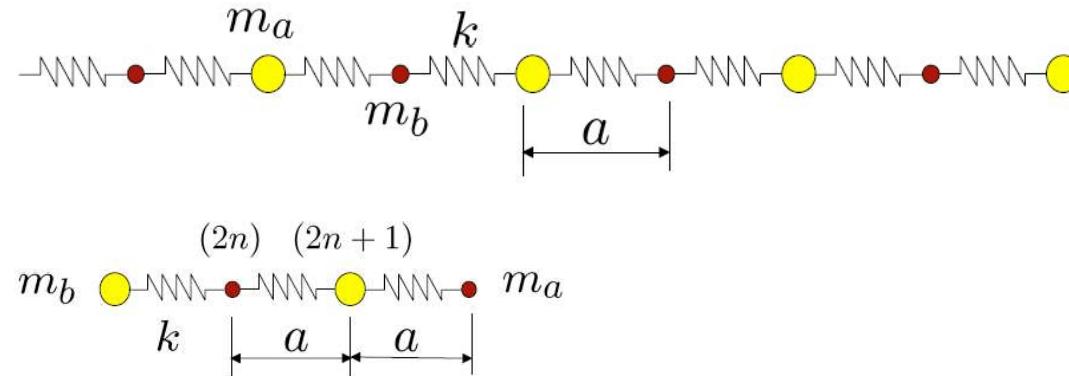
$$Z_{dis}(\omega) = j\omega\rho$$





- Smart distributed skin for synthesis of boundary acoustic impedance
- Challenge: extension of the concept for structural vibrations
- Take advantage of the specific behavior of periodic structures in terms of wave propagation
- Design of unit cells based on global performances
- Use of passive/active smart concepts (control, adaptive, multifunctional)
- Focus on damping consideration

Let's consider a biatomic lattice :

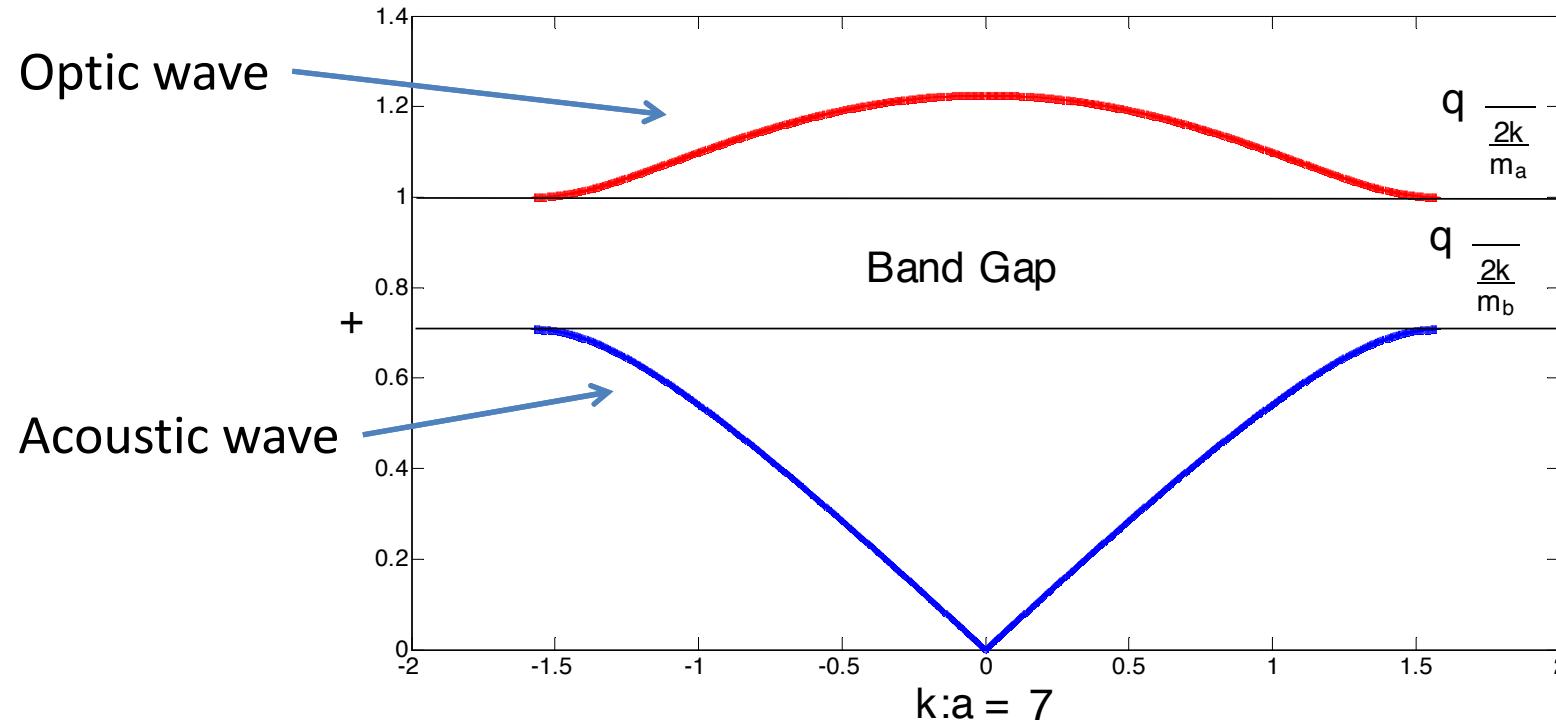


$$-\omega^2 m_a u_{2n} + 2k u_{2n} - k(u_{2n+1} + u_{2n-1}) = 0$$

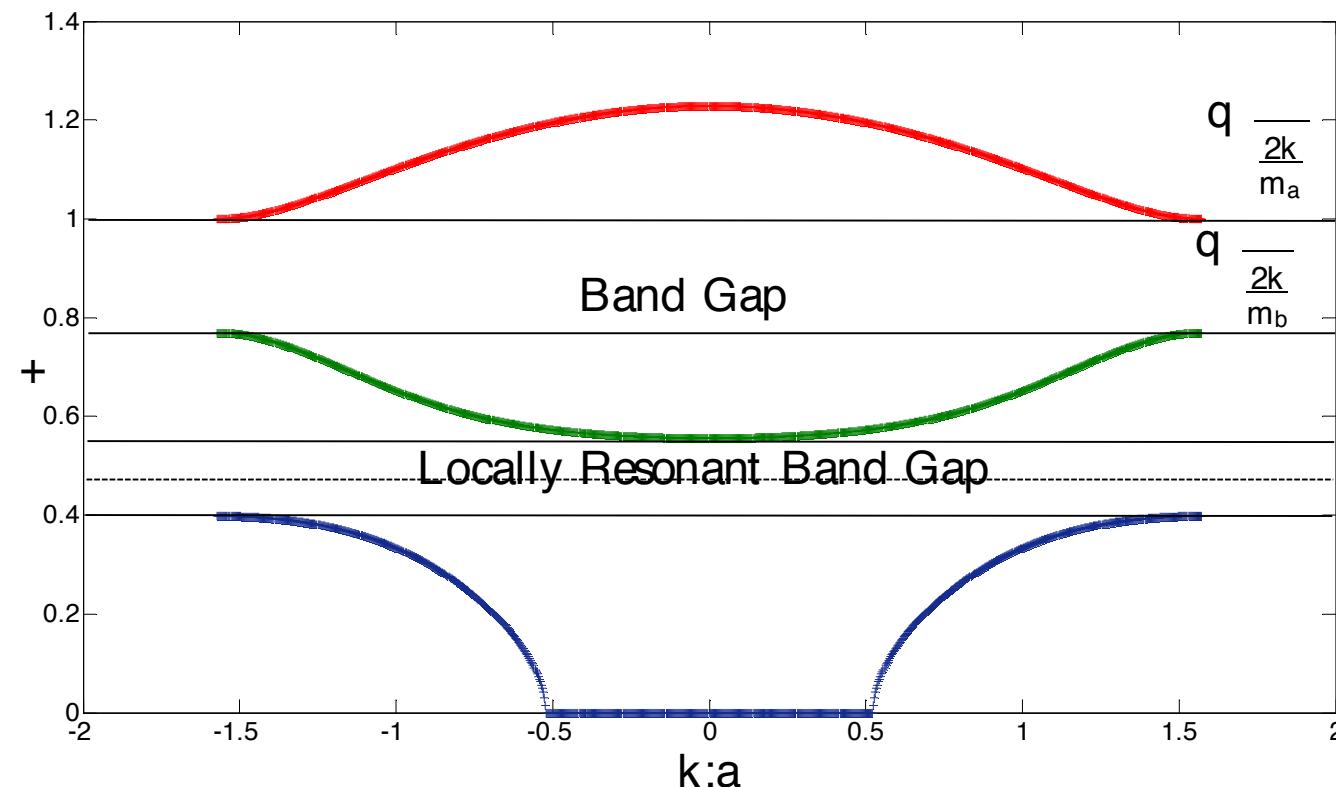
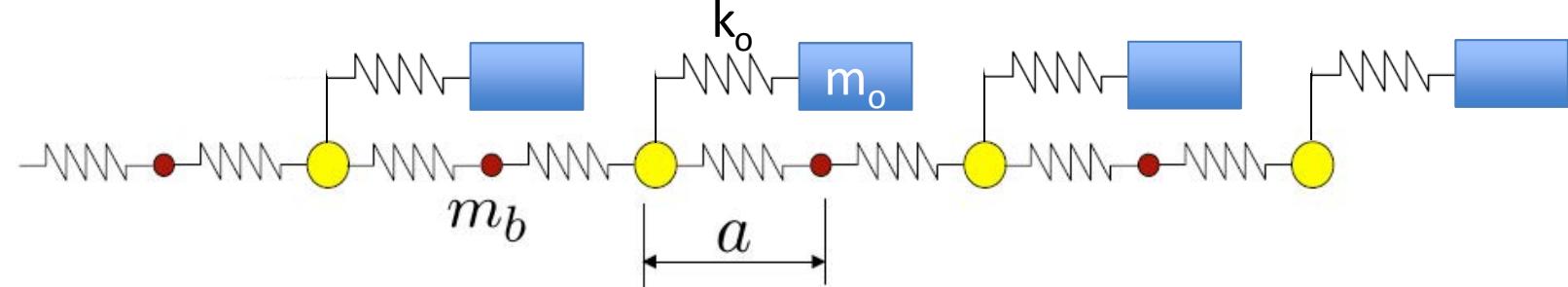
$$-\omega^2 m_b u_{2n+1} + 2k u_{2n+1} - k(u_{2n+2} + u_{2n}) = 0$$

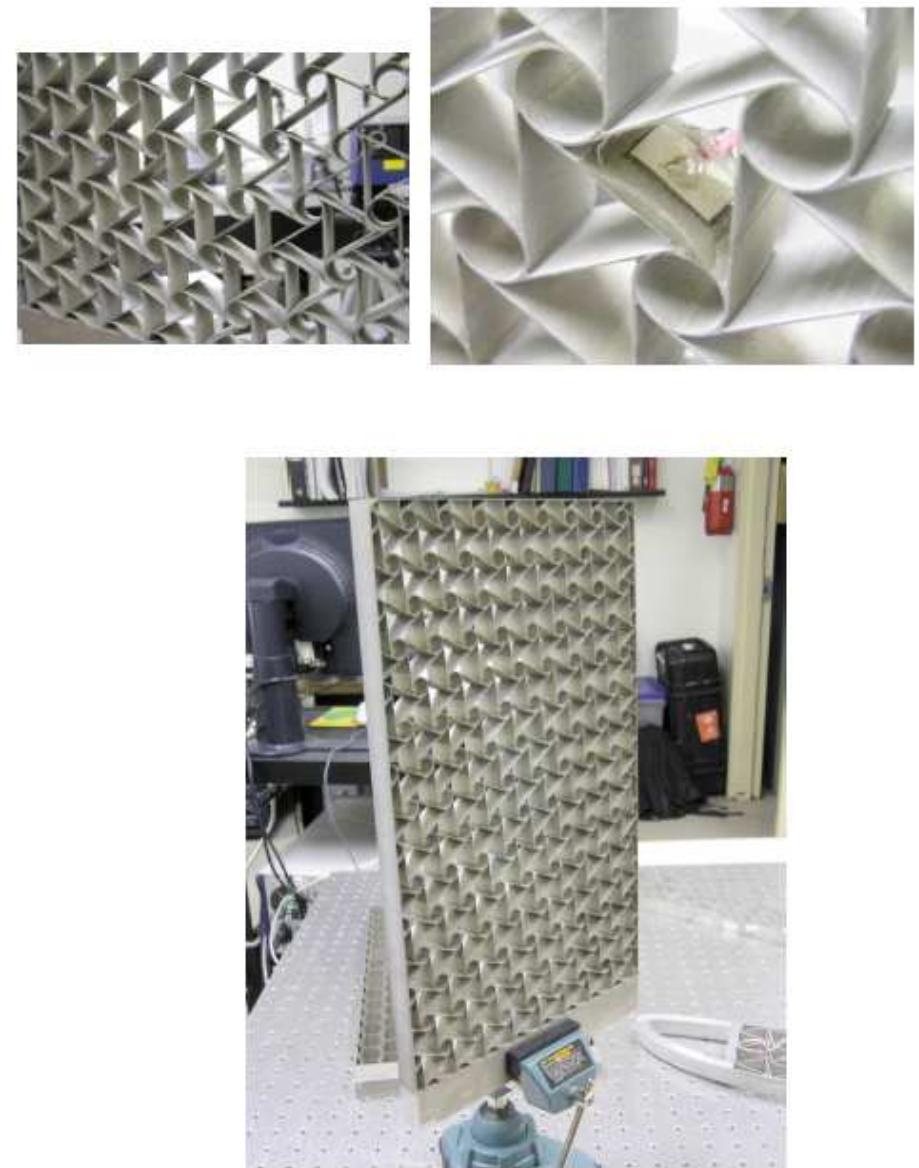
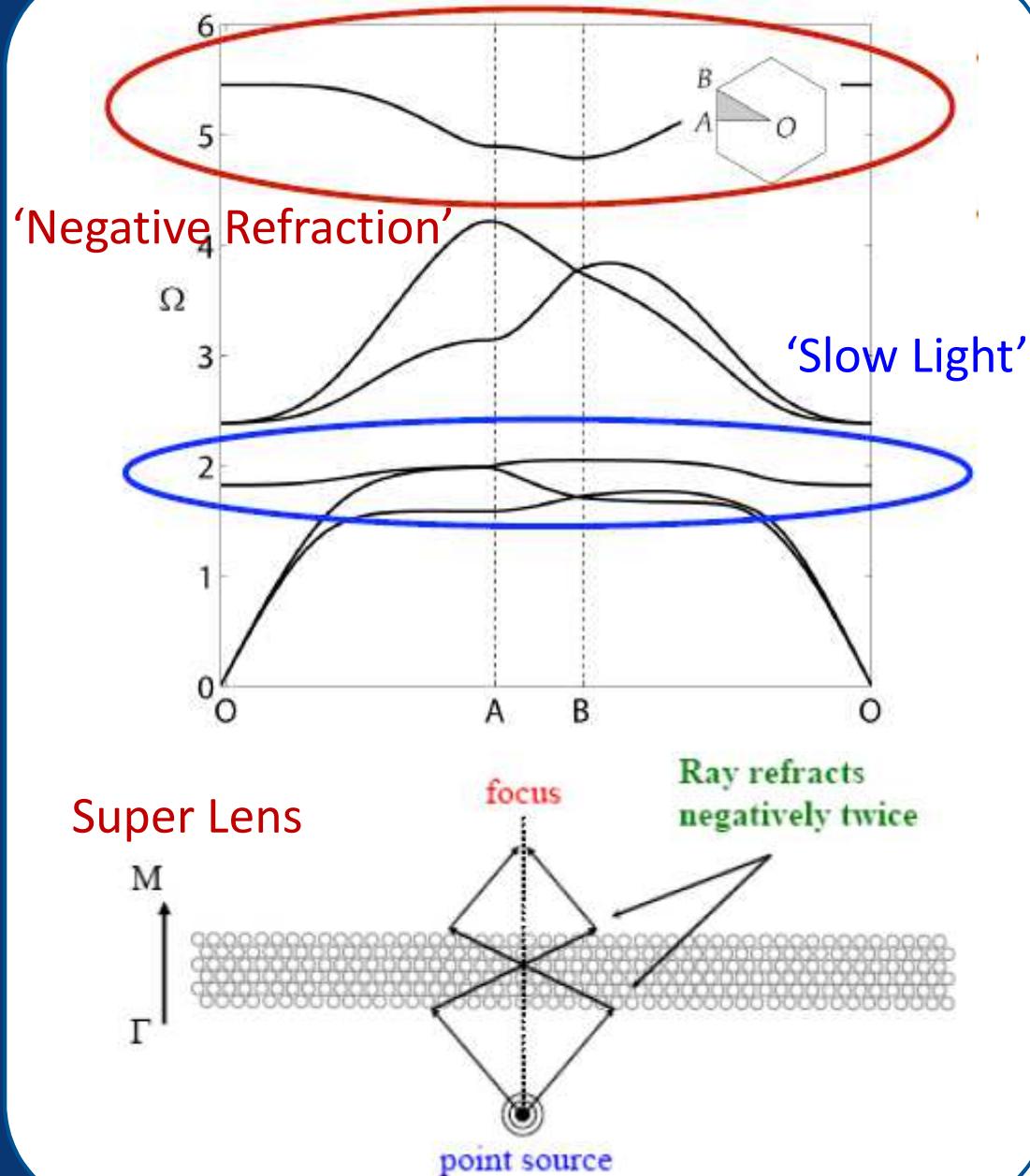
$$u_{2n}(\omega) = u_a(\omega) e^{j\kappa x_{2n}} = u_a(\omega) e^{j2a\kappa n}$$

$$u_{2n+1}(\omega) = u_b(\omega) e^{j\kappa x_{2n+1}} = u_b(\omega) e^{j(2n+1)a\kappa}$$

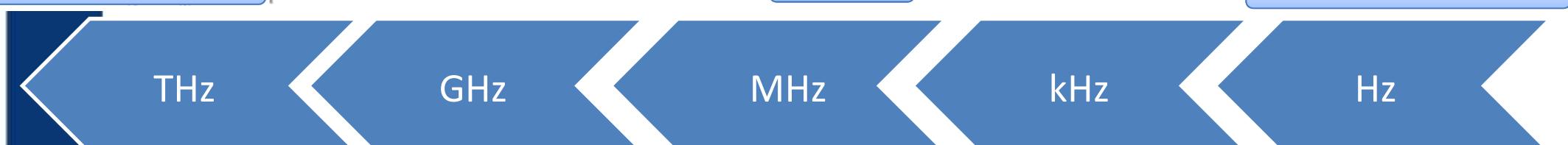
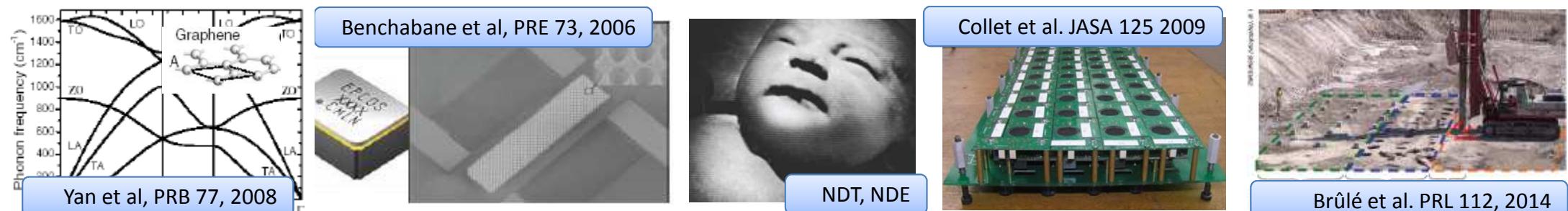
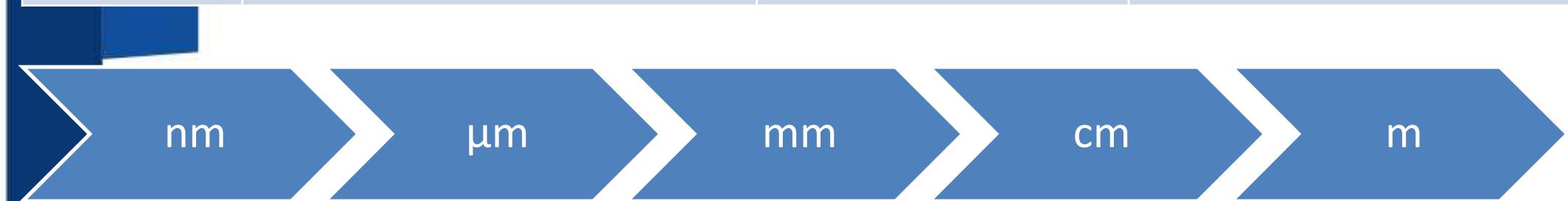


Let's consider a biatomic sonic lattice :



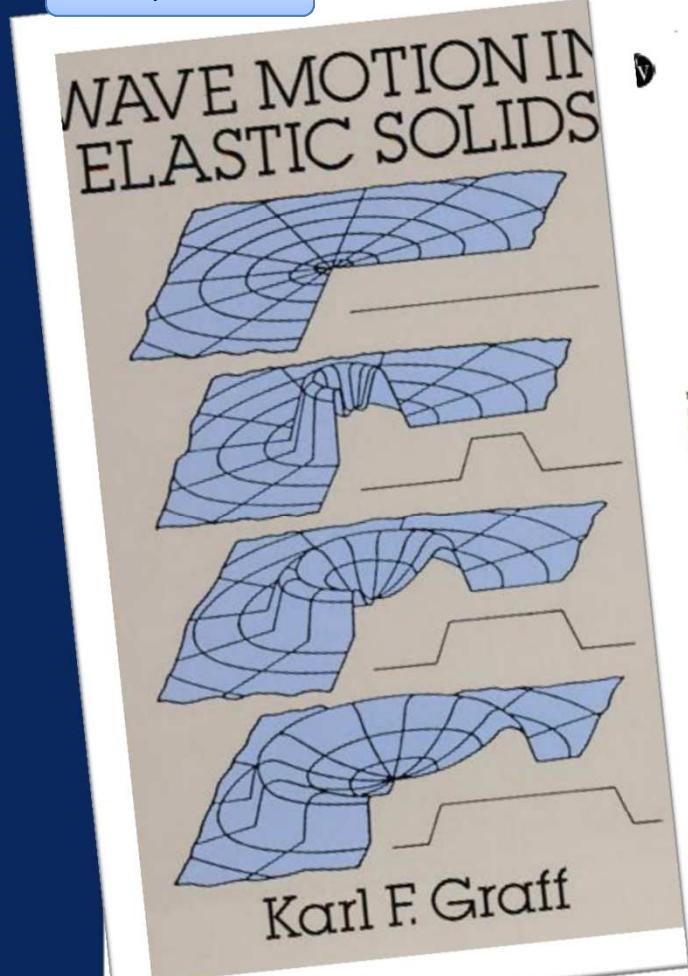


| Structure                 | Physical properties                                  | Waves support                               | Gap   |
|---------------------------|--|---|---|
| <b>Crystalline</b> solids | Periodic arrangement of atoms $\sim 5 \text{ \AA}$   | Electrons ( $\Psi$ ) <b>Schrödinger</b> eq. | Absence of <b>electron</b> states             |
| <b>Photonic</b> crystal   | Periodic modulation of $\epsilon, \mu$ (macro scale) | EM (E,B) <b>Maxwell</b> eqs.                | Absence of states of the <b>EM</b> field      |
| <b>Phononic</b> crystal   | Periodic modulation of $\rho, E, v$ (macro scale)    | Elastic (u) <b>Elasticity</b> eqs.          | Absence of states of the <b>elastic</b> field |



# An arbitrary choice of 3 top-level references

Graff, 1975



Mead, JSV, 1996

## WAVE PROPAGATION IN CONTINUOUS PERIODIC STRUCTURES: RESEARCH CONTRIBUTIONS FROM SOUTHAMPTON, 1964–1995

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(Received 1 November 1995)

After brief reference to some early studies by other investigators, this paper focuses mainly on methods developed at the University of Southampton since 1964 to analyze and predict the free and forced wave motion in continuous periodic engineering structures. Beginning with receptance methods which have been applied to periodic beams and rib-skin structures, it continues with a method of direct solution of the wave equation. This uses Floquet's principle and has been applied to beams and quasi-one-dimensional periodic plates and cylindrical shells. Sample curves of the propagation and attenuation constants pertaining to these structures are presented. A limited discussion of the transfer matrix then follows, after which the method of space-harmonics is introduced as the method best suited to the prediction of sound radiated from a vibrating periodic structure. Reviewed next are some theorems and variational principles relating to periodic structures which have been developed at Southampton, and which form a basis for finding natural frequencies of finite structures or for computing free and forced wave motion by energy methods. This has led to the finite element method (in its standard and hierarchical forms) being used to study wave motion in genuine two-dimensional and three-dimensional structures. Examples of this work are shown. The method of phased array receptance functions is then introduced as possibly the easiest way of setting up exact equations for the propagation constants of uniform quasi-one-dimensional periodic structures. A summary is finally presented of the limited and early work performed at Southampton on simple disordered periodic structures.

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### 1. INTRODUCTION

Elwyn Richards' early vision and pioneering zeal in the study of aeroplane noise at Southampton had a "Coanda effect" upon those of us involved in structural teaching and research. We were inexorably drawn into the study of structural vibration caused by the noise of the early jet engines, which were shaking and shattering flimsy aeroplane structures in pieces. Something had to be done about it! While quieter engines were yet to be developed, less responsive and more fatigue-resistant structures had to be designed and developed. EJR gave much encouragement to three of us to work to this end—B. L. Clarkson, the late T. R. G. Williams and myself. His reputation and fund-raising ability drew the attention of the U.S. Air Force, which awarded us generous grants for vibration and

<sup>†</sup> Formerly of the Department of Aeronautics and Astronautics, 1952–1991.  
495  
ISSN 0885-6420/96/020495-15 \$12.00/0

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Corresponding author.  
Manuscript received April 17, 1993; final manuscript received December 30, 1993; published online May 2, 2014. Assoc. Editor: Chin An Tan.

Hussein, Learn, Ruzzene, ASME Applied Mechanics Review, 2014

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## Dynamics of Phononic Materials and Structures: Historical Origins, Recent Progress, and Future Outlook

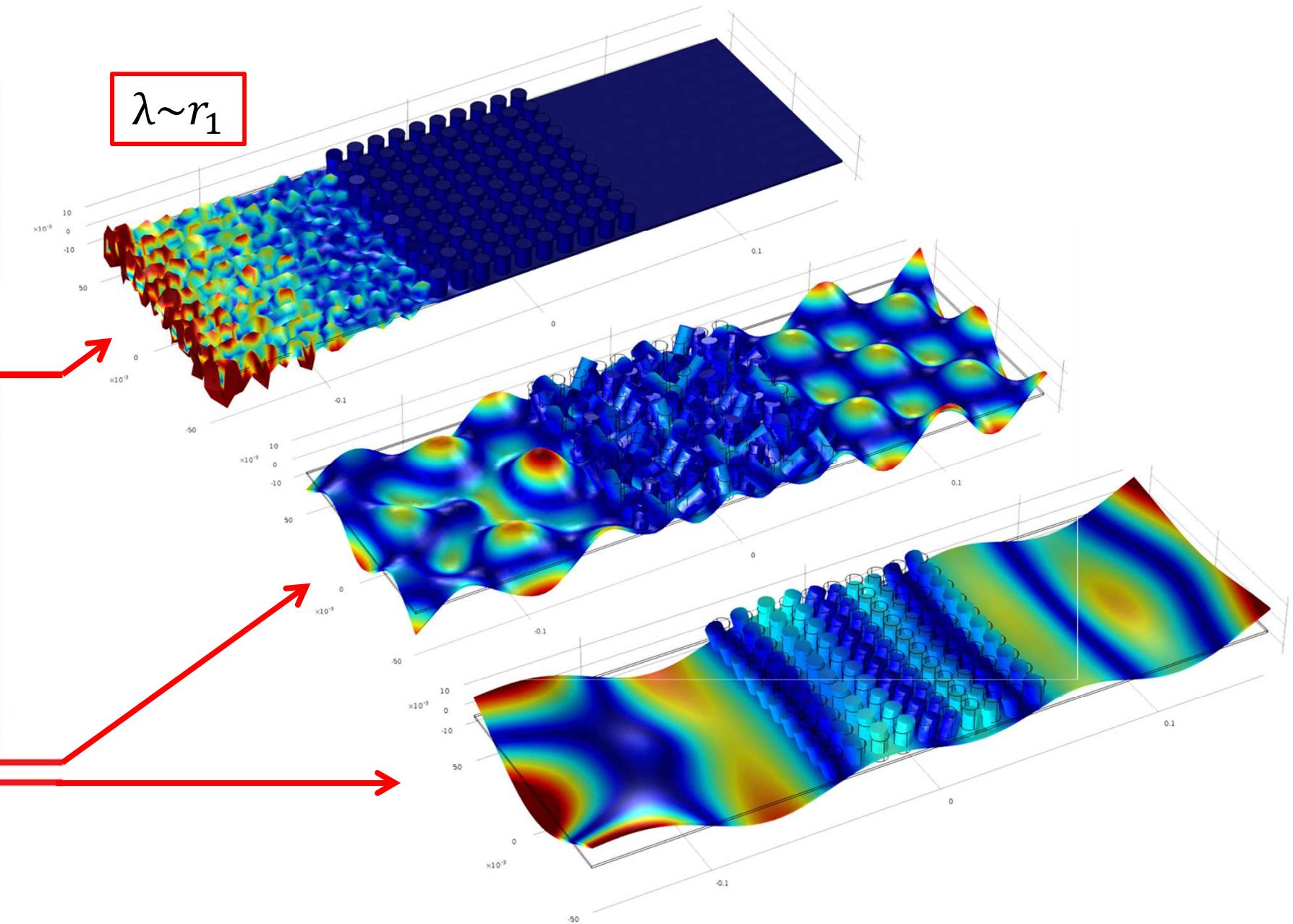
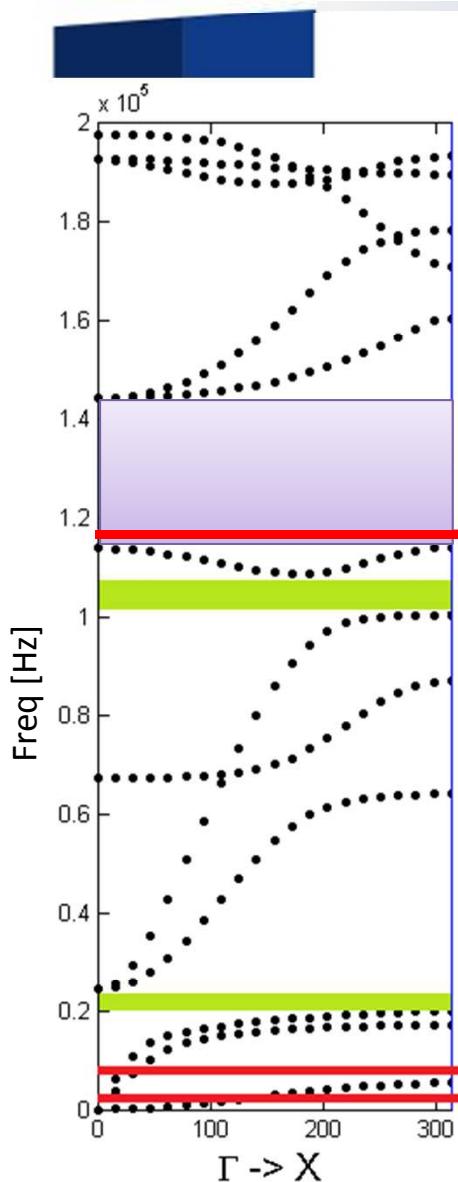
The study of phononic materials and structures is an emerging discipline that lies at the crossroads of vibration and acoustics engineering and condensed matter physics. Broad speaking, a phononic medium is a material or structural system that usually exhibits some form of periodicity, which can be in the constituent material phases, or the internal geometry, or even the boundary conditions. As such, its overall dynamical characteristics are compactly described by a frequency band structure, in analogy to an electronic band diagram. With roots extended to early studies of periodic systems by Newton and Rayleigh, the field has grown to encompass engineering configurations ranging from trusses and ribbed shells to phononic crystals and metamaterials. While applied research in this area has been abundant in recent years, treatment from a fundamental mechanics perspective, and particularly from the standpoint of dynamical systems, is needed to advance the field in new directions. For example, techniques already developed for the incorporation of damping and nonlinearities have recently been applied to wave propagation in phononic materials and structures. Similarly, numerical and experimental approaches originally developed for the characterization of conventional materials and structures are now being employed toward better understanding and exploitation of phononic systems. This article starts with an overview of historical developments and follows with an in-depth literature and technical review of recent progress in the field with special consideration given to aspects pertaining to the fundamentals of dynamics, vibrations, and acoustics. Finally, an outlook is projected onto the future on the basis of current trajectories of the field. [DOI: 10.1115/14026911]

physics, this diagram represents the backbone of electronic structure theory, credited for forming a basis for the classification of crystals into metals, semiconductors, and insulators. In mechanics, this band diagram is precisely a representation of the dispersion relation describing the nature of free wave propagation in an elastic (or acoustic) medium.

Looking closely at the study of periodic systems in the past half-century, we find that researchers in vibrations and acoustics and more broadly from the mechanics community at large, have conducted a considerable amount of work on key theoretical foundations, concepts, and analysis techniques that are relevant to periodic systems in other nonmechanics disciplines. Arguably, the two most motivating applications in mechanics, going back to the 1950s and extending through the 1990s and beyond, have been composite materials (which conveniently have been modeled as periodic structures) [3,4] and aircraft structures (which naturally exhibit some degree of periodicity emanating from the present aircraft introduced primarily for strengthening and stiffening purposes) [5,6]. Other areas related to mechanical and civil engineering include multiblade turbines [7–9], impact resistant foundations [10–12], and multistory buildings and multispan bridges [13,14].

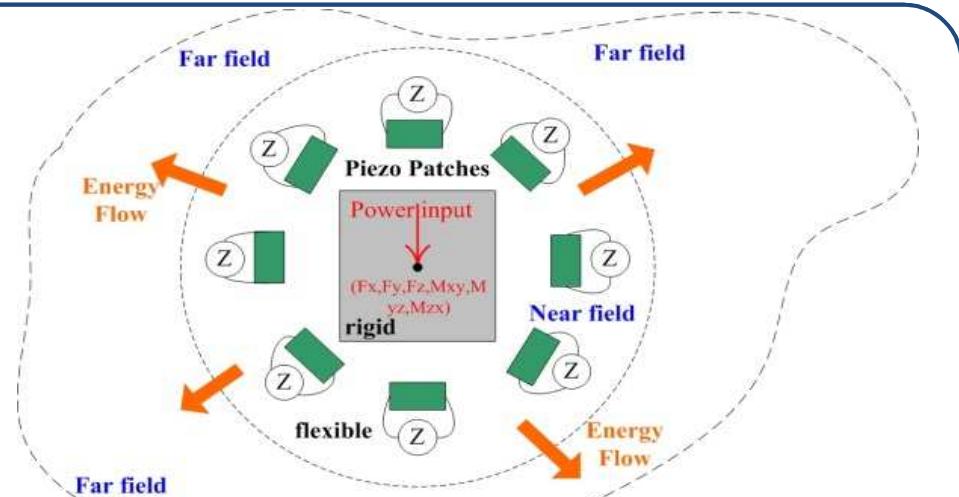
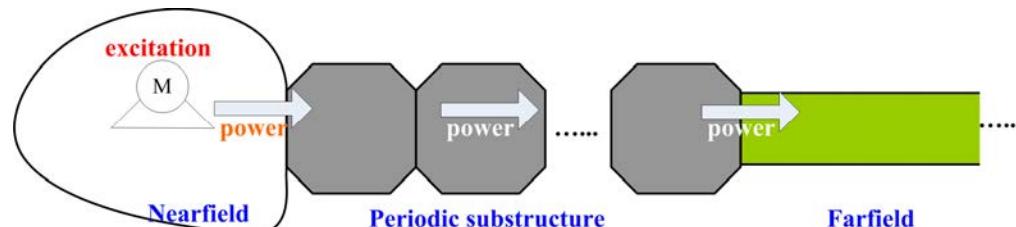
In recent years, starting in the early 1990s, the field has experienced a resurgence with the introduction of phononic crystals [16–21], and, roughly a decade later, with the study of acoustic metamaterials [22], which may be also broadly considered as examples of phononic materials. A phononic crystal is a composite or nonuniform material consisting of one, two, or more material phases (solid and/or fluid) arranged periodically in space. It is not much different from periodic composite materials studied earlier in the engineering literature, with the only difference that

## And now... back to real (simulated) life: integration of a phononic crystal as interface on a finite structure



# Is Band Gap the optimal solution?

1D

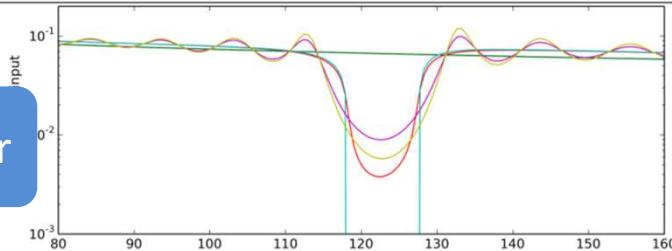


2D

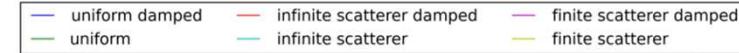
Local modes not excited



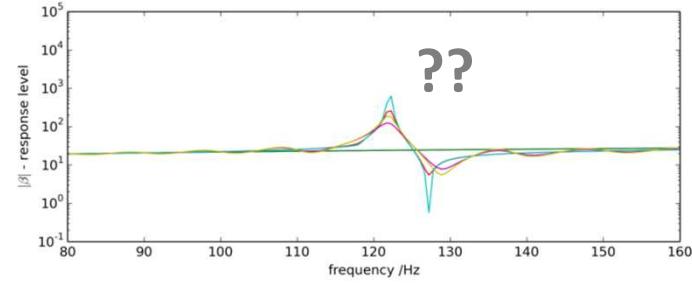
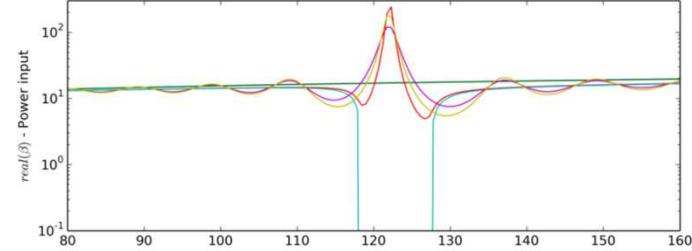
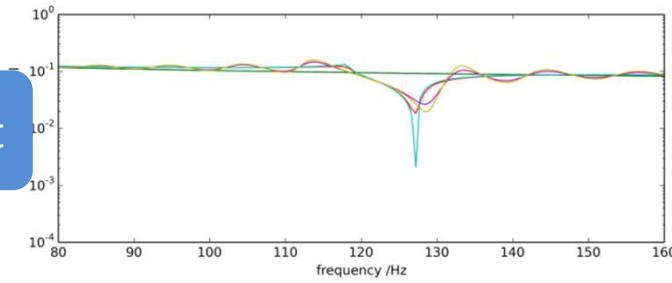
Output Power



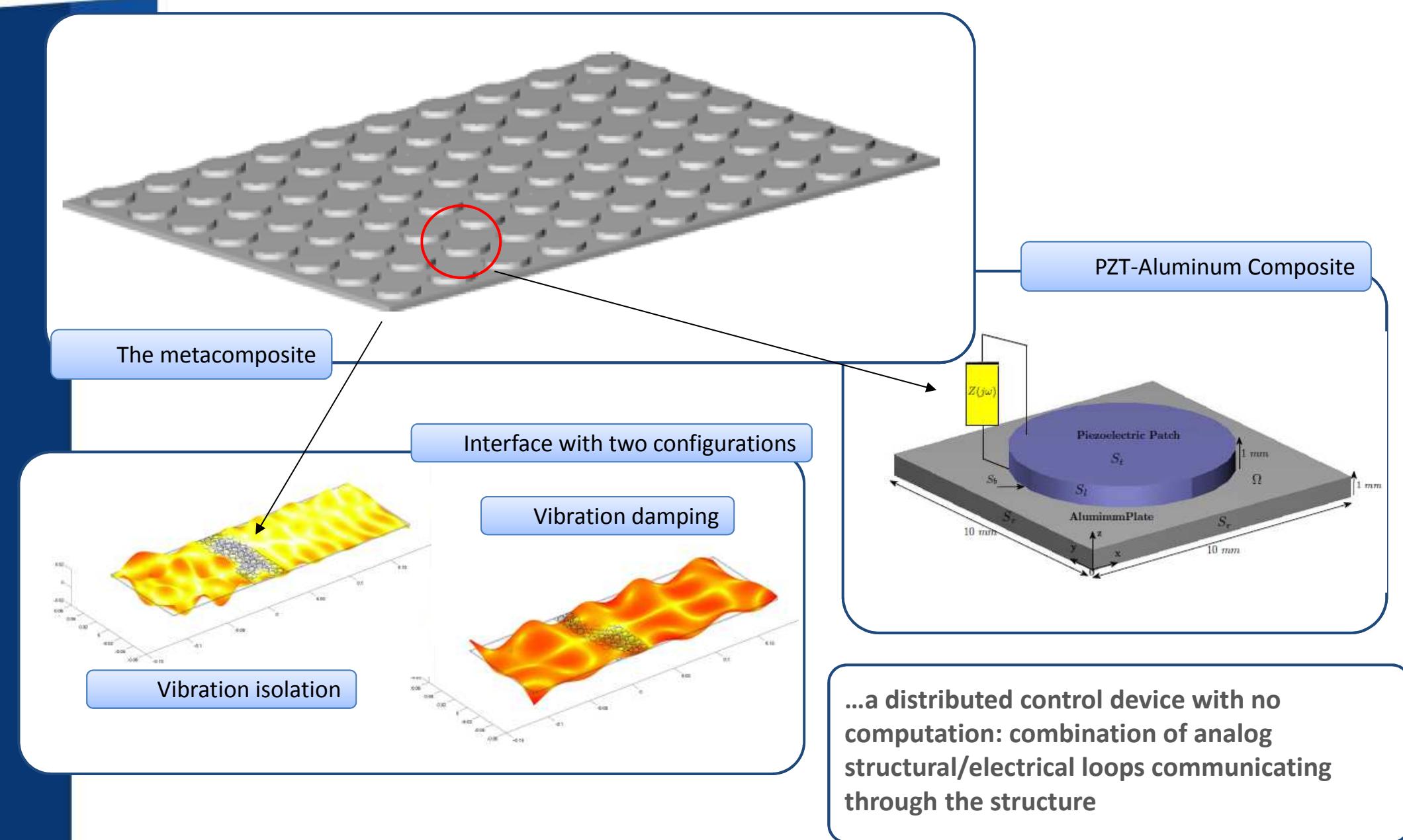
Local modes excited



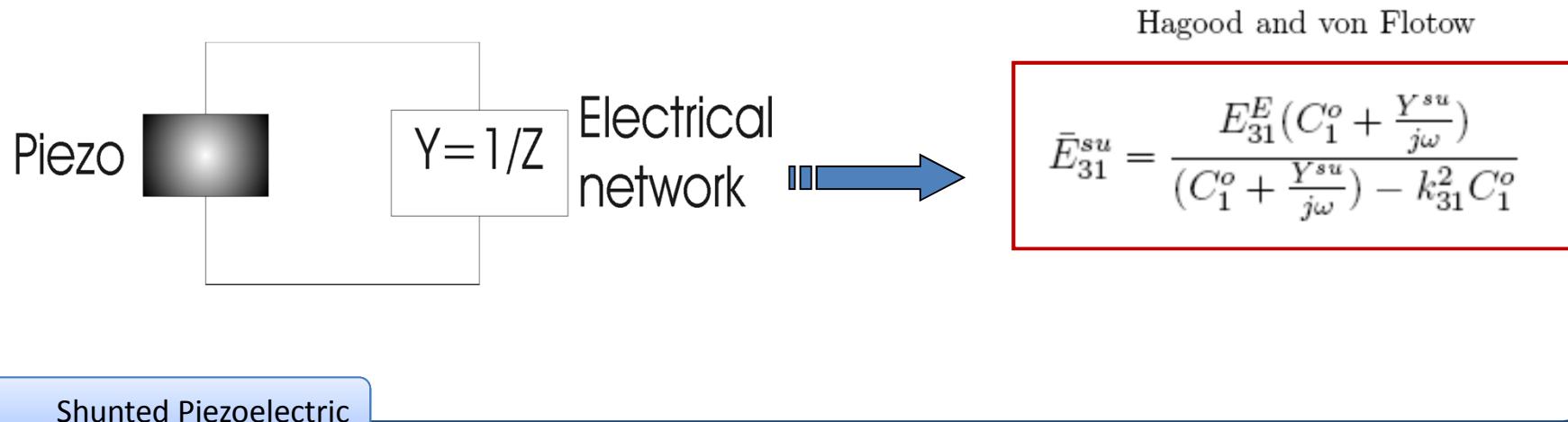
Displacement



# Application: design of a reconfigurable metacomposite for 2D structural functions



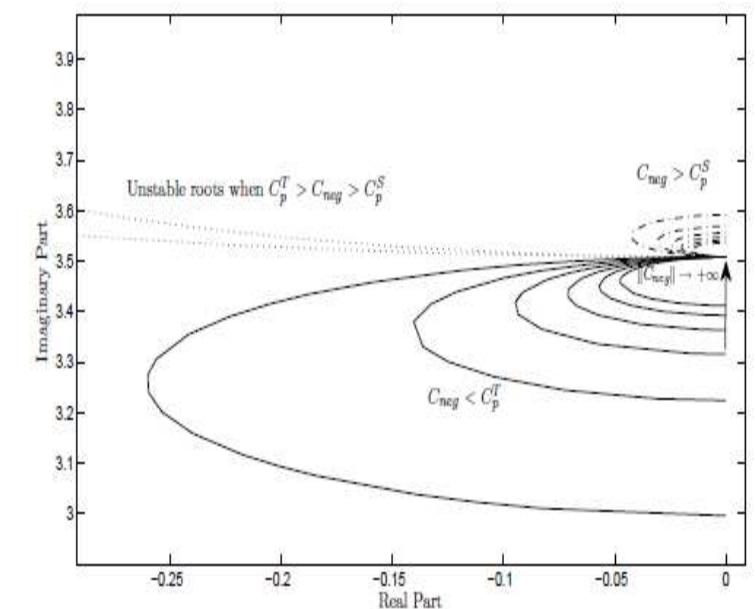
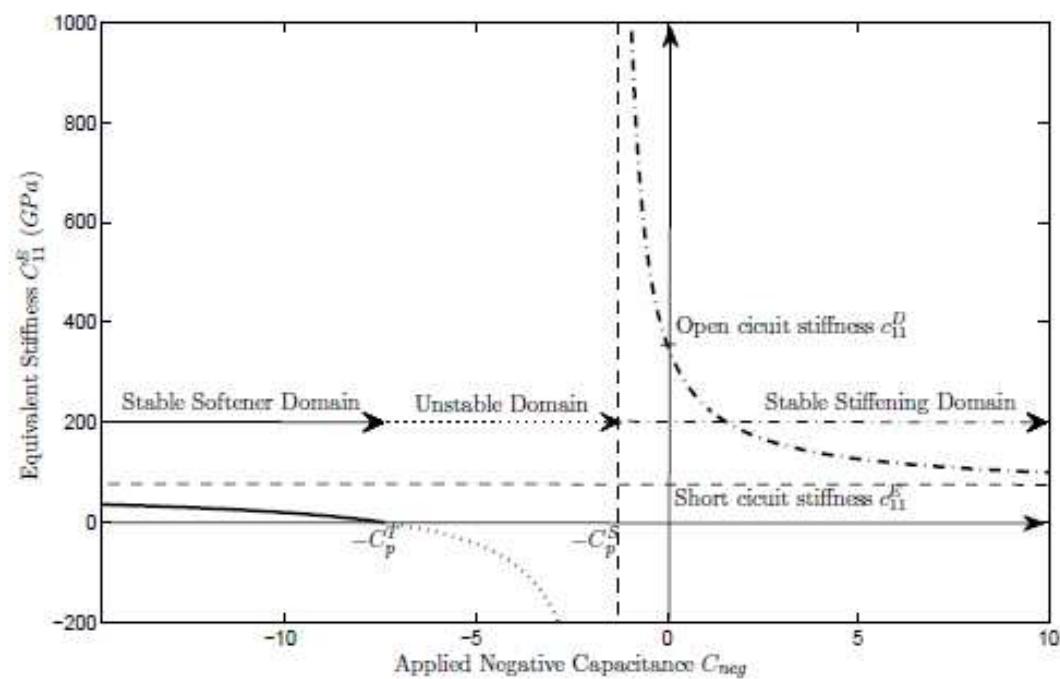
# Application: design of a reconfigurable metacomposite for 2D structural functions

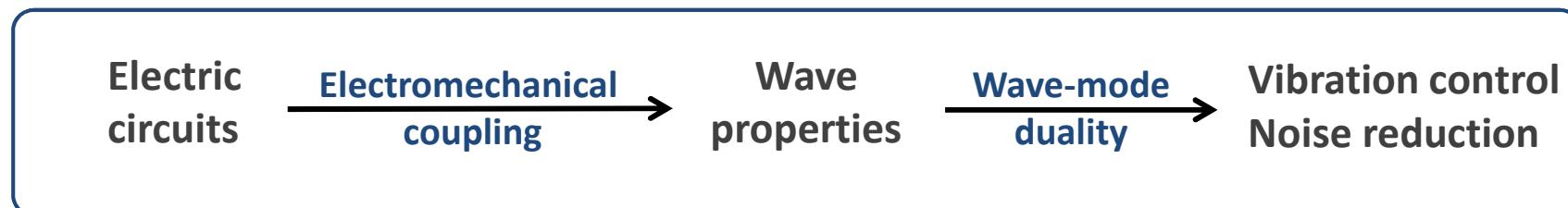
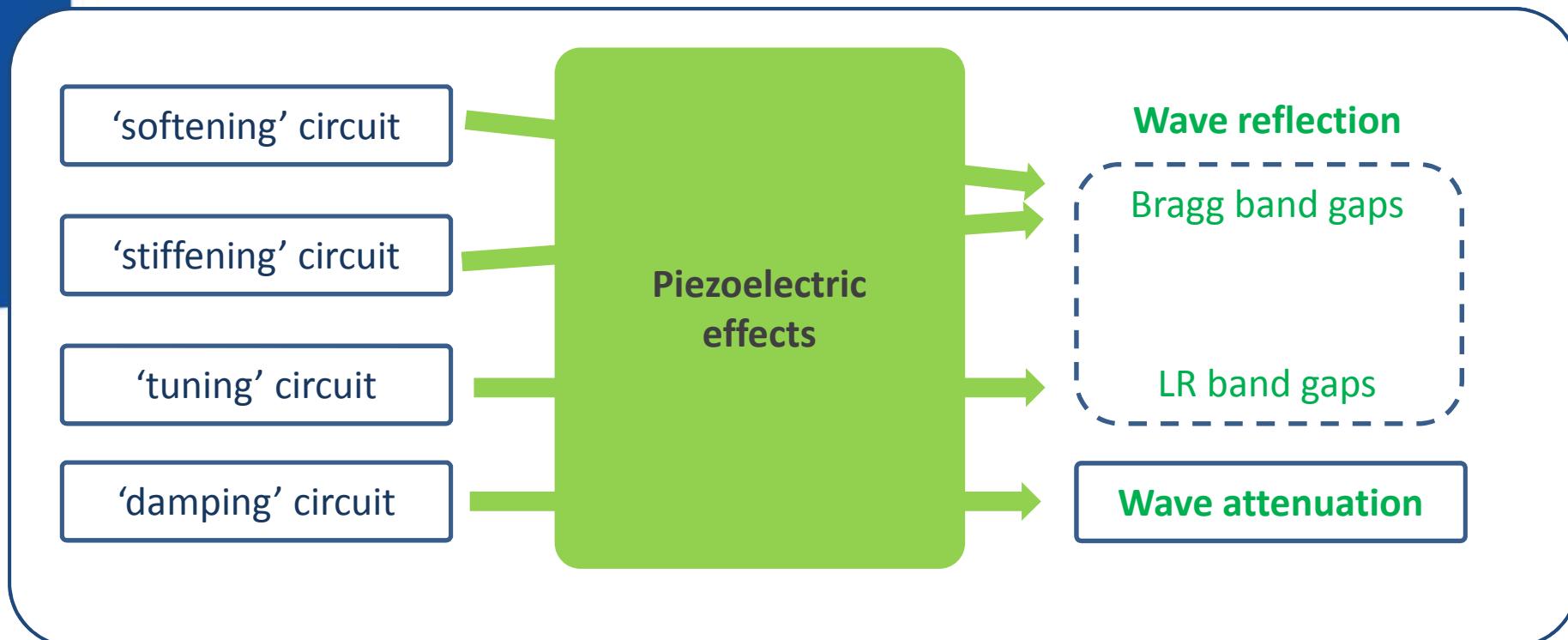


Shunted Piezoelectric

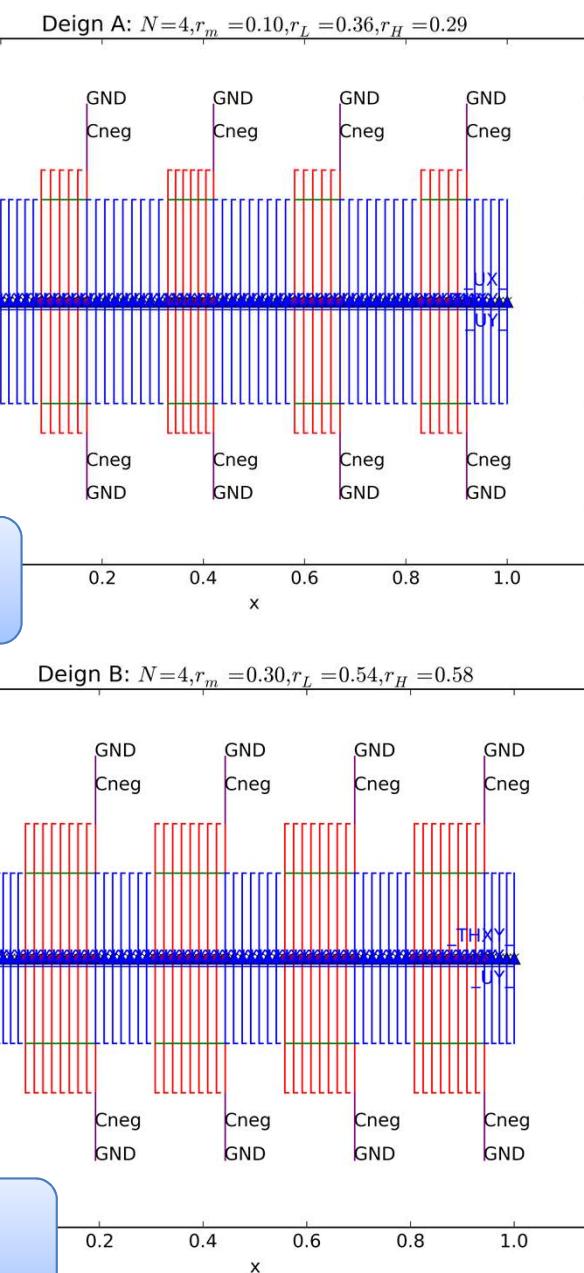
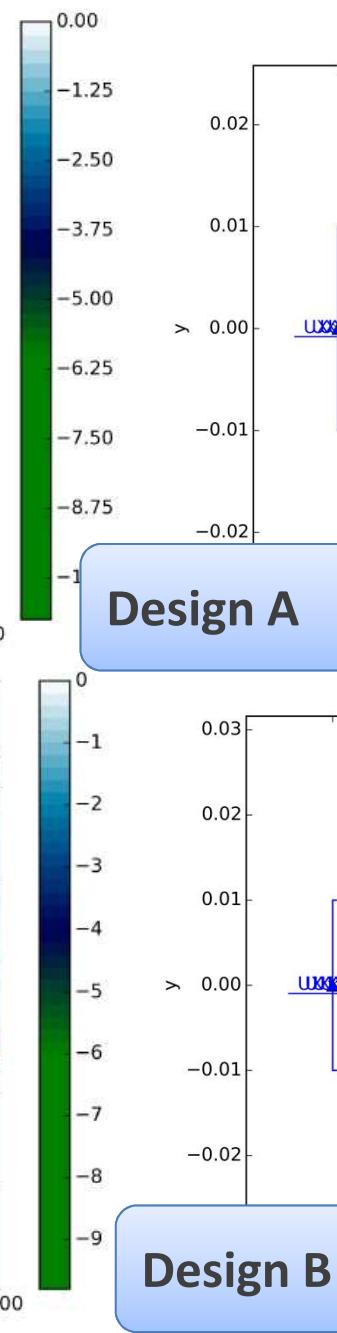
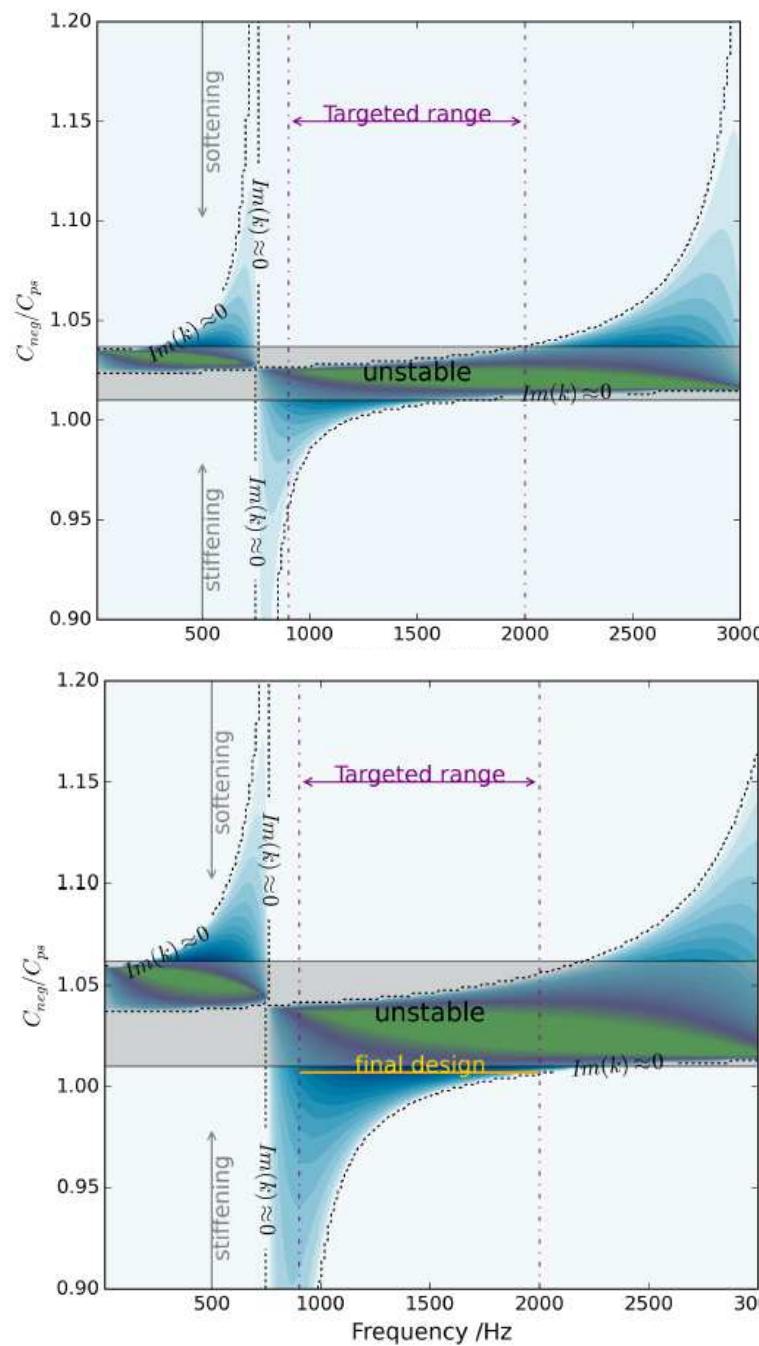
Equivalent Stiffness

Modal Control

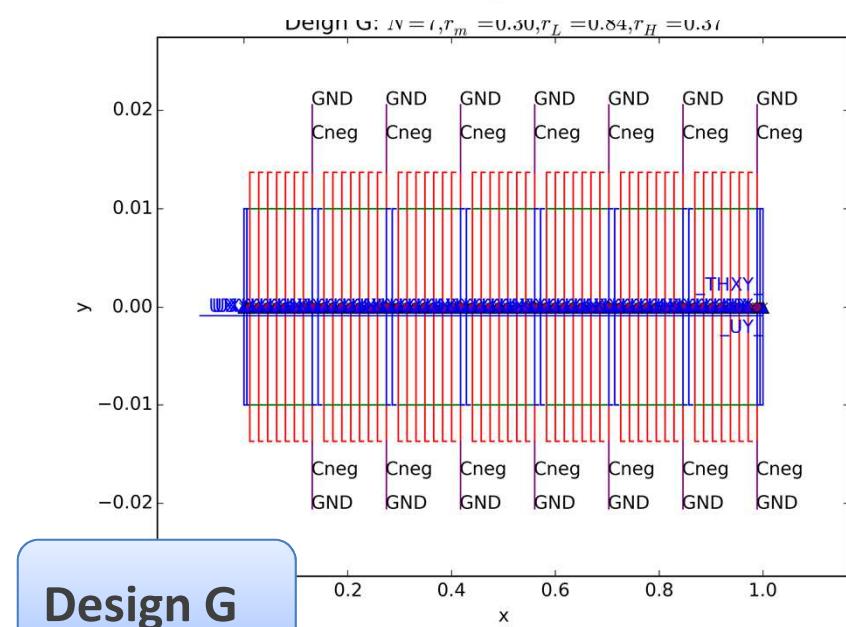
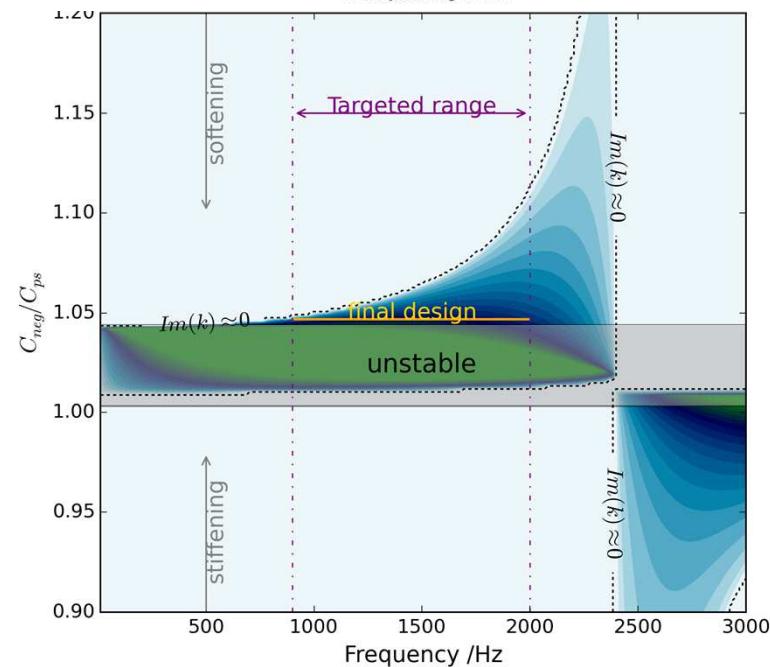
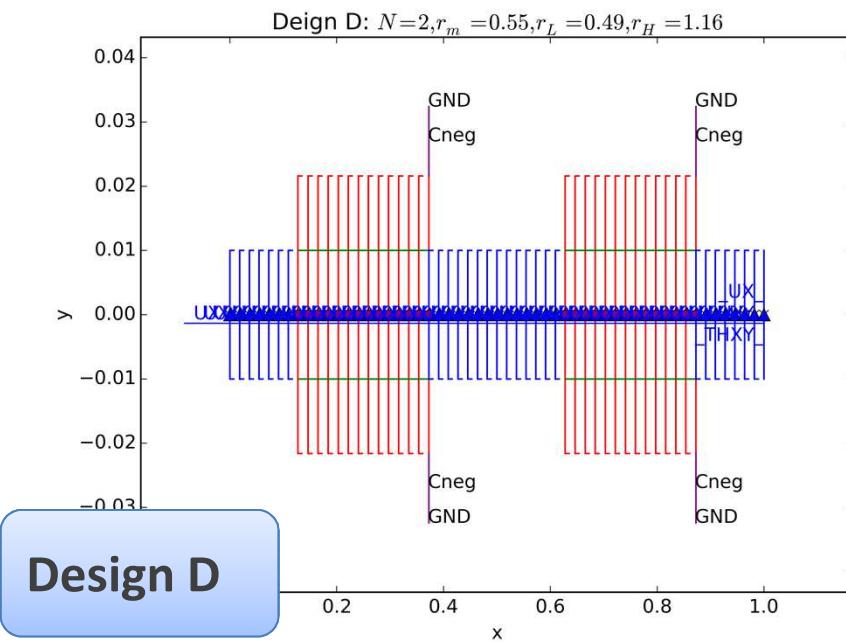
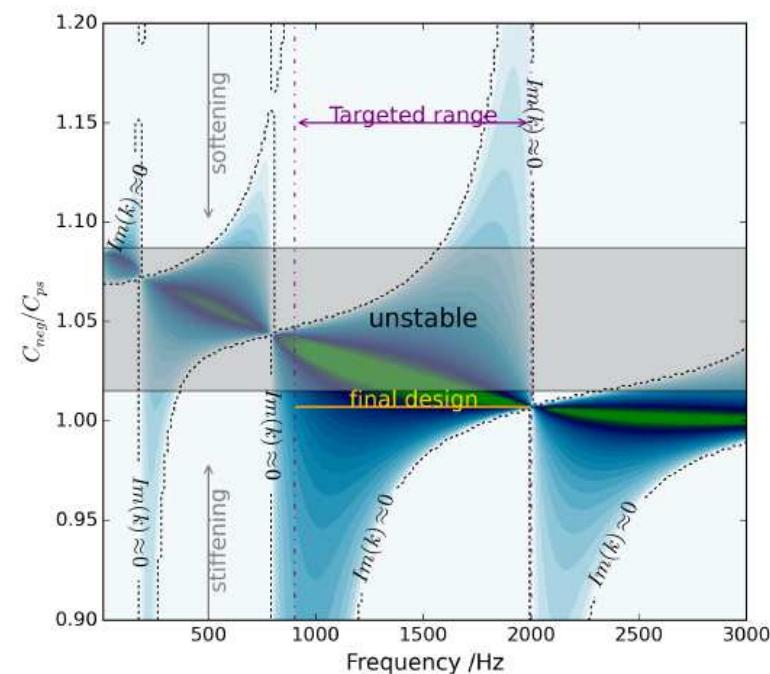




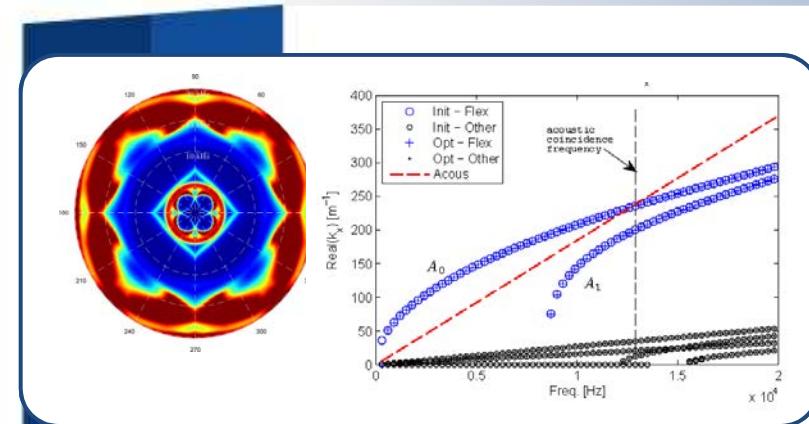
# Application: design of a reconfigurable metacomposite for 2D structural functions



# Application: design of a reconfigurable metacomposite for 2D structural functions



# Application: design of a reconfigurable metacomposite for 2D structural functions



- Efficient tool for computation of dispersion diagrams
- Multiphysics damped system

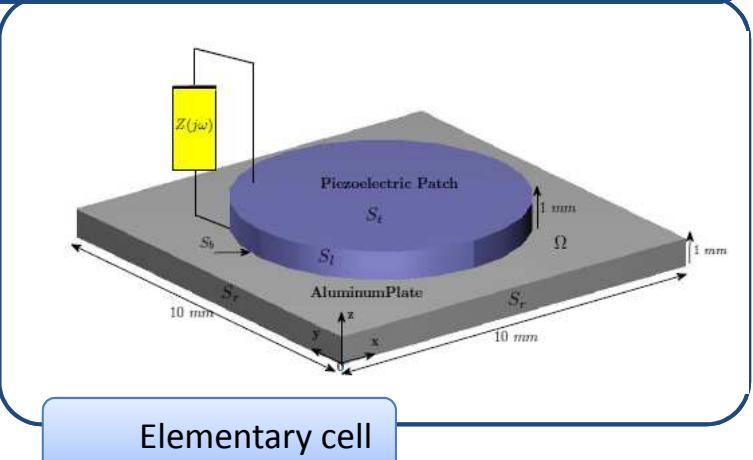
*How to choose  $Z(w)$  for specific functionalities?*

*Minimize group velocity of flexural waves: vibration & acoustics limitation*

*Case REFL:* Stop propagation of flexural waves

*Maximize electric energy dissipation in shunt*

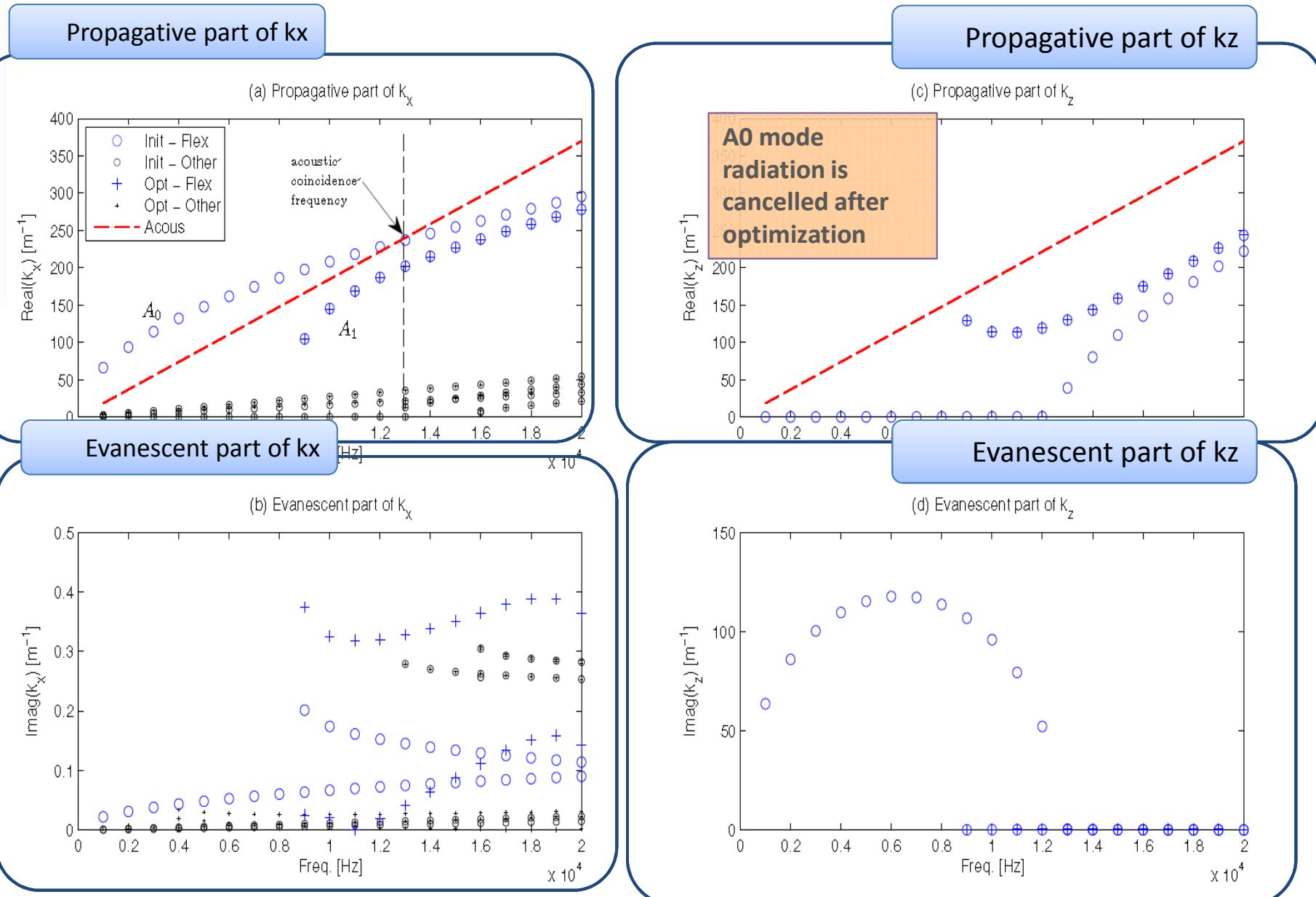
*Case ABS:* Maximize dissipation



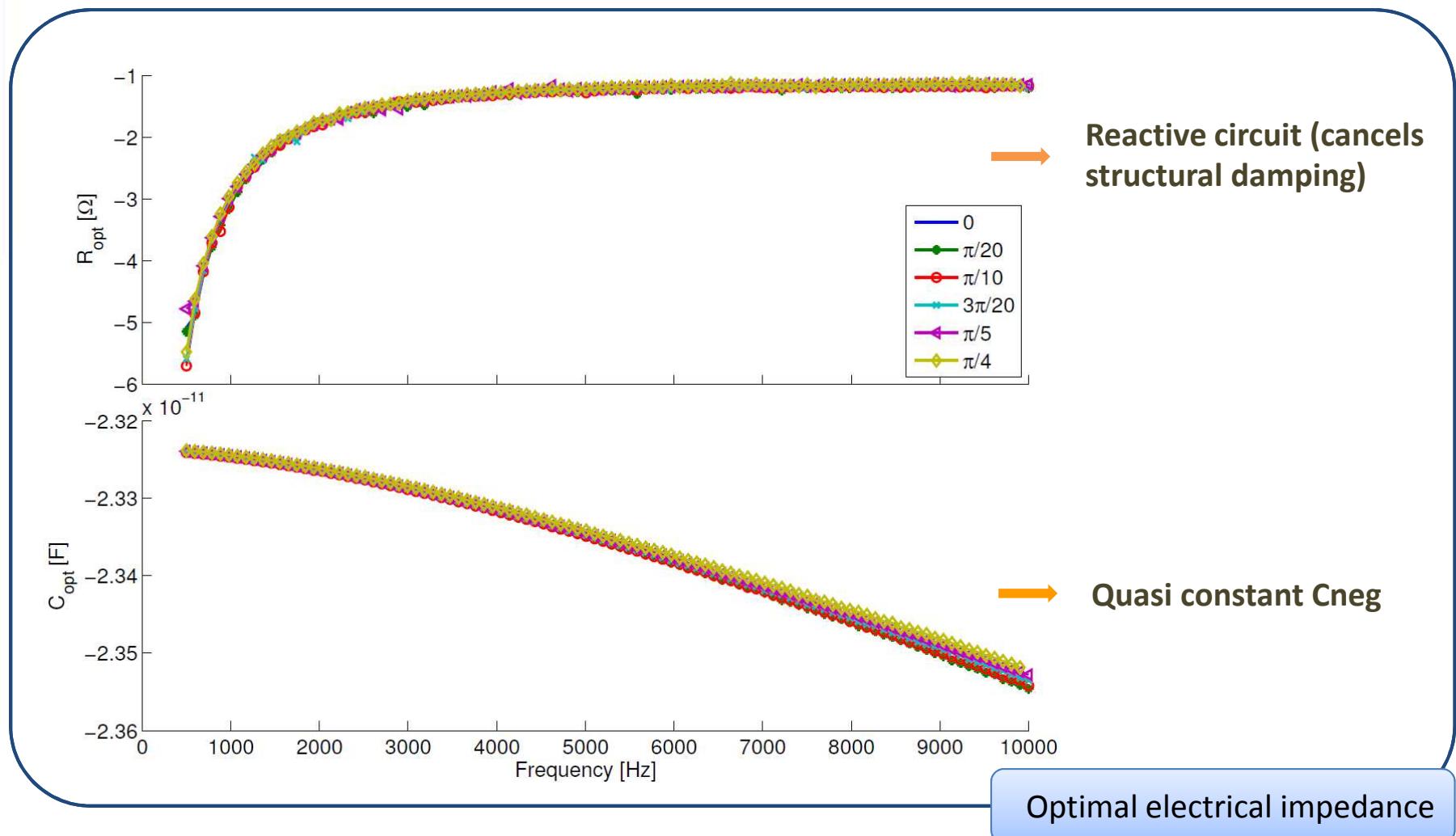
Elementary cell

*Optimization procedure:  
find optimal  $Z(w)$*

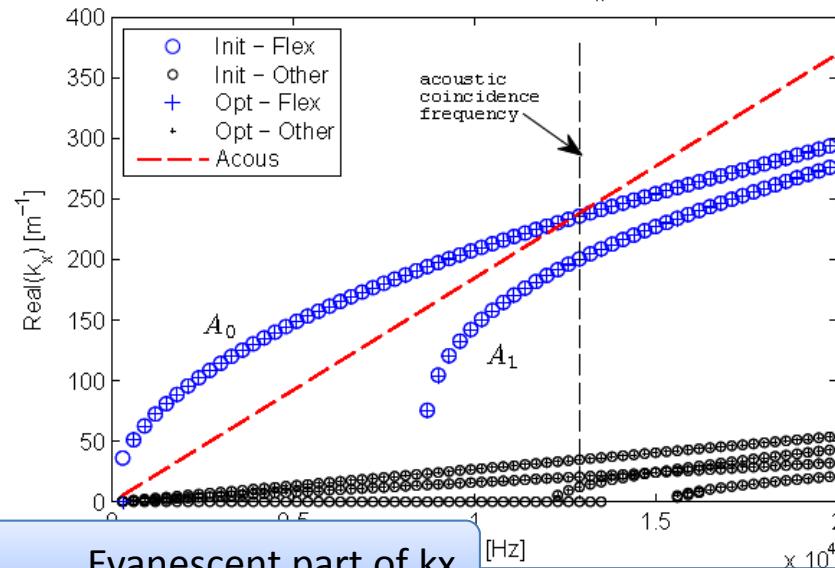
# Case REFL: Stop propagation of flexural waves



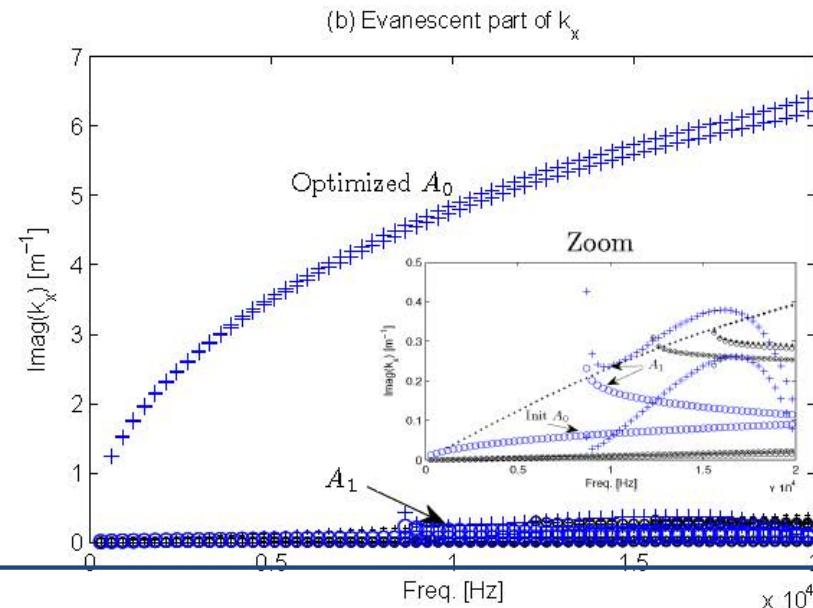
# Case REFL: Stop propagation of flexural waves



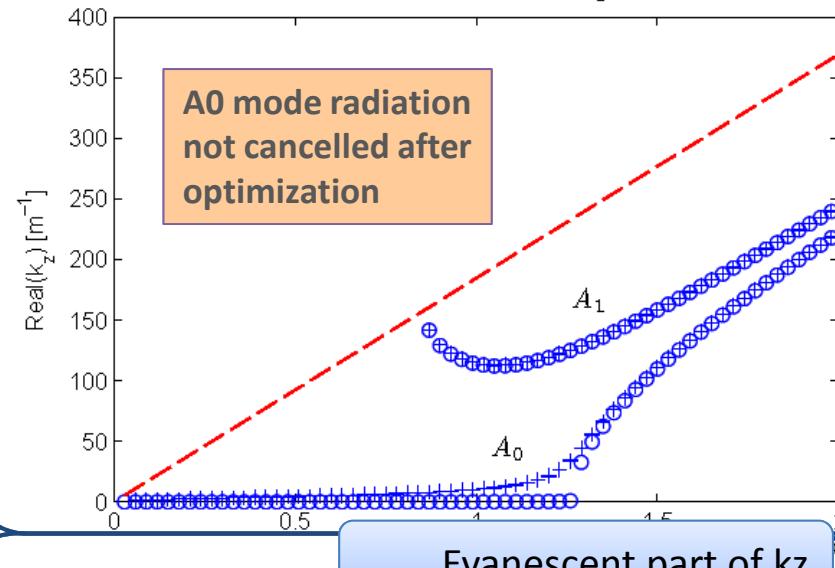
Propagative part of  $k_x$



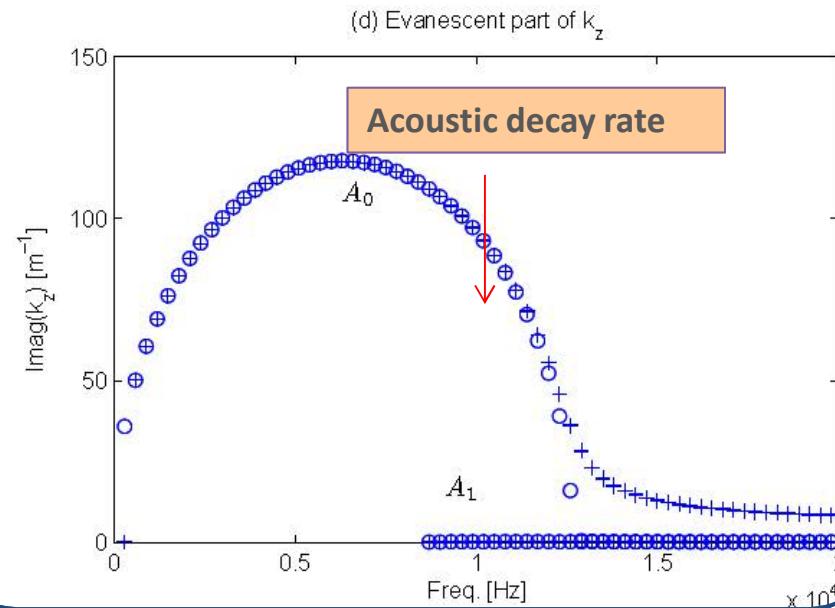
Evanescence part of  $k_x$

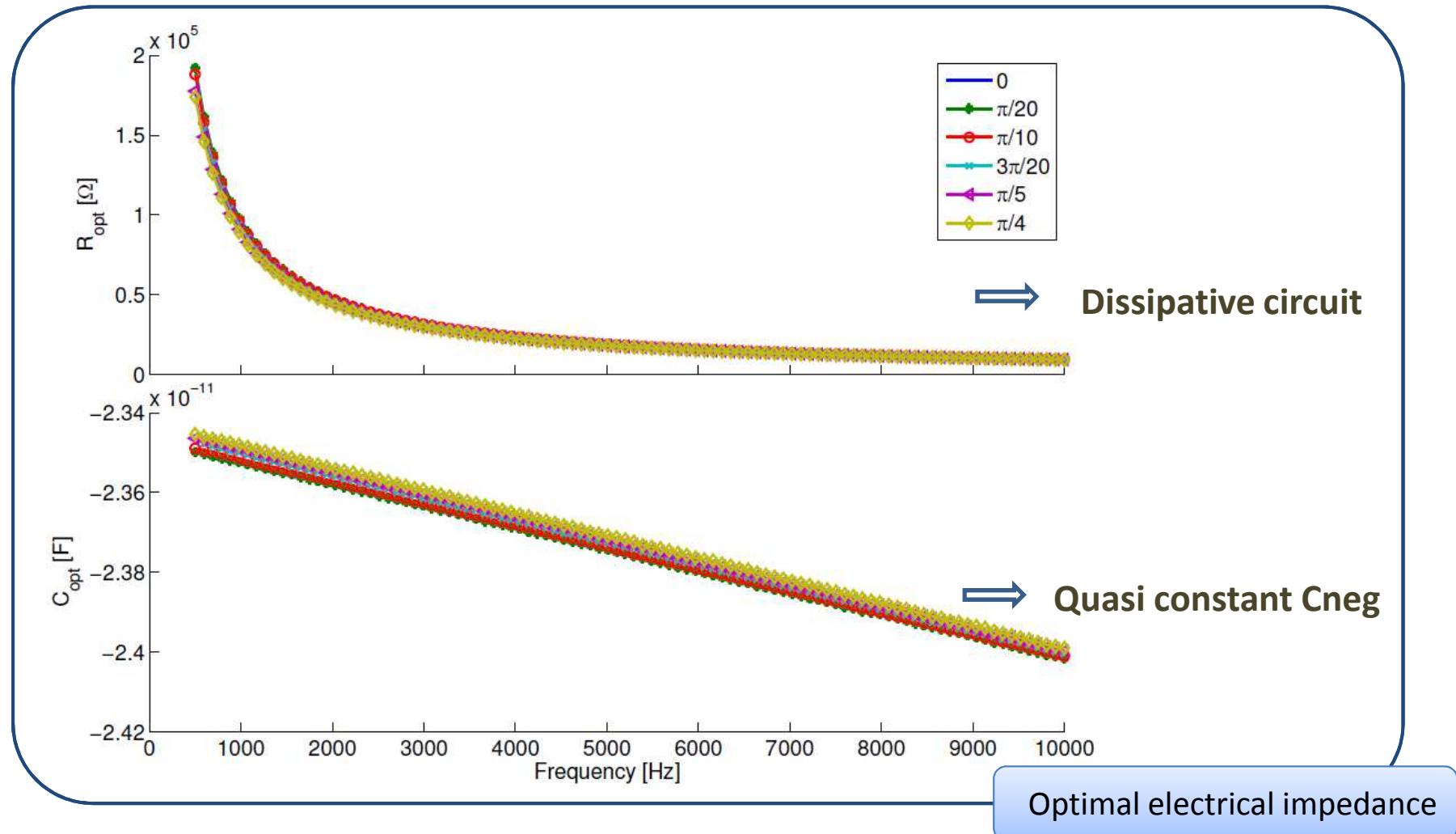


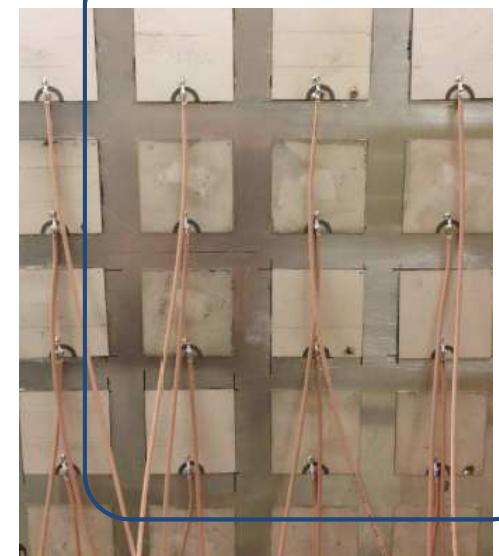
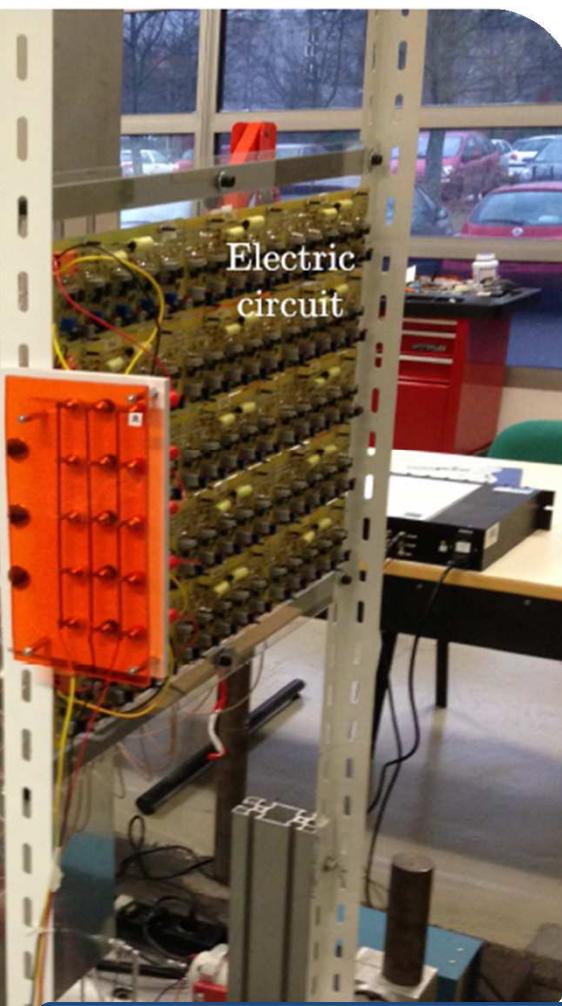
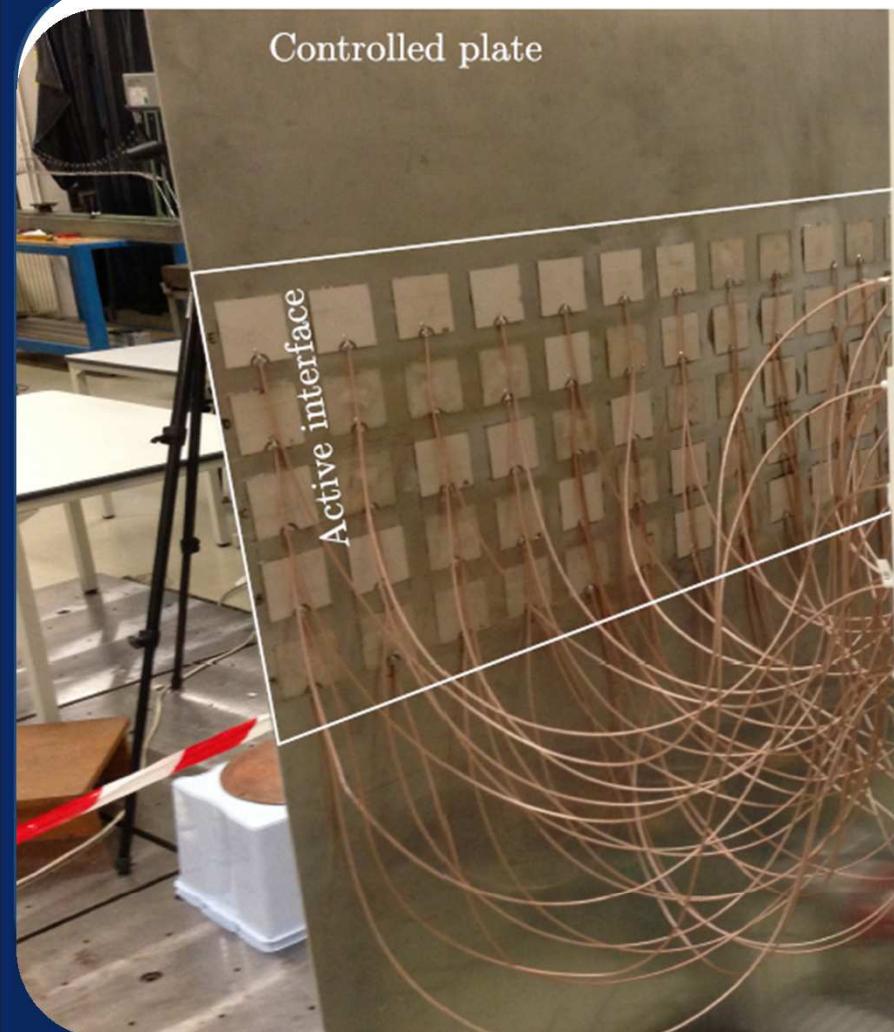
Propagative part of  $k_z$



Evanescence part of  $k_z$

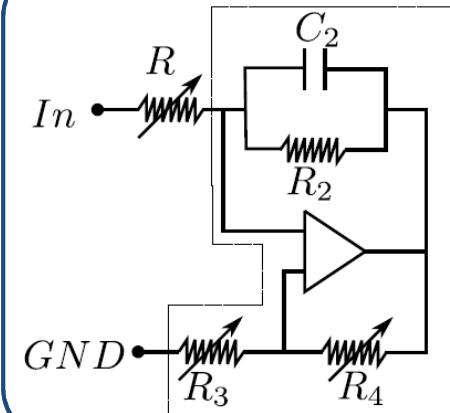


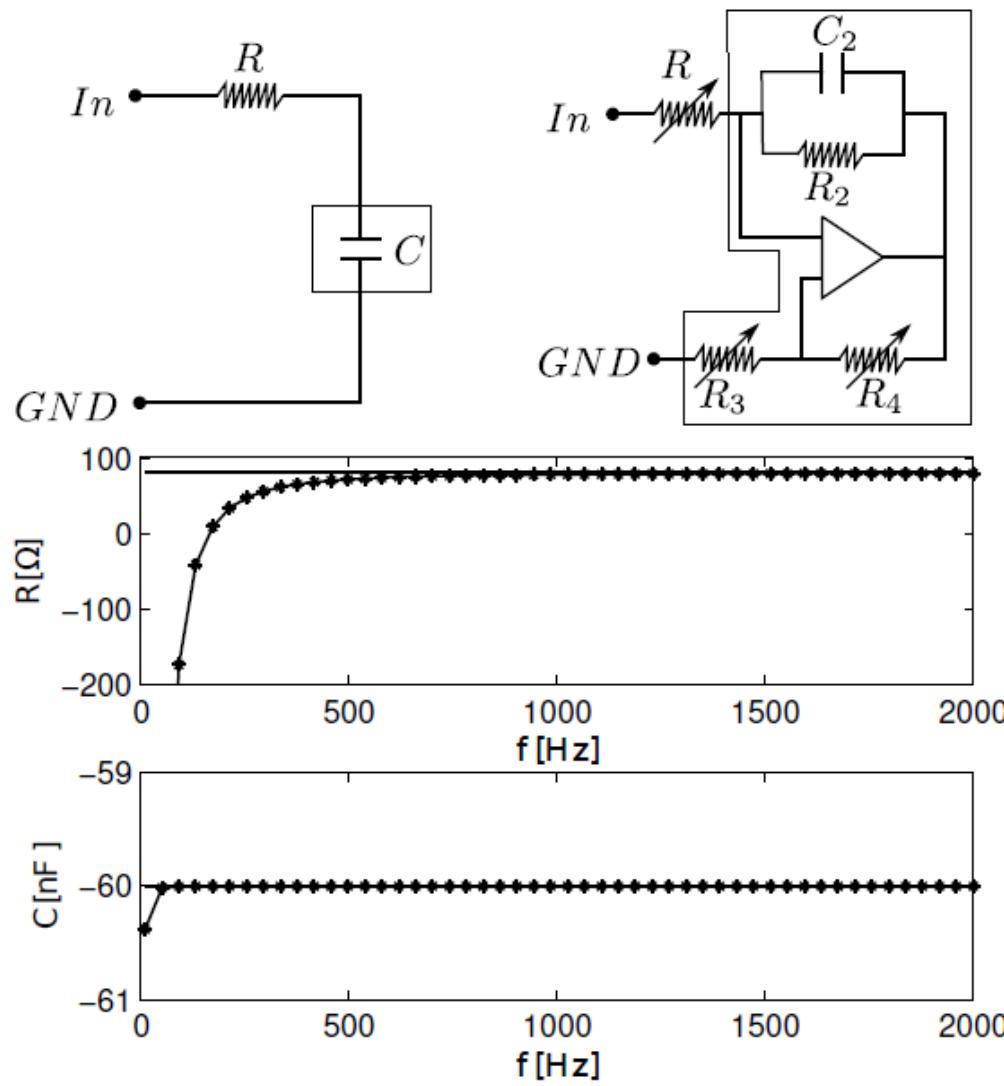




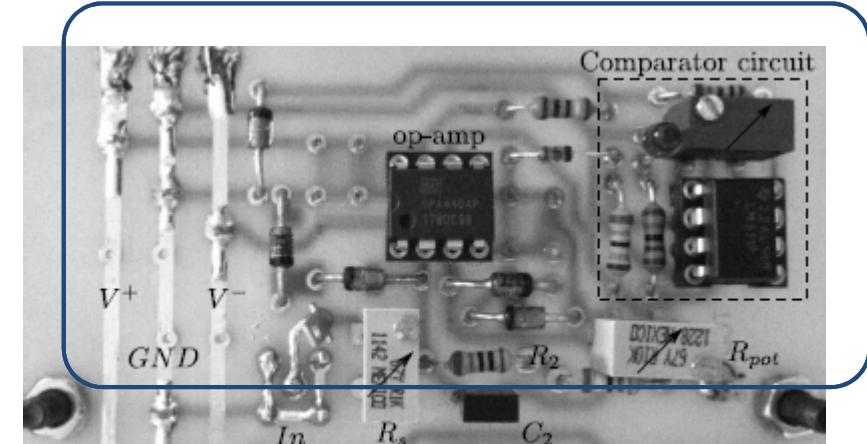
### Semi-active system:

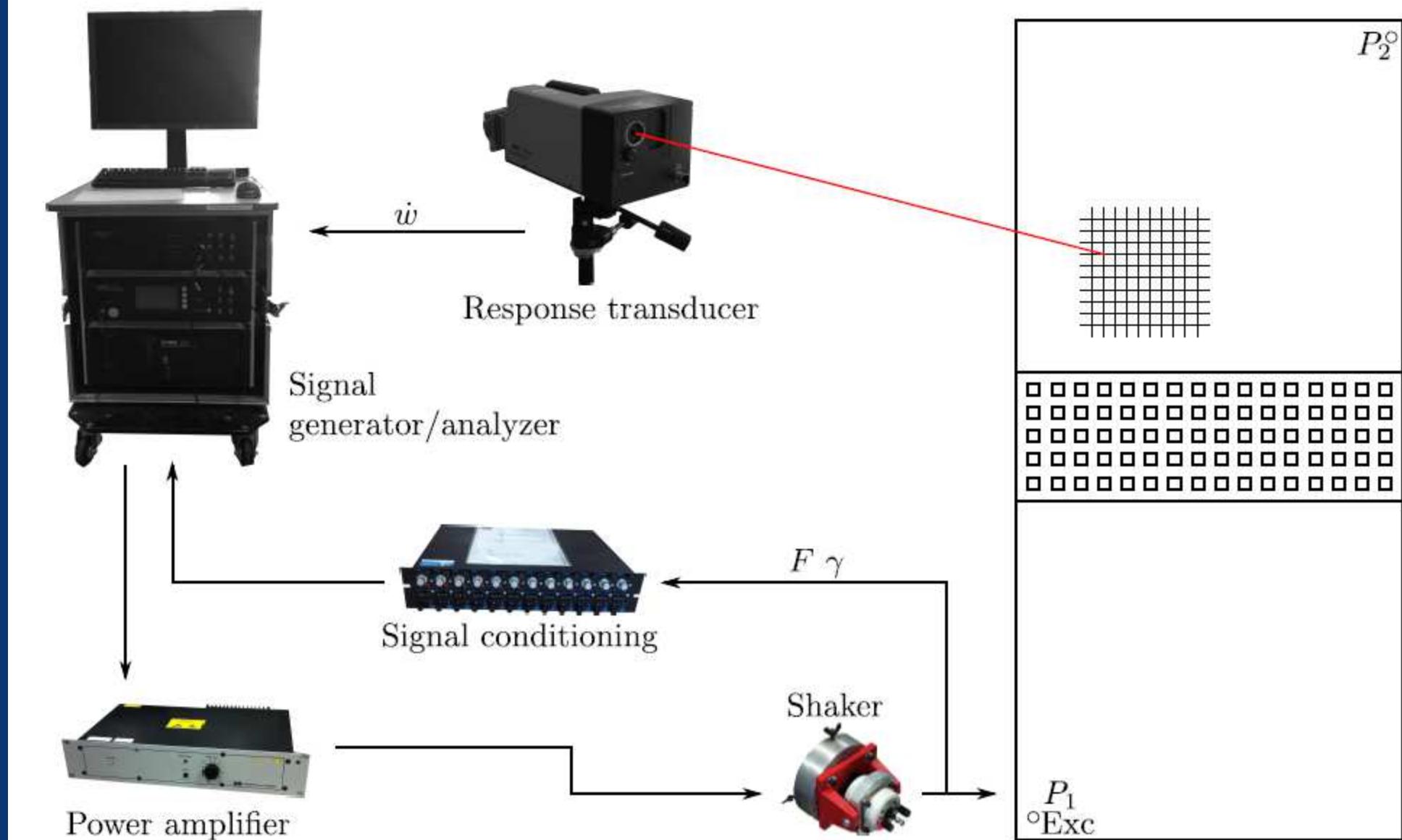
- No control loop => robustness
- Need only to power Op-Amps





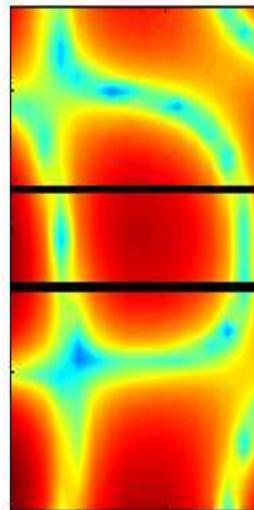
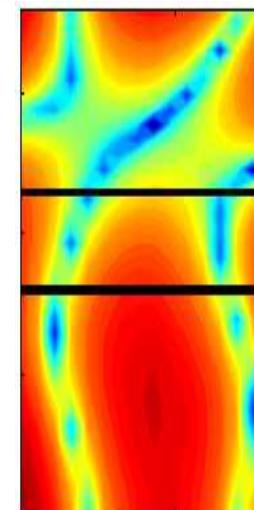
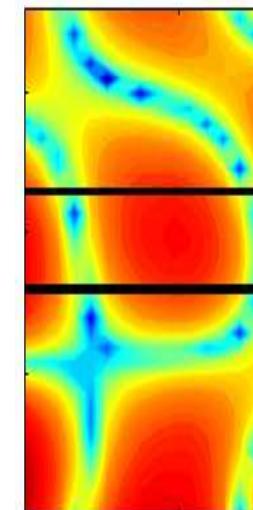
$$Z_{eq} = R_s - \frac{R_3 R_2}{R_4 (1 + i\omega R_2 C_2)}$$



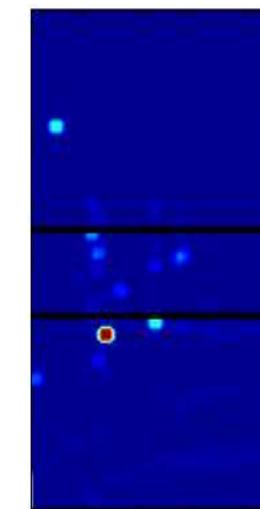
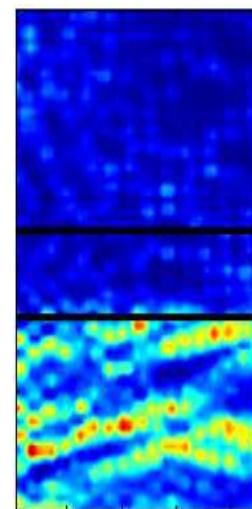
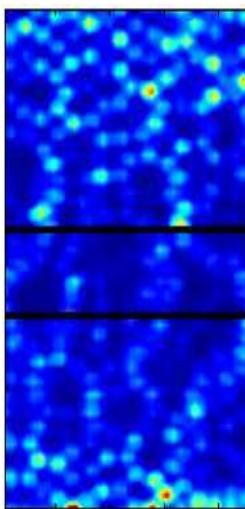


Measurement @ 25 Hz

Ctrl off

Ctrl on *Case REFL*Ctrl on *Case ABS*

Measurement @ 3000 Hz



**Energy issues**

Not a fully passive system

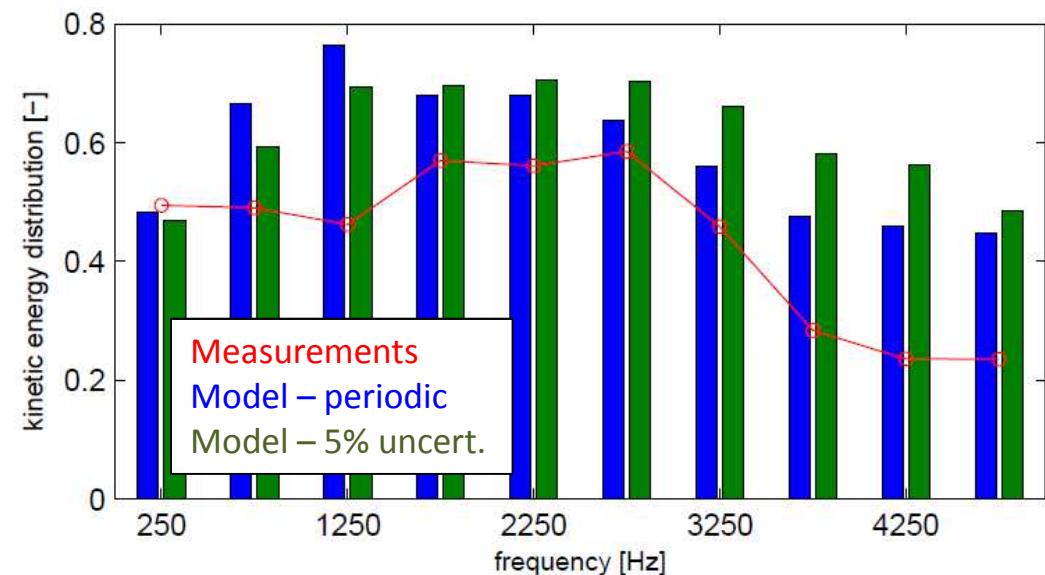
- Energy required for Op-Amps powering (**12 w**)
- Very low energy consumption (no difference measured between the Ctrl ON / Ctrl OFF configurations)
- Could be self-powered using simple energy harvesters

**Robustness issues**

Check impact of:

- Uncertainties in impedance shunts  
=> low effect
- loss of a patch  
=> low effect

Distributed strategy => high robustness



## Concepts

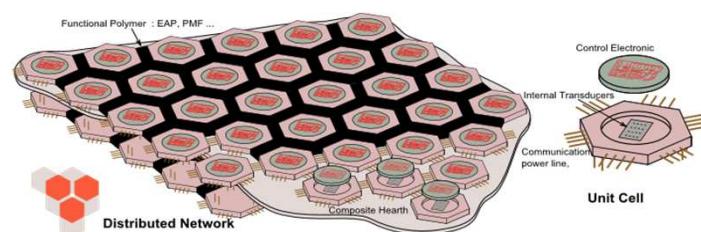
- **Periodic systems**
- **Smart individual cells** (multifunctionnal, reconfigurable, adaptive...)
- **Integrated systems**
- **Finite Elements Approach / multiphysics**
- **Global design strategy**

## Results

- **Whole 2D space computation with frequency dependent physical behavior**
- **Impedance optimization**
- **Reconfigurable concept**
- Validation of the **smart interface** on finite structure
- **Practical implementation**
- **Experimental validation**

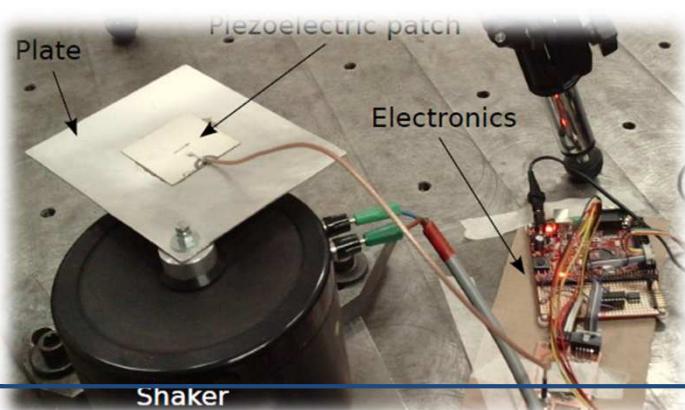
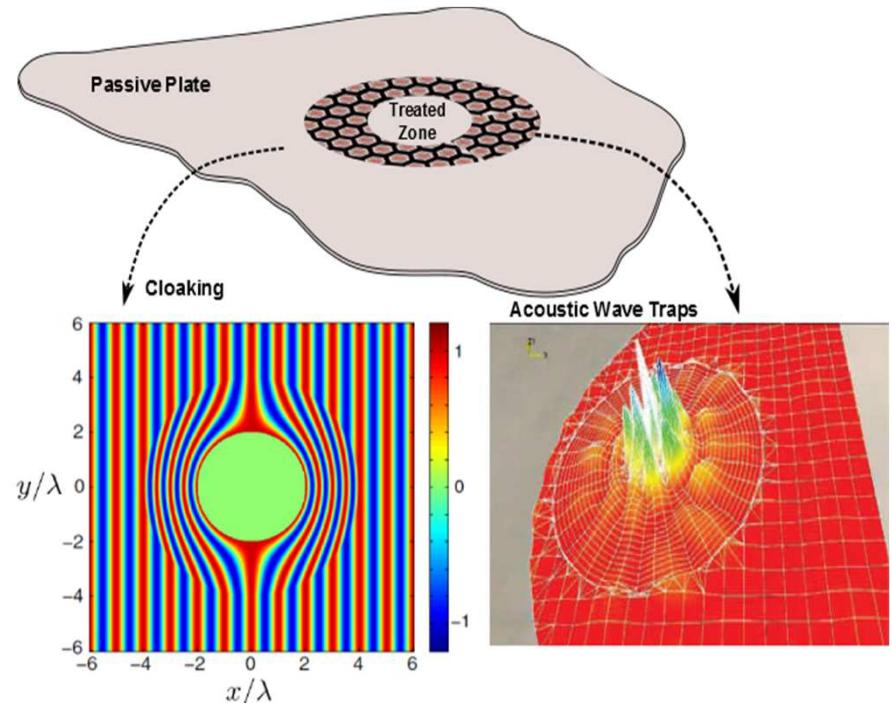
## Future steps for the metacomposites

- Toward **fully integrated metacomposites**
- Combination of the concept with **DSP**:
  - Achieve **new functionnalities**
  - **Self reconfiguration**



## Future functions for the metacomposites

- Multiscale Network modeling and optimization for **Cloaking** and **Wave traps**
- Associated Material programming network and algorithme
- Robust design tools
- Toward innovative, integrated and autonomous smart metacomposite for Vibroacoustics...



- **Integrated programmable circuit**
- Design for distributed implementation
- Programming interface

need more details?

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*Adaptive Metacomposites for Vibroacoustic Control Applications*

Cover of IEEE Sensors Journal 14(7), 2014

<http://dx.doi.org/10.1109/JSEN.2014.2300052>



F. Tateo, M. Collet, M. Ouisse, M. Ichchou, K.A. Cunefare, P. Abbe

*Experimental characterization of a bi-dimensional array of negative capacitance piezo-patches for vibroacoustic control*

Journal of Intelligent Material Systems and Structures, 2014

<http://dx.doi.org/10.1177/1045389X14536006>

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