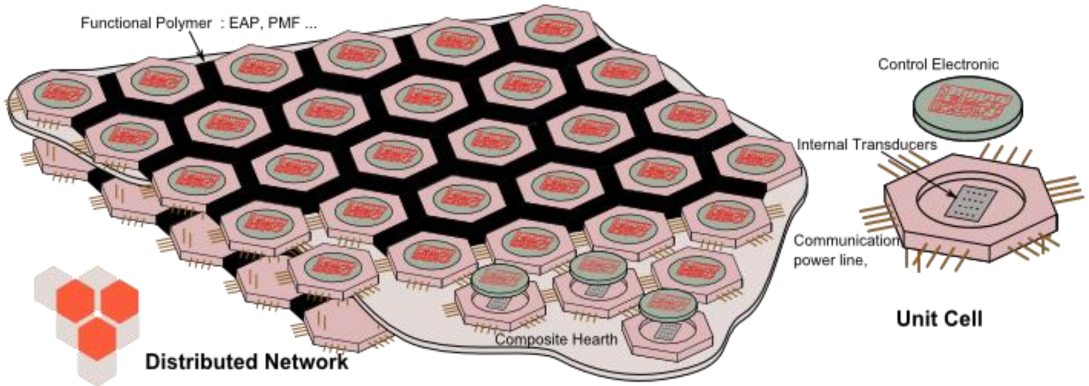
Laboratoire de Tribologie et Dynamique des Systèmes

Métacomposite commandable pour la réflexion et la focalisation de l'énergie vibratoire



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Laboratoire de Tribologie et Dynamique des Systèmes

LTDS UMR 5513

http://ltds.ec-lyon.fr

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_2 (**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_2 emission (5-15%), noise control....)

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

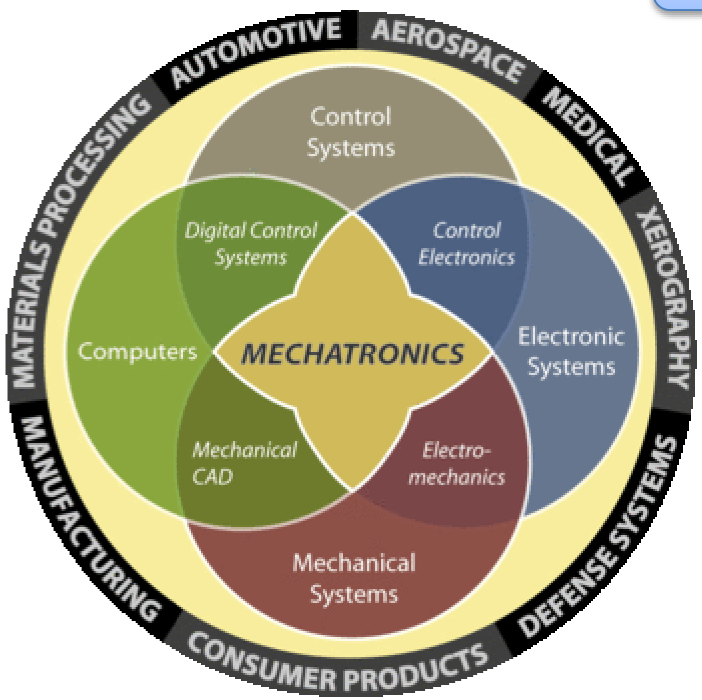
FR & EC research strategies, Clean Sky , DREAM EU Project s, AIAA's Emerging Technologies Committee (ETC) …

Context and Issues

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

Morphing….

a.

Figure 8: a. Variable Geometry Chevron Thrust Reverser Sleeve mounted on GE90-115B engine; insert shows the cover removed and 60-Nitinol flexure actuators, b. 777-300ER flight test of VGCs.

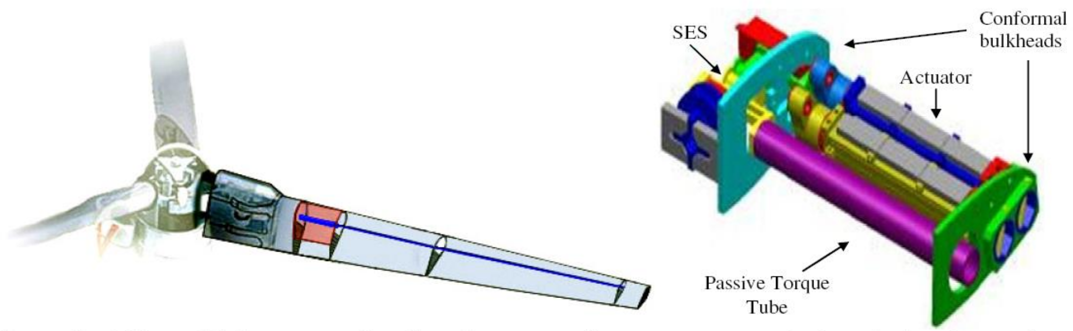
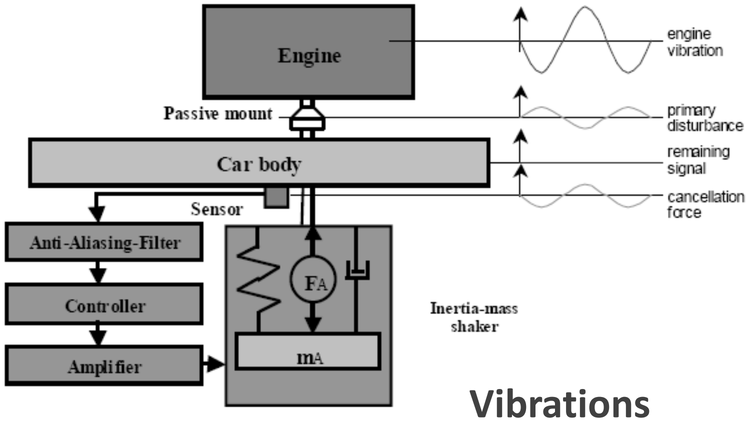


Figure 4: a) Rotor blade system showing placement of actuator system (red region) at base of rotor, b) schematic of actuator system, including antagonistic actuators (blue and yellow), passive torque tube (purple), and strain energy shuttle (SES) [12].

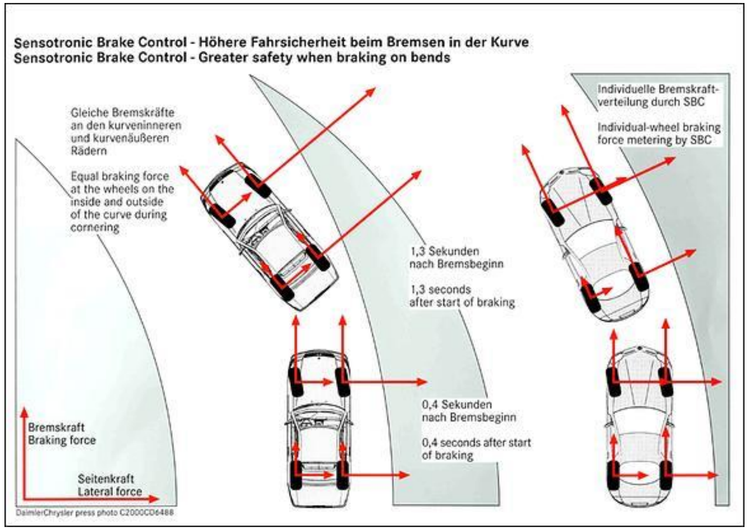
NASA : OVERVIEW OF BOEING'S SHAPE MEMORY ALLOY BASED MORPHING AEROSTRUCTURES SMASIS 2008

Context and Issues

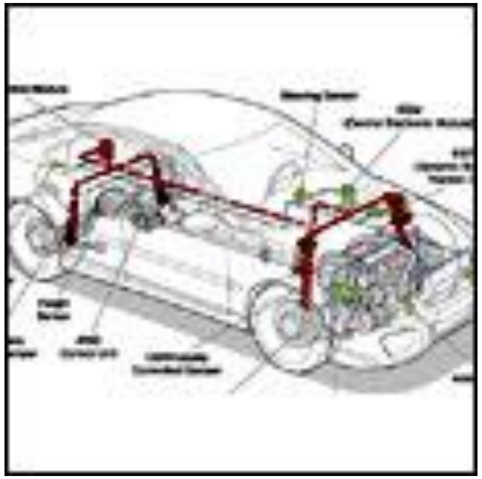


Vibrations

Figure 1: Schematic representation of an AVC system.

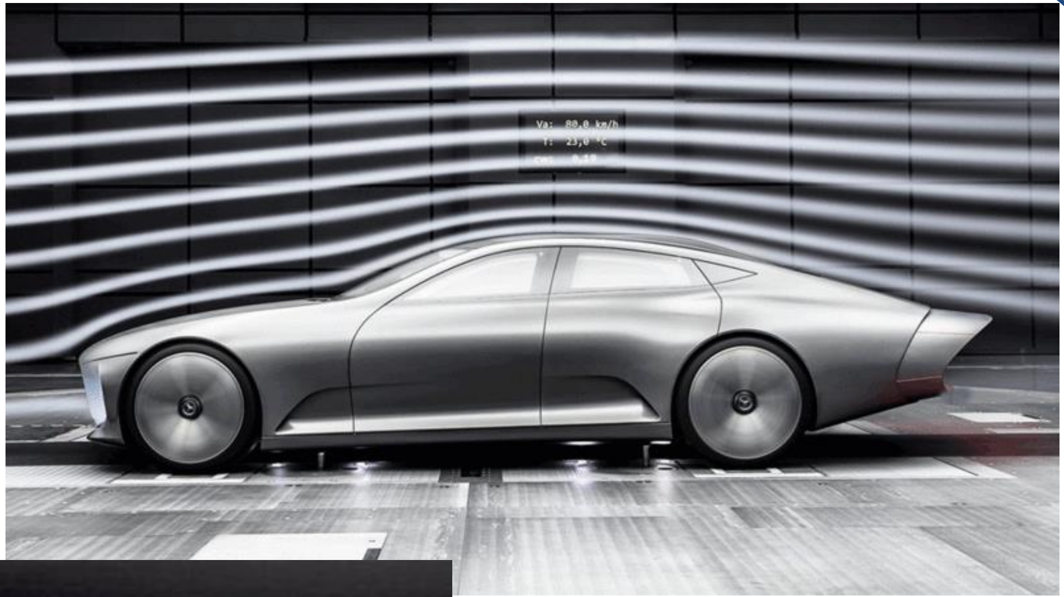


Trajectory



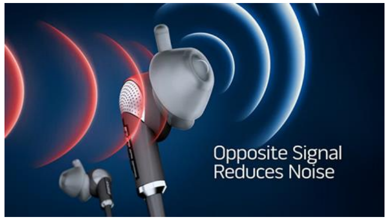
Suspensions Actives

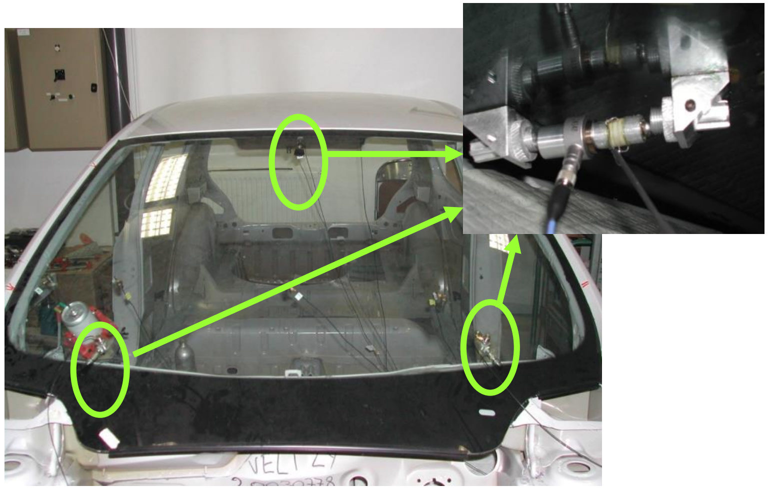
Morphing

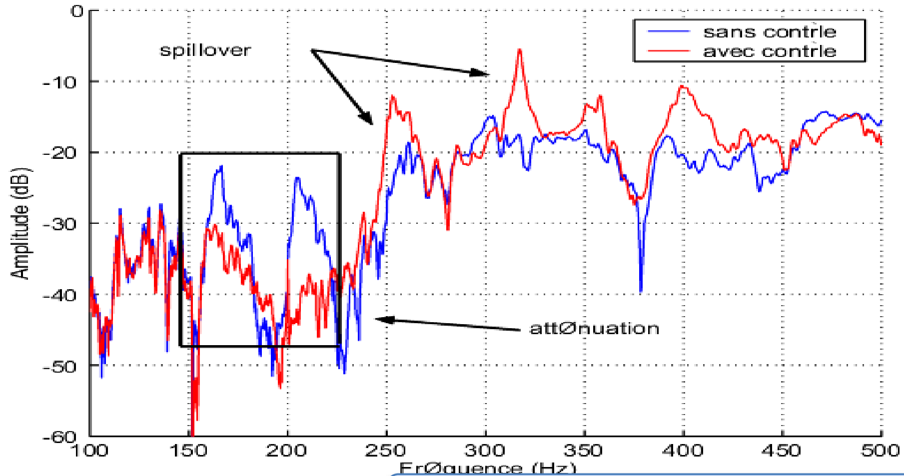


Aerodynamic

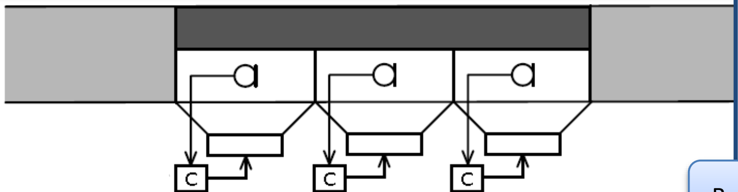
ANC / AVC Strategies

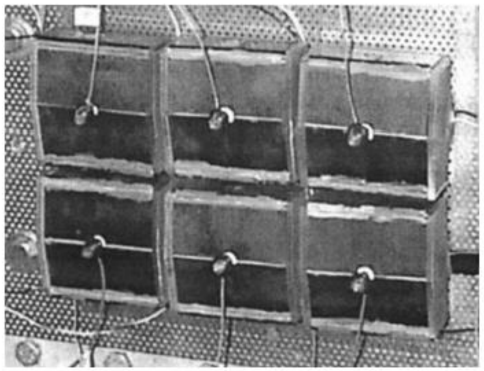


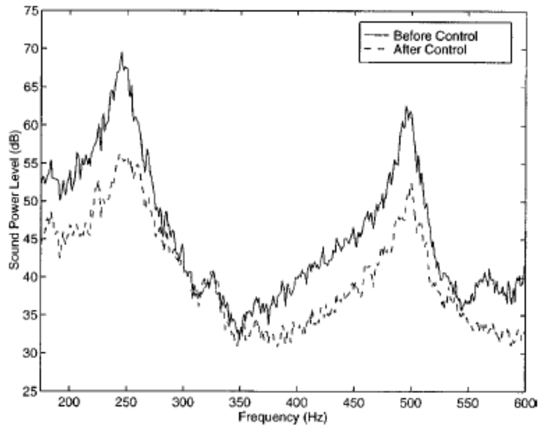




Collocated Active Damping [Monnier, JSCHM, 2001])







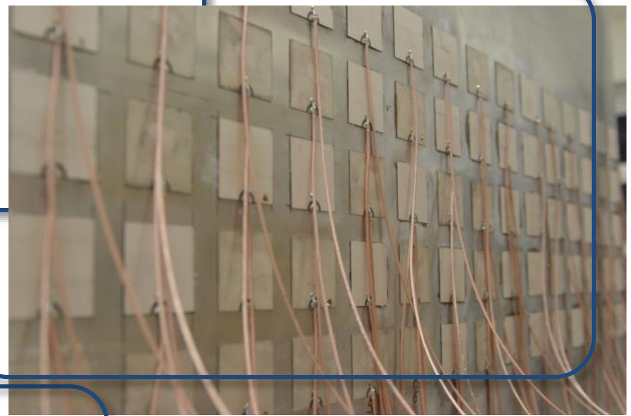
Broadband control using active-skin and structural acoustic sensing [Fuller, JASA, 2000]

From Structural Control to Material Programming

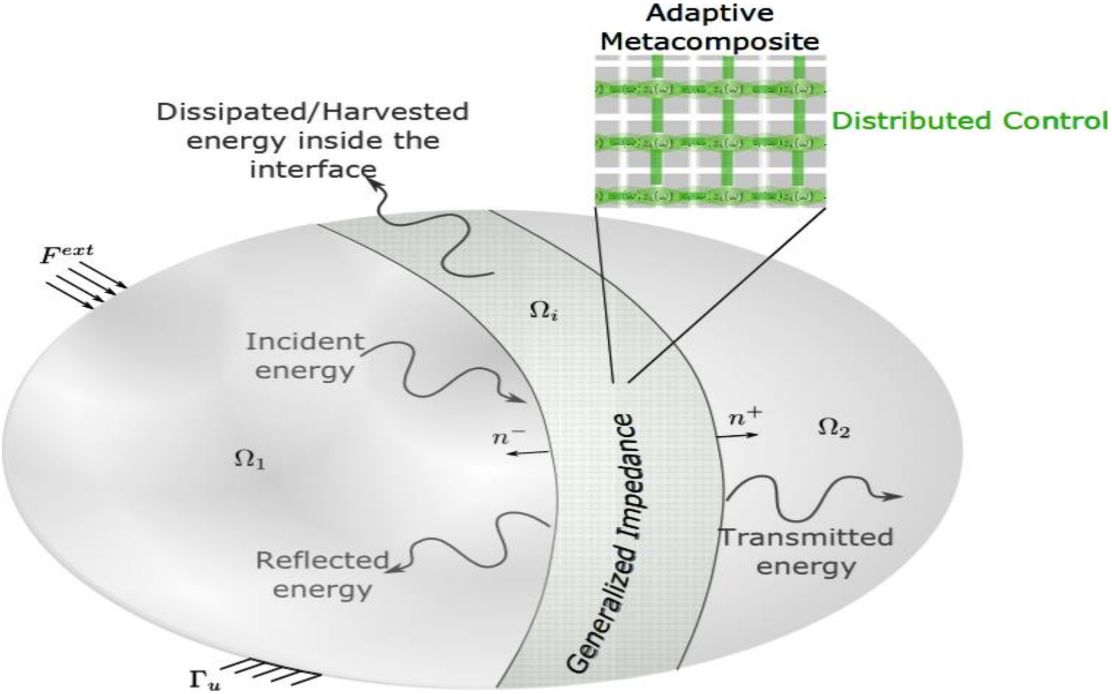
Classical approaches of **ANC or AVC** is difficult to apply into real fully distributed applications :

- 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

From Structural Control to Material Programming

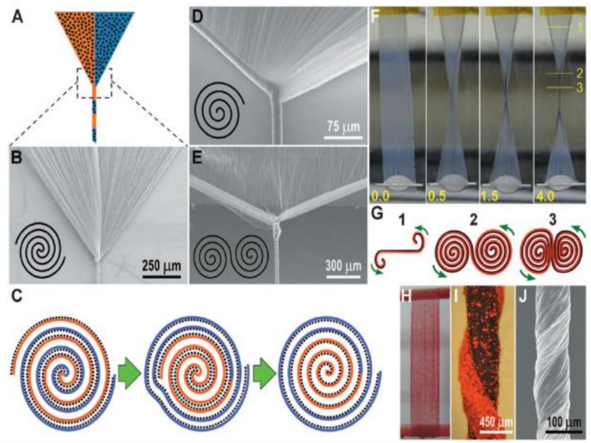
Research in Programmable Matter Directed by Carnegie Mellon and Intel

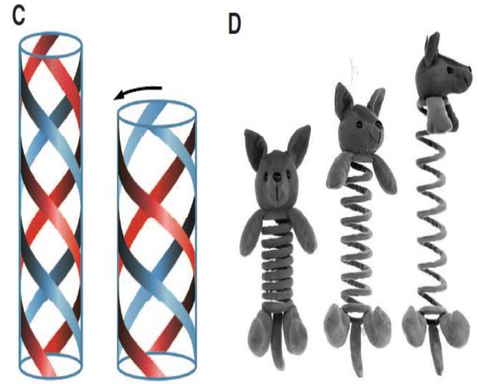
Morpheus Lab Univ Maryland

Harvard Microrobotics Lab

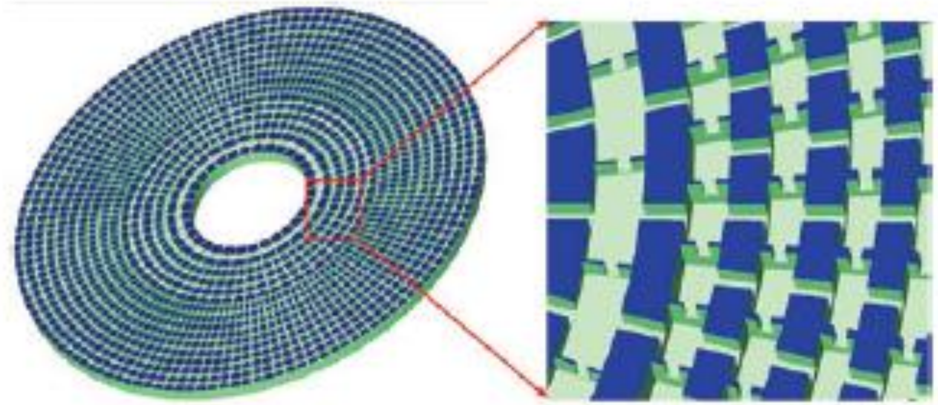
From Structural Control to Material Programming

A sequence of images demonstrating the self-folding of a 4D printed multi-material single strand into the world of MIT

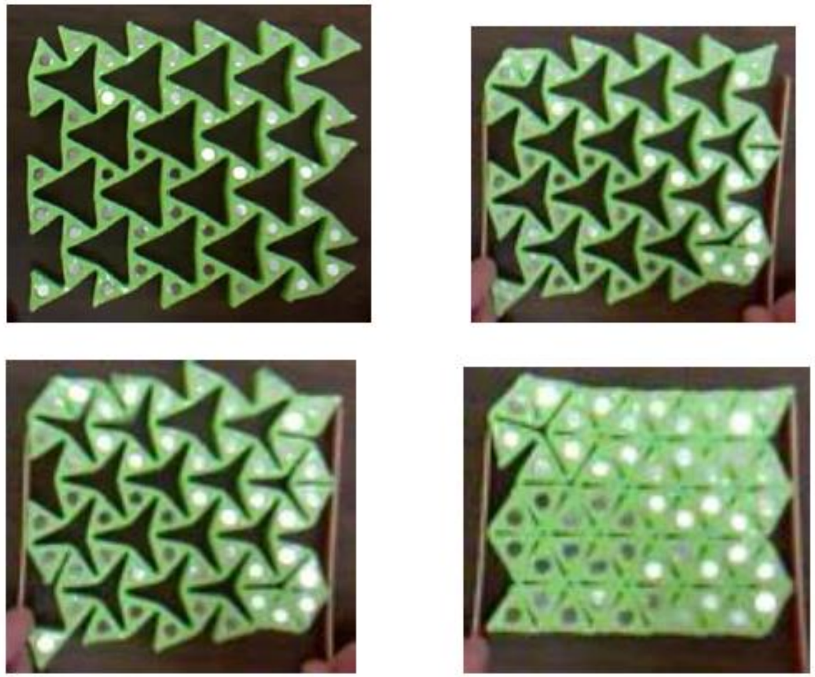




M.D Limaet al Biscrolling Nanotube Sheets and Functional Guests into Yarns, Science 331, 51, 2011



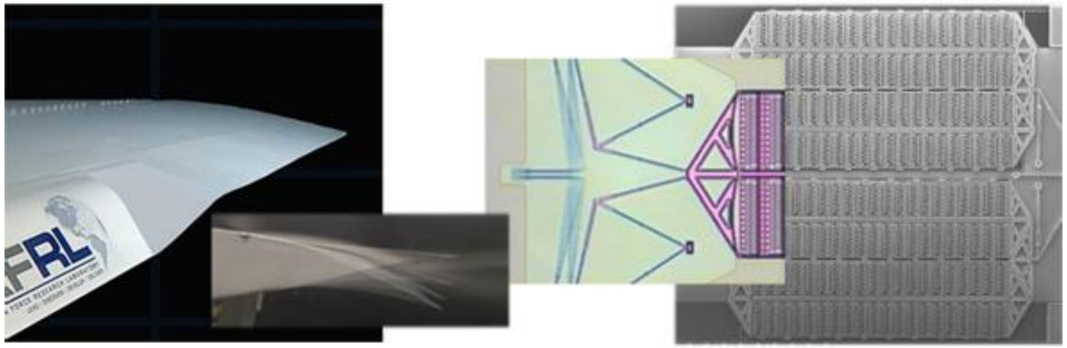
S. Zhang, C. Xia and N. Fang,
“Broadband acoustic cloak for ultrasound waves”, PRL, 106,2,2 4301, 2011



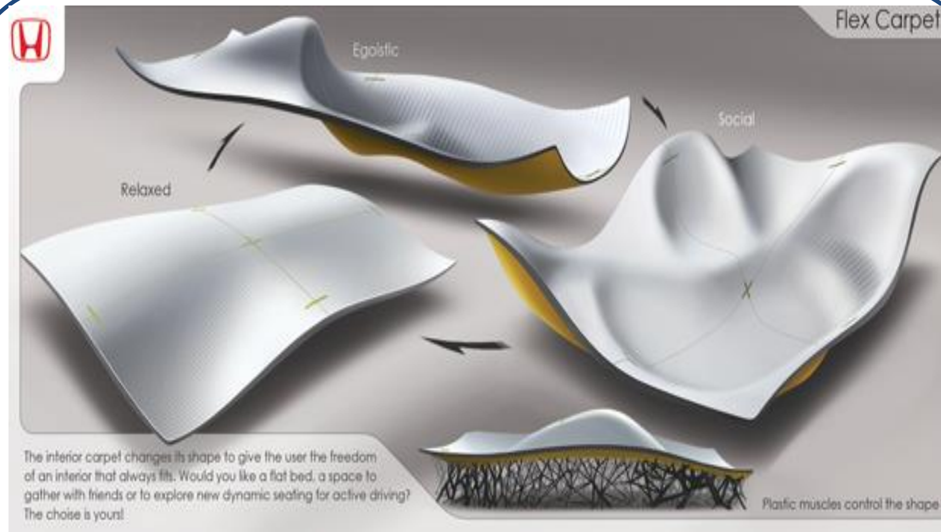
M. D. Schaeffer; M. Ruzzene, “Wave propagation in 2D magneto-elastic kagome lattices”, Proc. SPIE 9064, SMS 2014

From Structural Control to Material Programming

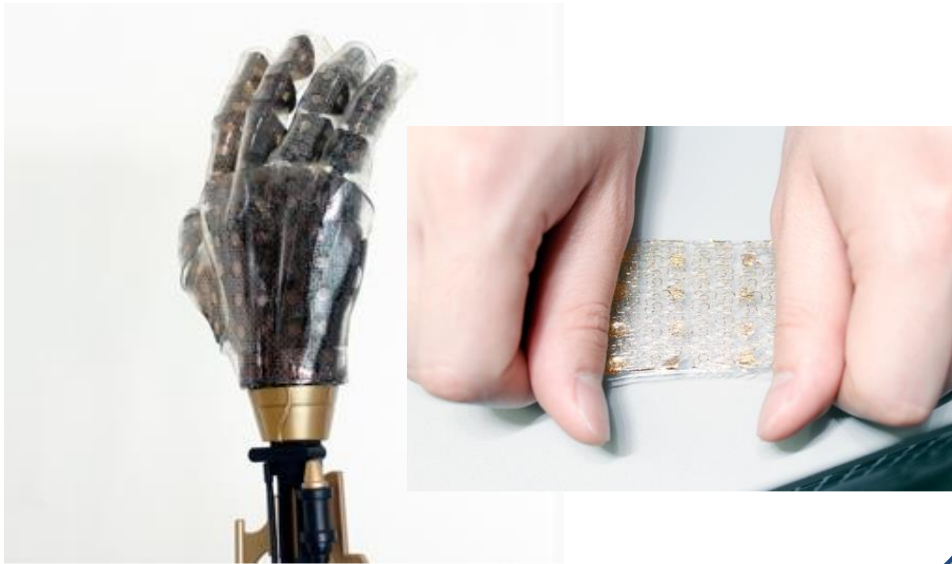
Morphing….



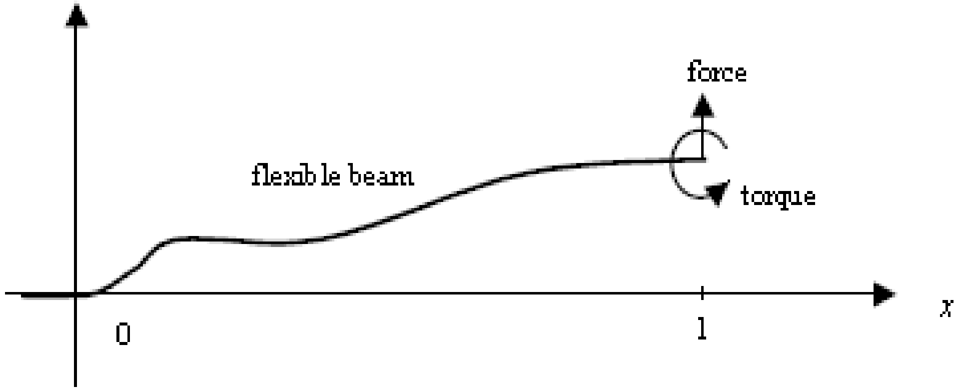
Avec des matériaux adaptatifs ‘programmés’



Et mesures



Generalized Impedance operator for beams



G. Monseny, LAAS report, Toulouse, 2002

$$\begin{cases} \partial_t^2\theta + \partial_x^4\theta = 0 \\ \theta(x,0) = \theta_0(x) \\ \partial_t\theta(x,0) = \theta_1(x) \\ \theta(0,t) = 0 \\ \partial_x\theta(0,t) = 0 \\ \partial_x^2\theta(1,t) = u(t) \\ \partial_x^3\theta(1,t) = v(t), \end{cases}$$

Mechanical System

$$\begin{cases} \partial_t^2\theta + \partial_x^4\theta = 0, \quad x \in (0,1) \\ \partial_x^2\theta(1,t) = -\partial_t\theta(1,t) - \sqrt{2}\partial_t^{1/2}\partial_x\theta(1,t) \\ \partial_x^3\theta(1,t) = \sqrt{2}\partial_t^{3/2}\theta(1,t) + \partial_t\partial_x\theta(1,t), \end{cases}$$

Controlled Mechanical System :

Pseudo derivative operator

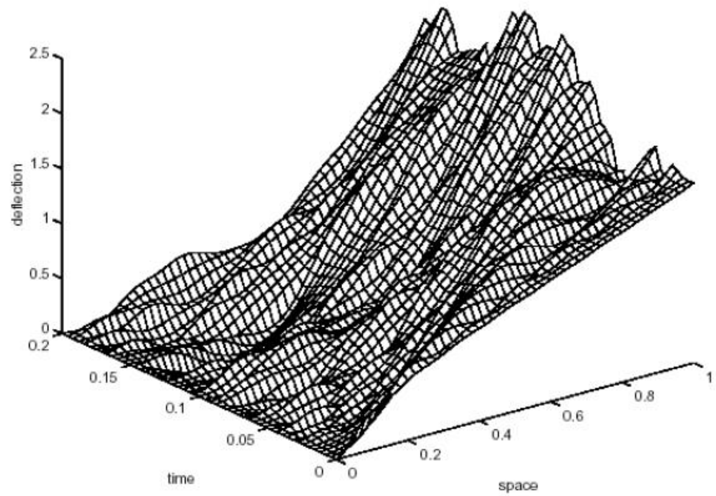


Figure 2: Autonomous beam

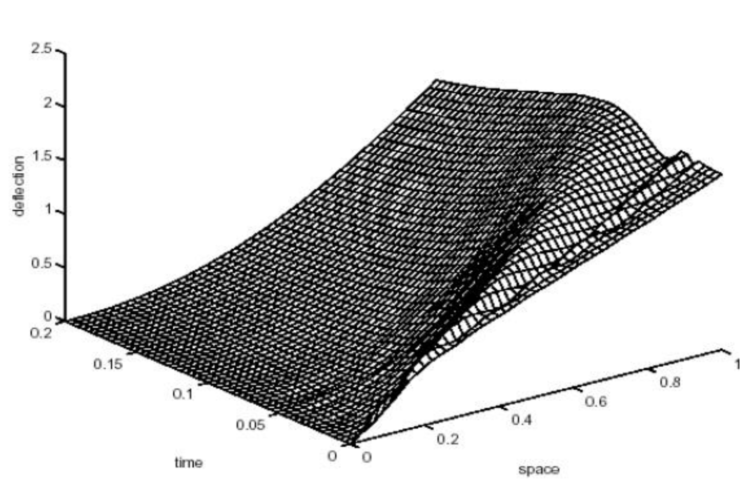
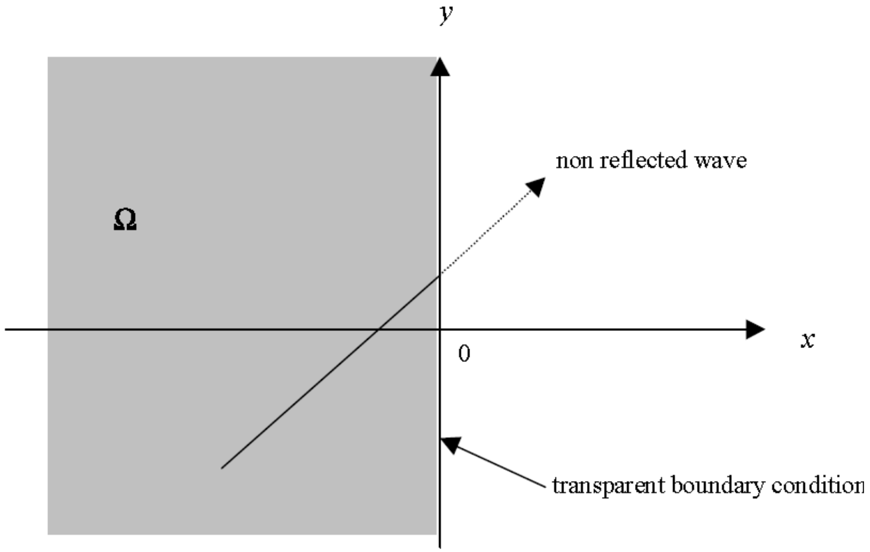


Figure 3: Beam with feedback Z_0

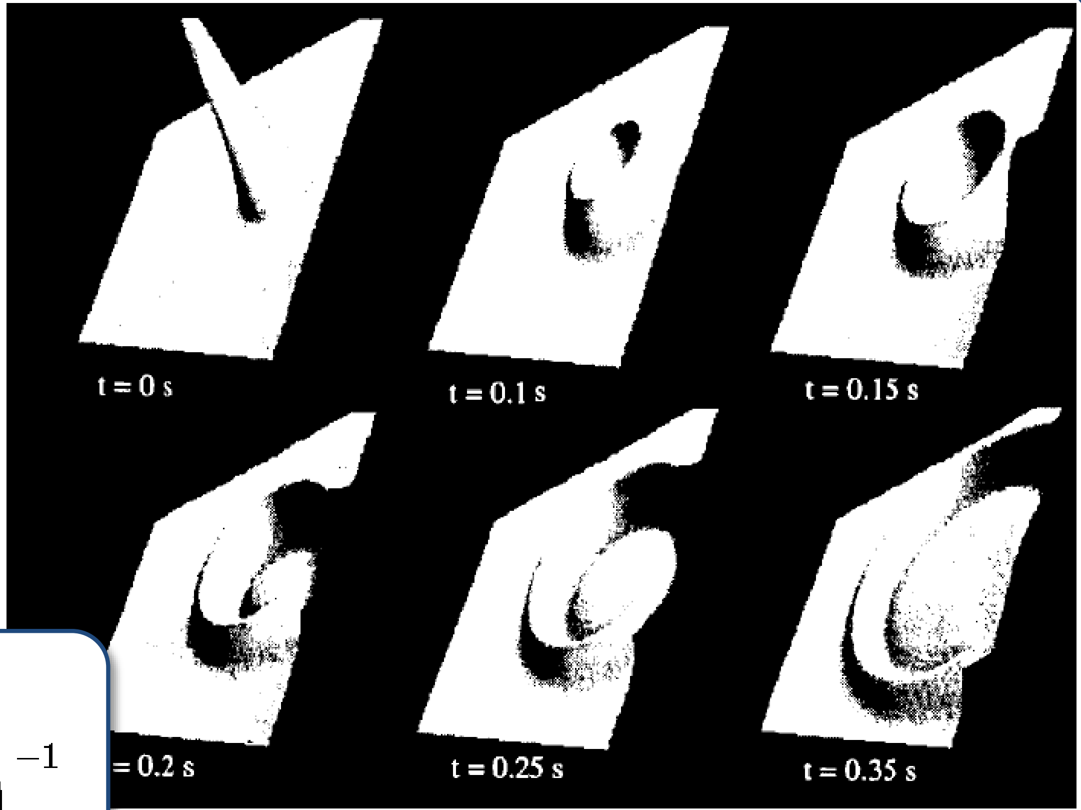
Generalized Impedance operator for acoustics



$$\begin{cases} \partial_t^2\theta - \Delta\theta = 0 \ \text{ on } \Omega_\theta \times \mathbb{R}_t^{+*} \\ \theta(0,y,t) := v(y,t) \\ w(y,t) := \partial_x\theta(0,y,t), \end{cases}$$

Acoustic System

G. Monseny, LAAS report, Toulouse, 2002



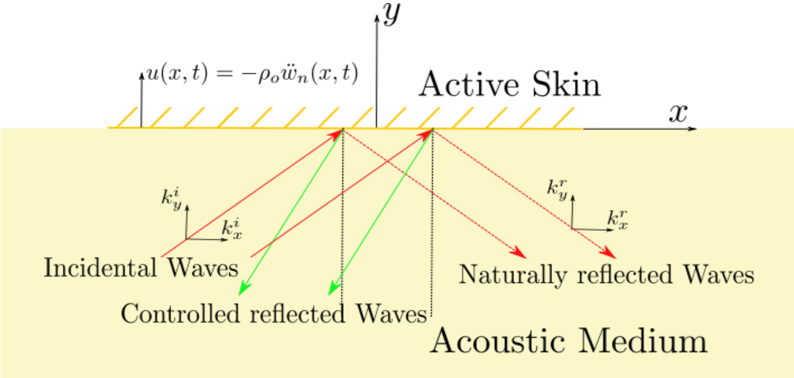
$$v := \mathcal{K}w$$

$$\mathcal{K} = -\left(\sqrt{\partial_t^2 - \partial_y^2}\right)^{-1}$$

Controlled System :

Pseudo derivative operator

Application: design of an active skin for acoustics



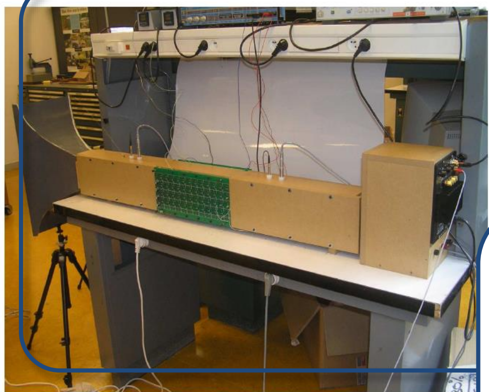
$$\left\{ \begin{array}{l} \frac{1}{{c_0}^2}\frac{\partial^2 p}{\partial t^2} - \Delta p = 0 \quad \text{on } \Re_y^{-*} \times \Re_x \times \Re_t^{*+} \\ \frac{\partial p(x,0,t)}{\partial y} = u(x,t) \\ y(x,t) = p(x,0,t) \end{array} \right.$$

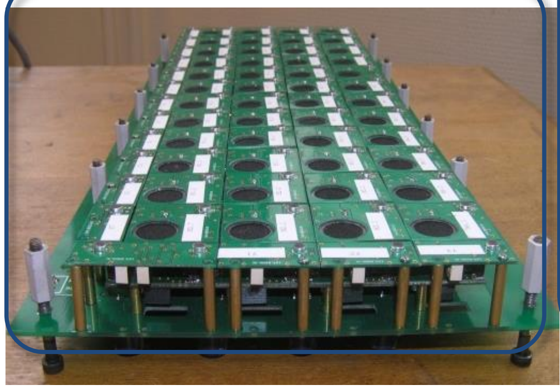
The physics

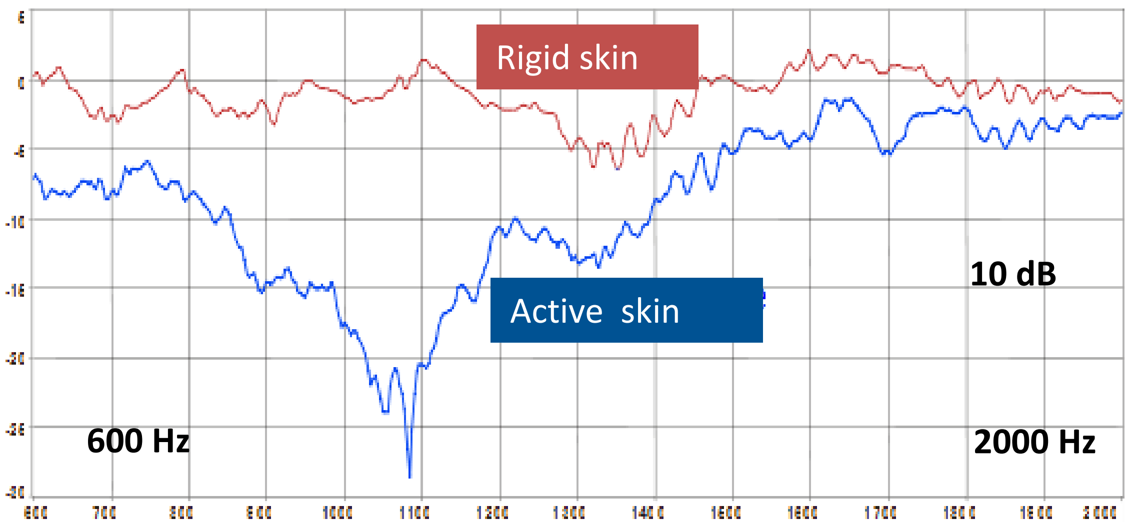
Control law that guarantees **kx<0**:

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

Finite difference estimation of 1st-order derivatives





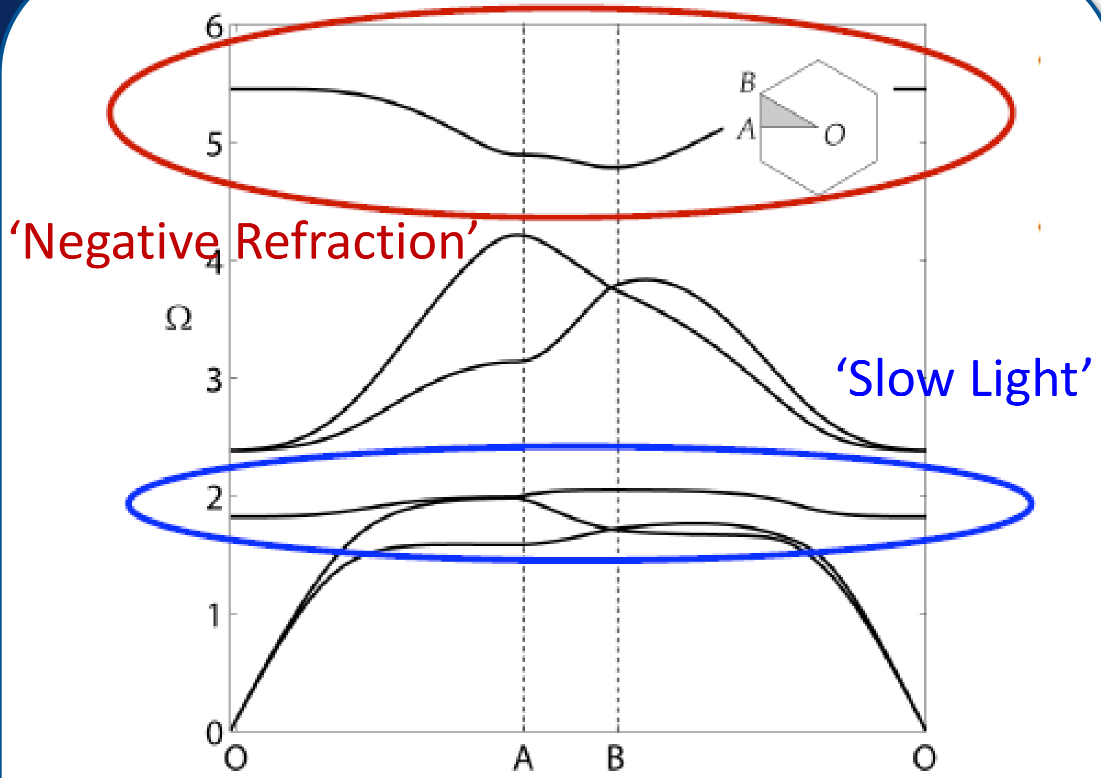


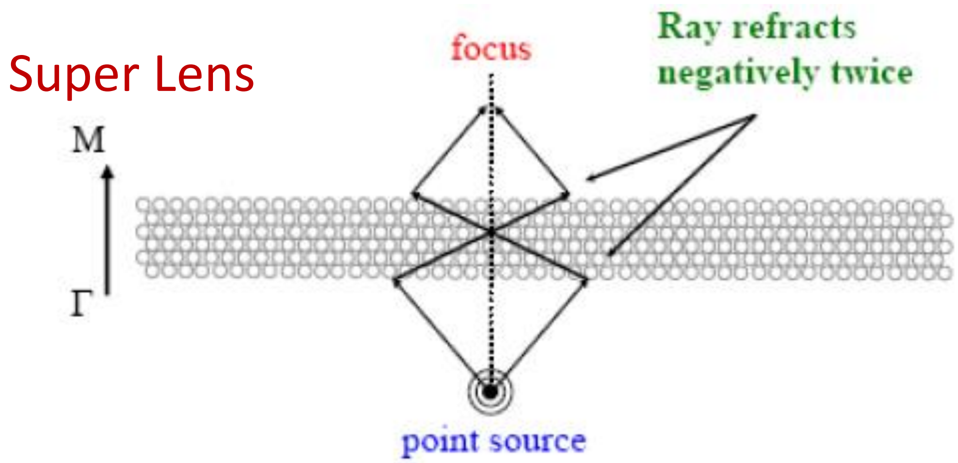
P. David, M Collet et al., SMS, 19(3), 2012

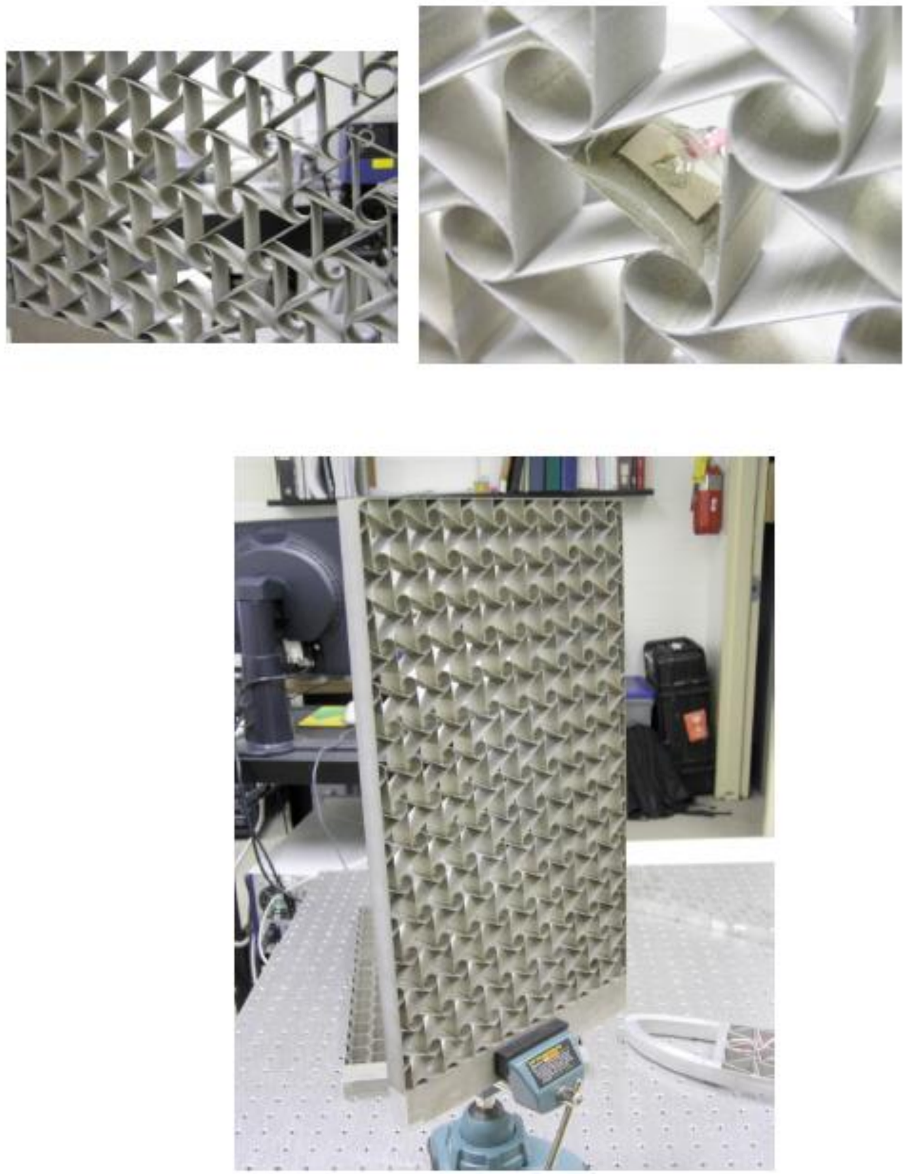
Towards smart distributed interfaces

- **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

Band Gap and other effects – back to basics





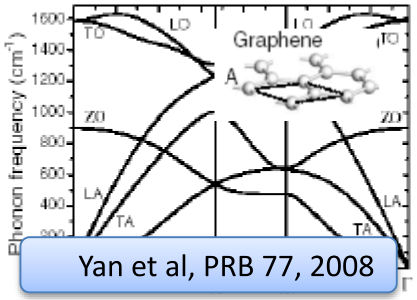


Chiral Lattice Georgia Tech

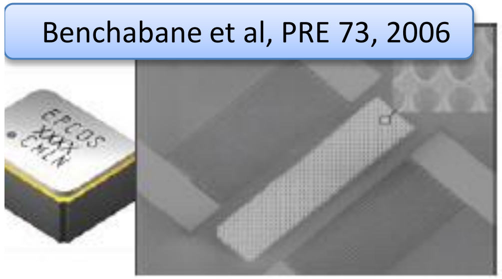
Physics of periodic structures

Structure	Physical properties	Waves support	Gap
Crystalline solids	Periodic arrangement of atoms ~ 5 Å	Electrons (Ψ) **Schrödinger** eq.	Absence of **electron** states
Photonic crystal	Periodic modulation of ε, μ (macro scale)	EM (E,B) **Maxwell** eqs.	Absence of states of the **EM** field
Phononic crystal	Periodic modulation of ρ, E, ν (macro scale)	Elastic (u) **Elasticity** eqs.	Absence of states of the **elastic** field

nm → µm → mm → cm → m

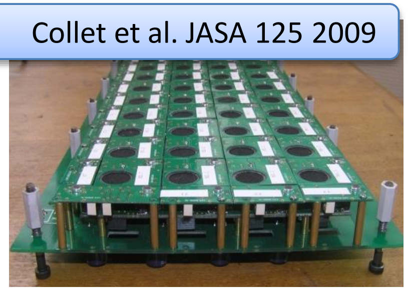


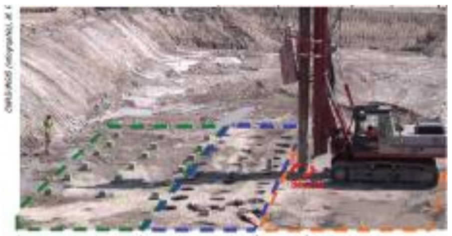
Yan et al, PRB 77, 2008



Benchabane et al, PRE 73, 2006


NDT, NDE

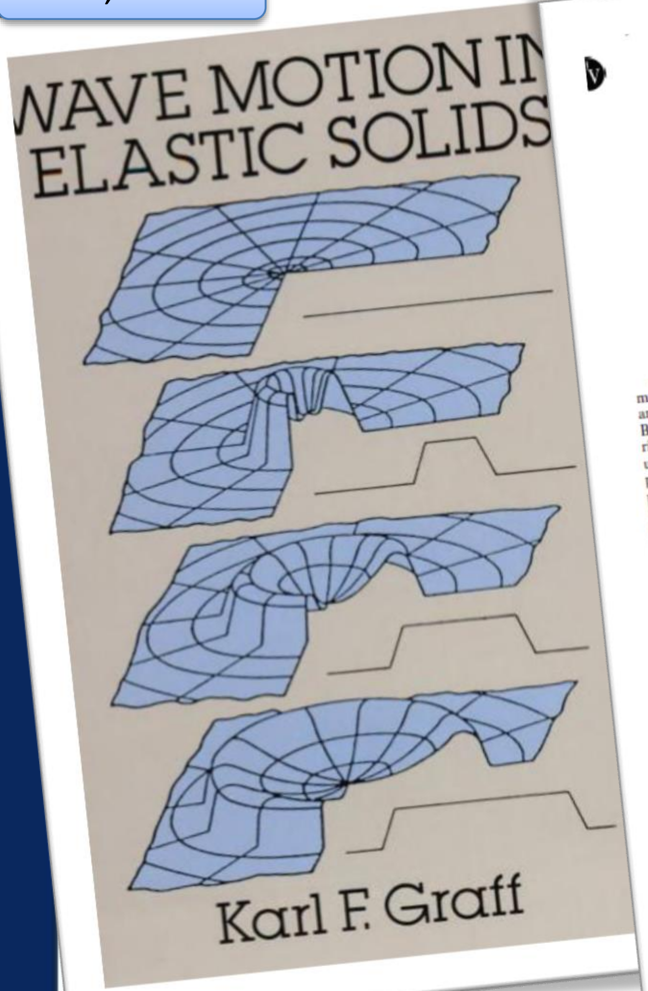

Collet et al. JASA 125 2009


Brûlé et al. PRL 112, 2014

THz ← GHz ← MHz ← kHz ← Hz

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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Institute of Sound and Vibration Research, University of Southampton, Southampton SO17 1BJ, England

(*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.

1. INTRODUCTION

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

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

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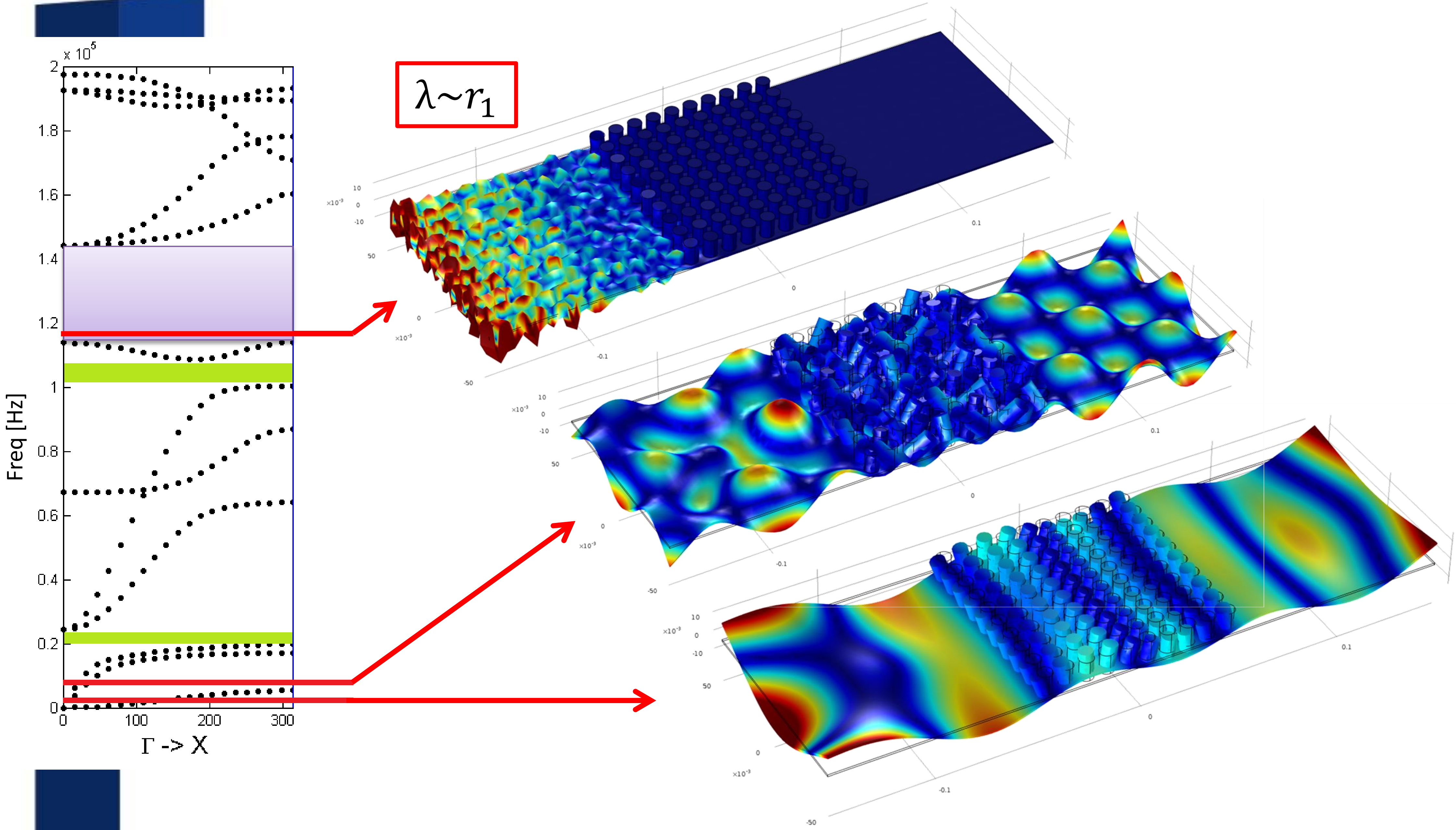
[DOI: 10.1115/1.4026911]

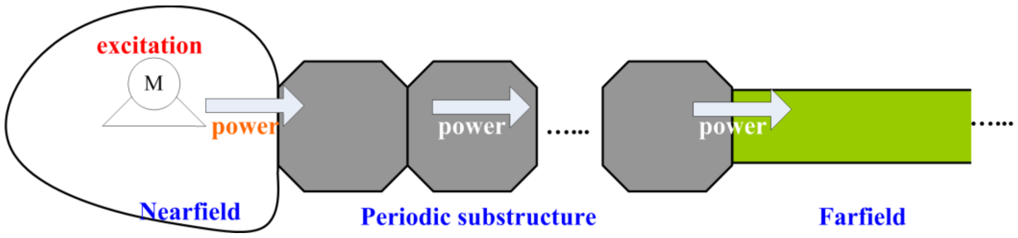
Introduction

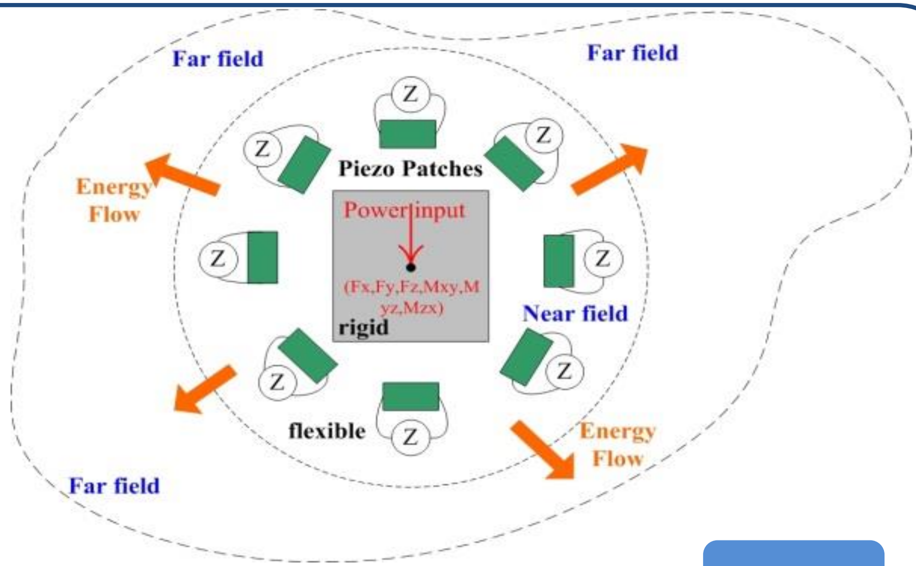
And now… back to real (simulated) life: integration of a phononic crystal as interface on a finite structure



Is Band Gap the optimal solution?

1D



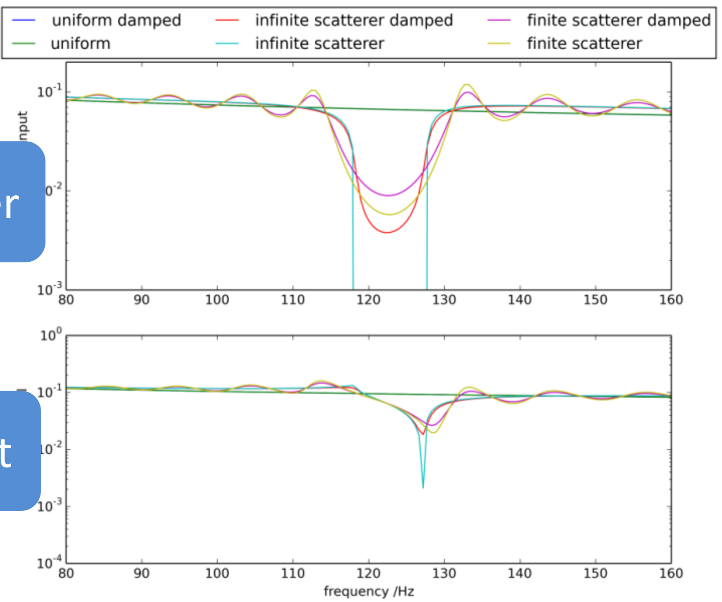


2D

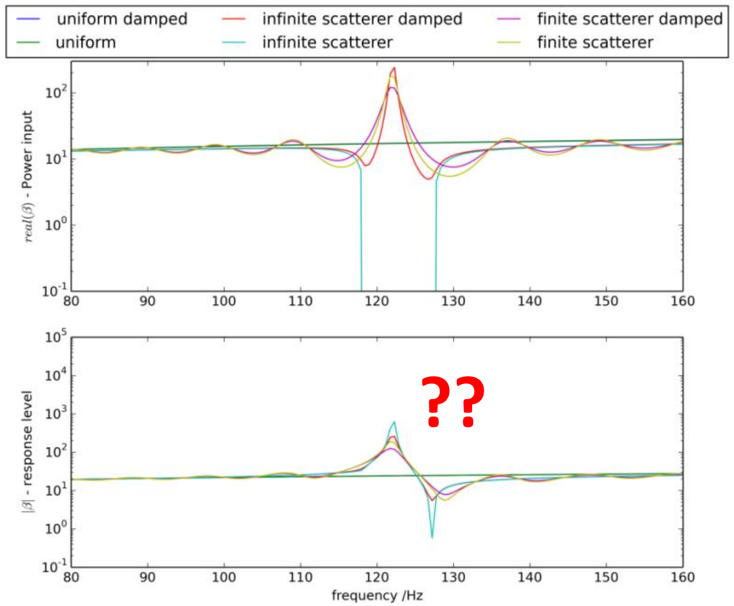
Output Power

Displacement

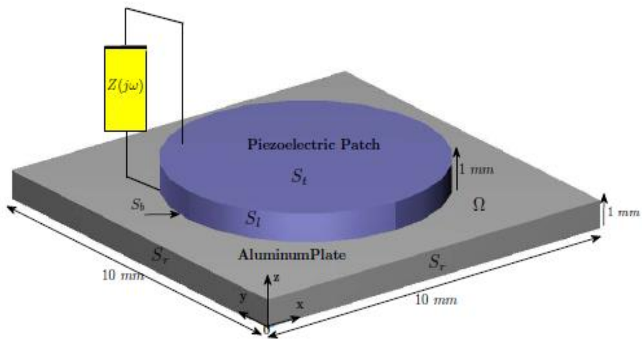
Local modes not excited



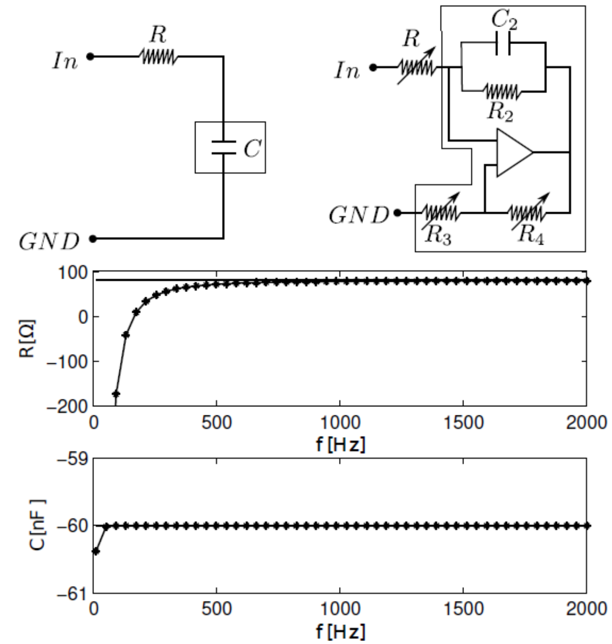
Local modes excited



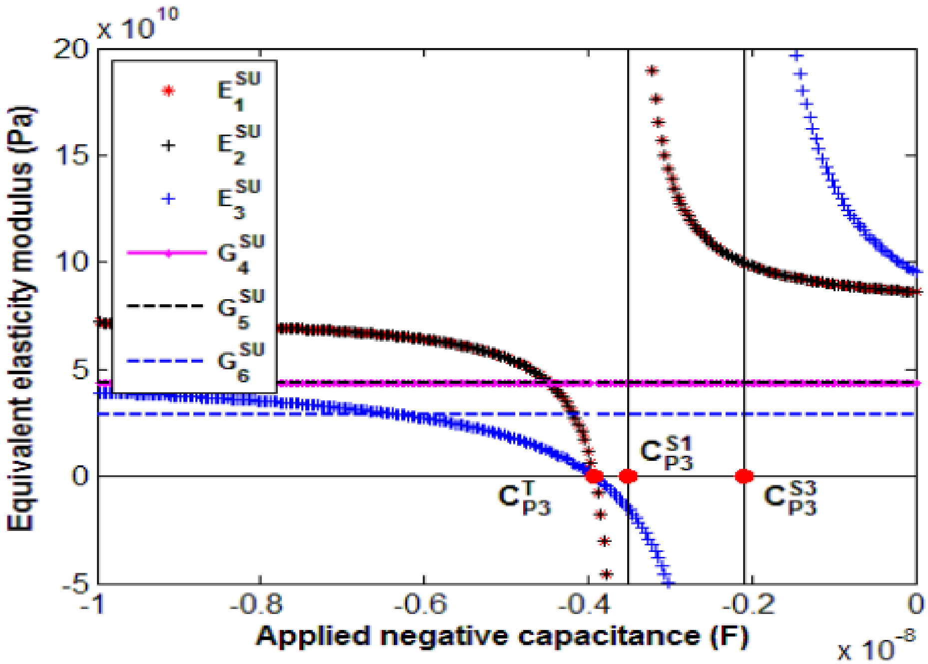
Design of a reconfigurable metacomposite for 2D structural functions

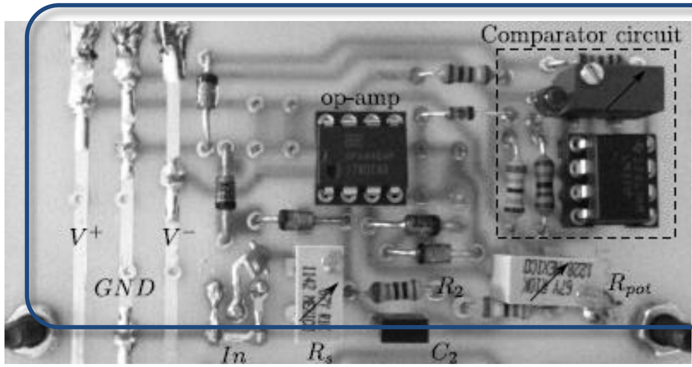


Elementary cell

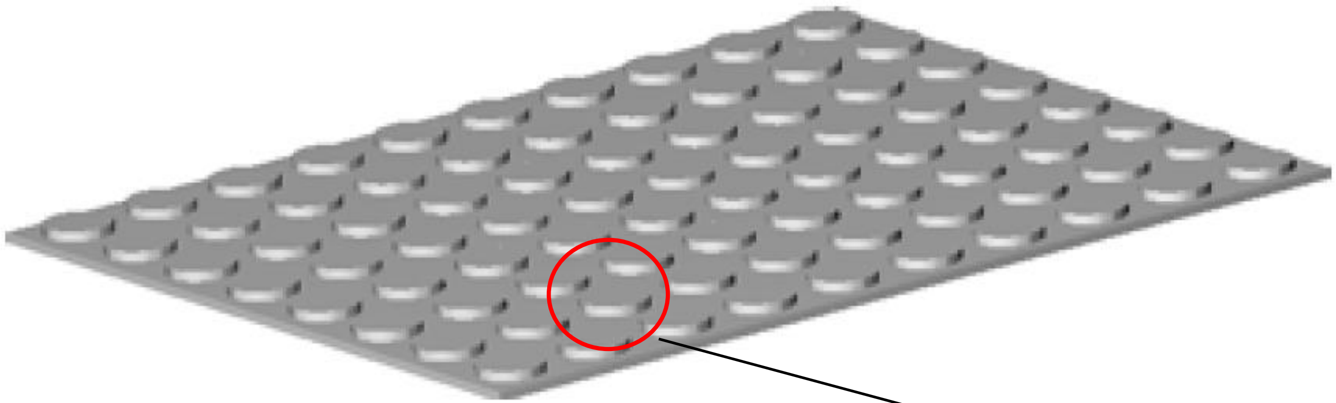


$$Z_{eq} = R_s - \frac{R_3 R_2}{R_4\left(1 + i\omega R_2 C_2\right)}$$



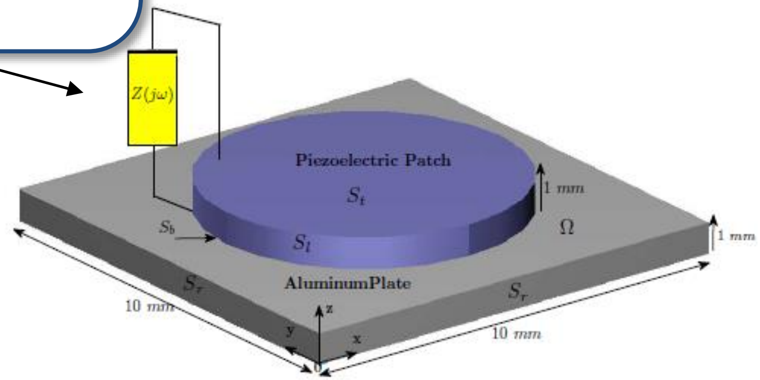


Design of a reconfigurable metacomposite for 2D structural functions

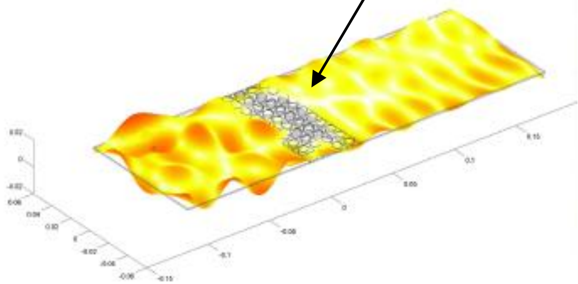


The metacomposite

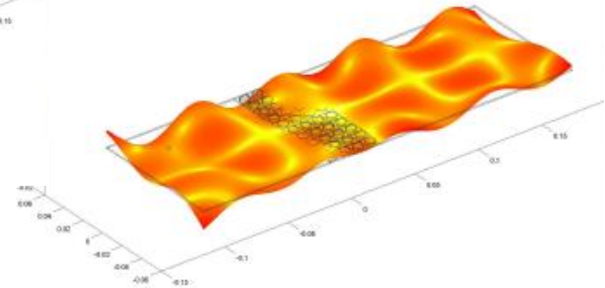
PZT-Aluminum Composite



Interface with two configurations



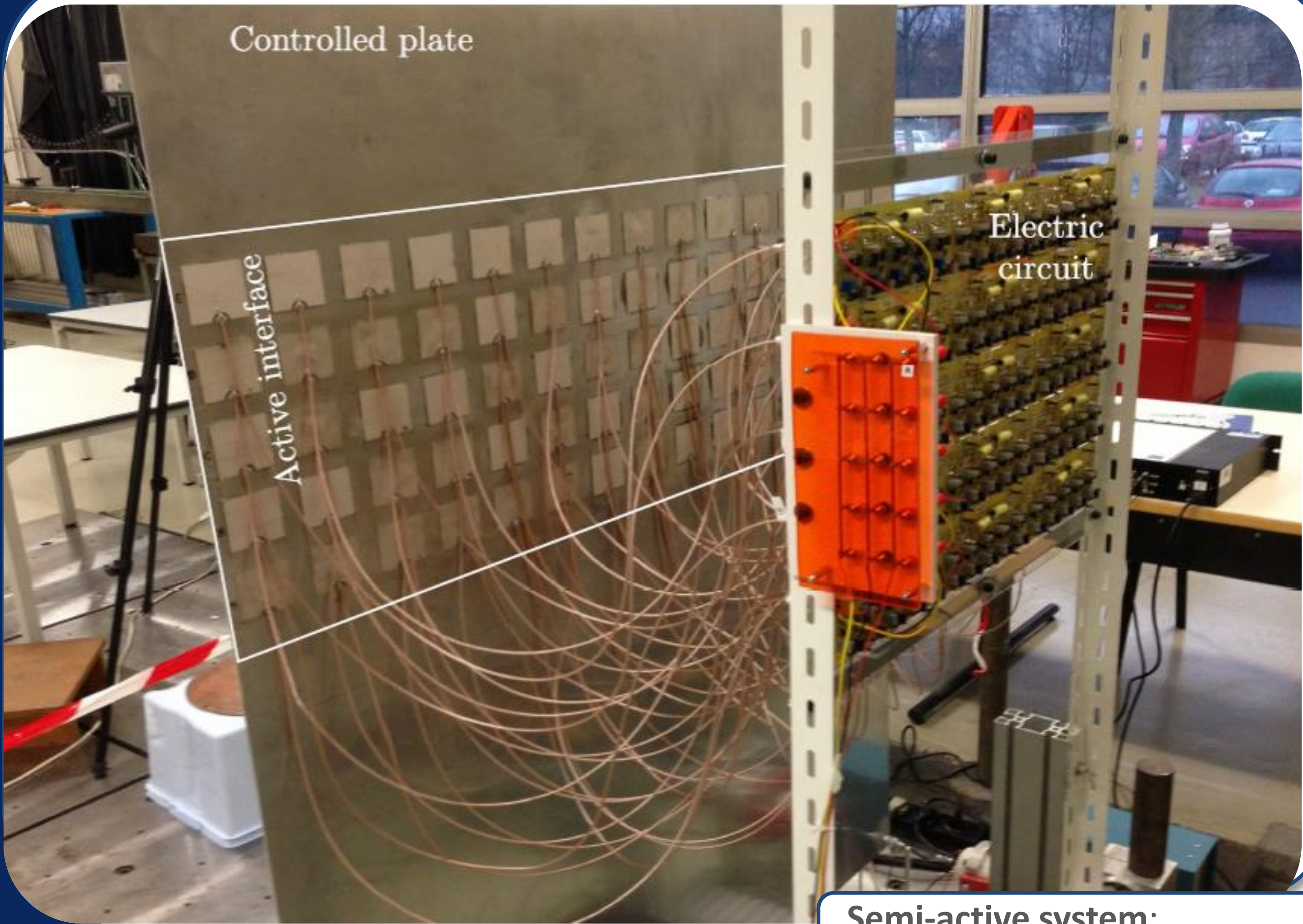
Vibration isolation

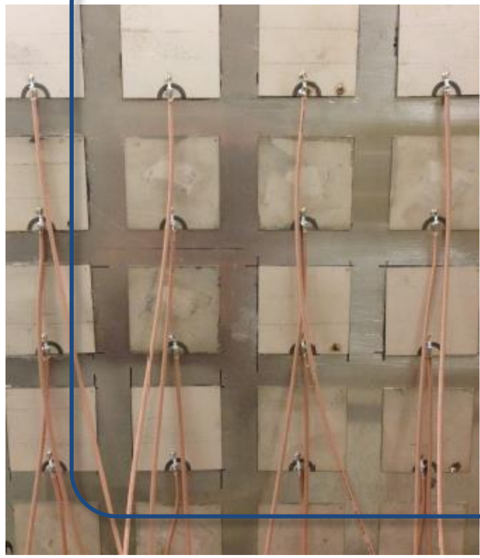


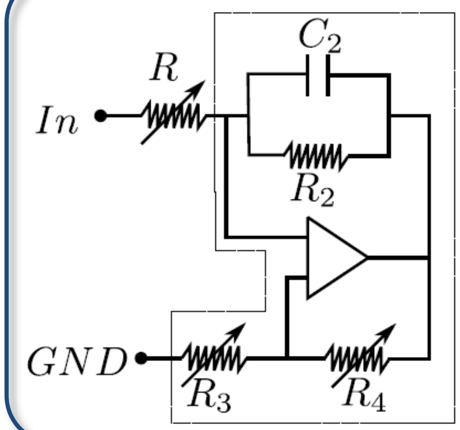
Vibration damping

…a distributed control device with no computation: combination of analog structural/electrical loops communicating through the structure

Absorption and Reflexion





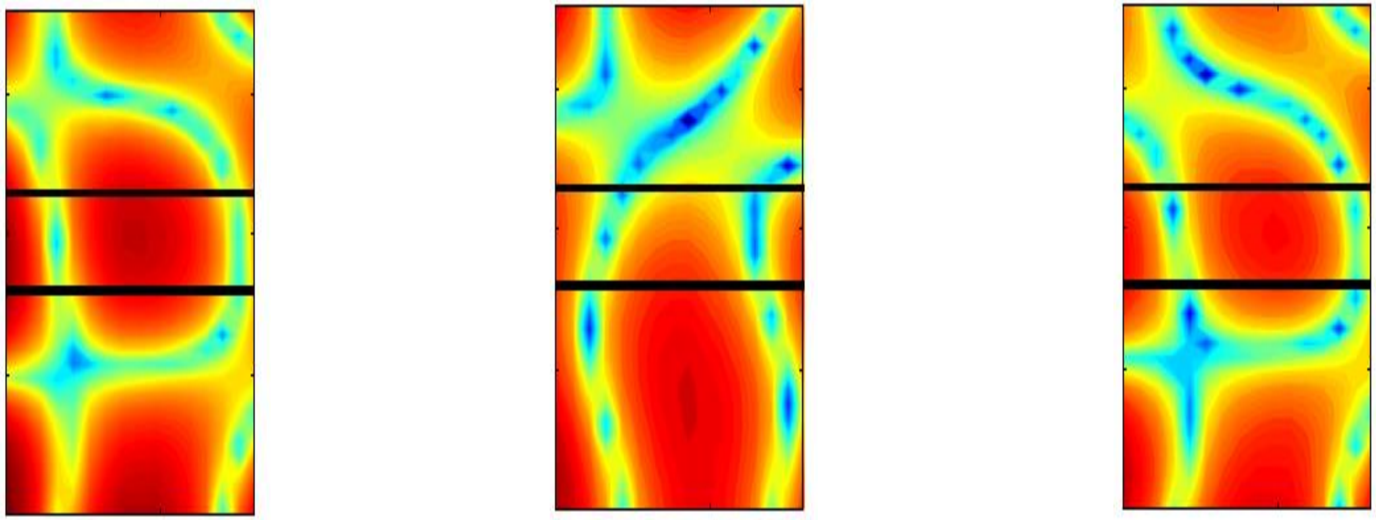


Semi-active system:
- No control loop => robustness
- Need only to power Op-Amps

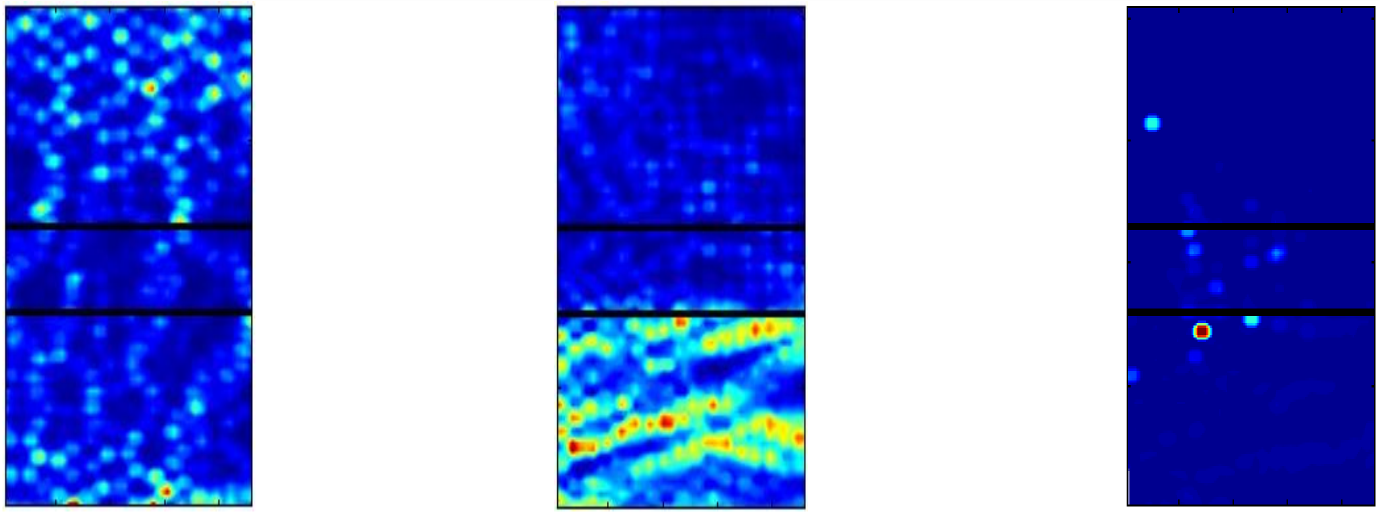
Absorption and Reflexion

Ctrl off | Ctrl on *Case REFL* | Ctrl on *Case ABS*

Measurement @ 25 Hz

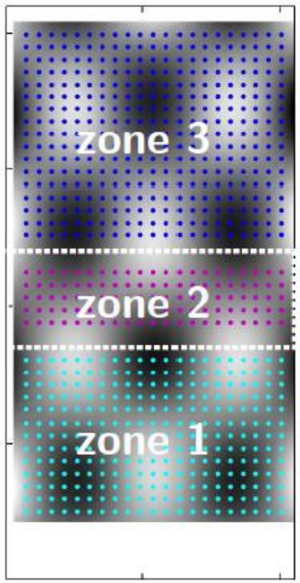


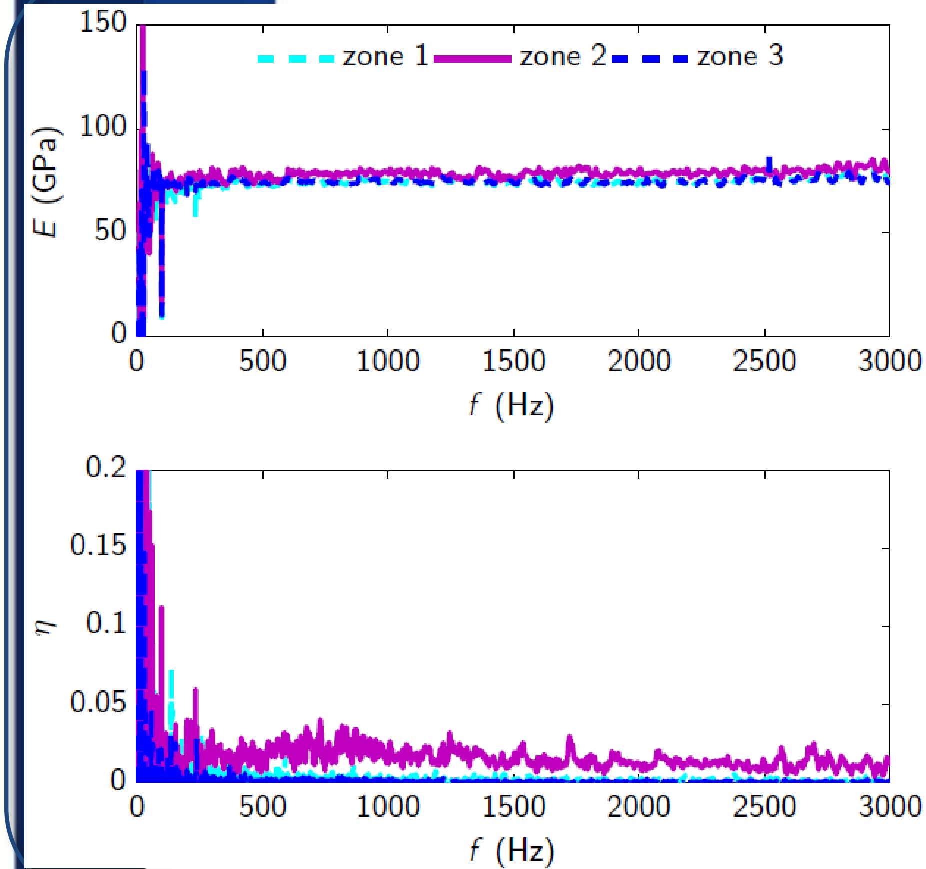
Measurement @ 3000 Hz



Global efficiency in terms of apparent properties

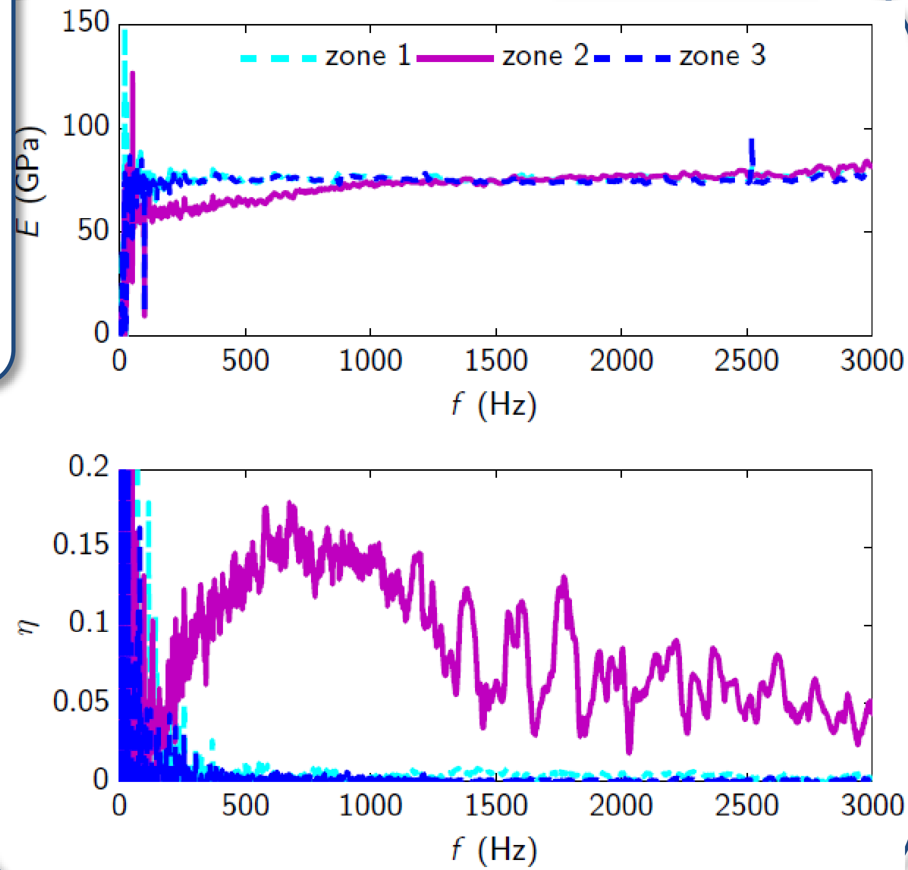
- RIFF technique
- Experimental results
- Coll. with C. Pezerat & F. Ablitzer (LAUM)
- Large increase of damping capability





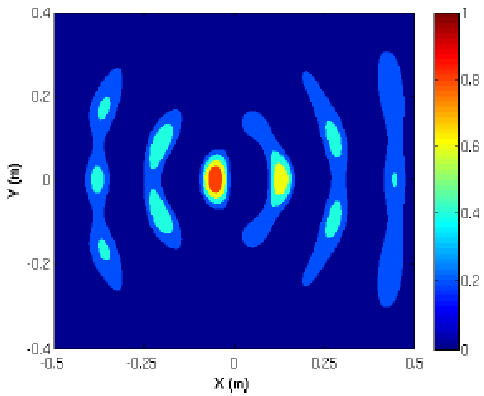
Shunt OFF

Case ABS

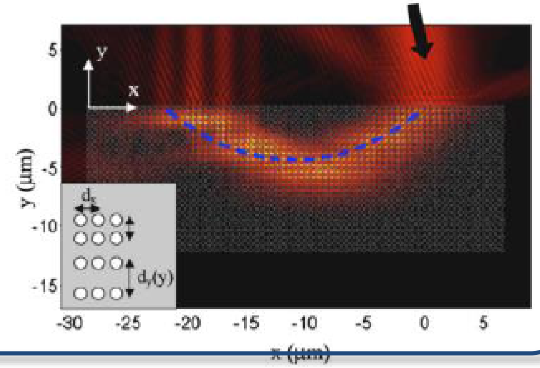


Gradient Index : Adaptive Lens

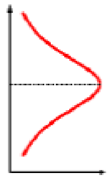
Gradient index (GRIN) devices :



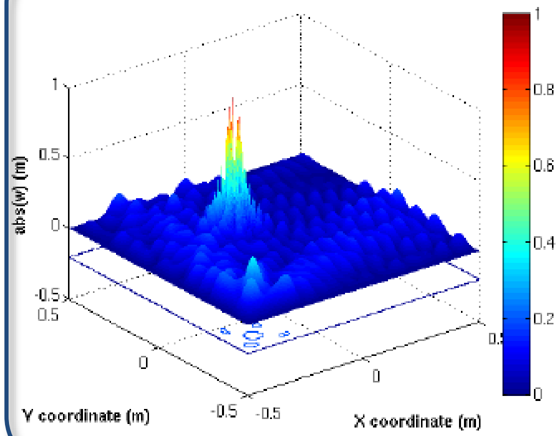
Lens
(e.g.: S. Lin et al., 2009)



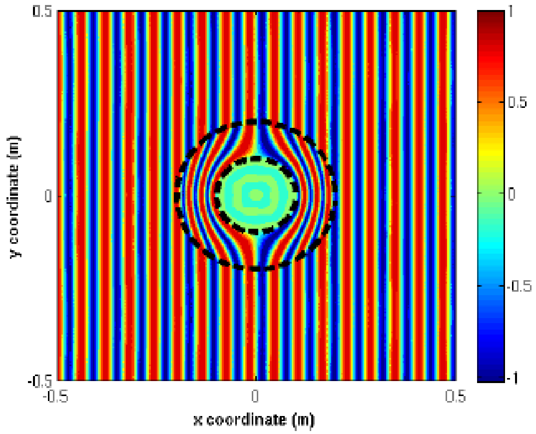
Wave bender
e.g.: (E. Centeno et al., 2006)



$$E(x,y), \mu(x,y)$$
$$\rho(x,y), h(x,y)$$

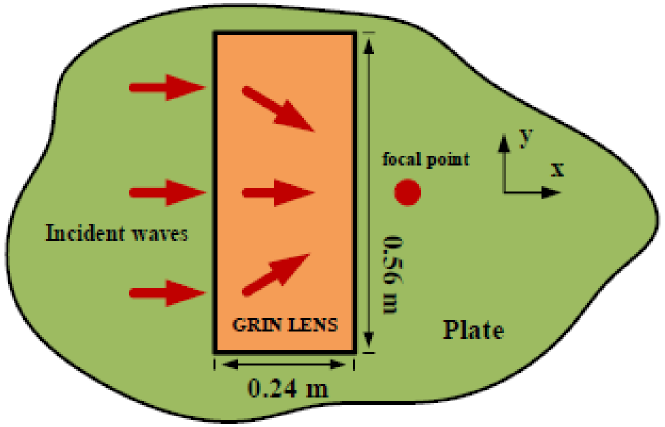


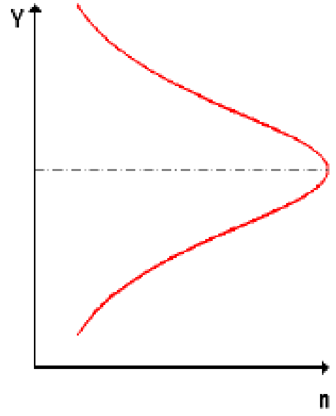
Acoustic black hole
(e.g.: V. Krylov, 2014) /
acoustic wave absorber
(e.g.: A. Climente et al., 2013)



Cloak shell
(e.g.: Norris, 2008)

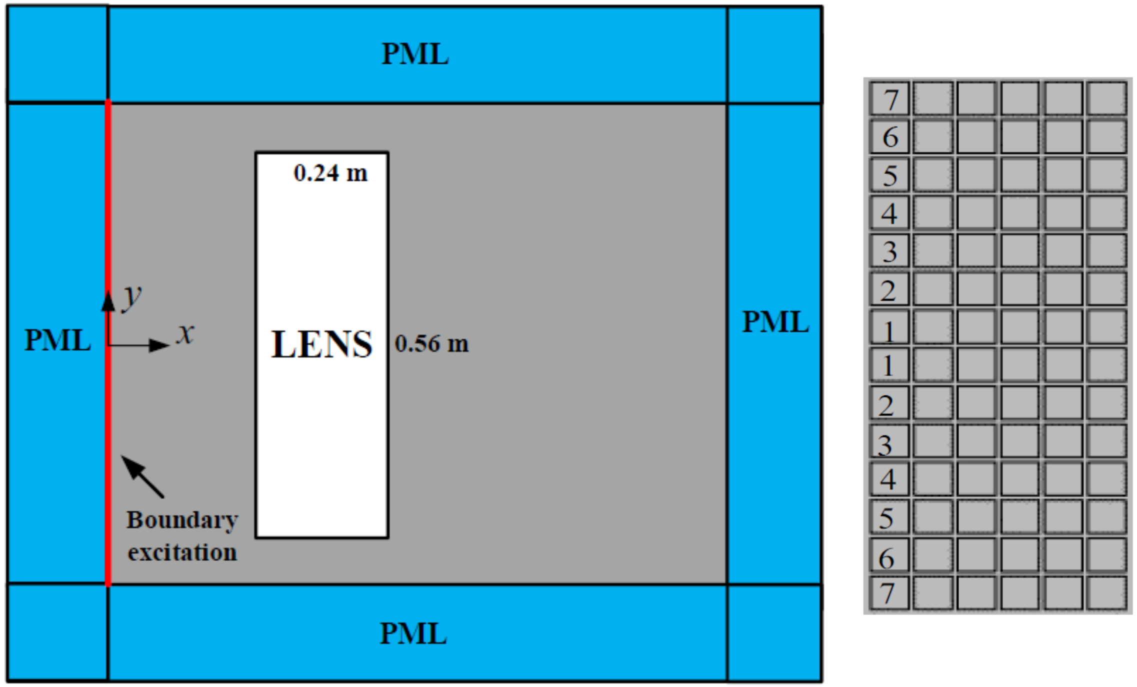
Gradient Index : Adaptive Lens

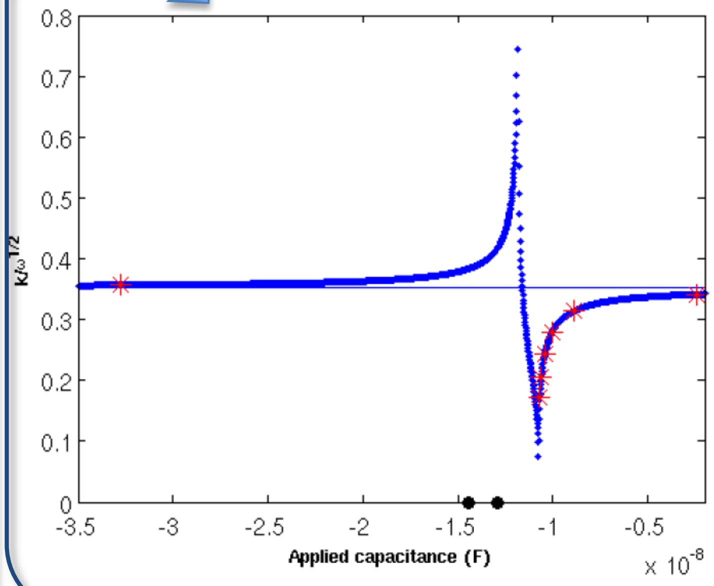




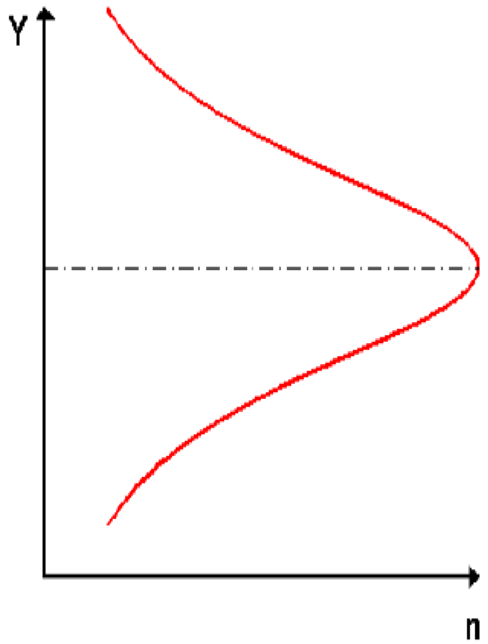
Refractive index

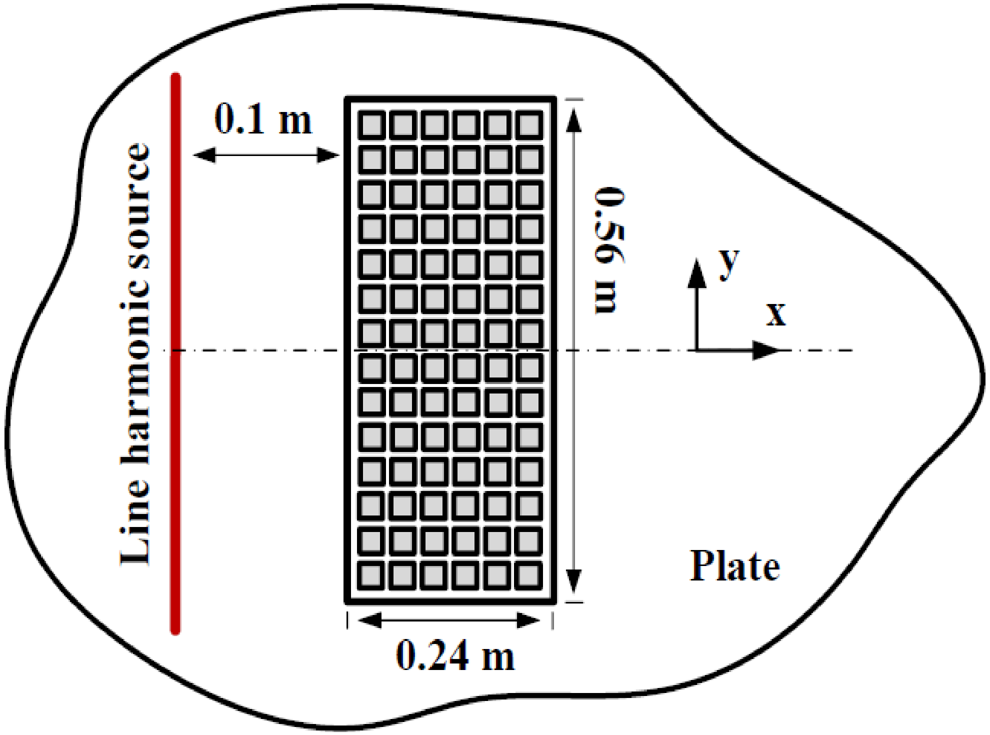
$$n(y) = \mathrm{sech}[\alpha(y - y_0)]$$





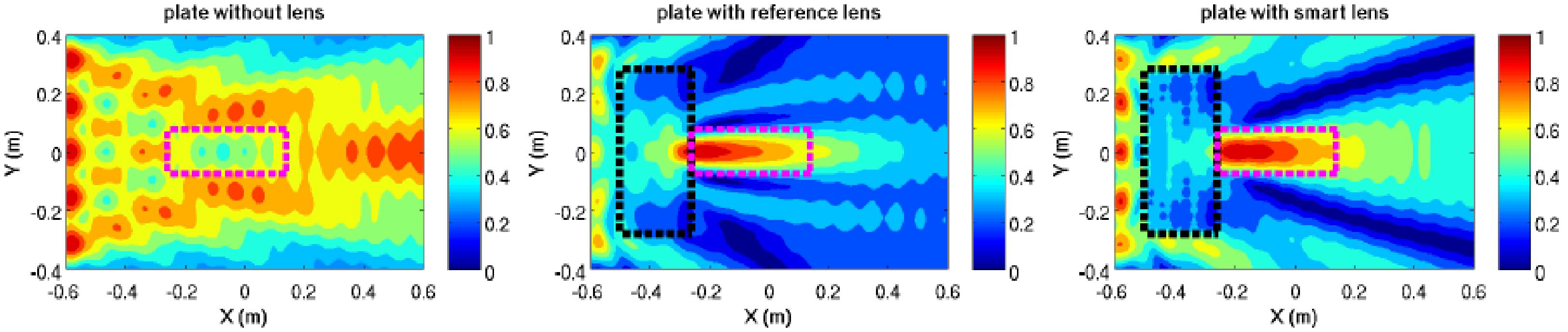
Plane Wave



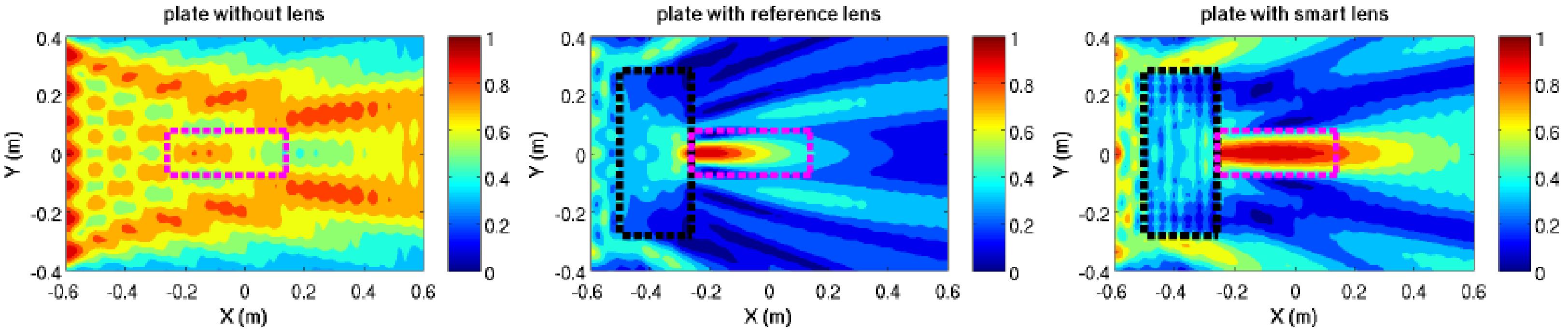


Gradient Index : Adaptive Lens

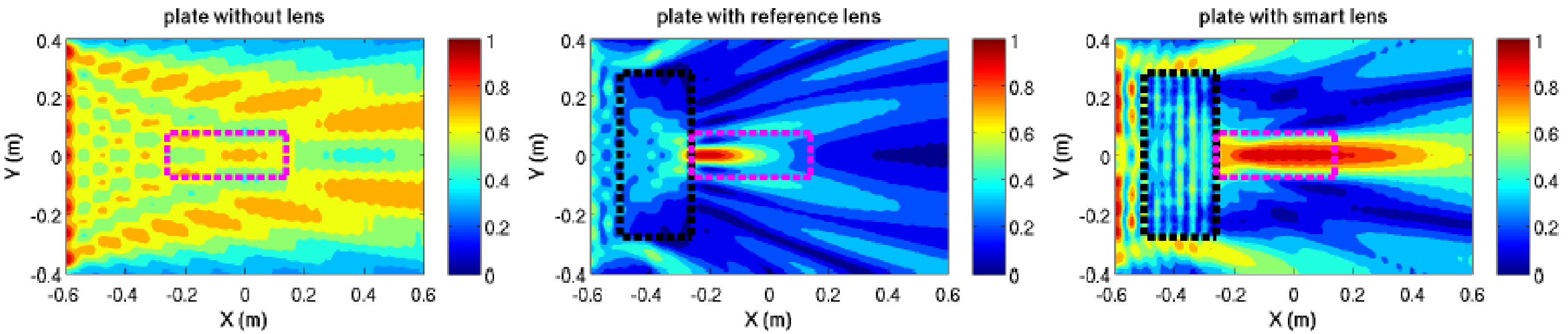
2000 Hz:

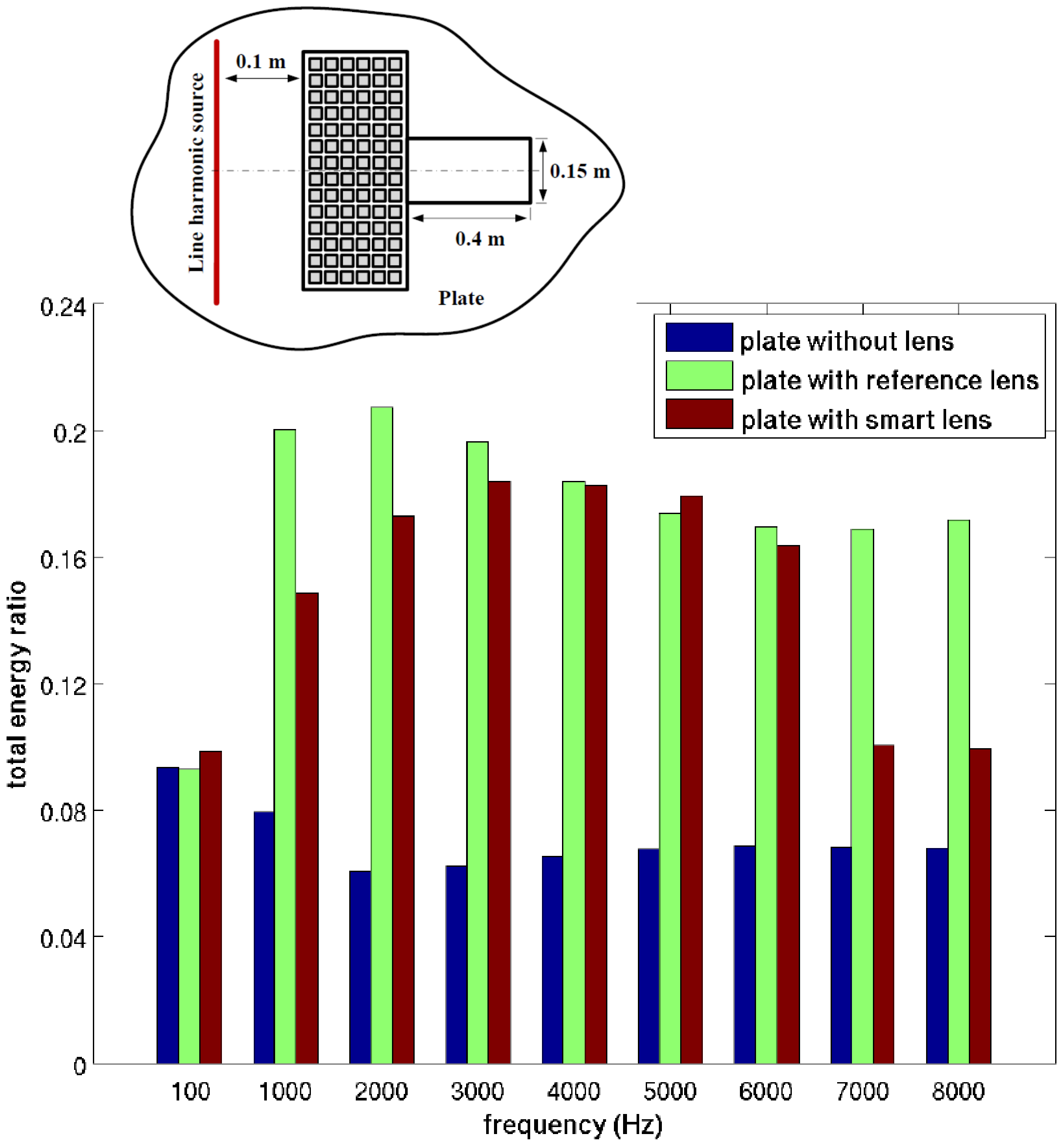


4000 Hz:



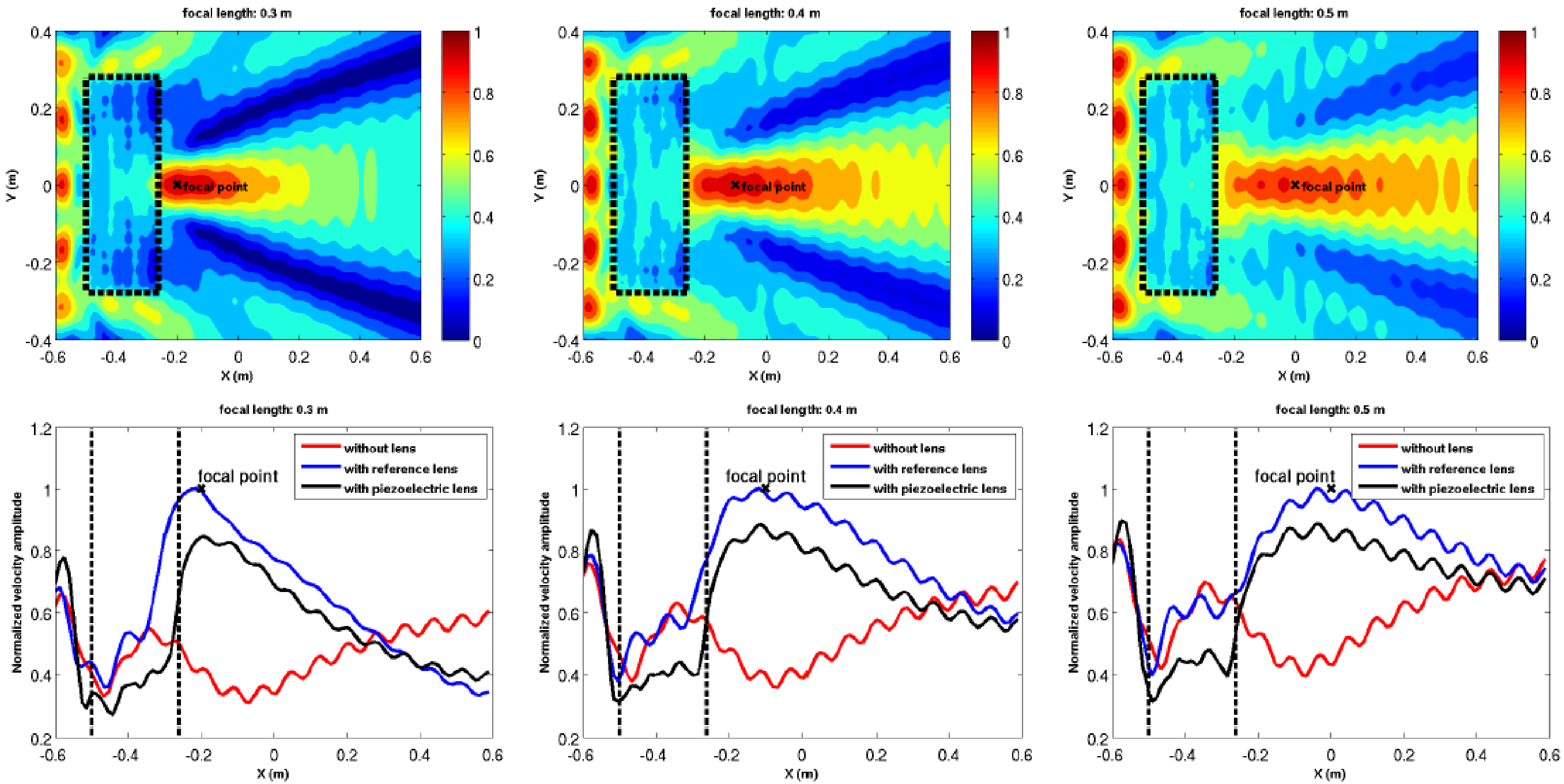
6000 Hz:





0.1 m
Line harmonic source
0.15 m
0.4 m
Plate
plate without lens
plate with reference lens
plate with smart lens
total energy ratio
0
0.04
0.08
0.12
0.16
0.2
0.24
100
1000
2000
3000
4000
5000
6000
7000
8000
frequency (Hz)

Tunability of the focal point

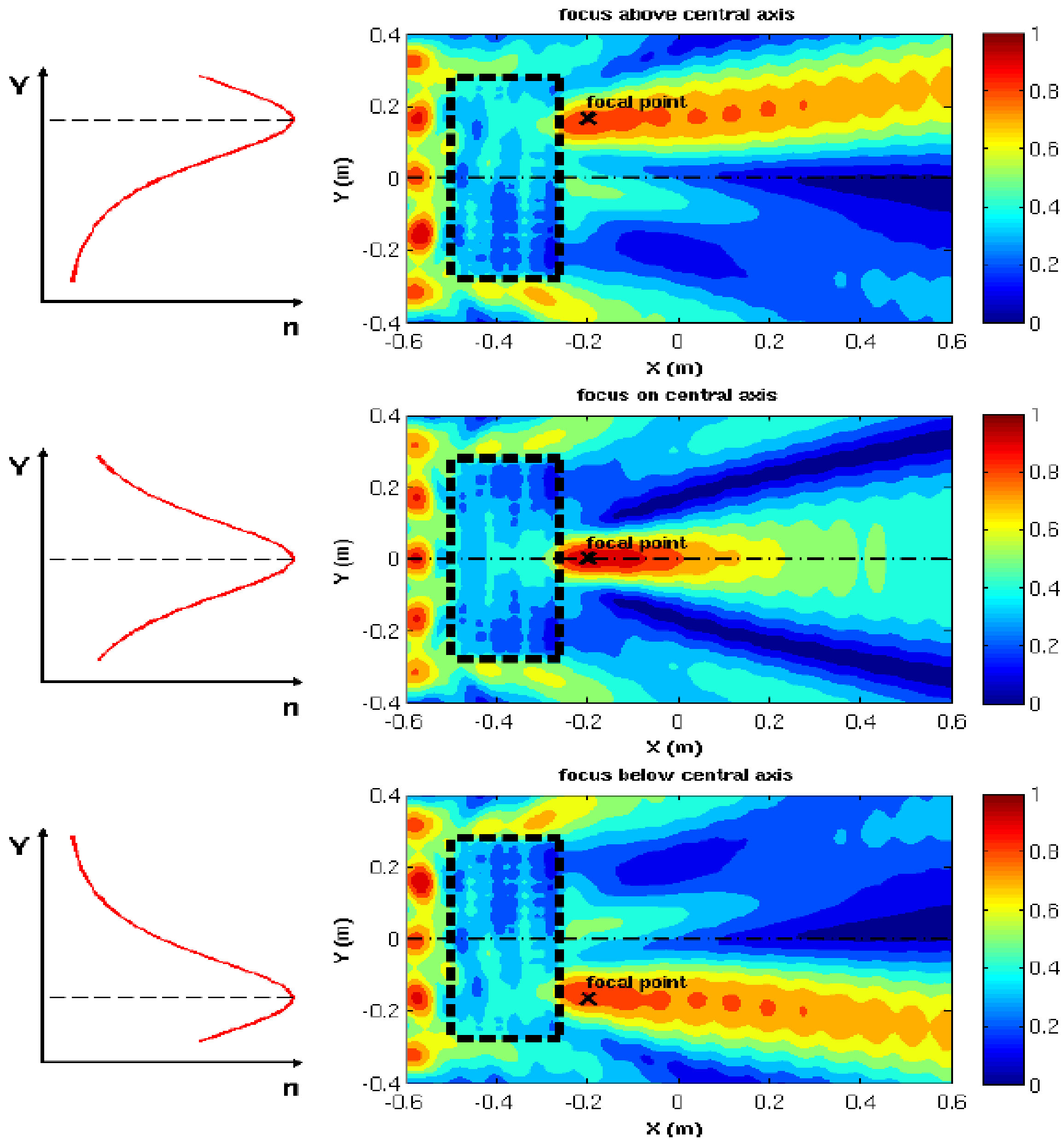


Focal length: 0.3 m **Focal length: 0.4 m** **Focal length: 0.5 m**

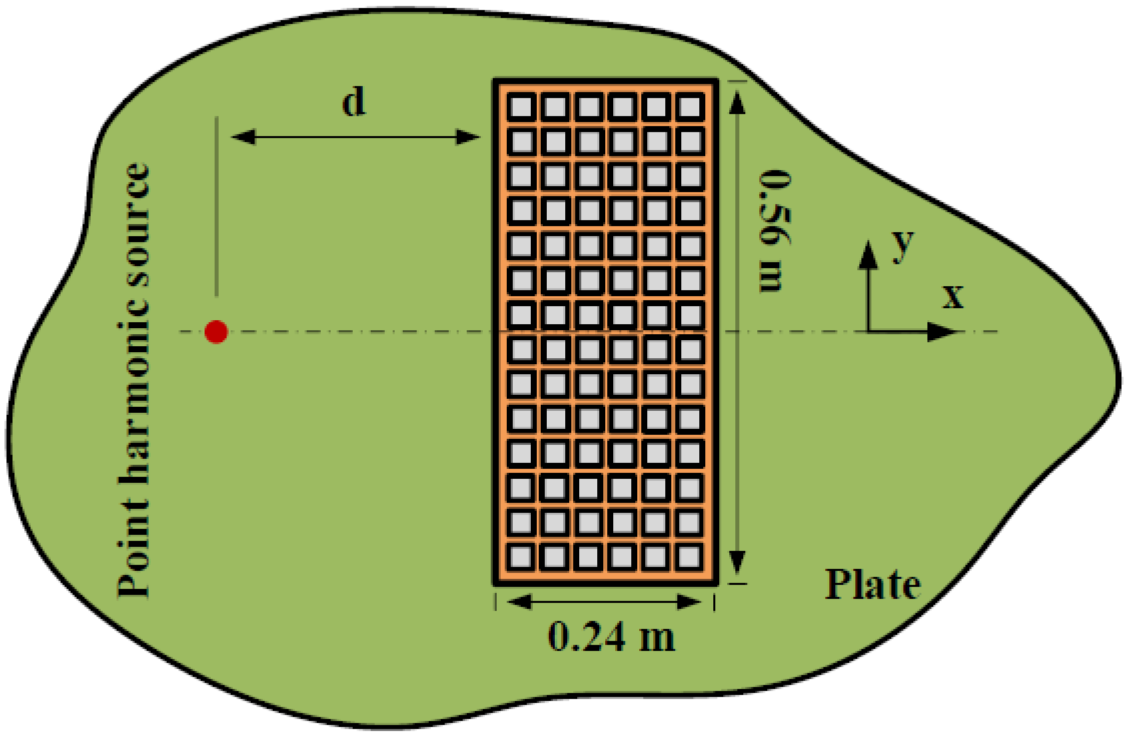
Gradient Index : Adaptive Lens

Tunability of the focal point

At 2000 Hz

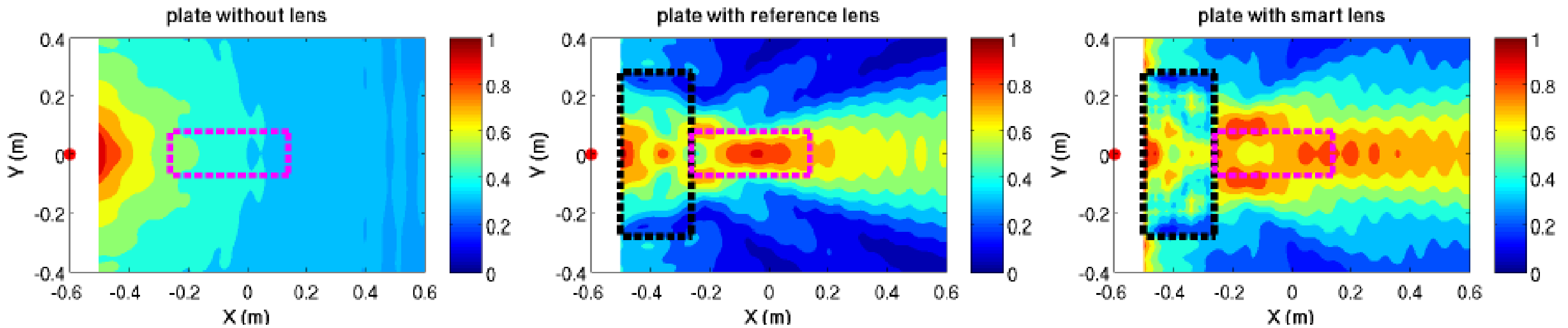


Near field point source

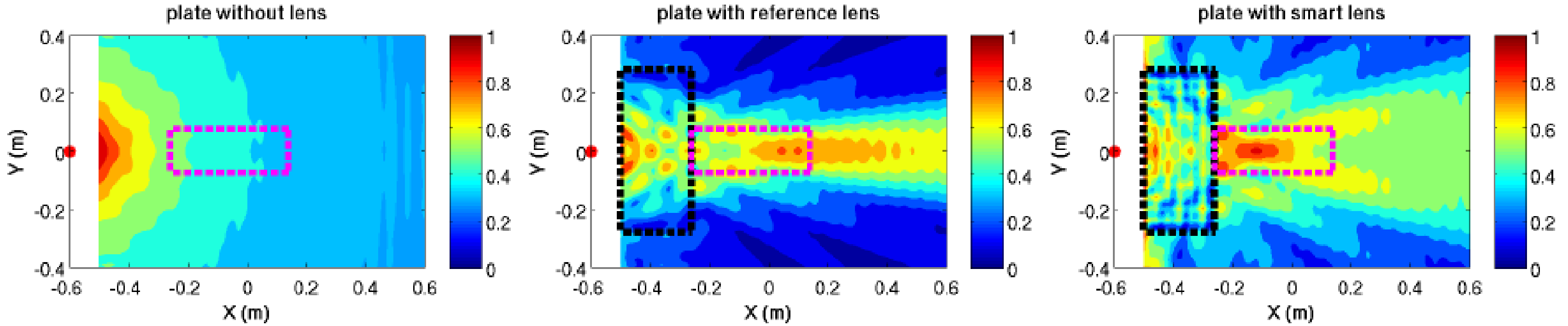


Gradient Index : Adaptive Lens

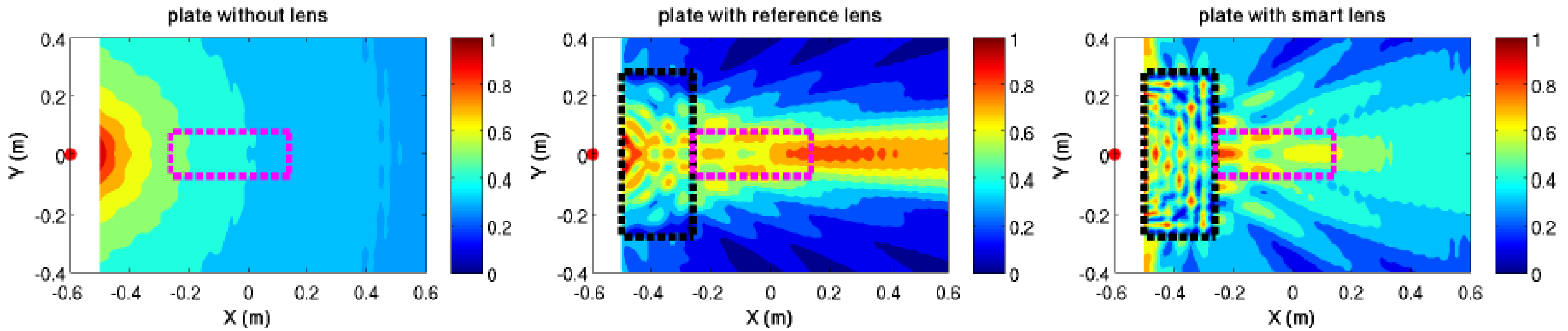
2000 Hz:



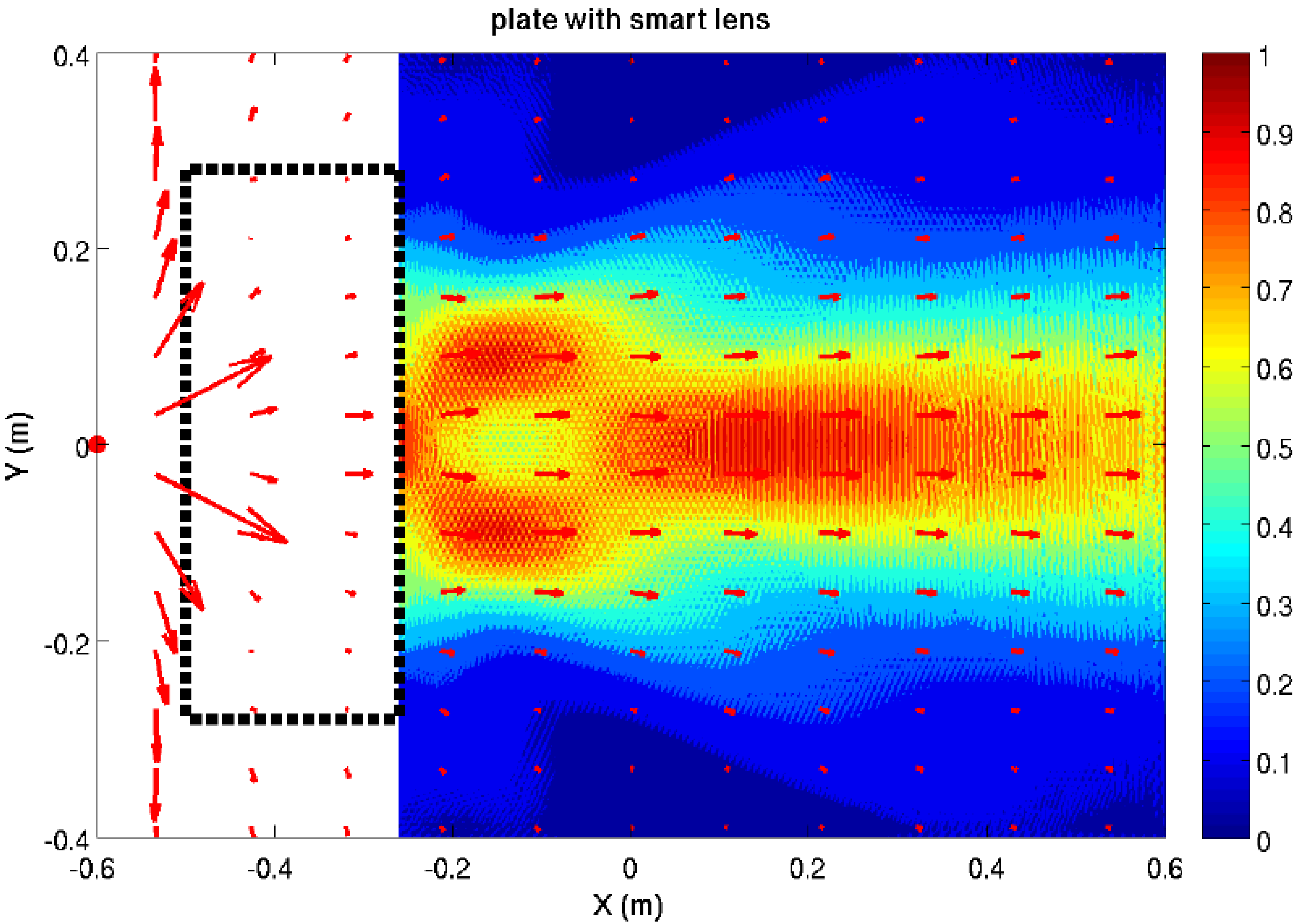
4000 Hz:



6000 Hz:

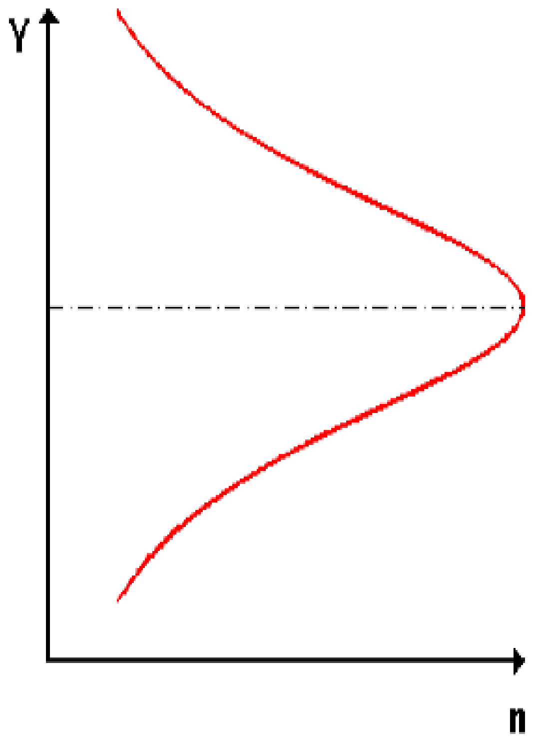


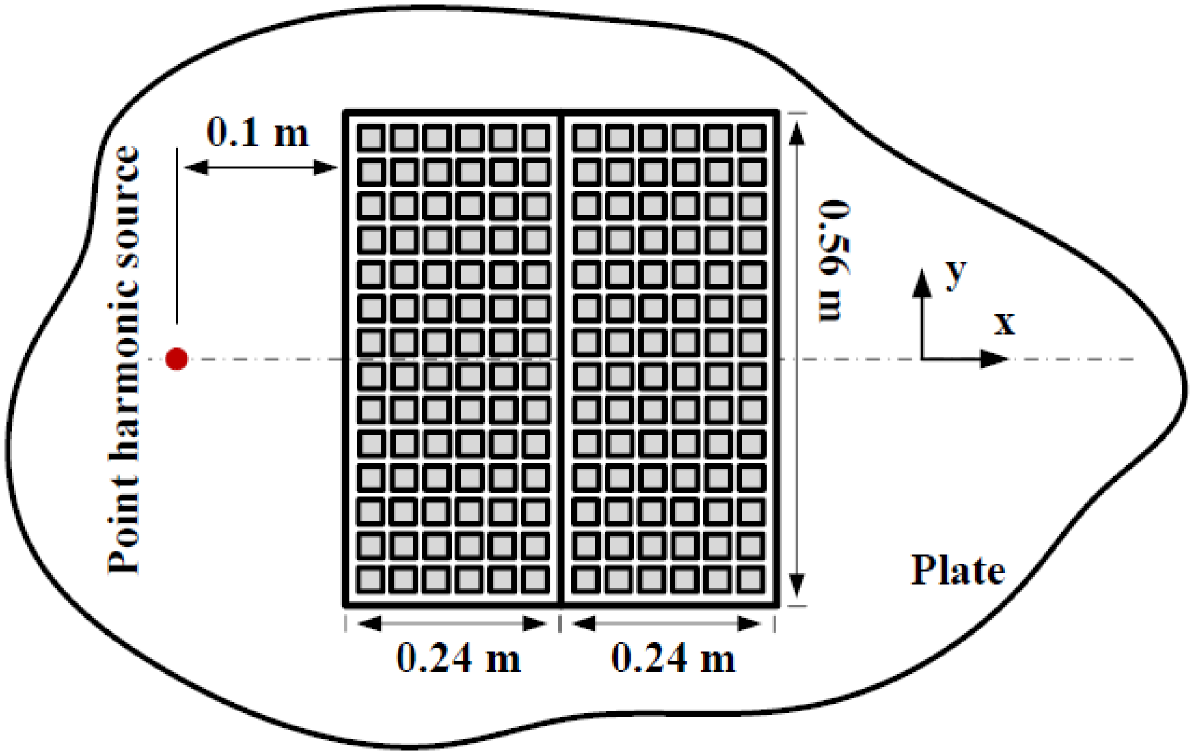
Gradient Index : Adaptive Lens



At 2000 Hz

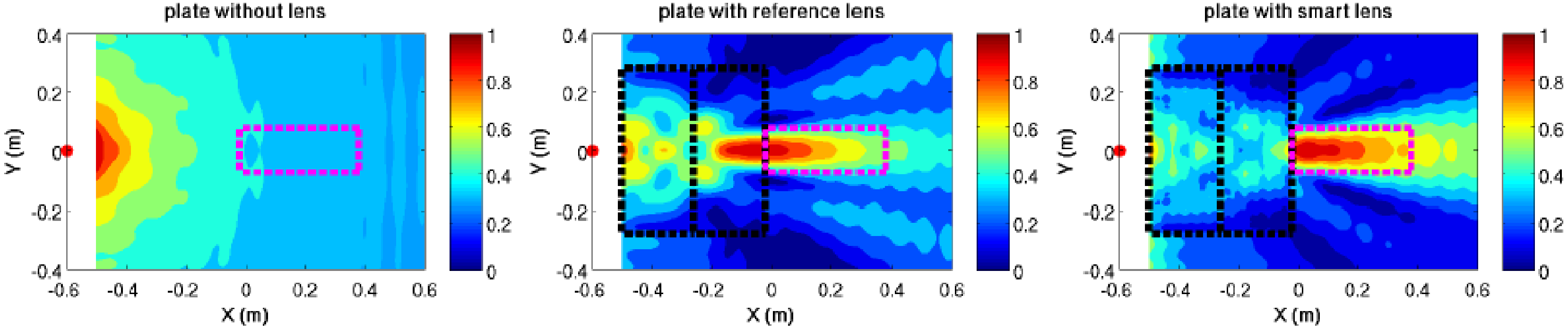
Double Lens configuration



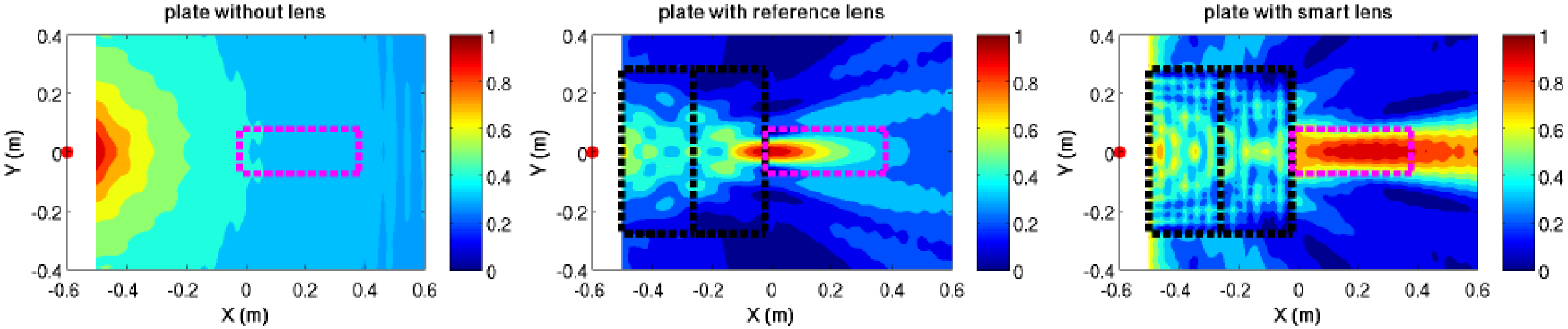


Gradient Index : Adaptive Lens

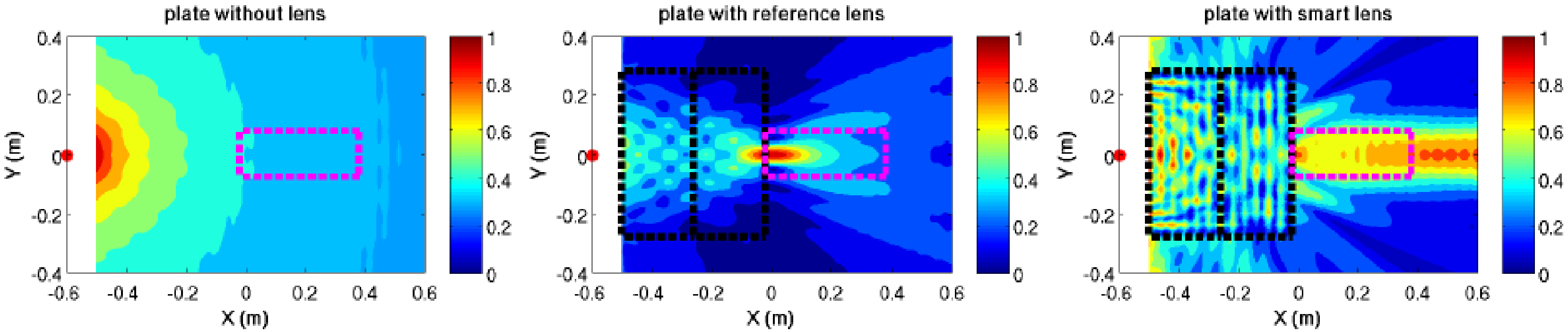
2000 Hz:



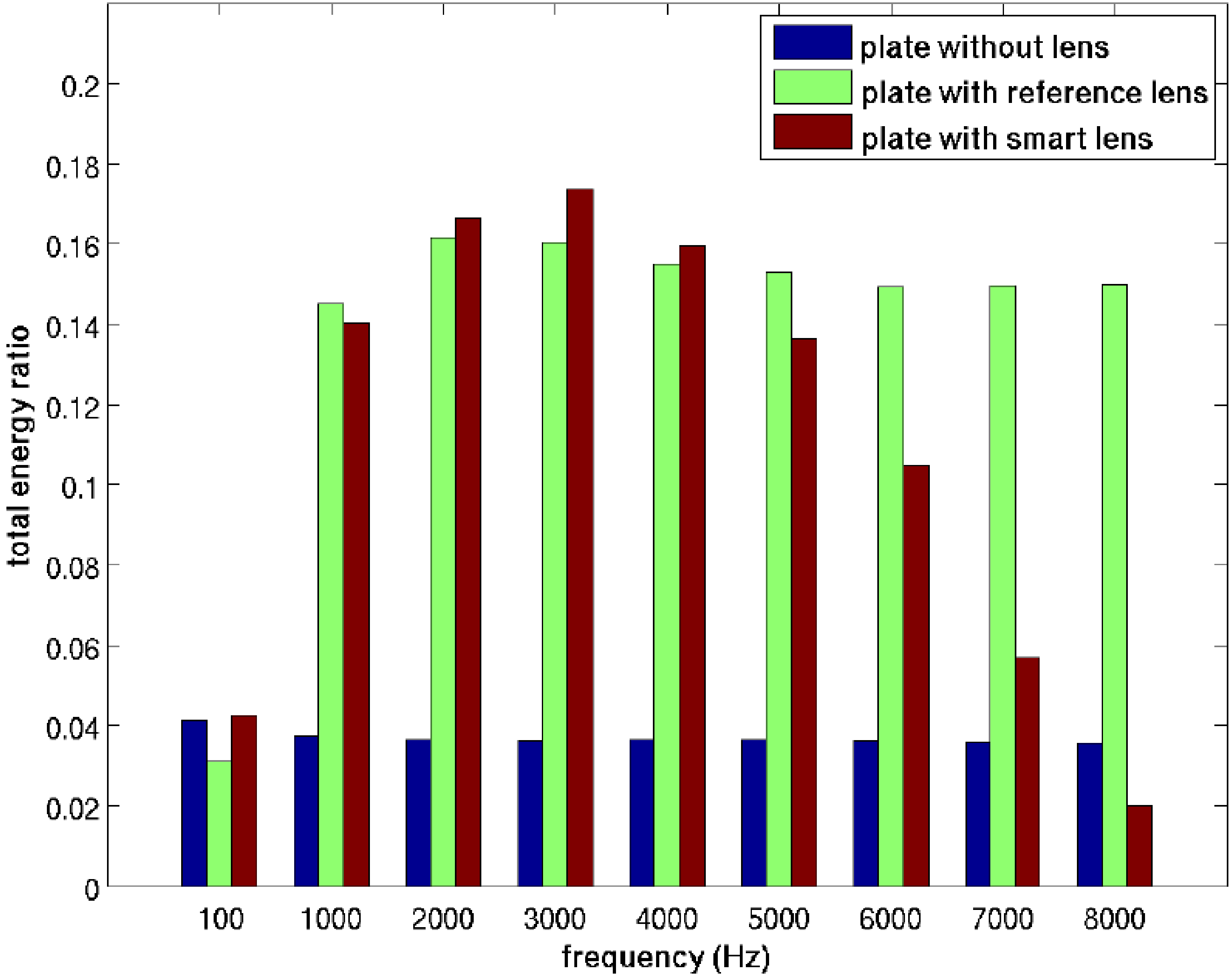
4000 Hz:



6000 Hz:



Gradient Index : Adaptive Lens



Conclusions

Concepts

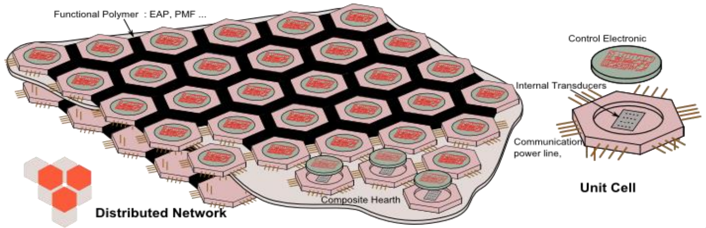
- **Periodic and Gradient** systems
- **Smart** individual cells (multifunctionnal, reconfigurable, adaptive…)
- **Integrated** systems
- **Global design strategy**

Results

- **metacomposite for 2D structural functions:**
  - ❑ **Mirror**
  - ❑ **Absorption**
  - ❑ **Focusing**
- **Impedance** optimization
- **Reconfigurable** concept
- Validation of the **smart interface** on finite structure
- **Practical** implementation
- **Experimental** validation

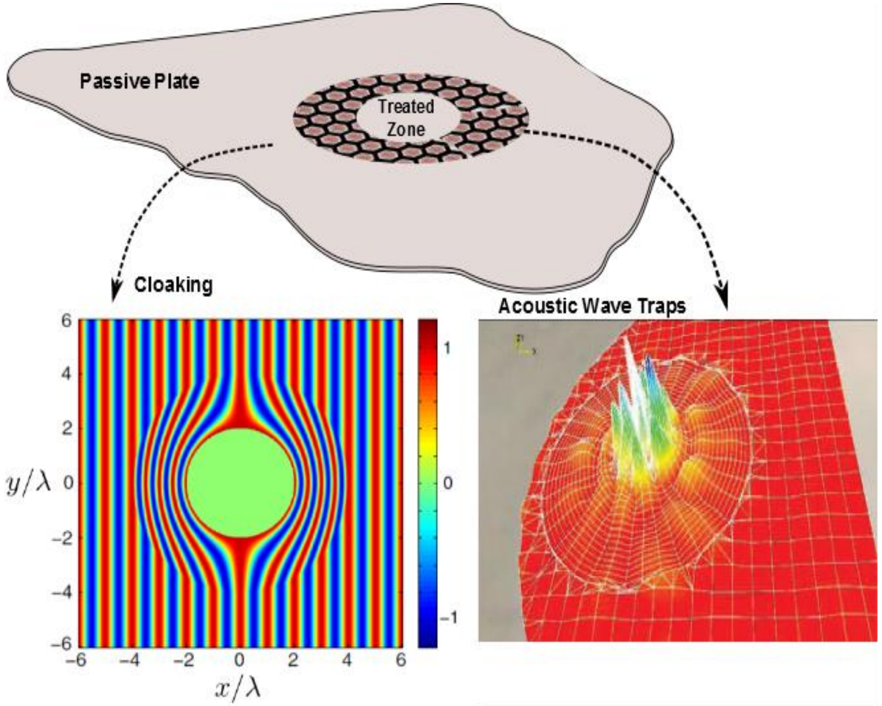
Future steps for the metacomposites

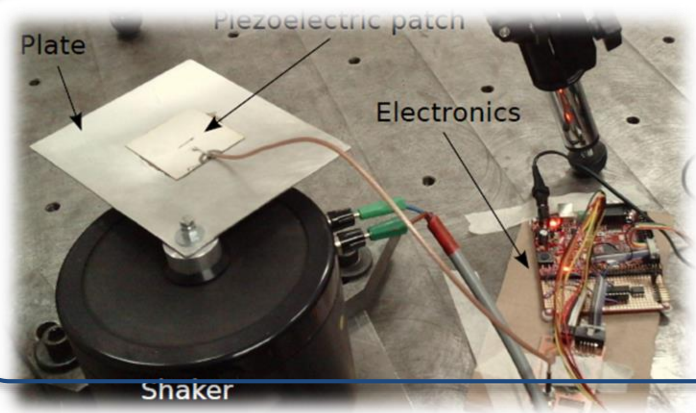
- Toward **fully integrated metacomposites**
- Combination of the concept with **DSP**:
  - Achieve **new functionnalities**
  - **Self reconfiguration**



Future functions for the metacomposites

- Multiscale Network modeling and optimization for **Cloaking** and **Wave traps** and **Non Linear waves**
- Associated Material programming network and algorithms
- Robust design tools
- Toward innovative, integrated and autonomous smart metacomposite for Vibroacoustics…





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

need more details?

M. Collet, M. Ouisse, F. Tateo
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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