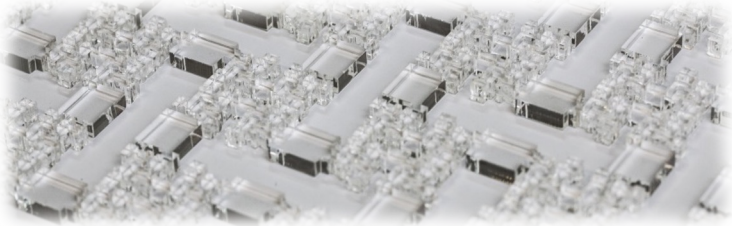
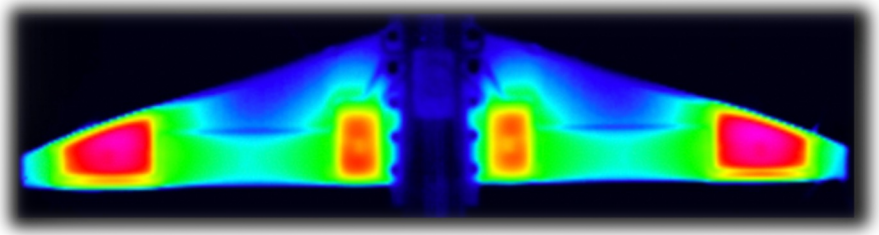
femto-st SCIENCES & TECHNOLOGIES

Adaptive Metamaterials for Vibration and Acoustic Control





Morvan OUISSE (FEMTO-ST)

ACKNOWLEDGEMENTS

CONTRIBUTORS & FUNDINGS

FEMTO-ST: Emmanuel FOLTETE, Gaël CHEVALLIER, Pauline BUTAUD, Emeline SADOULET-REBOUL,, Gaël MATTEN, Kaijun YI, Flaviano TATEO, Kévin BILLON, David RENAULT, Benoît VERDIN,

EPFL: Hervé LISSEK, Romain BOULANDET

GEORGIA TECH: Massimo RUZZENE

LTDS: Manuel COLLET, Sami KARKAR, Emanuele de BONO, Adrien PYSKIR, Kaijun YI

ANR
H2020
ITN
Labex ACTION
EUR EIPHI
Labex CELYA
Région Bourgogne Franche-Comté
SAFRAN
Stellantis

For sure, some are missing in my list. Apologies in case, just tell me and I will offer a drink!

CONTEXT

STRUCTURAL **LIGHTWEIGHTING**
ENVIRONMENTAL CONCERNS
COMFORT & SAFETY

SIZE & **MASS**
DAMPING CONTROL
STRUCTURAL **RELIABILITY**
ADAPTATIVITY

NEW VIBROACOUSTIC CONTROL STRATEGIES
PASSIVE, ADAPTATIVE, ACTIVE SOLUTIONS

PROGRAMMING STRUCTURES: **OPENING THE PATH TO NEW VIBROACOUSTIC BEHAVIORS**

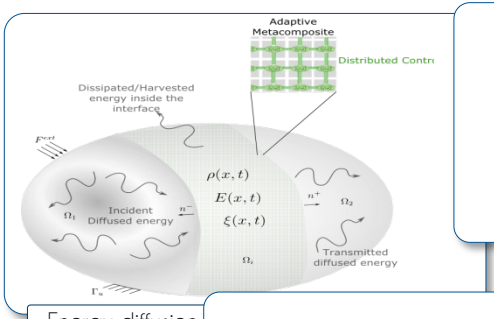




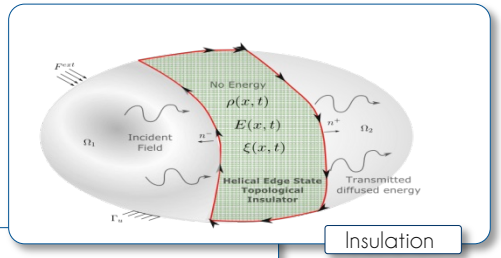
CONCEPT: CELLS ASSEMBLY

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

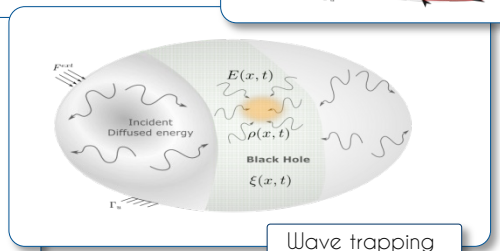
INTERFACE PROGRAMMING



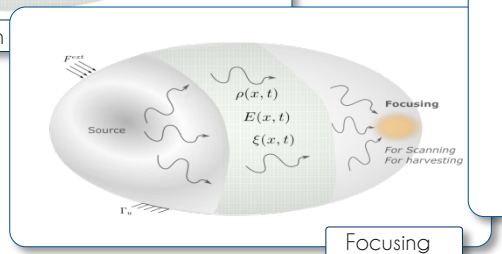
Energy diffusion



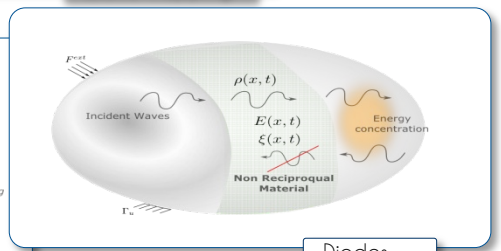
Insulation



Wave trapping

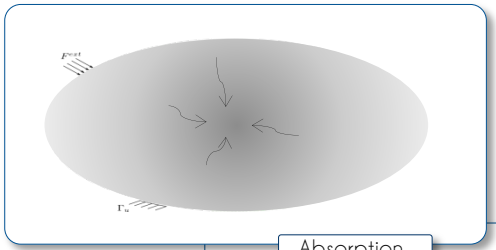


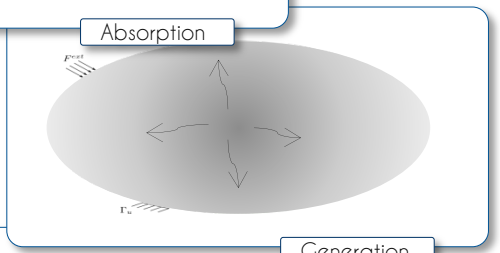
Focusing

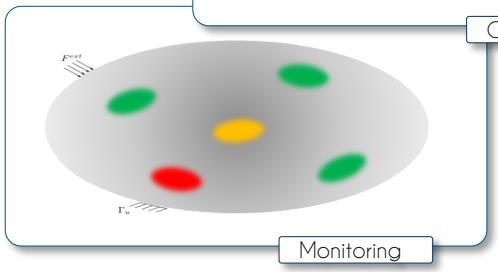


Diodes

INTERNAL PROGRAMMING

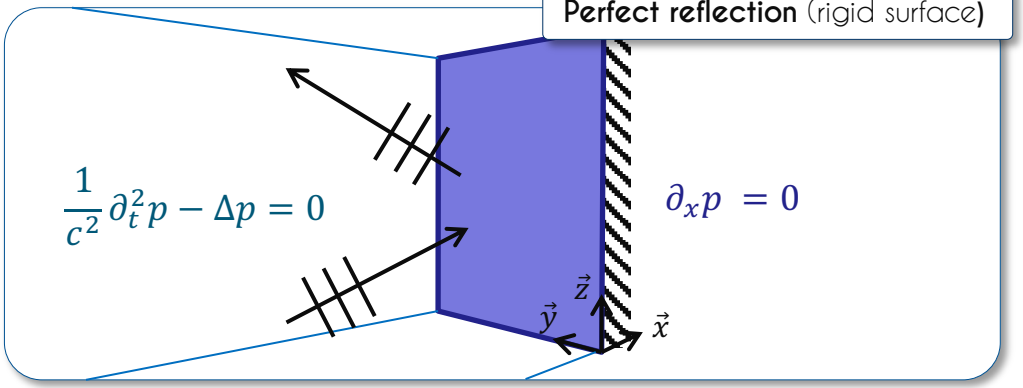

Absorption

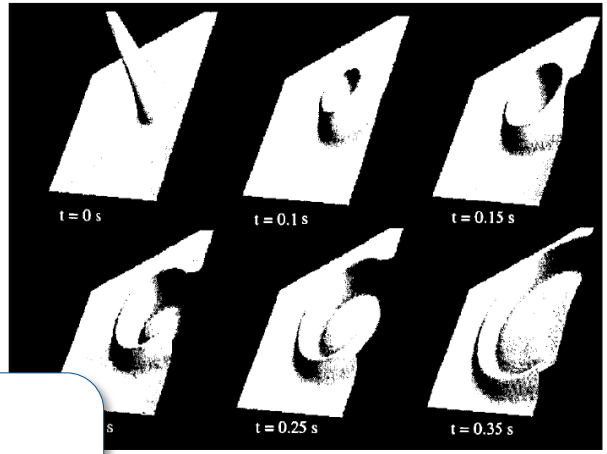

Generation

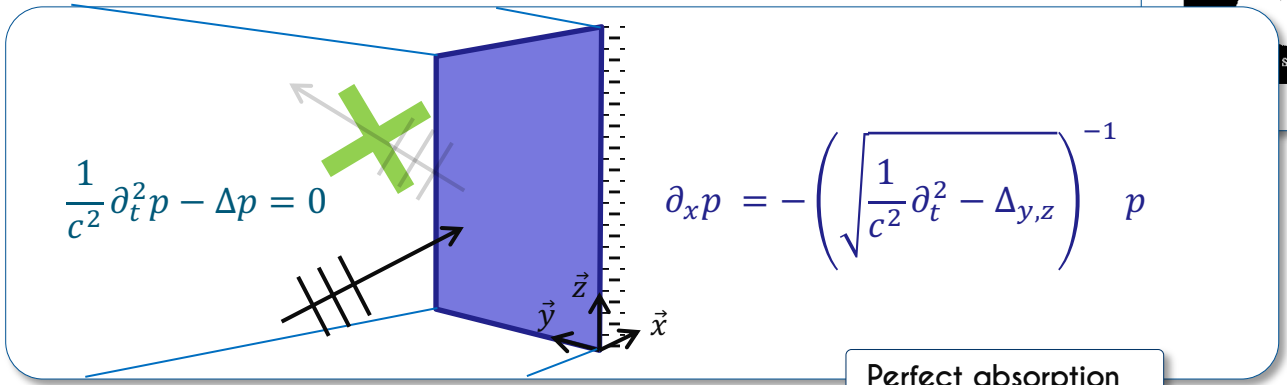

Monitoring

HOW TO REACH PERFECT ABSORPTION FOR ACOUSTIC WAVES IN 2D/3D?

Perfect reflection (rigid surface)







Perfect absorption

Also available for **1D structural vibrations**

How can we **realize** the **pseudo-derivative operator**?

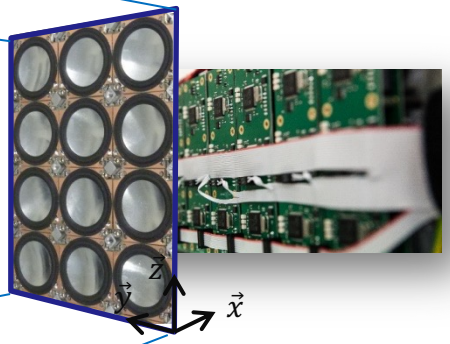
Montseny 2002

EXAMPLE

HOW TO REACH PERFECT ABSORPTION FOR ACOUSTIC WAVES IN 2D/3D?

Practical almost (?) perfect absorption

$$\frac{1}{c^2}\partial_t^2 p - \Delta p = 0$$

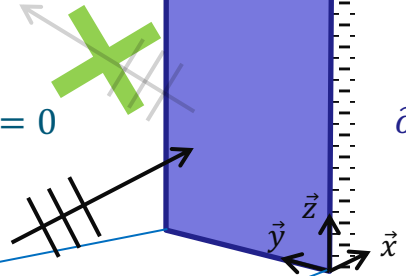


$$\tilde{\partial}_x p = -\left(\sqrt{\frac{1}{c^2}\tilde{\partial}_t^2 - \tilde{\Delta}_{y,z}}\right)^{-1} p$$

The ideal boundary condition is replaced by a **periodic distribution of unit cells** including **sensors**, **actuators** and **electronics**

What about **practical applications**?

$$\frac{1}{c^2}\partial_t^2 p - \Delta p = 0$$



$$\partial_x p = -\left(\sqrt{\frac{1}{c^2}\partial_t^2 - \Delta_{y,z}}\right)^{-1} p$$

Perfect absorption

Collet *et al.* J. Ac. Soc. of Am. 2009

HOW TO REACH PERFECT ABSORPTION FOR ACOUSTIC WAVES IN 2D/3D?

Practical implementation: local control of the acoustic impedance

- Mechanical dynamics of the SDOF piston mode (loudspeaker)

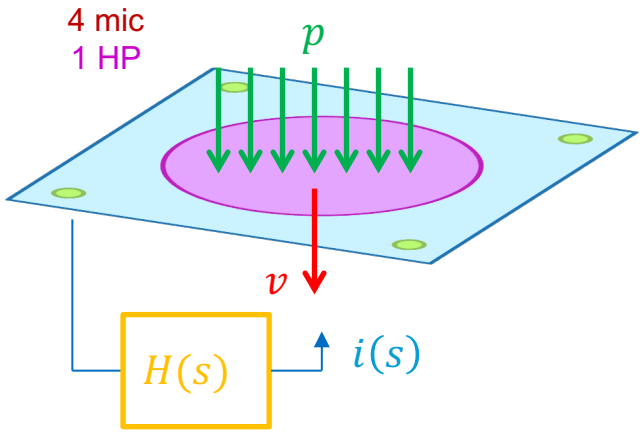
$$Z_m(s).v(s) = S_d.p(s) - Bl.i(s)$$

- Mechanical impedance (open-circuit)

$$Z_m(s) = sM + R + \frac{1}{sC}$$

- Transfer function (local control)

$$H(s) = \frac{i(s)}{p(s)} = \frac{1}{Bl}\left(S_d - \frac{Z_m(s)}{Z_c(s)}\right)$$



- Target impedance

$$Z_c(s) = \frac{p(s)}{v(s)} = \mu_1 \frac{sM}{S_d} + R_{at} + \mu_2 \frac{1}{sCS_d}$$

$$f_{eff} = f_0 \sqrt{\frac{\mu_2}{\mu_1}}$$

$\mu_1 = 0.7$

$\mu_2 = 0.26 \rightarrow 400\ Hz$
$\mu_2 = 0.5 \rightarrow 550\ Hz$
$\mu_2 = 0.7 \rightarrow 660\ Hz$
$\mu_2 = 1.03 \rightarrow 800\ Hz$
$\mu_2 = 1.61 \rightarrow 1000\ Hz$

EXAMPLE

HOW TO REACH PERFECT ABSORPTION FOR ACOUSTIC WAVES IN 2D/3D?

Practical implementation: non-local control of the acoustic impedance

- Mechanical dynamics of the SDOF piston mode (loudspeaker)

$$Z_m(s).\,v(s) = S_d.\,p(s) - Bl.\,i(s)$$

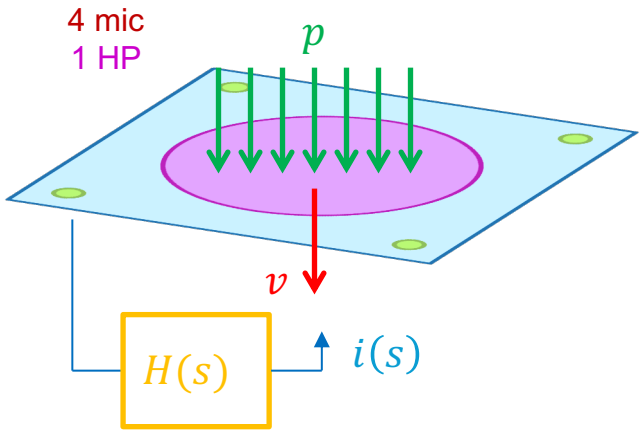
- Mechanical impedance (open-circuit)

$$Z_m(s) = sM + R + \frac{1}{sC}$$

- Transfer function (local control)

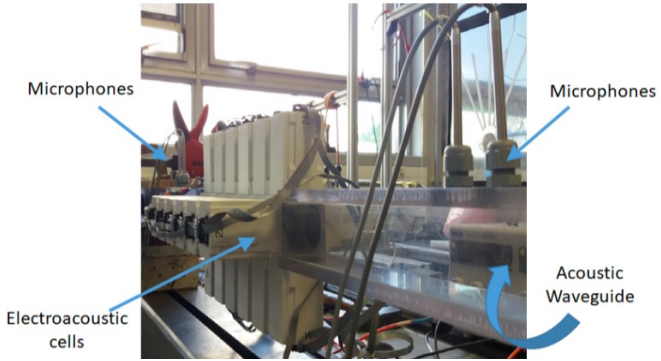
$$\frac{i(s)}{p(s)} = \frac{1}{Bl}\left(S_d - \frac{Z_m(s)}{Z_c(s)}\right) p(s) + \frac{Z_m(s)}{s\,Z_c(s)}\, c_a\, \frac{\Delta p(s)}{\Delta t}$$

Non reciprocal term

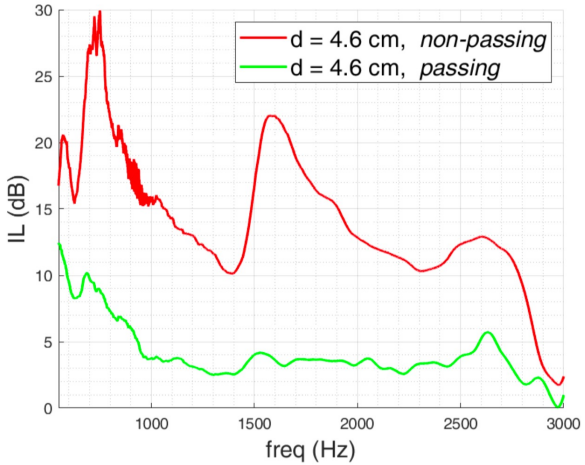


1D VALIDATION: ACOUSTIC DIODE

1D distribution of unit cells

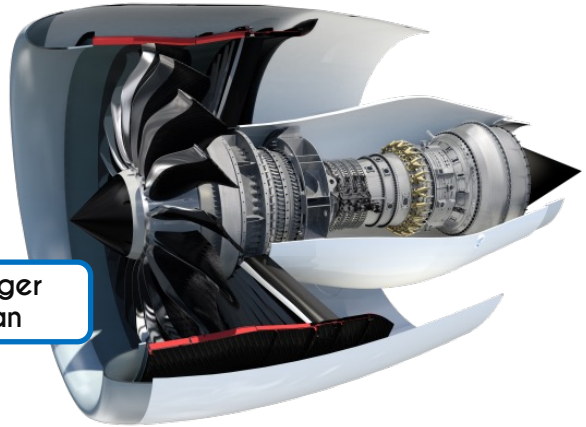


Experimental evidence



TOWARD NACELLE INTEGRATION

Ultra-high bypass ratios (UHBR) turbofan engines



Larger Fan

Less space for acoustic liners

Next generation acoustic treatments?

driven by

Fuel consumption

Shorter Nacelle

More low-frequency components

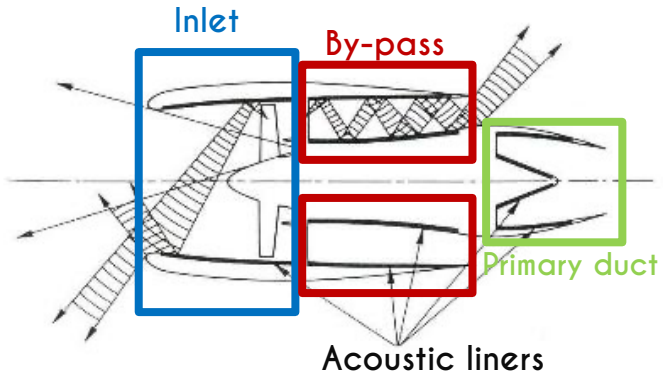
Performance with limited surfaces

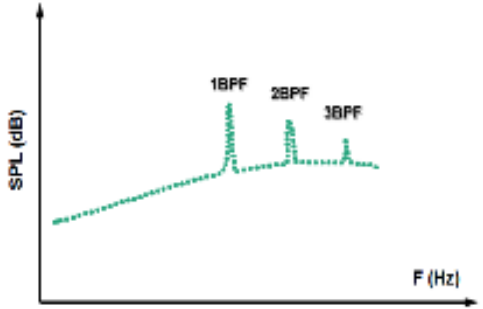
Break the quarter-wavelength rule

Full 3D circumferential geometries

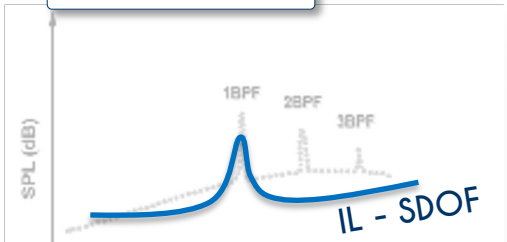
Challenges

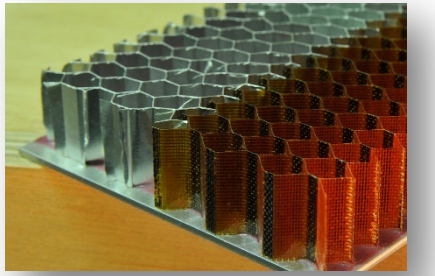
TOWARD NACELLE INTEGRATION

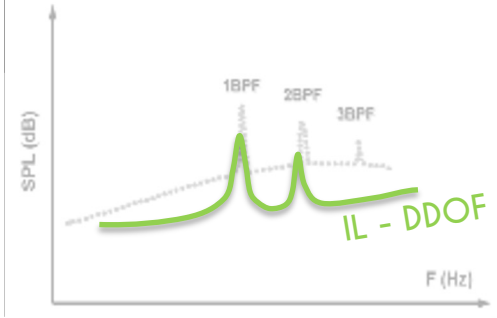


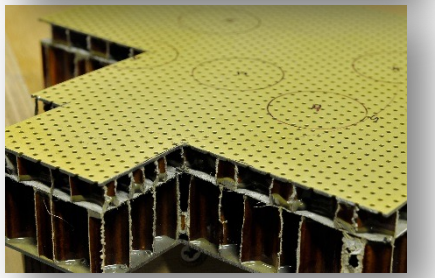


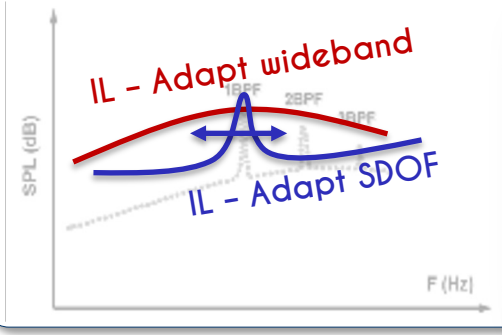
Passive solutions

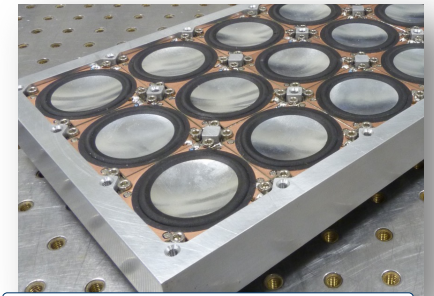








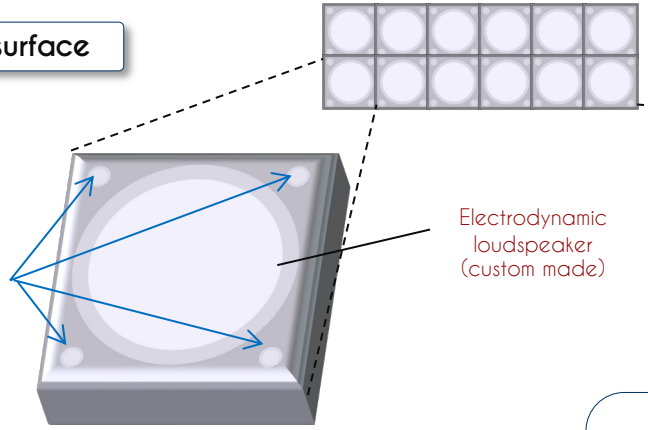




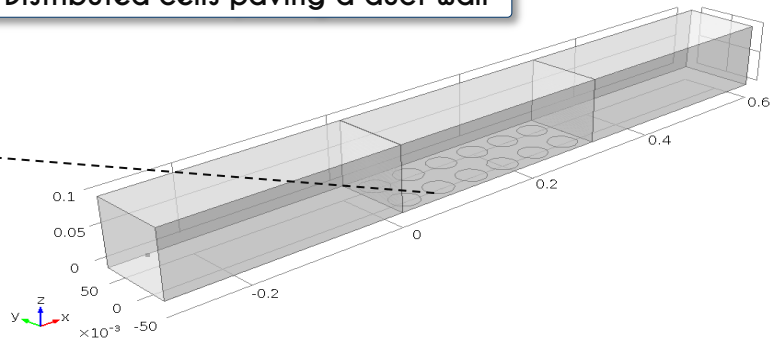
Adaptive distributed skin

TOWARD NACELLE INTEGRATION

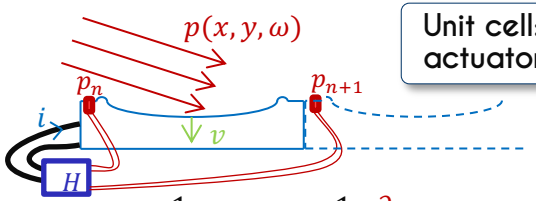
Adaptive metasurface



Distributed cells paving a duct wall

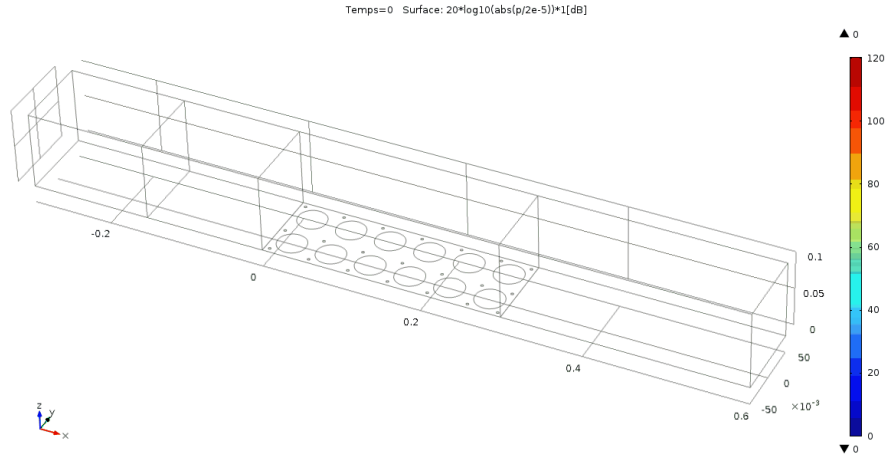


Unit cell: sensor, actuator, electronics

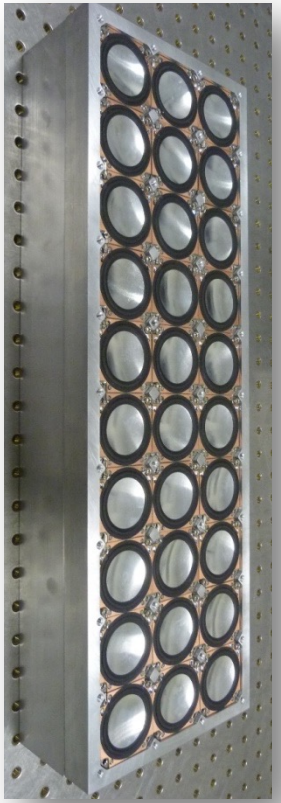


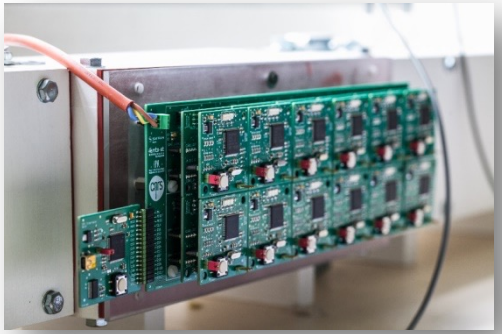
$$v(\omega) = \frac{1}{\rho c_a} p(\omega) - \frac{1}{j\omega\rho} \frac{\partial p}{\partial x}(\omega)$$

Simulation results

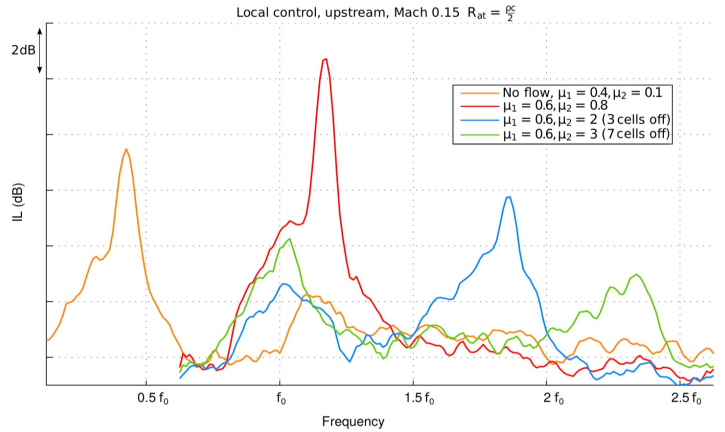


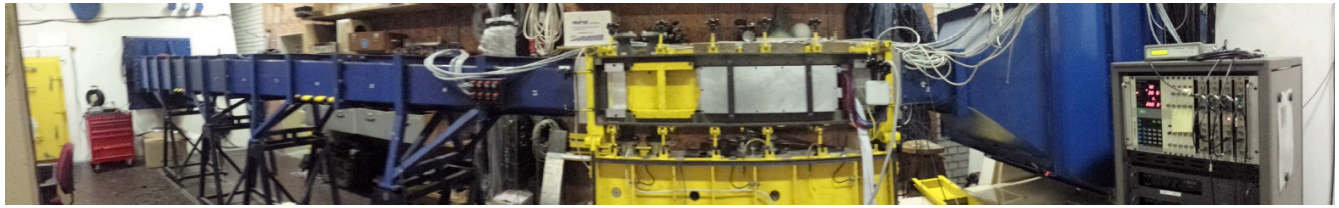
TOWARD NACELLE INTEGRATION





Experimental results

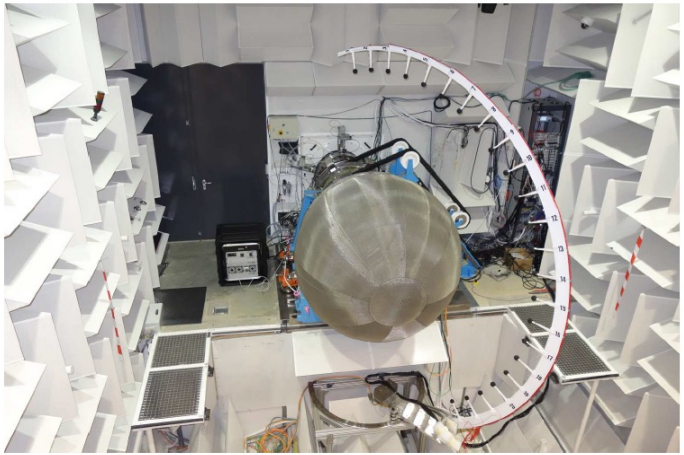


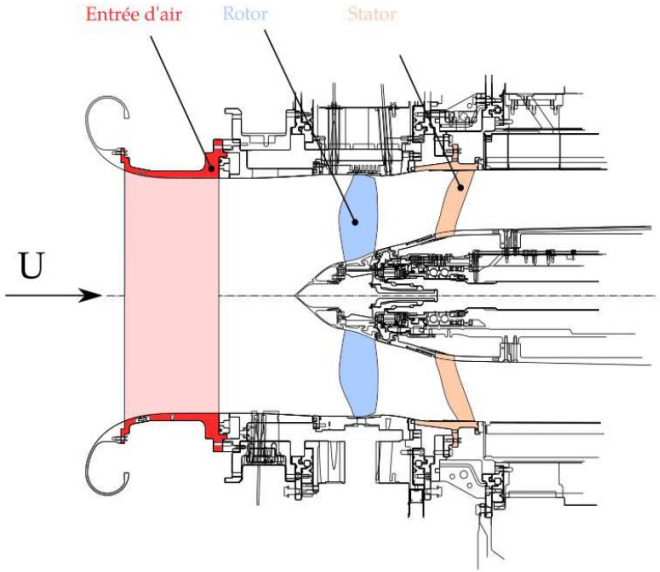


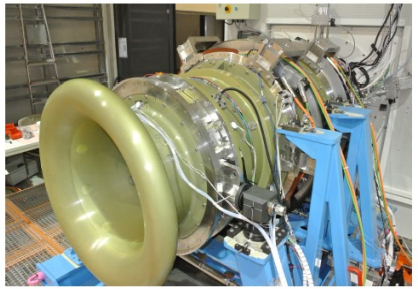
Performances measured at NLR acoustic liners test facilities, 10/2016 (flow / M 0.3 amp.)

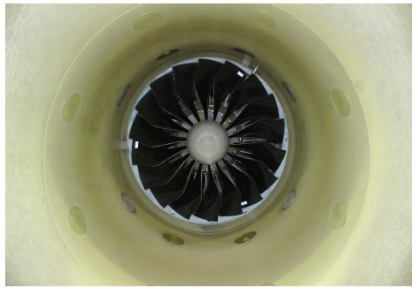
Boulandet *et al.* J. Sound Vib. 2018

PHARE: A TESTBENCH DEDICATED TO ACOUSTIC LINERS CHARACTERIZATION





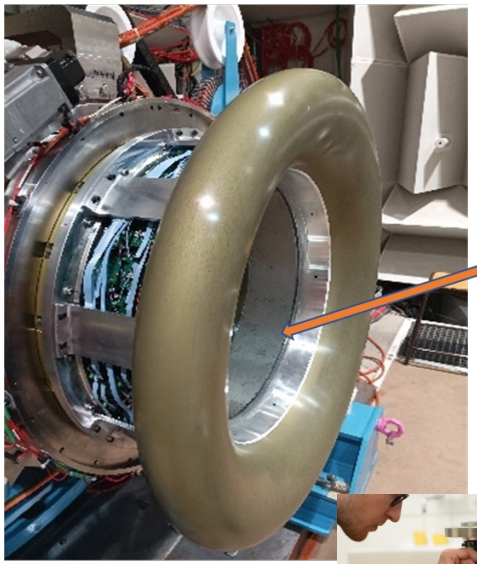


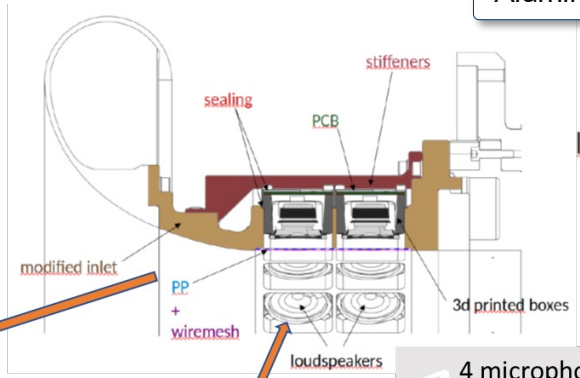


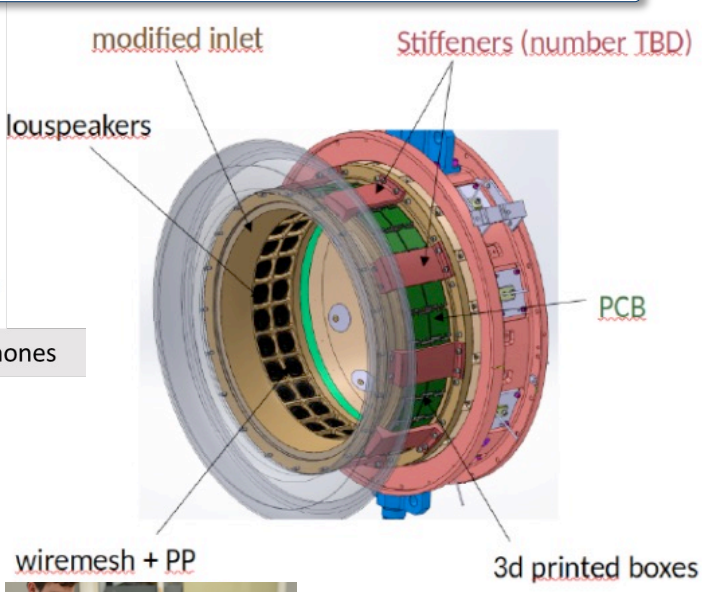
- PHARE-2 / ECL-B3 test-rig at Ecole Centrale de Lyon, LMFA.
  - test-rig is instrumented using 176 microphones.
  - upstream measurement using the external microphone array of 27 microphones.

THE ACTIVE LINER

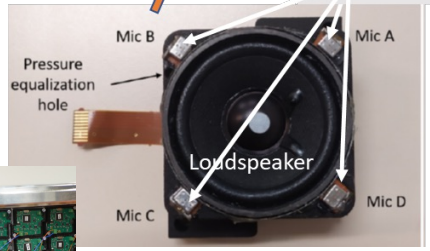
Aluminum frame, 2x28 cells, covered by a wiremesh

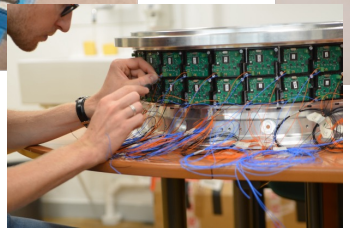


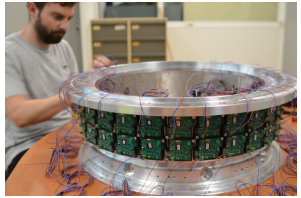




4 microphones







Clean Sky 2

SALUTE
Smart Acoustic Lining

This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement N°821093

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LTDS Laboratoire de Tribologie et Dynamique des Systèmes
EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
SAFRAN

THE ACTIVE LINER

Preliminary results (submitted for publication)

Insertion Loss - Liner tunability: IL vs. engine order

SALUTE
Smart Acoustic Lining

Clean Sky 2

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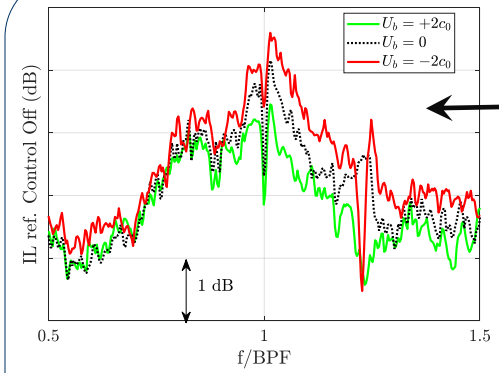
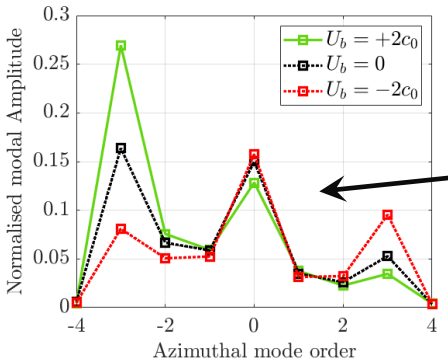
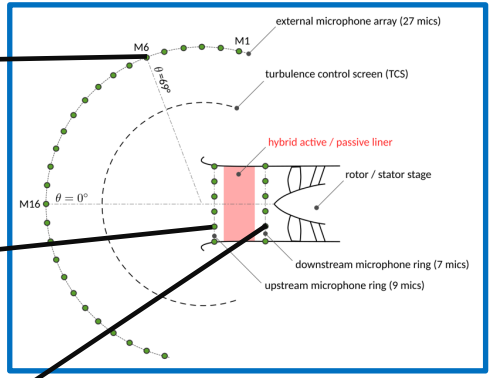
SAFRAN

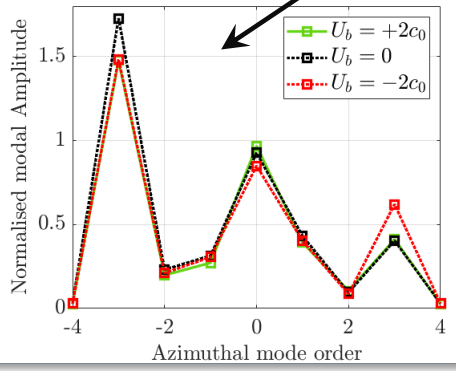
THE ACTIVE LINER

Preliminary results (submitted for publication)



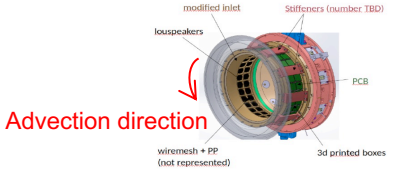






Non-reciprocity confirmed

Improved performances wrt local impedance control.



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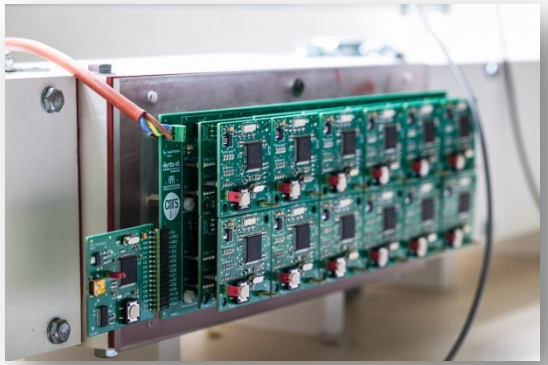
EXTENSION TO VIBRATION CONTROL?

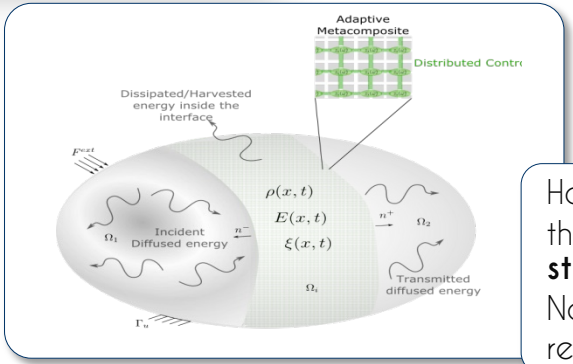


Acoustic control

Fully integrated active control system
Same thickness as **passive solutions**
Higher IL performances (pics & wideband)
Ability to **track** main components of spectrum
Fully **reconfigurable**: open access to DSPs
Harware-in-the-loop possibilities

Based on **a priori known** interface behavior law

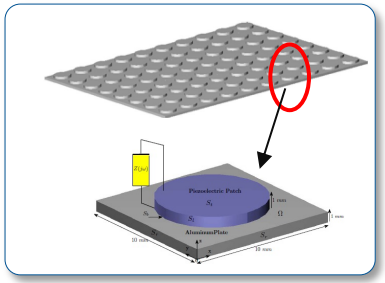
$$\partial_x p = -\left(\sqrt{\frac{1}{c^2}\partial_t^2 - \Delta_{y,z}}\right)^{-1} p$$

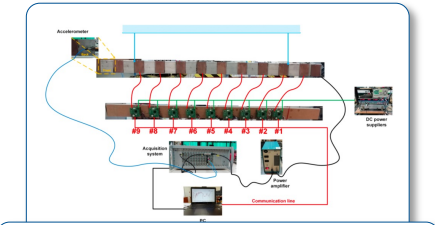


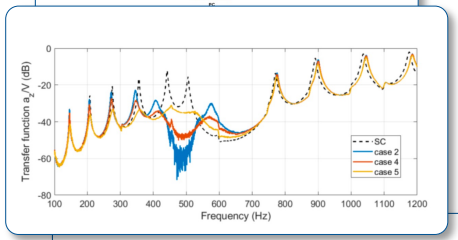
How can we extend the concept to **structural vibrations?**
No explicit law for real-life structures…

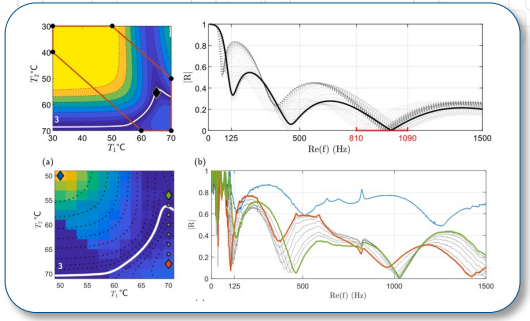
Use **advanced tools** to **optimize** the (multiphysics) **unit cell of the interface** to reach **optimal functionalities**

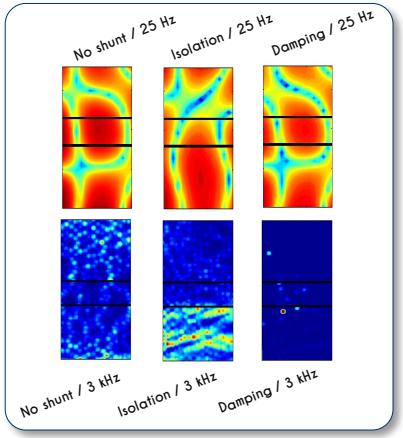
VIBRATION CONTROL: ADAPTIVE SYSTEMS FOR ADVANCED FUNCTIONALITIES

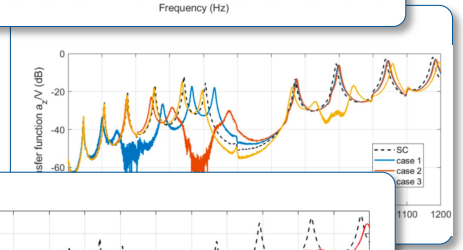


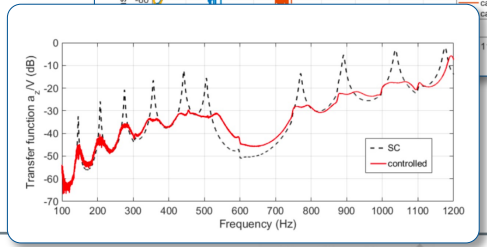


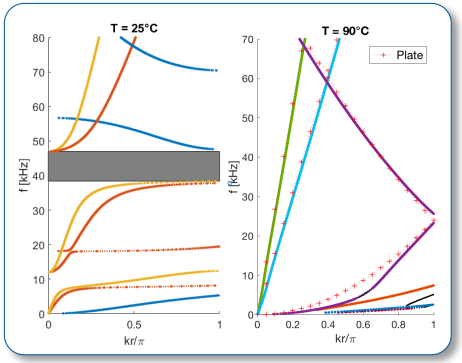


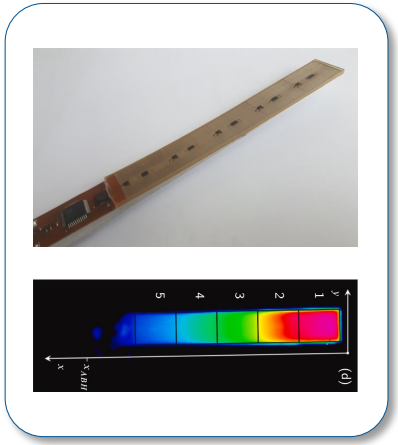






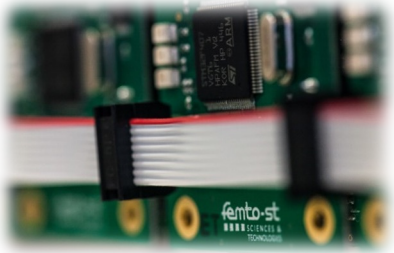


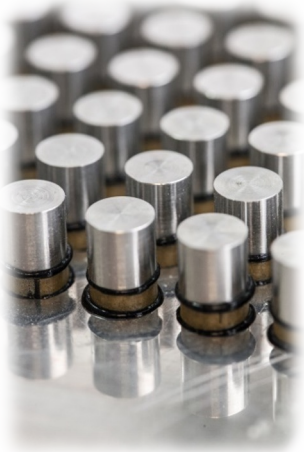


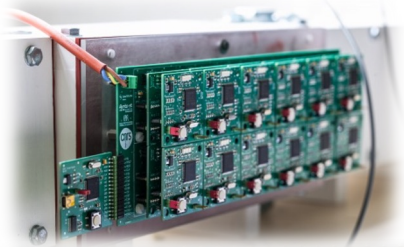


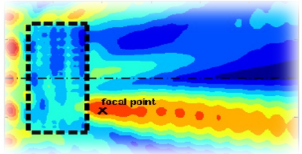
THANK YOU

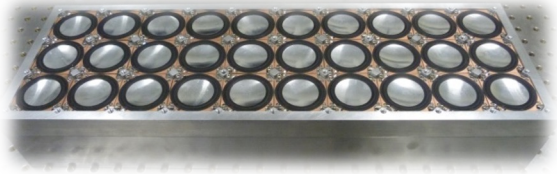
CONCLUSIONS

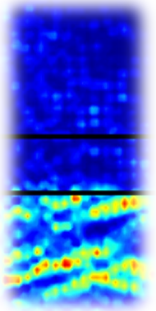


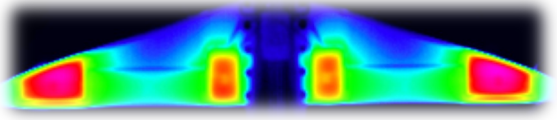












Structural programming: a new paradigm to provide novel functionnalities to structures

Mathematical, physical & technological challenges

Taking advantage of **smart materials & structures** to **control energy propagation**

Key point: **distributing the systems** at the **heart of the matter**

Points not addressed in this talk but that may be discussed:

- **low energy consumption** compared to classical active control strategies
- **very high robustness**
- **real time adaptability**

WANT MORE?

- **Come and see me for additional discussions**
- All publications accessible at https://members.femto-st.fr/morvan-ouisse/ or https://scholar.google.com/citations?user=3VPRDFsAAAAJ

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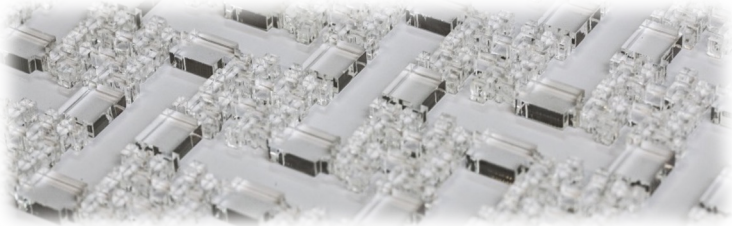
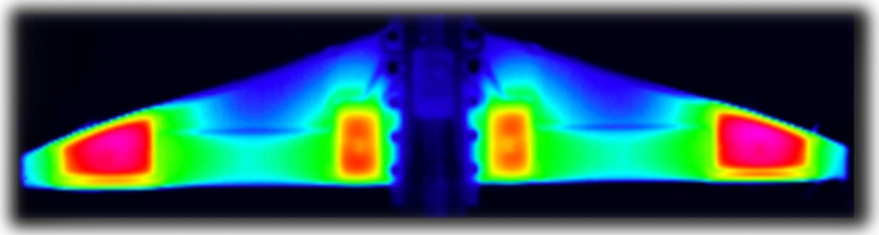
Adaptive Metamaterials for Vibration and Acoustic Control





Morvan OUISSE (FEMTO-ST)