Adaptive Metacomposites: Material Programming for Vibroacoustic Control

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Summary: Research activities in smart materials and structures are very important today and represent a significant potential for technological innovation in mechanics and electronics. The growing interest of our society in the problem of sustainable development motivates a broad research effort for optimizing mechanical structures in order to obtain new functional properties such as noise reduction, comfort enhancement, durability, decreased ecologic impact, etc. In order to realize such a multi-objective design, new methods are now available which allow active transducers and their driving electronics to be directly integrated into otherwise passive structures. This new concept could allow fine control of the material physical behaviour to induce new functional properties that do not exist in nature and that cannot be introduced by passive approaches. In this sense, we can speak of "integrated distributed adaptive metacomposites" that merges with the notion of programmable material. Through two different examples dealing with active acoustical impedance and elastodynamical interface, this paper present used theoretical tools for designing specific applications of this new technology.

Keywords: Adaptive Control, Distributed Control, Mechatronic, Composite.

1. Introduction

Constant research for developing new materials better adapted for more efficient human applications, incorporating more and more new constraints such as the environmental damage (environmental impact, noise, recycling ...) led to study a new class of artificial multifunctional composite materials: the Metamaterials. These new materials presenting specific physical properties due to their micro or nano structuring, were originally developed to synthesize new electromagnetic permittivity indices or negative permeability [1]. But in recent years, new research efforts have shown that the concepts could be transcribed in other areas of physics such as acoustics, mechanics or even robotics [2][3]. Thus, the realization of new structured materials has led to obtain very interesting new physical features that can lead to the design of integrated multi-functional structures capable of controlling their shape, vibrations [4] or distribution of acoustic and/or photonics energy [5,1]. Mainly based on achievement of periodic structures at different scales, the experimental realizations are essentially passive and cannot be adapted in time.

In recent years, the technological revolution observed in the areas of Micro Electro Mechanical Systems can deeply extend the spectrum of future development of adaptive structures. One can now imagine full integration of hybrid systems consisting of adaptive materials, electronics, computing resources and power systems. The next generation of composite structures called "smart metacomposite" should take full advantage of these technological advances for optimizing their behaviour [6]. This new technology should lead to new relevant applications for noise and/or vibration control, for achieving integrated surface actuators or achieving micro-acousto-optic devices for adaptive applications in telecommunications and health monitoring of structures...

The use of integrated and periodically distributed active (or hybrid) systems of transduction could allow fine control of the material physical behaviour to induce new functional properties that do not exist in nature and that cannot be introduced by passive approaches. In this sense, we can speak of "integrated distributed adaptive metacomposites" conform to the notion of programmable material [7]. This new approach represents a new challenge for creating intelligent hybrid materials.

This paper aims at showing two examples of such new metacomposites for controlling acoustic and mechanical power flow. In the first part, the concept of active acoustical skin is introduced and experimental validation is carried out. The second part deals with smart mechanical interfaces for controlling absorption and transmission of elastodynamical energy.

2. Active acoustic skin: metacomposite for impedance control

2.1. Introduction

This part presents the acoustical capabilities of a network of distributed transducers connected with suitable controlling strategy integrated as adaptive metacomposite for controlling acoustical impedance. The theoretical active skin can be depicted as a distributed interface in which a suitable control operator imposes the skin displacement as a function of the measured parietal pressure as presented in Figure 1. The objective of the proposed strategy is to cancel positive group velocity of acoustic wave propagating in interaction with the metacomposite. Thus all incoming waves intercepting the smart liner only transport energy in the negative (Ox) direction and became evanescent for the positive (Ox) component of the wave number.

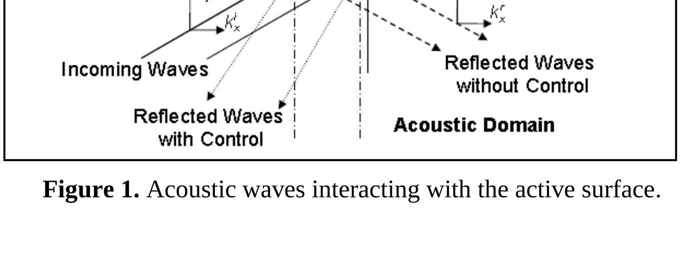

Figure 1. Acoustic waves interacting with the active surface.

2.2. Technological Integration of the acoustic adaptive metacomposite

The control strategy based on partial differential equations (PDE) is obtained by using suitable mathematical tools and appears as an advection equation [6]. The theoretical implementation is validated for annihilating positive reflection of 2D acoustic waves. Its stability and robustness margins are also described in [8].

To experimentally implement the method, the control strategy is discretized as a first order time-space operator. The obtained quasicollocated architecture, composed of a large number of sensors and actuators, provides high robustness and stability. The proposed system is made of a periodically distributed set of active cells including one loudspeaker, one microphone and a DSP and conditioning electronics components as depicted in Figure 2 [9]. The system is also implemented as an active liner in which all individual cells compute the local loudspeaker control signal by using pressure measurement coming from adjacent ones. Two identical control devices have been built, each composed of 4x12 cells, giving (9x36) cm^2 of active surface as shown in Figure 2.

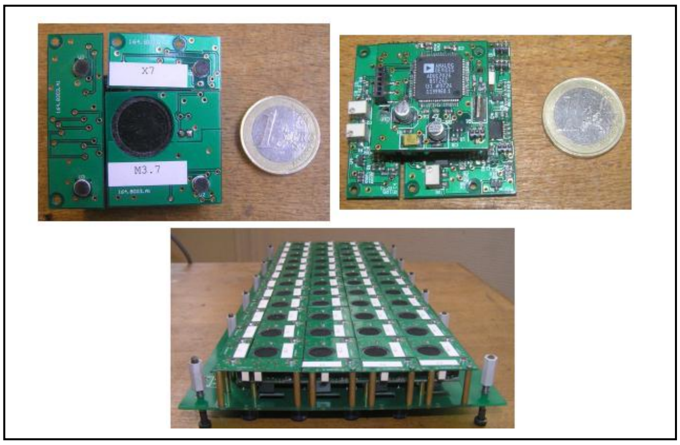

Figure 2. Individual active acoustic cells and general view of the realized liner made of 4x12 cells.

2.3. Experimental characterization

The experimental set-up is composed of a chipboard tube with rectangular cross-section, audio amplifier with source loudspeaker on the input, two devices with active surface and non-reflecting acoustic termination on the output. General view of the measurement device is presented in Figure 3.

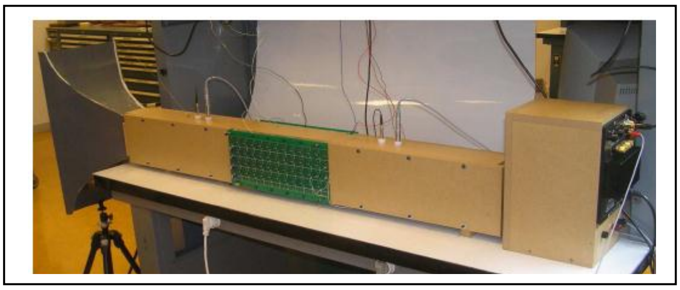

Figure 3. Acoustic waves interacting with the active surface.

The experimental results are plotted in Figure 4. The obtained pressure transfer functions between right and left part of the active acoustical skin with and without control show up how the realized active liner made of metacomposite can substantially modify sound reflectivity of the acoustical interface and reduce the propagation of acoustic waves outside the duct. The induced transmissibility is decreased of about 30 dB at the maximum efficiency. The efficient frequency band of the active system is situated between 800 Hz and 1.5 kHz. The first cutting frequency is induced by the loudspeaker dynamic while the second comes from the computational time of cell's DSP for computing the distributed command.

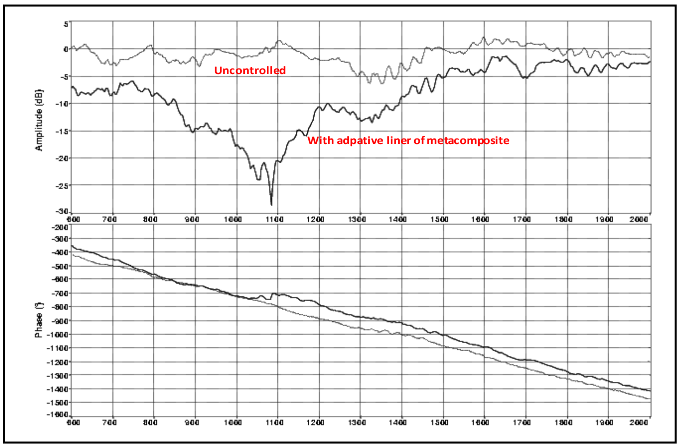

Figure 4. Transfer function between the input and output microphone,—active surfaces with control; · without control.

2.4. Conclusion

We have designed individual cells with an integrated microcontroller, sensor and actuator, power supply, signal amplification and conditioning, and especially the possibility of interconnection of many such cells in the area network, a so-called adaptive liner based on metacomposite. The metacomposite has a great merit of being very effective and allows an important attenuation of the acoustic transfer without the necessity of very strong displacements of the membrane interfaces [9]. It is thus possible to use this technique with transducers produced on a silicon base with thin deposits of PZT layers as actuator elements. The proposed method appears also to be suitable for use with distributed MEMS transducers to reduce noise in large frequency band.

3. Smart mechanical metacomposite: how to control absorption and transmission of elastodynamical energy

3.1. Introduction

The concept of metacomposite is adapted here to the control of energy flow in 2D elastodynamical wave guides. The proposed metacomposite appears as an application of periodic structures theories usually connected to metamaterial and vibration control by shunted piezoelectric smart materials. Both concepts are employed to design adaptive metacomposite with controlled behaviour.

Specific numerical approaches for modelling and optimizing 2D smart metacomposites have been developed [10,11]. The proposed methodologies are based on the Floquet-Bloch theorem in the context of elastodynamic including distributed shunted piezoelectric patches [10]. Indicators allowing the optimization of the shunt impedance for specific performance objectives are presented.

3.2. The studied metacomposite

The considered metacomposite is made of piezocomposite cells connected to specific electrical impedance (Figure 5). The supporting plate material is standard aluminium with 0.1 % of hysteretic damping ratio and the piezoelectric material is PZT 2.

The developed numerical tools [10] allow the optimization of the piezoelectric shunt impedance Z(ω). The first criterion is used to enhance the metacomposite capability for decreasing structural energy transmission. It is based on the minimization of the flexural wave energy velocities [10]. The second criterion improves wave's absorption. It is based on the computation of the dissipated electrical energy into the electrical shunt [10].

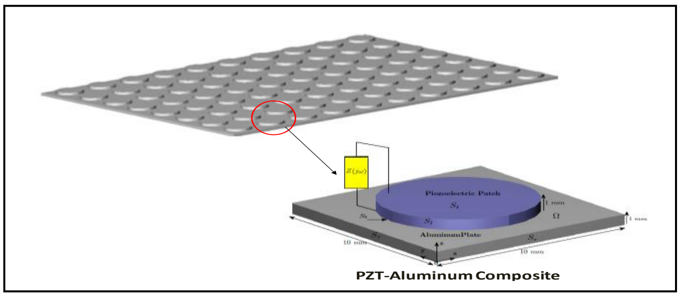

Figure 5. Metacomposite made of piezocomposite cells.

3.3. Energy propagation with optimal impedance

Dispersion curves obtained with open shunt circuit and optimal impedances controlling transmission and absorption are plotted in Figure 6. We observe a deep modification of A0 mode when transmission is controlled on the left part of Figure 6. The corresponding energy velocity is also largely decreased and such metacomposite appears as an energy barrier for flow carried by mechanical bending movement. Absorption optimisation does not lead to the same behaviour. We do not observe energy transmission cancellation (dispersion curves of propagative modes are not modified) but only a strong increase of the waves decay rates (i.e the ratio between real and imaginary parts of the complex wave numbers).

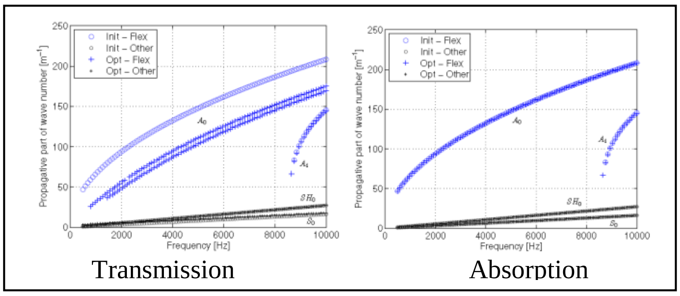

Figure 6. Propagative parts of the wave number kx along (Ox), (only propagating waves included). o: initial value of shunt; +: optimal value of shunt. Large marks correspond to flexural waves, small marks correspond to other waves.

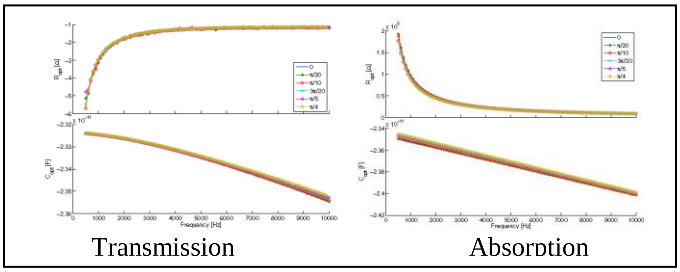

Figure 7. Optimal electric impedance, represented as equivalent resistances and capacitances, obtained along 6 direction forming an angle with (Ox) axis of n20 with n being all integers.

The corresponding optimal impedances are plotted in Figure 7. We immediately observe that both criteria lead to connect quasi constant negative capacitance for adjusting the reactive part of the electrical impedance to the mechanical one. When transmission is targeted, the optimal resistance (the active part) is negative in order to control the natural dissipative term added into the model and lead the system to a fully conservative one. For absorption, the resistance is positive to damped waves into the periodic metacomposite.

4. Conclusion

In this paper, we present designs and characterizations of two applications of integrated metacomposites made of periodically arranged adaptive cells for controlling vibroacoustique power flow in air and in structure. This study provides methodologies to optimize electromechanical behaviour of metacomposites for 2-3 D wave guides application. The main purpose of this work was first to present the dedicated numerical approaches suitable to compute and optimize the multi-modal wave dispersions or interface impedance. Experimental applications highlight the real potentialities of such technology for controlling complex vibroacoustic interaction by demonstrating its robustness and efficiency.

Such concept can be extended to different functionalities like shape control or new generation of smart and integrated Structural Health Monitoring systems that can be used of prognostics. These extensions are one of the main aims of ACTION project established at FEMTO-ST institute.

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