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Synthetic impedance for adaptive piezoelectric metacomposite

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Abstract

The ongoing improvements in the size and in the power of micro-controllers allow to implement real-time computations of digital filters or control laws. With audio dedicated components, it becomes easier to integrate the control of piezoelectric transducers directly inside structures with discretized feedback controllers. It paves the way to more intelligent systems with adaptive capabilities. Through the z-transform, the behavior of an electrical impedance or of a controller can be written as a recurrent equation directly computable by a micro-controller. Yet the signals are sampled and quantified and it is necessary to run the computations at least twice as fast as the higher frequency f the controlled structure. The delay induced by the computations and the conversion of the signals has to be taken into account to insure the stability of the control. Finally, the type of computation (fixed or floating point) can be a technological problem. This paper highlights the experimental implementation of integrated controlled structures with regards to the technological constraints

1. Introduction

1.1. Background

A need to lighten mechanical structures has been expressed for many years by the aviation and the space industries. Indeed, both environmental and economic concerns led to a necessary reduction of fuel consumption. If great improvements have been made on the engine design and the aerodynamic of plane and rockets, it is the development of light composite materials that created a breakthrough in the structures weight reduction and so in a decrease in the fuel consumption.

But if these new materials are lighter, they also are stiffer and do not damp the vibration as much as former materials would have done. It is an issue for the comfort of the airline passengers exposed to acoustics emissions but also a challenge for the space industry because of the payload damage hazard.

1.2. Vibration suppression

Appeared in the late seventies[1][2], a solution based on piezoelectric transducers has been proposed[3]. By choosing wisely the location of the transducers, it is possible to damp vibrations in a chosen frequency band or to

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suppress some structure resonance modes. A technique consists in affixing thin piezoelectric patches (see Figure 1) on the structure to be controlled and to electrically shunt it with an impedance. This solution is passive as no external energy is required[4].

  By doing so, the piezoelectric coupling is changed as is the mechanical behavior of the structure. This technique is convenient because the transducer is both a sensor and an actuator but with a reduced weight compared to a standard sensor/controller/actuator system. The piezoelectric transducer can be modeled by a voltage source in series with a capacitance. With the shunt, the global system can be seen as a filter or a feedback controller. Three type of shunt can be found in literature[5–9]:

- Resistive shunt
- Resonant shunt
- Negative capacitance shunt

Resistive and resonant shunts are efficient but not on a broadband of frequencies. On the other hand the negative capacitance has been proven to be efficient from a few hundreds up to a few thousand kHz

While some resistive and the resonant shunts can be made with passive components (coil, resistor, …), high inductance and negative capacitance involve the use active components into a circuit that simulates the behavior of negative capacitance. The system is no more passive but semi-active in that sense that the external energy is used only to feed the passive-like circuit but not to directly inject energy in the structure.
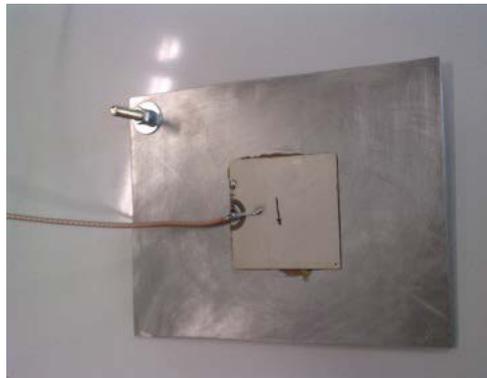
Fig. 1. 50x50mm piezoelectric transducer on an aluminium plate.

2. Digital implementation of the shunt

2.1. Introduction

  In the context of smart systems and intelligent structures, the shunted piezoelectric patches are ideal for integration into the materials because of their small thickness. However once the fabrication is over, any modification of the shunt impossible. As explained in the introduction, the resonant and resistive shunt can be made with passive components such as resistors and coils. But the negative capacitance shunt requires operational amplifiers. In that case, it is necessary to tune the resistors to change the equivalent negative capacitance. It is experimentally done with potentiometers. It can be a solution for systems where a small number of transducers is required but not for distributed systems with dozens of piezoelectric patches.

  To cope with tuning issues and to create real time interaction between a user and a controlled system, a programmable shunt is necessary[10]. That is why a digital design with user-interaction capabilities is proposed.

2.2. Architecture

  Creating an equivalent electrical impedance with a circuit comes to insure a relationship between the current flowing through the transducer and the voltage between its two electrodes. This relationship is computed by a micro-controller with a recurrent equation. It is possible to drive the current in the circuit depending on the voltage between the electrodes or the opposite. For practical reasons, it is easier to drive the current and measure the voltage. The operating cycle of the design circuit is given on Figure 2. The system operates in four steps:

- Measure the voltage using an ADC (Analog to Digital Converter),
- Calculate the current that should flow in the circuit with a micro-controller,
- Generate a voltage image of the current with a DAC (Digital to Analog Converter)
- Drive the current with a voltage/current converter
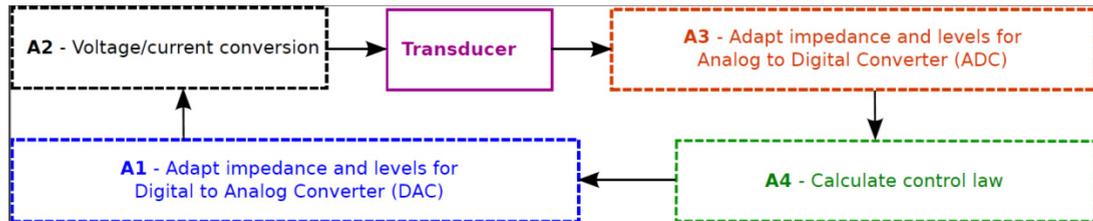
Fig. 2. Global architecture of the system.

The objective is to control vibrations in the audible frequency band that is to say up to 20 kHz. According to the Shannon theory the signals must sampled at least 40 kHz. The circuit is based on a micro-controller that embeds a 12 bits analog to digital converter (ADC) and digital to analog converter (DAC). By calculating the current to be driven as a function of the voltage between the electrodes of the transducer, the shunt behavior can be chosen. Given the bandwidth, the control is executed at 96 kHz, as commonly used in audio applications. An antialiasing filter is added before the ADC to cut frequencies above the maximum frequency of the system. Here, a first order low pass filter with a 20 kHz cutoff frequency has been used.

But the piezoelectric effect can lead to high voltages, alternatively positive and negative and the micro-controller cannot handle such signals so it is necessary to adapt the levels of the signals to maintain the measured voltage between 0 and 3.3V. A dedicated card (see Figure 5) has been designed to drive the current (block A2 of) in the circuit and to shift and attenuate the voltage between the two electrodes (blocks A31 to A35 of Figure 3).

Moreover the voltage between the two electrodes is saturated to +/- 30V with Zener diodes to protect the electronics.
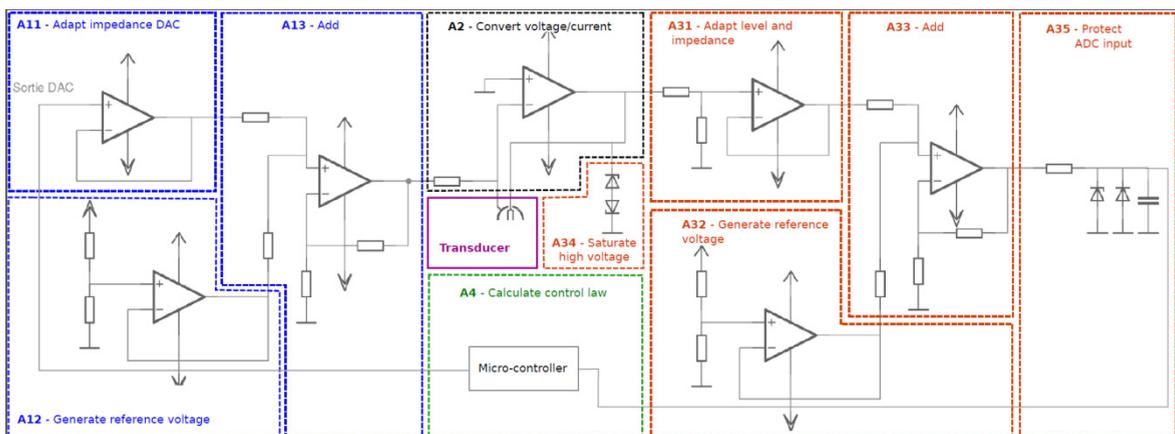
Fig. 3. Detailed architecture of the system.
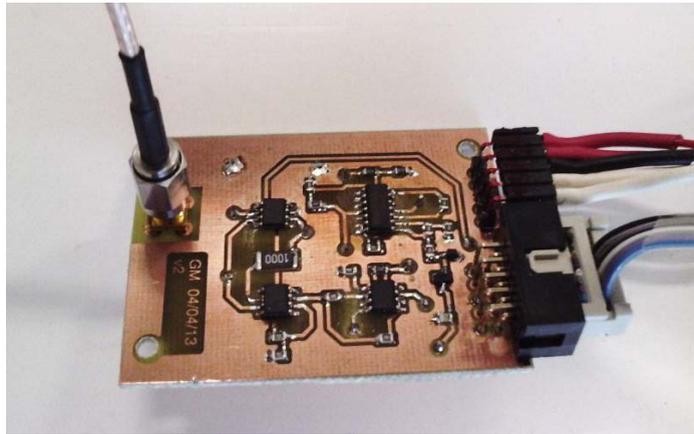
Fig. 4. Power interface.

3. Experimentation

3.1. Objective

The objective of the experiment is to validate the digital implementation of the shunt. As shown on Figure 5, an aluminum plate is controlled by a P189 piezoelectric 50x50mm patch. A shaker applies a white noise on the lower left corner of the plate and a laser vibrometer measure the speed response on the upper right corner. By doing so, the maximums of amplitude appear at the eigen frequencies of the plate. For this experiment, a simple resistive shunt has been implemented, the driven current being proportional to the measured voltage at the terminals of the transducer. A digital acquisition chain generates the white noise that is then amplified and applied on the plate by the shaker. The analog output of the vibrometer and the generated white noise are then analyzed. The frequency response function is extracted by the acquisition chain that runs a fast Fourier transformation.

3.2. Results

The Figure 6 shows the results for a resistive shunt with different values. With the current implementation, the values R1 and R2 are not the resistance of the shunt but are proportional to it. Due to the geometry of the plate and the location of the transducer, all the modes cannot be controlled. The Figure 6 highlights the damping of particular mode, with almost 8 dB attenuation in the speed at the upper right corner of the plate. The parameters of the shunt are modified through a serial RS232 bus.

The delay between the input and the output of the shunt has been measured and is about a sampling step. The power of the full system is up to 1W depending on the implemented shunt. For now the system is based on a development board of the micro-controller and a power adaptation card has been designed. A unique card including both the digital and the analog power electronics should have the same dimension as the piezoelectric patch.
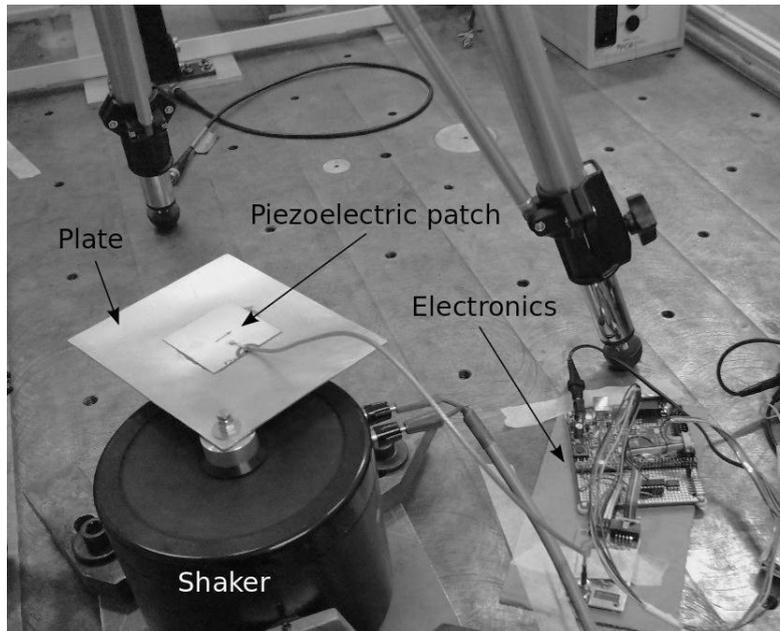
Fig. 5. Experimental set-up.
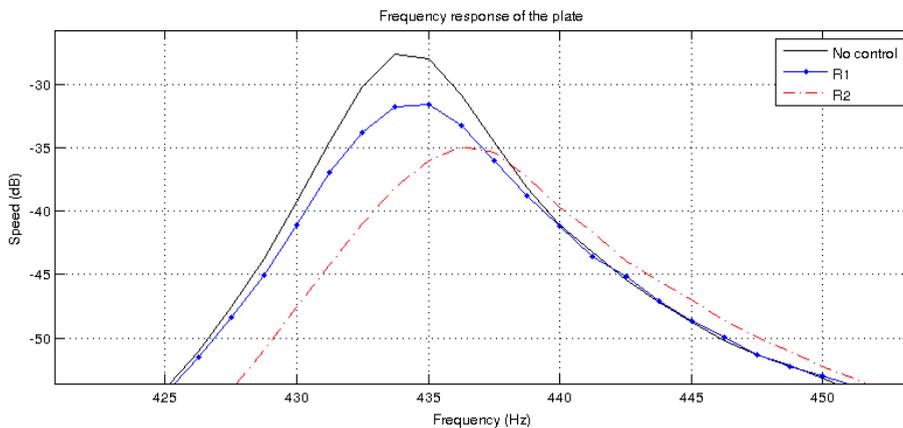
Fig. 6. Resonance attenuation with a resistive digital shunt.

4. Conclusions and perspectives

The system presented in this paper is a digital tunable synthetic impedance for shunting piezoelectric transducers. Vibration suppression using thin patch of piezoelectric materials showed its efficiency, although the tuning of has a strong influence on the damping efficiency of the system. With the design presented in this paper, the parameters of the control can be modified online through a serial bus. The resistive shunt has been successfully implemented and tested but the digital negative capacitance circuit did not show the same efficiency as the analog one. The performances of this synthetic impedance should be improved with dedicated audio components.

At last, the programmable shunt paves the way to large distributed remotely tuned systems and to the implementation of auto-adaptive strategies.

Acknowledgements

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