# FIBERS-BASED COMPOSITE STRUCTURES WITH INTEGRATED PIEZO-CERAMICS

## DESIGN APPROACH OF SMART DEVICES

T. Dessolier[1] , R. Lachat[1] and Y. Meyer[1*]

[1]IRTES-M3M, UTBM, 90010 Belfort Cedex, France
Email: thibault.dessolier@utbm.fr, remy.lachat@utbm.fr

[*]Corresponding author's email :
yann.meyer@utbm.fr

## ABSTRACT

*Currently, in different industrial fields as transport or aerospace, a research effort is lead concerning structural weight reduction. One of the most promising solutions is the use of composite structures and, in particular, the fibers-based composite structures. In the same time, there is an intensification of the operational dynamic environment and an increase of durability requirements. One way to manage this point is to design and manufacture adaptive composite structures. To integrate new functionalities inside mechanical structures, it is necessary to develop a real fully distributed set of transducers and to include them at the heart of composite materials that is to say during the manufacturing process.*

*In this paper, a design approach based on engineering system theory is developed for fibers-based composite structures including several piezoceramic transducers, electrically independent. These structures are manufactured in our laboratory. Several characterization needs are identified so as to well-design these complex structures. An experimental non-destructive procedure based on the analysis of anti-resonance and resonance frequencies of the transducers is proposed for determining the initial material coefficients of interest. Moreover, an experimental process is identified to obtain the global mechanical parameters of the fibers-based composites we produced.*

# 1 INTRODUCTION

Currently, in different industrial fields as transport or aerospace, a research effort is lead concerning structural weight lightening [1, 2]. One of the most promising solutions is the use of composite structures [3] and, in particular, the fibers-based composite structures [4], due to their high stiffness, their low mass density and their low damping factor. In the same time, there is an intensification of the operational dynamic environment and an increase of durability requirements [5]. These different expectations seem to be contradictory. One way to manage this point is to design and manufacture integrated smart composite structures. These structures have to be able to modify their mechanical properties with respect to their environment (e.g. active vibration control), to interact with other structures (e.g. mechatronic) or with human beings (e.g. fatigue management).

To integrate new functionalities inside mechanical structures (in particular, for large structures) for active vibration control, mechatronic, energy harvesting or fatigue management, it is necessary to develop a real fully distributed set of transducers and to include them at the heart of composite materials that is to say during the manufacturing process. To reach this goal, it is absolutely necessary to limit the cost of the numerous transducing elements, the electric connections or the control tests with respect to the global system cost and, in the same time, to well-know the electromechanical behavior of the smart structure in order to well-design the system controller. The classical approach using an identification process applied to the final structures is not relevant for large distributed transducers networks or for mass production.

The paper is organized as follows. Section 2 gives the technical requirements to design and manufacture adaptive composite structures. The core elements for all the smart structures are listed. The specific requirements due to the approach selected are detailled. The design approach is introduced in section 3. In section 4, the experimental characterization needs, essential for the design step, are presented. Two set of results are given for the characterization of piezoceramics and of an in-house glass fibers-based material. Finally, concluding remarks are discussed.

# 2 TECHNICAL REQUIREMENTS

## 2.1 Core elements

To design an adaptive mechanical structure, some elements are essential. First of all, transducers have to be implemented. Different physical principles can be used. In our laboratory, the developments are based on the use of piezoelectric transducers. Their main advantage is their large operating frequency range. It can be compatible with the automotive applications ([6 Hz 250 Hz]) or with the equipments for aircraft ([6 Hz 3000 Hz]). A controller and a control strategy have to be selected. Basically, there are two main possible choices: a centralized controller and a decentralized controller. In a centralized control strategy, one electric component is designated as the master controller. It creates the actuators input signal by using the sensors signals and so it is responsible for managing the actuators. In a decentralized control strategy, the paradigm is different. The sensor output signal is locally managed by a component and the control signal is only injected on the actuators close to this sensor. The local behavior modifications allow to obtain an overall controlled behavior. A control electronics is also needed. Electrical conductors are necessary to connect all the tranducers, electrically independent, with the control electronics and the electric power supply. Of course, all the added elements have to allow the manufacturing of planar or specific shaped structures with a limited thickness modification.

### 2.2 Approach developed

Conventionally, the transducers, in particular the piezoelectric ones, are glued onto the structure to be controlled and the electronics is located out of the structure. Our approach is significantly different. We wish to design, build and optimize composite structures based on matter fibers with a large distributed and integrated piezoceramic network. The idea is to protect the transducing elements and their electric connections and to industrially develop end products in plug-and-play mode. Furthermore, the integration of transducing elements at the heart of the material is the first step to develop, through the integration of micro and nano structures, programmable or controllable matter.

To integrate these new functionalities at the heart of composite structures (in particular, for large structures), it is necessary to develop a real fully distributed set of transducers and to include them during the manufacturing process. To reach this goal, several major constraints and manufacturing requirements were identified. It is necessary to:

- *Electrically connect a large number of transducers* so as to act on the whole structure.
- *Make electrically-independent each transducer.* This is a particular issue for the development of carbon fibers-based composite structures which are naturally conductive.
- *Limit the thickness variations due to the piezoelectric inclusions.* These inclusions inside the material will inevitably modify locally the thickness of the structure. This fact may be limited by the use of thin piezoceramics (about 200 $\mu$m). However, the electric connection by conventional welding is not possible because of the resulting overthickness. A special connection technique was specifically developed.
- *Achieve specific shaped structures* (for instance, bi-concave structures) so as to adapt to a wide range of applications (for instance, the vibration control of a car fender or the vibration isolation of an aeronautical launcher cap).

To address these constraints and requirements, a manufacturing specific method has been developed. In particular, this method uses the composite manufacturing features either by infusion technique, used in particular to manufacture large structures, or by the RTM (Resin Transfer Moulding) technique, used to manufacture mechanical parts with tight tolerances. Examples of structures manufactured in our laboratory with these processes are depicted in figures 1, 2, 3 and 4.

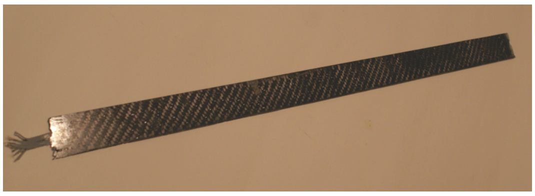

Figure 1: Beam manufactured with carbon fibers including four piezoceramic transducers

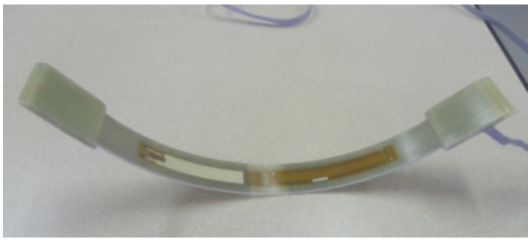

Figure 2: Curved beam manufactured with glass fibers including two PVDF transducers and two MFC transducers

## 3 DESIGN APPROACH

The development of the manufacturing process is still ongoing. In parallel, a design approach is also developed. Of course, the idea is to be able to design these complex structures that is

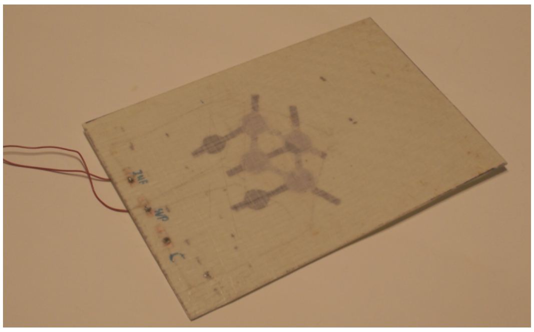

Figure 3: Plate manufactured with glass fibers including eight piezoceramic transducers

Figure 4: Kart center fairing manufactured with vegetale fibers including nine piezoceramic transducers

to say to be able to predict the final behavior of the structure in a predesign step. For this, the system engineering tools are exploited. First of all, the Product Breakdown Structure (PBS) is built. A simplified version of this PBS is given in figure 5. The product is broken down in sub-systems and in components. This process is iterative and is repeated for different depth levels. This process is stopped when the components are indivisible, are commercial off-the-shelf components or can be designed by only one development team in the project team. Once the down tree obtained, it is necessary to establish the system architecture. The different elements of the product tree are organized with respect to their interfaces. Thus, the interfaces between the components are defined. The major issue of a complex system design is not the individual design of the components, in general managed by one project team. The major issue is to design the components interacting with their environment and with the other components. To summarize, the key point of a good complex system design is to manage and well-design the interfaces between the components. Figure 6 is an example of a simplified sytem architecture established for an adaptive composite structure.

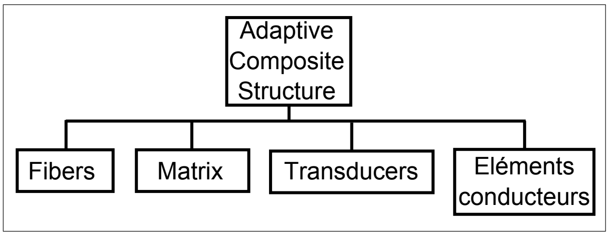

Figure 5. Simplified Product Breakdown Structure of an adaptive composite structure

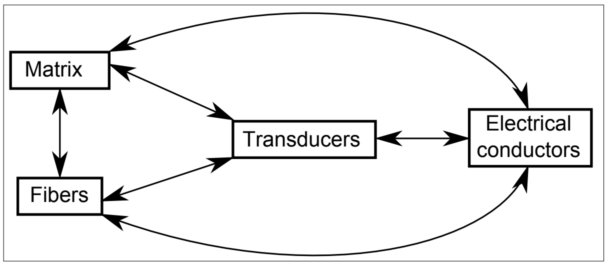

Figure 6. Simplified system architecture of an adaptive composite structure (Interfaces management)

## 4 EXPERIMENTAL CHARACTERIZATION NEEDS

Based on the design approach selected, it is possible to establish the essential experimental characterizations. It is absolutely necessary to well-know the overall system behavior with the integrated piezoceramic transducers so as to properly design the system controller. The classical approach using an identification process applied to the final structures is a priori not relevant for large distributed transducer arrays or for a mass production. Indeed, the idea is to avoid uncertainty and costly and time-consuming works. Our approach is based on an experimental approach upstream by predicting the overall physical parameters of the manufactured composite structure. The system architecture is used to specify the experimental characterization needs and so the procedures to be developed. Consequently, it is necessary to develop :

- *a characterization method of the piezoceramics.* In an industrial point of view, it corresponds to an input control for the piezoceramics. A non-destructive process, based on the vibration analysis of poles and zeros of the transducers, is developed and used for obtaining the coupling coefficients of interest [6].
- *a characterization method of the manufactured composite material.* Once the manufacturing process stabilized, the composite must be fully characterized using a set of tests allowing to have access to materials nominal parameters and their uncertainty. For this, two major methods are exploited. The classical characterization process is based on the use of material testing machines and strain gauges [7, 8]. Another vibration characterization is also used : the resonalyser method [9, 10].
- *a characterization method of the integrated piezoceramics.* The idea is to be able to produce a generic behavior modeling from the input control data so as to assess the drift of material parameters and coupling coefficients, when integrating the piezoceramics inside the material. Specific samples are manufactured. Piezoceramics, perfectly characterized, are encapsulated in a composite structure with tight dimensions around the transducers. The idea is to limit the effects due to the overall structure, the wires length, the electric connections, the cross-talk ...Finally, the same process used as input control is applied to these new samples.
- *a characterization method of the electric interfaces.* The electrical connection process, in particular between the transducers and the electrical conductors, requires to assess the influence of process parameters on the quality of electrical contacts.
- *a characterization method of the cross-talk between the active elements.* It is necessary to evaluate the cross-talk between the transducers so as to establish dedicated design rules. This feature depends on the wires distance and the electric connection technology used.

In the following subsections, the first methods are applied and the results obtained are given.

### 4.1 Characterization method of the piezoceramics : Application to low-cost thin disks made of piezoceramics

For this study, 40 low-cost piezoceramic samples are measured and analyzed. The material coefficients of these samples are calculated according to the experimental procedure presented in [6].

In table 1, only the average material coefficients and their standard deviation are given. Let the reader note that the mass density, $\rho$, is measured according to [11] (the minimum quantity

| Parameter of interest | Unit | Nominal value | Standard deviation $(\%)$ |
|---|---|---|---|
| $2a$ | mm | 24.7 | 0 |
| $\rho$ | $Kg.m^{-3}$ | 7227 | 0 |
| $2b$ | $\mu$m | 135 | 5 |
| $\varepsilon_{33}^{T}$ | $F.m^{-1}$ | 1894 | 3.9 |
| $\varepsilon_{33}^{S}$ | $F.m^{-1}$ | 1195 | 6 |
| $k_t$ | - | 0.17 | 6.2 |
| $k_{31}$ | - | 0.34 | 4.6 |
| $k_p$ | - | 0.59 | 4.9 |
| $e_{33}$ | $C.m^{-2}$ | 5.00 | 6.5 |
| $e_{31}$ | $C.m^{-2}$ | 19.95 | 6 |
| $C_{11}^{E}$ | $N.m^{-1}$ | $1.01e^{11}$ | 1.4 |
| $C_{12}^{E}$ | $N.m^{-1}$ | $3.50e^{10}$ | 2.7 |
| $C_{33}^{E}$ | $N.m^{-1}$ | $8.19e^{10}$ | 5.2 |
| $\sigma_p$ | - | 0.34 | 2.8 |

Table 1. Parameters of interest from the measured data

doesn't permit to compute a standard deviation) and the disk diameter has a very small deviation probably due to the manufacturing process used. The measurements are completed by a mechanical quality factor measurement for the radial mode vibrations with the 3-dB method [11, 12]. The average mechanical quality is 49.4 with a standard deviation of 18.2 $\%$. The standard deviation values show a quite good manufacturing homogeneity despite of a low cost. Let the reader remark a quite low planar coupling coefficient, $k_p$ and, globally, the coupling and piezoelectric coefficients are quite limited. This fact has to be managed by the strategy used for modifying the structure behavior.

### 4.2 Characterization method of the manufactured composite material : the resonalyser method

The Resonalyser method is a material identification technique following a reverse engineering scheme. Under in-plane stress assumptions, the in-plane elastic properties, given in equation (1), can be determined by a dynamic modulus identification using the resonant frequencies [9, 10]. Basically, this method uses resonance frequencies measured on rectangular plate specimens, so-called Poisson test plates, and two beams samples so as to identify orthotropic material properties. Moreover, an inverse technique is used to update the material properties in a numerical model of the test plates and the beams. The main advantage of this method is the simple apparatus necessary for the measurements and the simple numerical models used.

$$\left\{\begin{array}{c}\epsilon_{11}\\ \epsilon_{22}\\ \gamma_{12}\end{array}\right\}=\left[\begin{array}{ccc}\frac{1}{E_1} & -\frac{\nu_{12}}{E_2} & 0\\ -\frac{\nu_{21}}{E_1} & \frac{1}{E_2} & 0\\ 0 & 0 & \frac{1}{G_{12}}\end{array}\right]\left\{\begin{array}{c}\sigma_{11}\\ \sigma_{22}\\ \tau_{12}\end{array}\right\} \qquad (1)$$

This method was applied to an in-house composite material made of glass fibers. The structure has a 2 mm thickness. A fiber rate of around 35 $\%$ is obtained. A glass fiber mat is used. Consequently, the final structure is transverse isotropic, that is to say $E_1 = E_2$ and $\nu_{12} = \nu_{21}$. The first results are given in table 2. The repeatability tests are ongoing so as to produce the standard deviation. This part is particularly time-consuming. Let the reader note that the classical formula for the isotropic materials, $G = \frac{E}{2(1+\nu)}$, is in good agreement with the identified parameters.

| Parameter of interest | Unit | Nominal value | Standard deviation $(\%)$ |
|---|---|---|---|
| $\rho$ | $Kg.m^{-3}$ | 1630 | ? |
| $E_1 = E_2$ | $GPa$ | 13 | ? |
| $\nu_{12} = \nu_{21}$ | $-$ | 0.2 | ? |
| $G_{12}$ | $GPa$ | 5.5 | ? |

Table 2: Parameters of interest from the measured data for an in-house glass fibers-based composite material

## 5 CONCLUDING REMARKS

A design approach of fibers-based composite structures integrating transducers is detailled. The experimental characterization needs are clearly expressed. Two examples of identified data of interest are given for low cost piezoceramics and a glass fibers-based material manufactured in our laboratory.

The next steps of this work are the development and the reliability of the different characterization processes. After this, all the obtained data will be combined to develop a predictive behavioral model. The idea is to provide a pre-design tool for engineers.

## ACKNOWLEDGEMENT

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