AAPG2023	DETOX	PRC
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CES 42 - 98 – Axe H 11 – Capteurs, imageurs et instrumentation		

Development of numerical and **E**xperimental **T**ools for optimal **O**rganic piezoelectric transducer networks: SHM of comple**X** structures

I. Pre-proposal's context, positioning and objectives

1) Context

The actual need for monitoring sensitive parts of new devices and structures require the development of Structural Health Monitoring (SHM) strategies. They are expected to be nonintrusive, low energy consuming and robust. They participate to the strong development of **smart structures**. Piezo-based ultrasounds are one of the preferred technical solution to perform SHM, especially in thin structures acting as a guide for the propagating waves sensing remotely structures such as **airplane parts, wind turbine blades, pipes, railways, pressure tanks**… Waves that are guided by solid structures exhibit a large variety of behaviors in terms of mode number, propagation velocity, polarization, radiation pattern and coupling with transducers and damages. These complex behaviors are both challenges (limited number of transducers) and opportunities (rich experimental information) in SHM. Thus, it is fundamental for each monitored structure to have its own optimized SHM system at both scales: the transducer and the network scales, for taking best advantage of the inspection.

Ultrasound based piezoelectric transducers allow **remote sensing** based on the elastic wave propagation carrying information of possible damages over long distances. **Piezoelectric transducers** can be used both as sensors and actuators. The actual dominant technology is based on PZT (Lead Zirconate Titanate) ceramics, which exhibit excellent sensitivity to mechanical strain and efficient actuation. Nevertheless, their rigidity, thickness and manufacturing process reduce shape versatility and integration possibilities. Furthermore, they contain Lead, known as toxic. An increasing number of research teams are working on an alternative material in the SHM context : **P(VDF-TrFE)** (PolyVinyliDene Fluoride-TriFluoroEthylene) [1–3]. It is an **organic piezoelectric polymer** presenting many advantages: It is very **lightweight** and has low acoustic impedance, high compliance and **broadband** acoustic properties. P(VDF-TrFE) can be **solution-process deposited** and thus **printed** allowing to **freely design** any desired flexible transducers shape, even at the prototype level, on planar, curved or more complex geometries. However, it has poorer piezoelectric properties than PZT.

2) Positioning

DETOX aims at developing the necessary tools for the design and fabrication of organic piezoelectric transducer networks optimized for SHM of a given structure. In other words, **to one structure corresponds one optimized transducer network**. We believe that P(VDF-TrFE) is the ideal candidate to achieve this development thanks to its conformability, its ability to take easily any desired shape and its low intrusiveness. The few recent publications in this area focus on the behavior and integration process of the P(VDF-TrFE) transducers and are restricted to canonical or well-known geometries: circular [4], square [1] or interdigited [2]. Today's commercial solutions such as Accelent Smart layer® only allow non-optimized PZT transducers encapsulated in a matrix forming a network. Our approach is to take advantage of the freedom of shape offered by the P(VDF-TrFE) manufacturing techniques used and developed in the project to design **innovative geometries for optimizing overall SHM performance.** Thus, the project will overcome the limitations of PZT and compensate for the poorer piezoelectric properties of P(VDF-TrFE). To achieve this goal, the optimization will be performed at both the transducer level and the network level as functions of the mechanical properties of the structure and the chosen SHM method. To summarize, DETOX is an ambitious project **at the interface of transducer design, physical acoustics and preventive maintenance applications**. It is related to both, fundamental and applied aspects of **axis H11 "*Capteurs, imageurs et instrumentation*"**. It addresses the whole analysis chain, **from transducer design to measurement processing, for *in situ* and *operando* nondestructive characterization and imaging of the structure**. It federates three research laboratories (I2M, IMS and PIMM) and a technical center (CETIM) contributing to the industrial valorization of the research results.

3) Objective: one structure, one optimized transducer network

DETOX is based on recent **preliminary results** obtained by IMS and I2M showing the potentiality of printed P(VDF-TrFE) ultrasound transducers (image WP 2 in Figure 1) working as emitter or receiver for SHM and NDT applications [5]. The corresponding experimental signals are presented in Figure 1 (illustration of WP 3). To achieve the optimal design, fabrication and implementation of the transducer network, following tasks are required: (1) an efficient **multiphysics numerical model**, (2) versatile **printing techniques** for efficient transducer integration, (3) a double optimization method based on a **SHM** method able to take into account **the complexity of an industrial structure** and (4) its assessment on two **industrial demonstrators**. These items correspond to the four workpackages that will be led mostly in parallel with strong interactions all-along the project between the partners.

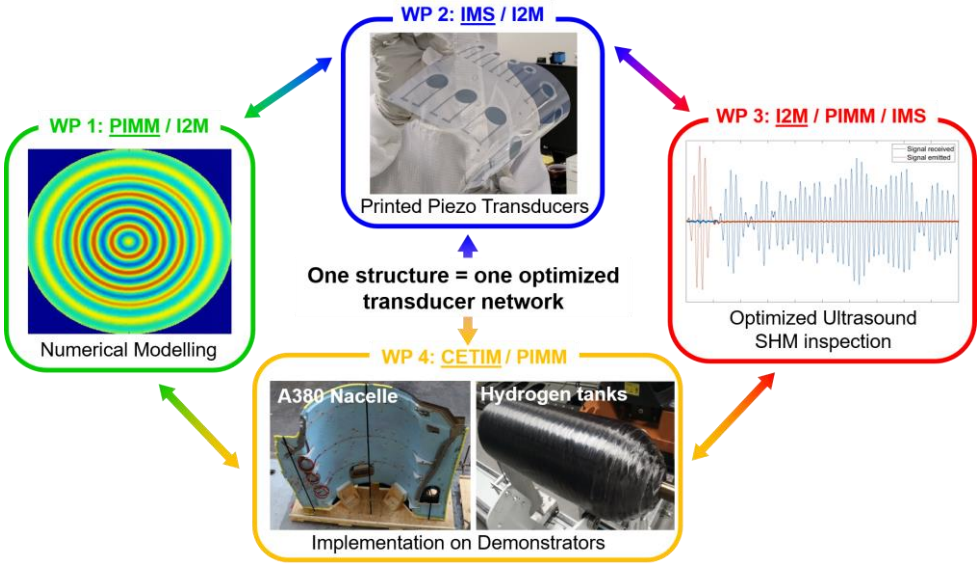

Figure 1: General view of the workpackages, with their leader, main contributors and interactions.

WP 1: Developing an efficient modelling of the instrumented structure: one structure, one metamodel (PIMM, I2M)

Optimizing the transducer network requires numerous wave propagation computations in large structures implying a potentially high computational cost. The purpose of this part is to build a **metamodel** able to model efficiently the acoustic field radiated by the transducers. The main development steps are: (1) defining the input physical parameters; (2) performing a **design of experiments** for the numerical computations [6–8]; (3) using a **model order reduction** that feeds (4) a **neuronal network** algorithm [9, 10]. The metamodel will be a fast and complete modelling tool including all the physical phenomena involved: piezoelectricity, wave propagation and interaction with damages. The suitability of the numerical tools and the **characterization of the P(VDF-TrFE)** material properties will be based on comparison with **experiments** performed with a **3D Laser Velocimetry tool**.

WP 2: Improving the piezoelectric transducers printing processes for large surfaces and setting a connecting environment (IMS, I2M)

The existing printing processes have limitations when printing on large surfaces in terms of thickness uniformity and production yield. These limitations have to be overcome for the active piezoelectric layers, the electrodes, as well as the electric wiring. An optimization of the printing process of both electrodes and piezoelectric layers will be carried out throughout an experimental plan that will investigate the impact of printing and annealing parameters on the transducer performances. In addition, we aim to print simultaneously and directly electrical lines and pads on the structure to limit additional noise from potential mismatch between the electrical connections of the flexible transducers and conventional electronic board. The transducers will be made by means of two printing methods to minimize the risks of WP2: well-established **screen-printing** and spray coating available at ELORPrintTec clean-room. Based on our preliminary results, flexible transducers will first be printed by

screen printing on thin, **flexible substrate** (PEN, Parylene) and subsequently reported on the structure (especially on curved surfaces) to be inspected. In order to improve the **transducer integration within the structure**, the different layers will then be **printed directly onto 2D planar structures** (composite plates provided by CETIM), suppressing the use of substrate and glue. In parallel, spray coating will be investigated to allow fully integrated printed piezoelectric transducer in structure of any shape (3D, curved surfaces…). Although challenging, **spray coating** is also selected for its easier potential **industrial integration**.

WP 3: Optimizing the transducer network for SHM (I2M, PIMM, IMS)

There are **two optimization scales** when designing the transducer network. First, **each transducer** should be optimized individually. For instance, dual sensors allow descriminating A0 and S0 Lamb waves [11] but using P(VDF-TrFE) gives the freedom to extend the concept to non-circular shapes fitting the wavelengths in all directions of an anisotropic medium. Then **the network** itself is optimized thanks to the metamodel developed in WP 1. In some methods, a dense cluster, composing for instance a matrix array [12] is beneficial. In other cases, a sparse network where transducer location is so far rather empirical is more appropriate. First quantitative objective functions will be defined depending on the SHM method to achieve rational optimization. Two kinds of methods will be investigated: those already SHM-oriented which are based on a single interaction of the wave with the damage [13–15] ; and those able to use the reverberated field such as topological imaging [16–19]. Using the reverberated field brings a richer information on the damage which is especially profitable when using a small number of transducers [18, 20]. However, this makes the system more sensitive to temperature and boundary condition changes. Finding a suitable truncation time for the measurement, which balances richer information with the desired robustness, is a solution we aim to investigate.

WP 4: Building a demonstrator for monitoring a real complex structure (CETIM, PIMM)

This workpackage aims at providing a **demonstrator of the complete system** involving **optimization, fabrication and monitoring**. It will be performed on two different structures corresponding to actual major issues: aeronautical structures and hydrogen pressure tanks. The PIMM owns two large parts of the Airbus A380 fuselage that will be used as a first real size demonstrator. CETIM owns a filament winding machine for building a hydrogen pressure tank. Achieving this second demonstrator is expected to be more challenging because of the uneven surface of the tanks, the strong cylindrical anisotropy and the heterogeneity as it is made of a liner and winded composites. This WP will also focus on the dedicated **electronic conditioning** to enhance both emission and reception signal to noise ratio. The type of connectors will also be studied to ease the integration. The overall performances of the SHM systems will be evaluated in terms of detection probability and localization accuracy.

II. Consortium

1) Coordinator

Samuel Rodriguez (40 years old, University of Bordeaux, I2M). The coordinator has strong background on ultrasonic defect imaging in complex structures. He has skills in both numerical modelling and experimental setup implementation. He is a specialist of topological imaging methods [17–20] steming from inverse problem community. They rely on a fast estimation of the topological sensitivity [21] used as a space-dependent indicator of variations between the experimental medium and a numerical model of the defect-free medium. They overcome the limitations of the classical methods used in medical and NDT applications and arouse the interest of industrial partners with whom the coordinator conducted projects (SNCF, Ariane Group). In parallel, he also participated to a large art and science project called Snowball supported by the University. Thus, he has **experience in transdisciplinary projects** and in **building bridges between upstream research and applications**.

2) Consortium

The achievement of DETOX requires the contribution of **four complementary partners** covering all the scientific and applicative aspects of the project. The researchers of IMS and I2M involved in DETOX

have been collaborating for two years and obtained promising preliminary results [5, 22] at the base of the project. IMS will take care of the transducer fabrication. I2M and PIMM will work together on the numerical modelling aspects and on the SHM method development. PIMM and CETIM have extended expertise on applied SHM and thus will work on realistic experimental applications.

Partner 1: I2M, UMR 5295 (Bordeaux). The department of Physical Acoustics of I2M is an established research team interested, among others, in linear and non-linear Non-Destructive Evaluation (NDE) of a large range of materials and components. **Pr. A. Meziane** and **Dr E. Ducasse** will bring their expertise in **numerical modelling** and analyses of wave propagation and complex interaction with defects, complementary to the **experimental skills** of the coordinator. The project will also benefit from **numerous experimental facilities** such as the **3D Laser Velocimetry** device.

Partner 2: IMS, UMR 5218 (Bordeaux). **Dr. Damien Thuau** is Associate Professor at Bordeaux INP since 2017. His research activities focus on **design and fabrication of organic printed microsystems** for sensors and actuators applications [23, 24]. He is coordinator of ANR JCJC 'DEFORM' (ANR-18-CE24-0020-01) 2019-2023. **Pr. Isabelle Dufour** has more than 20 years of experience in field of MEMS with expertise in resonant MEMS modeling and characterization [25, 26]. The project will benefit from both the **COMPONENT platform of IMS** for deposition techniques and the **ELORPrintTec EquipEx** for the printing equipment, a 1000 m² clean room facility dedicated to **printable organic materials**.

Partner 3: PIMM, UMR 8006 (Paris). **Dr. M. Rebillat, Dr. E. Monteiro** and **Pr. N. Mechbal** are members of the "Smart-Structure" team within the "Dynamic, Structure & Control" (DYSCO) group of the PIMM laboratory and are specialists in SHM, **numerical simulation**, and **machine learning**. They participated in several national and EU SHM projects: CORALIE (with SAFRAN Nacelle, 4 years – TRL1 to TRL5 on A380 nacelles), H2020 REMAP (achieved with EMBRAER) and are currently coordinating the H2020 MORPHO project. PIMM thus owns a **solid expertise in SHM**, where permanently bonded piezoelectric elements emitting ultrasonic waves are used to **monitor damages in actual structures**.

Partner 4: CETIM. SHM is responding to the transformation challenges of the mechanical industry and is therefore a strategic development axis for CETIM. In the DETOX project, it will bring its knowledge of industrial issues and needs and representative application cases on the one hand, and will actively contribute to the dissemination and exploitation of the project's results among mechanical companies. **Dr. F. Zhang** is PHD and Engineer in Materials Science from INSA Lyon, Lead Expert with **30 years of experience in NDT**. She was the coordinator of the PIA SCCODRA project on the monitoring of metallic components for the storage of radioactive waste [27], and a contributor to the FUI SIDCOF project focused on the development of a monitoring system for penstocks [28]. **D. Guillon** is a lead **Expert in composite materials**. He manages several projects and theses around the design, manufacture and control of thermoplastic composite tanks.

III. References related to the project (The publications of the consortium are in bold)

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