Post-doctoral position

"Design, optimization and validation of a FBPT & FBG network for the structural health monitoring of maritime composite structures"

Post-doctoral contract details :

- **Duration** : 12 months renewable, starting in November/December 2026.
- **Location** : Laboratoire PIMM, ENSAM, Paris.
- **Host team** : DISCOH team (see https://pimm.artsetmetiers.fr/equipes/discoh)
- **Salary:** Depending on experience
- **Industrial partners:** NAVAL GROUP, ARKEMA-Piezotech

Requested profile :

- Ph.D structural dynamics, ultrasonic waves, with numerical and experimental aspects
- Solid skills in numerical and experimental methods and scientific computation (Matlab or Python)
- Motivation to understand physics of waves propagation in thin structures
- Interest in signal processing and analysis of experimental data
- Strong will to be part of a consortium, to communicate results within it

ANR SMATSH project

Transition towards sustainable transport and more reactive and stealthy military vessels cannot be achieved without composite materials. However the use of Maritime Composites (MCs) for civilian ships or military vessels requires robust and efficient in-situ waves-based Structural Health Monitoring (SHM) algorithms to monitor them throughout their lifetime in a harsh environment. Unfortunately, waves based SHM algorithms for MCs are not yet available in a reliable and robust way. A first keylock is that MCs are complex (thick stacks, curved surfaces, salt immersion, and pressurization) and waves propagation within them is not well understood. Secondly, optimized transducers networks need to be designed given MCs specificities by combining promising technologies such as Flexible Polymer-Based Transducers (FPBT) and Fiber Bragg Gratings (FBG). Finally, associated waves-based SHM algorithms should be both data and physics driven in order to be as robust and as transferable as possible. The ANR funded SMATSH project thus aims to overcome these key limitations and to demonstrate that given a physical understanding of waves propagation in MCs, powerful dedicated French SHM solutions can be developed using FPBTs and FBGs coupled with physically informed (PI) machine learning algorithms. SMATSH scientific objectives are then to develop computationally efficient models to predict waves propagation in MCs, to optimize FBPTs & FBGs transducers networks for SHM purposes, and to design PI-SHM algorithms for MCs. The results will be illustrated by means of a semi-immersed smart ship hull part performing real-time SHM. SMATSH is structured around Naval Group (the European leader in naval defence) which will provide specifications, industrial demonstrator and validation as an end-user, PIMM laboratory (expert in wave-related problems and SHM) that will develop waves models and PI-SHM algorithms, and ARKEMA Piezotech (a spinoff of ARKEMA able to manufacture specific electroactive polymers) which will design and produce FPBTs.

Post-doctoral research objectives :

SMATSH relies on two types of transducers, FPBT and FBG. The objective of the proposed post-doctoral position is then to **optimize FBGs and FPBTs networks for SHM in MCs**. It can be divided into two parts: the optimization and manufacturing of a single FBPT (#1), and the optimization of a hybrid FPBTs and FBGs transducers network (#2). Results from a past project are already available regarding the first objective.

[OBJ #1] Single FPBT optimization and manufacturing

Standard piezoelectric ceramics (such as PZT) are brittle and cannot withstand the strains encountered by MCs in harsh environments. They are also unable to conform to curved structures and most of them contain leads. However, specific piezoelectric flexible polymer materials (such as Polyvinylidene Fluroide-co-Trifluoroethylene P(VDF-TrFE)) can overcome these limitations: compared to PZT, they offer flexibility, printability, low CO_2 footprint, and recyclability. They do not contain toxic lead in their composition, and are not as fragile and difficult to recycle as their inorganic counterparts. Their use has reached maturity in civil or defense applications [1]. A basic configuration for a P(VDF-TrFE) based FPBT is a P(VDF-TrFE) film (activated through electrical poling) with electrodes deposited on both film surfaces. Different techniques can be used to manufacture it depending on the desired thickness or shape, and various electrode geometries can be deposited using conductive polymers or standard metal deposition techniques [2]. P(VDF-TrFE) thus allows to build arbitrarily shaped polymer-based transducers with arbitrary electrode geometry [3] paving the way for finding optimal FPBTs for SHM. During a previous collaboration between ARKEMA and PIMM, an analytical model that predicts FPBTs transduction was derived allowing to design an optimal mono-modal FBPT (see Figure 1) with modal excitation selectivity capabilities [4]. This design choice was motivated by the waves-based SHM need for improved signal interpretation and hence better damage monitoring performances. However, electrode manufacturing is becoming tricky with complex geometries and electrical routing between electrodes breaks in FBPTs the axial symmetry required by the optimization. Furthermore, the use of electrodes is binary, either there is one or either there is none, which does not allow for a continuous and smooth design. **FBPTs transducers optimization relying solely on electrode geometry therefore severely limits design options, complicates the manufacturing process, and limits the resulting FBPTs performances**.

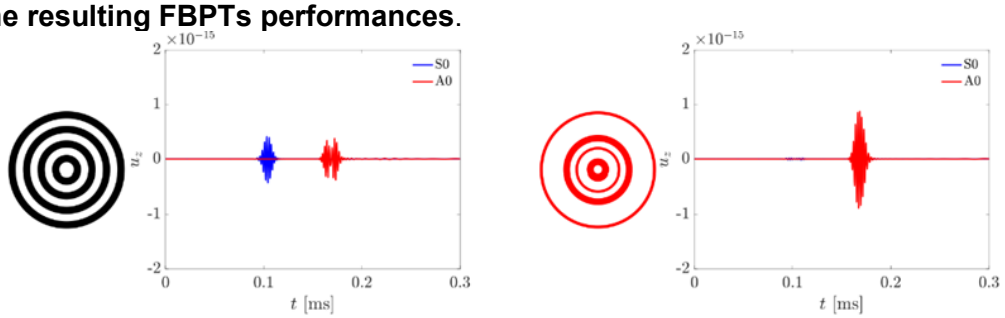


Figure 1: *Example of optimal design of FBPTs based on electrodes geometry. [Left] Regular state of the art spacing approach: dispersive wave (A0 and S0 modes). [Right] Optimal FPBT design: A0 mode selective excitation .*

Our objective is to make the best out of the smart transducing capability of the P(VDF-co-TrFE) material developed by ARKEMA. We will design optimal FBPTs capable of exciting a single ultrasonic wave mode by spatially adjusting polarization over the FBPTs area under a single electrode. Non-uniform polarization of piezoelectric polymers allows to locally modulate their piezoelectric properties: a precise control of the polarization step, where an electric field is applied to the film, allows to locally orientate the highly dipolar polymer molecules in their ferroelectric phase and to create a remnant polarization directly correlated to the piezoelectric coefficients. Optimization of polarization maps will then be carried out on the basis of the analytical model and of the tools already developed during previous collaboration between ARKEMA and PIMM. Optimized FBPTs design will first be validated using FE models adapted from previously existing ones and then manufactured by ARKEMA. Two different non-uniform polarization techniques will be implemented. The first one is Corona discharge where a high voltage (typically 15-20 kV) is applied to an electrode or a metallic mask, generating a localized electric field. The second one is a contact method where discrete electrodes or a conductive tip apply a voltage directly to specific areas of the polymer, ensuring targeted and adjustable

polarization. ARKEMA developed a strong know how to manage accurately both poling process. Contact method allows to manufacture precise and reproducible FPBTs, while Corona discharge allows large area films to be produced quickly and cost-effectively. Various techniques can then be used to check the actual state of local polarization. Directly by calculating local remanent polarization by measuring the polarization current when the electric field is applied, or indirectly by measuring the local d_{33} coefficient using the Berlincourt method, or very locally by measuring it using piezo-response force microscopy. Manufactured FBPTs will thus be experimentally characterized in order to validate the non-uniform polarization and to update ultrasonic waves related analytical and FEM models. We will then be able to **manufacture optimized FBPTs with non-uniform polarization for SHM purposes**.

[OBJ #2] Hybrid FPBTs and FBGs transducers network optimization

At the transducer network level, SMATSH aims to take the benefits of two promising transducers type, namely FBGs and FPBTs. The integration of multiple transducer technologies in a SHM system for MCs has already been pinpointed and has shown the ability to perform more effective hull inspections [5, 6]. Technologically speaking, FPBTs aim at emitting or measuring omnidirectional waves in the ultrasonic range (up to $500\ kHz$) whereas FBGs directionally target lower frequency vibrations (up to several kHz for spectrometer and to several $100\ kHz$ for edge filtering). FBGs are able to sense dynamical strains variations within ship hulls and thus to estimate stiffness degradation with a relatively low spatial resolution (order of m). On the other hand, FPBTs are able to carry out active or passive waves-based interrogation of MCs. Passive interrogation approaches can take the form of acoustic emission to detect damage premises or inter-sensor correlation approaches under external loading for damage detection and localization [7]. Active approaches are based on the use of one FBPT as an actuator and of the other as sensors and allow damage detection, localization, and size quantification using damage echoes contained in the measured signals [8]. Eventually, FBGs and FPBTs can also be used in a hybrid mode where FPBTs used as actuators are sending waves within the structure to be inspected and FBGs are measuring resulting signals in an edge filtering mode [9].FPBTs thus allow for damage monitoring with a fine spatial resolution (order of cm) and on demand by handling active or hybrid approaches. **FBGs and FBPTs are complementary transducers for damage monitoring and thus it makes sense to integrate them in the same network**.

Optimal SHM transducer networks will seek to distribute transducers as widely as possible over the structure to ensure that each point of the structure to be monitored is in the vicinity of one or more transducers [10, 11]. The question of network optimization in the SHM context is *in fine* related to the choice of the number, type (FBG or FPBT), and position of the transducers constituting the network. The more transducers there are, the easier it is to monitor damage, but the greater the consequences in terms of on-board weight and maintenance. Firstly, the cost function which will be optimized needs to be chosen. A first choice is to maximize the coverage of the monitored structure and to ensure that the waves will reach monitored areas with enough energy. Alternatively, another option is to maximize SHM algorithms performances for the different networks tested. Weight and monetary cost can also be considered as cost functions. In order to evaluate these costs functions, a physical model is required to estimate measured signals that will be used by SHM algorithms for the various considered network configurations. The simplest model relies only on waves velocities and attenuation as a ray-based approach [12]. Consequently, **network optimization can be achieved through appropriate costs functions (coverage, performance, weight, …) associated with a physical model allowing for rapid evaluation.**

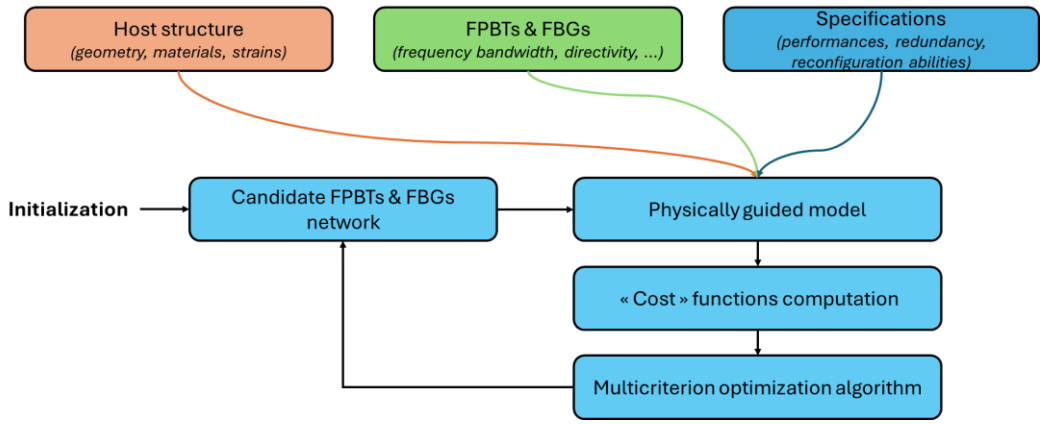


Figure 2: *Optimization loop for FBGs and FPBTs network optimization*

Our objective is to take benefits of the complementarity between FBGs and FPBTs and of associated SHM methods (passive, active, or hybrid). Targeted transducers network should be frugal and reconfigurable (able to switch from passive to active when docked, or from active to passive if stealth or energy savings are required) and also redundant (able to perform sufficiently even if some transducers are out of order due to their ageing or to the harsh environment). Redundancy is not really a weight issue here as FBGs and FPBTs are light and associated wiring can be printed. We will define different cost functions taking into account coverage, performance, reconfigurability and redundancy in order to optimize the network. Simultaneous optimization of these cost functions will be achieved using a standard multi-criterion optimization algorithm (see **Figure 2**). The proposed methodology will be applied and we will use a ray-based approach [12] as the underlying physical model predicting signals measured by a given network configuration and taking as inputs waves velocities and attenuations. Once an optimal network will be found, its SHM performances will be assessed numerically using a FEM simulation. It will then be manufactured and integrated into the demonstrator and its *in-situ* performances for SHM purposes will be experimentally evaluated.

Application process:

Please send your complete application (motivation letter, CV, recommendation letters and transcripts) to:

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