Supergen ORE Hub Award FF2020-1068

Smart Piezoelectric Metamaterials for Partial Discharge Monitoring

Project Summary

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1. Introduction

The cost of lost wind farm production due to subsea cable failure is significant. Between 2002 and 2015, the insurance losses due to cable failure were more than £140 million in the UK alone. Cable failures are particularly an ongoing issue in the offshore wind industry, reflecting a major challenge in offshore energy of designing a cost-effective and efficient electrical network to transmit power to shore [1]. Direct connection solutions, with each installation having its own landfall connection, are not appropriate for deeper water and more cost-effective solutions such as floating hubs or subsea radial arrays present significant challenges in terms of cable management [2]. The cost and risk of maintaining such arrays must be accounted for as much as the capital cost. Unlocking greater water depths and farm scale will require robust and cost-effective condition monitoring of offshore hubs which directly addresses the fundamental ORE challenge of reducing costs and risks by addressing interconnections between stages.

Cable failures are typically monitored through partial discharges. Monitoring partial discharges via acoustic emissions has distinct advantages over inductive or radio frequency techniques in terms of immunity to electromagnet interference, high electrical resistivity and low price [3]. However, the low sensitivity of the method and difficulty in localizing a source has prevented wide adoption of acoustic emission monitoring.

This project proposed to address this issue by designing and manufacturing a novel perovskite structured piezoelectric acoustic sensor with an anisotropic response tailored to a cable or termination. Using perovskite structured 3D printed piezoelectric materials acoustic sensors may be designed with tailored, directional, piezoelectric coefficients and acoustic impedances which are matched to the properties and environment of a cable or connector.

The sensors proposed offer direct tailoring of the piezoelectric coefficients of a material by additive manufacture of piezo-active lattices. Piezoelectric sensors fabricated in this way may have primary piezoelectric constants comparable to the d_{33} constant of a traditionally manufactured piezo-composite with a greatly reduced volume fraction. Previous reports on such structures have shown doubled piezoelectric voltage constants compared to piezoelectric polymer materials, suggesting their use in lightweight and highly responsive sensors [4]. The use of additive manufacturing allows a rapid iteration of the structure as well as the ability to design the sensor to conform to the radius of the cable or transmission link box, and to match the physical properties. The combination of extremely lightweight, high sensitivity and directional encoding promises a greatly enhanced ability to detect, characterise and locate partial discharges through acoustic emissions that is particularly suited to the challenging deep-water environment. The design space opened up by the 3D structured piezoelectrics had only recently been reported [5], with an early application being ultra-low noise underwater transducers [6]. Though the prospective benefits to condition monitoring are great, the novelty of this approach and the breadth of the potential meant application to acoustic emission detection had not been tested. However, tailoring traditional 1-3 piezoelectric composites in this manner had previously been shown to deliver sensitivity gains of up to 19.8 dB [7]. The proposed work therefore included an evaluation of the novel sensor's performance in terms of sensitivity gain and detection of partial discharges. And so, the feasibility of using such novel tailored piezoelectric sensors in cables and connections relating to floating hubs and land/sea connections could be investigated.

2. Project aims and objectives

The aim of the project was to address the research described above by carrying out two streams of work which were parallelized to some extent. Work under the first stream examined the design space of the perovskite structured sensors in terms of modelling and experimentation to develop a proof-of-principle sensor which would be evaluated for sensitivity in laboratory settings. The second work stream investigated acoustic emission partial discharge detection with a tailored 3D printed sensor in a cable or termination.

The objectives of the proposed researcher were:

1. Design and manufacture a perovskite structured 3D printed piezoelectric sensor that provides directional acoustic emission information.
2. Evaluate the response of the designed anisotropic piezoelectrics in laboratory partial discharge testing in terms of signal strength, sensitivity and noise.
3. Compare this method of partial discharge detection in cables/cable connectors with existing acoustic methods and hybrid methods.
4. Report on the feasibility of using smart piezoelectric sensors to localize acoustic emissions from partial discharges in cables/cable connectors and land/sea connections.

3. Summary of work conducted

The research program was divided into six work packages, following from the objectives above. The outputs from each work package are described in the subsections below.

WP1: Sensor design map

The first step of the work package was to conduct a short literature review of existing designs for anisotropic sensors. At that point in the project (2020), with the Covid pandemic constraints it was clear that projects applying such multi-scaled architectures had not advanced significantly. The literature review did highlight new studies on development and optimisation of 3D printed piezoelectric nano-composites. Significantly, these focussed more on energy harvesting than sensor design, but work was identified to inform later work packages relating to optimising the piezoelectric properties of nano-composites.

Work was also carried out to consider the various material structure designs that could be implemented through the project. This involved work to advance 3D printing of candidate structures, initially with standard 3D printing materials (Figure 1), then utilising 3D printable piezoelectric nano-composites (Figure 2). Numerous issues were faced in producing materials that were 3D printable in the appropriate structural design, yet could provide the piezoelectric sensitivity that would be required for the sensor's development. Work was carried out covering various chemical processes and using different materials, in order to improve the piezoelectric effect produced by the bulk material, and thus the tessellated structure. Multiple iterations, utilising different techniques (and printers), based on different materials were examined.

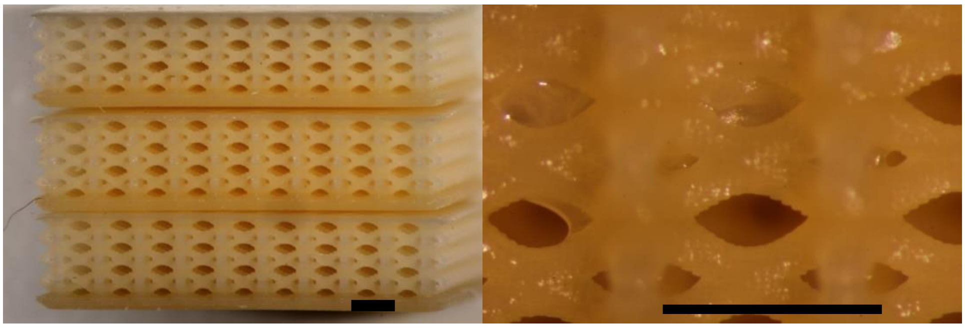

Figure 1: Example 3D prints of tessellated structures for sensors

Figure 2: Printed structures made with a polymer piezoelectric particle nano-composite.

WP2: Model development

Computer models of the structures for the new sensors were created, as shown in Figure 3. These were used to simulate stresses in the structure, as well as predict the piezoelectric effect and its directivity within the structure. Simulations of the different structural unit cells were carried out in order to examine the sensitivity and directional response of the different structures. This was correlated with number of struts, offset angle, and aspect ratio of struts (length : radius). It also took into account the limits of 3D printing techniques and materials available.

WP3: Iterative program towards sensitivity improvement

Initial work within the project showed inconsistency, and lack of sensitivity, in the piezoelectric materials being created. Typically, this produced piezoelectric sensitivity that was at best equivalent to traditional commercial piezoelectric thin-films (~ 2 to 30 pC/N). Work package 3 then concentrated a significant amount of work on improving the sensitivity of the custom made piezoelectric in order to create a sensor material appropriate to the aims of the project.

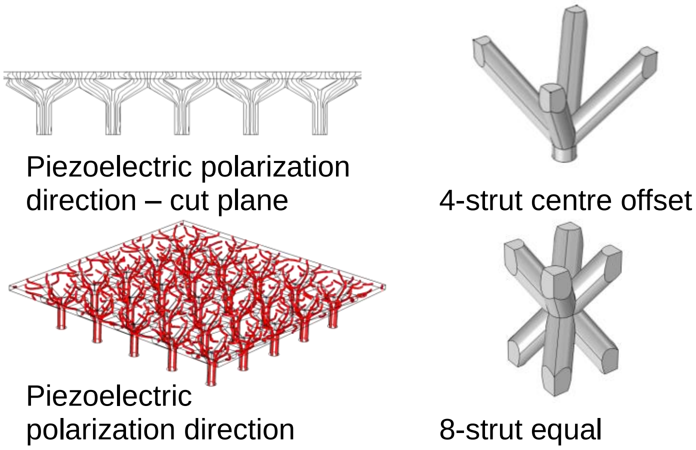

Figure 3: Computer models and simulations of the unit cells of tessellated structures for the sensor.

This led to the development of a new strategy to create highly elastic piezoelectric polymers with strong piezoelectric behaviour using the sugar-template method. Composite foams utilising 5nm PMN-PT (lead magnesium niobate-lead titanate) nanoparticles with 3D printer polymer and fine sugar were examined. A large number of variables were investigated in order to optimise the process for creating this piezo-polymer composite foam material, including mixture ratios, and curing and poling parameters. The project team also designed and implemented a new poling system. This was successful in creating materials of with piezoelectric sensitivity of up to 75 pC/N. Further, these materials displayed a relatively wideband frequency response suitable for detecting acoustic emissions from a partial discharge.

WP4: Development of laboratory test and detection

Within this work package the development of a laboratory experimental setup for creating and detecting partial discharges in a mocked cable system was carried out (see Figure 4 for example). Stable partial discharges were created by fractional removal of the cable from a joint. This allowed a recognizable partial discharge pattern (AC voltage) to be created. With the experimental setup established it was then possible to test the sensor response to partial discharge events.

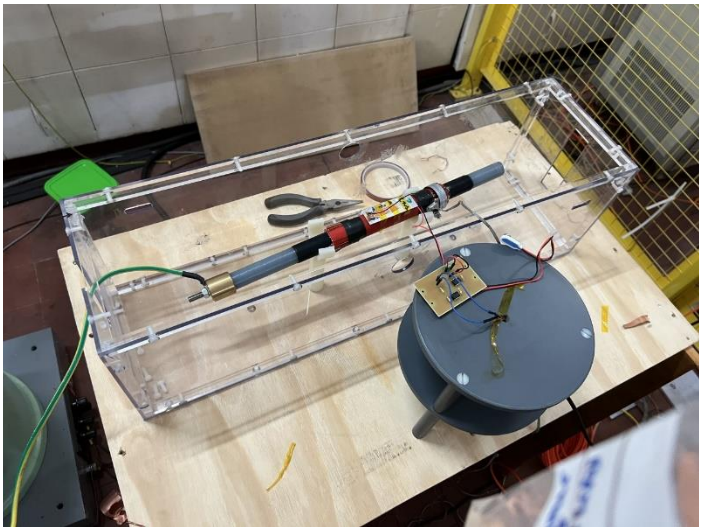

Figure 4: Photograph of the in-house experimental laboratory set-up in laboratory settings for recording induced partial discharges.

WP5: Embedded prototype

In this work package the design, computer modelling and simulation, and manufacture of 3D printed structured piezoelectric sensors was carried out. The sensor was designed to fit around a specific cable example within the laboratory setup described in the previous work package section. As shown in Figure 5, sensors were designed in CAD to fit a specific sample cable available in the laboratory. These were then 3D printed as casings, with piezoelectric elements then added before the final sensor structure was cured and poled (not shown in figure).

WP6: Testing and refinement

In this work package the acoustic emissions of experimentally simulated partial discharges were measured using the laboratory system. This was done using both the new sensors created through the project and a commercial acoustic sensor. Partial discharge events could be measured using both sensor types, as shown in Figure 6.

The new sensors created in this project significantly outperformed the commercial acoustic sensor, typically with a 300-400% increase in sensitivity to partial discharge acoustic emissions. These results are now being written up for a journal publication, and will form the basis of further funding applications by the project team.

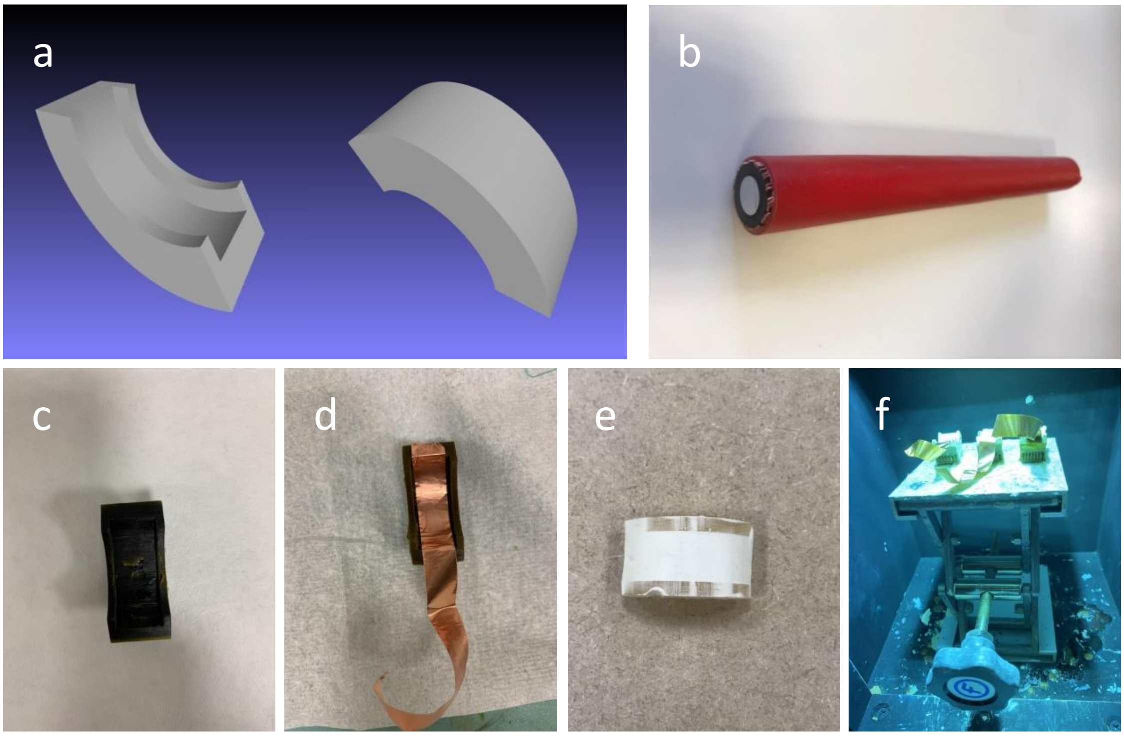

Figure 5: 3D Printed Sensors (a) Structure CAD designs, (b) Sample cable, (c) Printed external structure, (d) Structure with conductive tape, (e) Piezoelectric material in sensor, (f) UV exposure for curing.

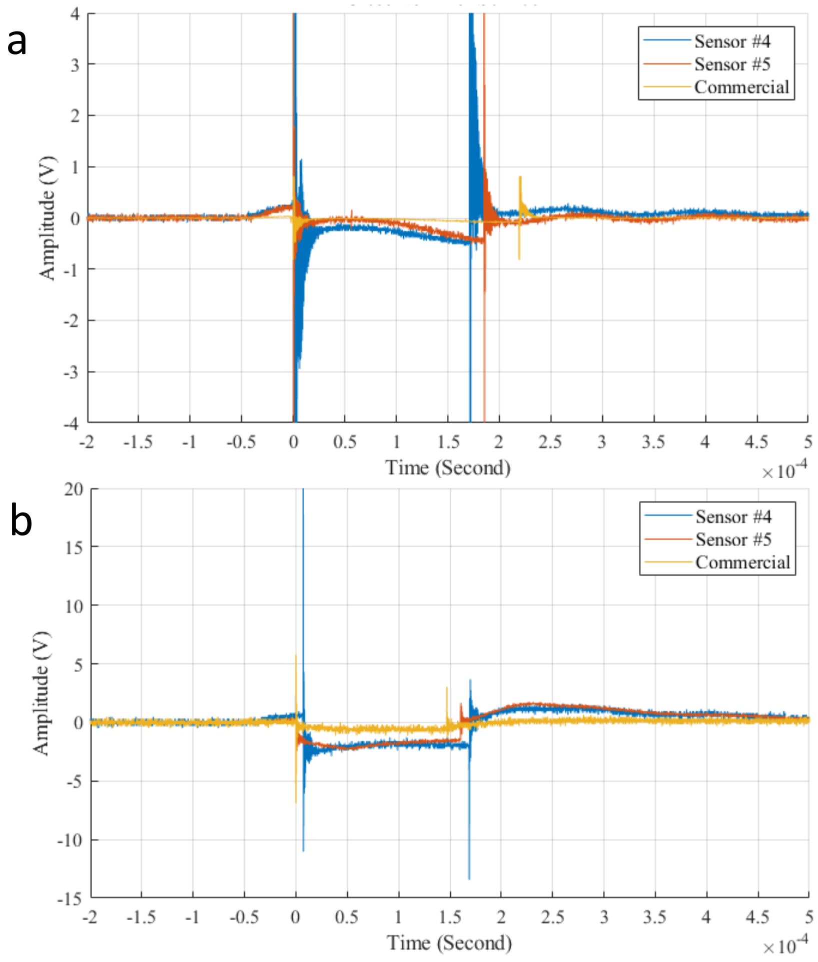

Figure 6: Partial Discharge Detection (a) weak partial discharge responses (sensor further from PD site), (b) stronger response as sensor close to PD site. (2nd PD occurs as the applied voltage reaches a suitable level.)

4. Summary of outputs and dissemination

One journal publication was completed as part of the project [8]. This paper explains some of the earlier project work to develop appropriate piezoelectric materials to use in the sensor device. A second paper is in preparation [9], describing the development of the partial discharge sensor, and will be submitted to a leading sensors journal. Two conference papers were presented as part of the project. The first of these was presented at IEEE International Conference on Flexible & Printable Sensors & Systems 2022 [10]. This paper describes the later work in the project to develop a new, more sensitive, piezoelectric material suitable for casting and printing, to use in the partial discharge sensor. The second conference paper was presented at the 10th European Conference on Renewable Energy Systems 2022 [11]. This paper describes more about the new piezoelectric material development, considering the requirements for a partial discharge sensor.

Prof Windmill gave an online talk about the project, and was a panel member, at the Supergen ORE Hub Annual Assembly January 2021 in the session "Tackling the research challenges: Sensing, control and electro-mechanics". Dr Mansour gave an online talk about the project at the Electrical Infrastructures Research Hub monthly technical meeting in July 2021. Dr Mansour also gave a talk about the project at the Supergen ORE Hub Annual Assembly in January 2022. Finally, Dr Reid gave a talk on the project at the Supergen ORE Hub Autumn Assembly at Oxford in September 2022.

Acknowledgements

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