Smart Self-sensing Composite Marine Propeller: Increased Maintenance Efficiency Through Integrated Structural Health Monitoring Systems

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Abstract. CoPropel is a Horizon Europe funded project which aims to develop marine propellers for cargo vessels that are more fuel and cost efficient to operate than their more common metallic counterparts. One of the areas the project aims to tackle is the maintenance aspect of marine propellers, which can be very cost intensive. This is due to the difficulty of inspection or maintenance since the components are underwater and quite significant in size, which may lead to the need for divers or dry-dock time. The way the project aims to address this is by taking advantage of the non-monolithic construction of the composite propeller to integrate a Structural Health Monitoring (SHM) system to monitor the strain, and subsequently infer the condition, of the propeller during operation without the need to stop for inspection. This paper explores the challenges encountered in the development of the SHM system, including: 1.) inspection requirements as set out by existing guidelines and regulations, 2.) sensor integration in the composite structure, 3.) data transmission from a rotating underwater component to a data acquisition system within the ship and 4.) usage of the acquired data for maintenance decision making. Feasible alternative systems are explored including Rayleigh Backscatter based Fibre Optic Systems (FOS) for distributed strain sensing as well as a strain gauge system with wireless underwater data transmission. Preliminary small scale underwater tests are conducted to evaluate the performance of the explored concepts under simulated operational conditions. Finally, we combine the strain data acquired from the SHM system with numerical models of the propeller through a multifidelity approach. The first aim is to create a better spatial distribution of the strain measurements across the propeller by fusing data from sensors covering a limited area, with strain data from numerical models that have better distribution across the propeller. The second goal is to provide digital twinning capability through the use of the numerical model to provide extrapolated estimates (calibrated by live sensor data) of maintenance requirements (i.e. remaining life) based on current and hypothetical operational profiles to better inform operators when making future operational decisions. Through the combination of the SHM system and digital twinning capabilities we provide increased

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data driven decision making capabilities to better improve operational efficiency and maintenance costs.

Keywords: Marine propulsion · Composite materials · Structural health monitoring · Digital twin · Underwater sensing · Rotating machinery

1 Introduction

Ship propeller blades are commonly constructed as monolithic metallic parts and are designed to be rigid to maintain the optimum geometry for hydrodynamic efficiency during operation [1]. Currently, there is growing interest in applying fibre reinforced composite materials as an alternative to metals due to their controllable stiffness that allows for hydroelastic tailoring of flexible propeller blades to provide better performance and fuel efficiency [1]. However, there is one added benefit of applying composite materials that has received less attention, which is the possibility to integrate sensors for condition monitoring due to the non-monolithic construction of composite blades. CoPropel [2] is an ongoing Horizon EU funded project (Grant agreement 101056911) that aims to develop a composite propeller with integrated strain sensors to enable Structural Health Monitoring (SHM), increase operational reliability and provide better information for preventive maintenance planning. Failure of the propulsive system (and its prevention) is still a significant contributor to costs in shipping [3], thus by having an integrated SHM system it is hoped to provide additional savings from the maintenance aspect.

Currently there exists frameworks for condition-based maintenance planning (such as ISO 19030) for ships based on measured parameters of their performance and diagnostics of the machinery [3, 4]. However, these measurements are either based on indirect parameters (such as speed, engine rpm and vibration) or diagnostics of machinery within the hull (such as engine and shaft) [3, 4]. Direct measurements of the propeller remain one of the most challenging tasks due to the fact that it is rotating, fully submerged underwater and usually has strict restrictions on any disturbance to the external hydrodynamic shape. Thus, these conditions impose limitations on the size of the equipment (must rotate), where it is installed (internally) and how data is transmitted back to the hull (must handle the rotation and water medium). In this paper we present the ongoing work to develop SHM solutions to tackle these challenges and what can be done with the data provided.

2 SHM Solutions Developed in CoPropel

There are 2 alternative SHM strain sensing solutions being explored in the CoPropel project: 1.) a Fibre Optic Sensor system (FOS) and 2.) a wireless strain gauge system. Figure 1 provides a general schematic of the propeller blade construction and sensor installation. The propeller blade will be constructed as a sandwich with a composite laminate skin and a sand core which can be made hollow at certain sections to store electronics or pass through wires. The FOS fibre will be integrated into the dry preform of the outer composite laminate while the strain gauges will be installed between the sand core and laminate. This will be done prior to the Resin Transfer Moulding (RTM) manufacturing process that will inject resin throughout the part and consolidate it. The strain gauges will be placed following the path of the FOS to allow for direct comparison of the train measurements as seen in Fig. 1. However, the sensor locations/topology shown in Fig. 1 are not final and serve to illustrate the concept.

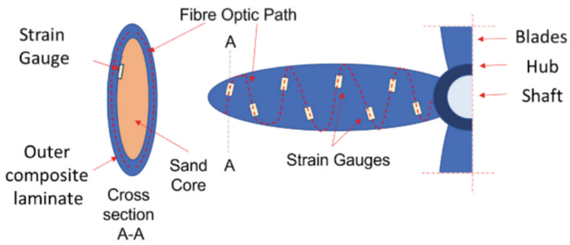


Fig. 1. Schematic of propeller blade construction and sensors (exact installation locations/topology is not final)

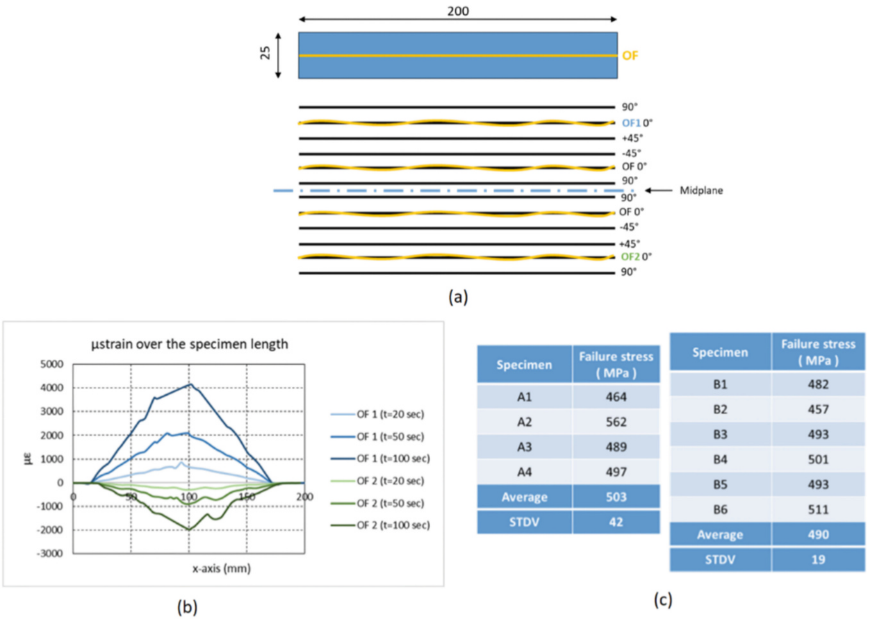
2.1 Fiber Optics Sensor (FOS) System for Strain Sensing

The FOS system employed in the propeller will be based on the Distributed fiber-optic sensors (DFOS) [5] that provide a continuous profile of measurements over the length of the optical fiber and thus are most suitable for large structural applications. When a light wave enters an optical fiber, the Rayleigh, Raman, and Brillouin back scattering light are simultaneously obtained. Fiber optic distributed sensing measures strain and temperature by processing spectral shift in the Rayleigh backscatter of optical fibers integrated in a structure. When the strain in the fiber changes, the spectrum of back-scattering signals will drift in terms of frequency. The amount of drift is proportional to the strain that is imposed to the optical fiber. Through relevant calculation of the measured and initial signals, the drift value can be obtained. Then, the strain value can be calculated from Eq. (1). The distributed strain information of the entire optical fiber can be obtained by scanning. [6]

$$\Delta_{\nu} = C_{\varepsilon} \cdot \Delta_{\varepsilon}, \tag{1}$$

In Eq. (1), Δv represents the value of the frequency drift of the Rayleigh spectrum, Δε is the change of strain in the optical fiber relative to the initial value, and Cεis the strain proportional coefficient of the optical fiber. The method described above is known as Optical Frequency Domain Reflectometry (OFDR). The Rayleigh system working with OFDR is the only one to offer mm range spatial resolution.

Preliminary experiments (three-point bending) have been conducted to ensure the functionality of embedded sensors and validate the minimum effect on the mechanical properties of the host material. Optical fibers were integrated to the middle of the width of each specimen at 4 different layers: 2 near the mid plane and the neutral axis of the specimen's section, 1 near the outer surface which will undergo compression and 1 near the outer surface which will undergo tension. The layup of the specimen and the optical fiber layout are presented in Fig. 2a. The optical fiber was integrated to the fabric during manufacturing using a painter to form lines as a guide to place the optical fibers at certain positions and plastic tubes at the ingress and egress points to protect the fiber. The integrity of the OF was checked after manufacturing via a laser. The embedded sensors monitored the structural integrity of the specimens during testing (Fig. 2b). The extracted data from the optical distributed sensor interrogator indicated that the strain increased over time as expected. Furthermore, the strain profile of the optical fiber under compressive stress and the optical fiber under tensile stress were representative of the specimen's deflection. The failure stress of the specimens with and without embedded optical fibers was compared to evaluate the host material's degradation. The obtained results indicate that the optical fiber does not act as a defect to the host material (Fig. 2c).



Specimen	Failure stress (MPa)
A1	464
A2	562
A3	489
A4	497
Average	503
STDV	42

Specimen	Failure stress (MPa)
B1	482
B2	457
B3	493
B4	501
B5	493
B6	511
Average	490
STDV	19

Fig. 2. Three-point bending test results: (a) Specimen geometry and fibre optic layout, (b) strain measurements from embedded optical fibres, and (c) failure stress of specimens without (A1–4) and with (B1–6) embedded optical fibres

To transmit the optical signal transmission from a rotating underwater component to the data acquisition system within the ship, a Fiber Optic Rotary Joint (FORJ) is being tested for small scale tests.

2.2 Wireless Strain Gauge System

The wireless strain gauge system is being developed as an alternative to the FOS system which can provide more flexible data transmission as the options for electrical signal transmission are wider than optical signal transmission. Figure 3 provides a schematic on the concept of the wireless strain gauge system, where the strain measurements are transmitted to the hull via magnetic coupling using thin coils on the propeller (rotating) and shaft sleeve (static). Magnetic coupling was chosen over Electromagnetic (EM) wave signal transmission (as commonly used in free air communication) as it is less affected by the water medium (where EM waves are heavily attenuated [7]) and the existence of the metallic shaft between coils provides support for the magnetic field coupling (as in electrical transformers).

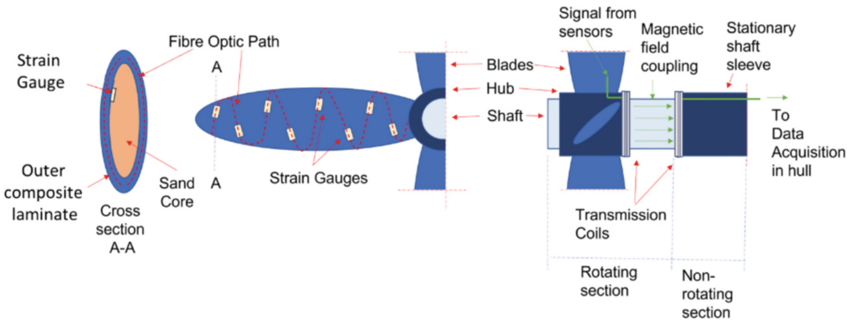


Fig. 3. Schematic of wireless strain gauge system

In order to achieve wireless data transmission, the strain measurements (in the form of voltage signals) need to be converted into oscillating signals [8]. This is done using a frequency modulation approach where the voltage signals of the strain measurements are transformed into a shift in a continuously oscillating sine wave. The strain measurements are then decoded at the data acquisition side by analysing the frequency component of the transmitted signal. Figure 4a shows the frequency modulation prototype that has been developed to test this concept. The frequency modulation is done using an AT microcontroller (MCU) which reads the voltage from the strain gauge and sends instructions to a DDS wave generator to generate a sine wave with the appropriate frequency. This approach was chosen as the MCU provides accurate control over the frequency modulation such that it is possible to accurately define the frequency bandwidth of each sensor to allow multiplexing of the signals. Thus, when there are multiple signals from different sensors it is possible to transmit it together on 1 line (in this case from the coils on the propeller and sleeve).

Figure 4b shows preliminary signal transmission tests done in various media (free air, water and salt water) using a 60 kHz 6Vpp signal and 1mH choke coils as transmitters and receivers. It was observed that the change in media does not significantly alter the transmitted signal strength, but it attenuates significantly with distance. Since the sleeve and propeller are usually spaced closely and in the actual case there will be a metallic shaft that can aid in signal transmission, this should not pose a significant problem.

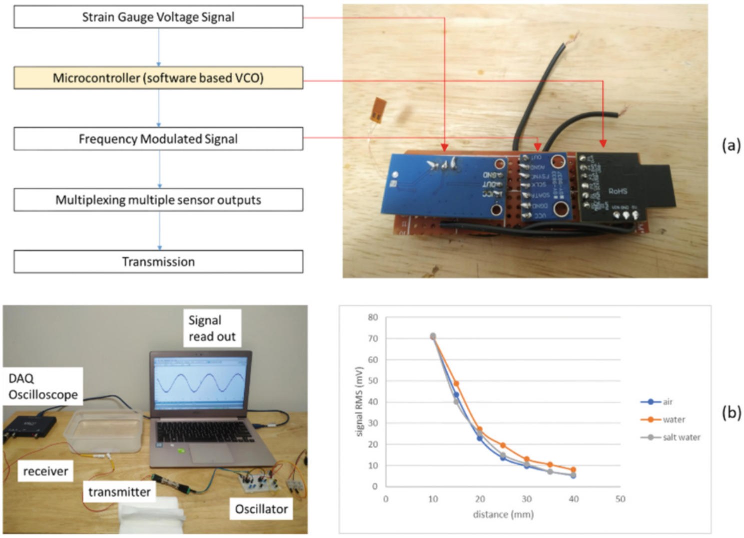


Fig. 4. Wireless strain gauge system: (a) prototype frequency modulation system and (b) preliminary transmission tests in different media

3 Data Driven Decision Making Using SHM Measurements

In order to provide better information regarding the condition of the propeller, the project will explore the use of a multifidelity approach to combine the numerical simulations conducted during the design phase (which have good spatial coverage) with the SHM measurements at discrete points/areas (which have good accuracy of the condition of the blade) to provide a more comprehensive visualisation (Fig. 5).

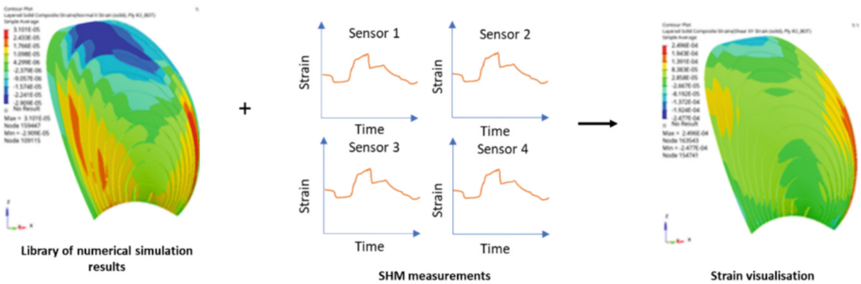


Fig. 5. Concept schematic of multifidelity approach for data visualisation

4 Conclusion and Future Work

The current work in the CoPropel project has identified 2 possible alternatives that are potentially suitable for addressing the challenge of SHM in ship propeller blades. initial prototypes and experimental tests have been presented that indicate promising results and further development and testing will be conducted as the project moves on to the small- and large-scale testing phases.

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