Description of Different Technologies for Ship's Hull Structural Health Monitoring

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ABSTRACT

Traditional ship maintenance protocols rely primarily on preventive strategies based on scheduled inspections or accumulated operational cycles. While effective in ensuring baseline safety, these approaches are often inefficient, leading to unnecessary maintenance or unanticipated failures. Structural Health Monitoring (SHM) systems enable a paradigm shift towards predictive maintenance by continuously assessing the ship's condition in real time. This paper, developed under the scope of the EDF dTHOR project, reviews current and emerging sensor technologies used for hull SHM. Particular attention is paid to acoustic signature monitoring, a key element in defense applications.

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INTRODUCTION

Ships are subjected to diverse internal and external loads that affect their structural integrity and, if unmanaged, may lead to critical failures. Incidents like the structural collapse of the MOL Comfort illustrate the risks of exceeding hull girder strength under extreme bending[1], emphasizing the need for Structural Health Monitoring (SHM) systems to enhance safety and reliability.

These loads can be categorized as global or local, and internal or external, with some overlap. Global loads, such as wave pressure, hydrostatic forces, cargo distribution, and propulsion, affect the entire hull and induce bending, shear, and torsion, leading to deformations like sagging and hogging. Local loads act on limited areas—such as slamming, equipment forces, or mooring tensions—creating localized stress concentrations.

Internal loads arise from mass distribution and machinery-induced forces, including propeller cavitation[2], while external loads result from buoyancy, wave impacts, and pressure variations[3]. Over time, these actions cause structural degradation, where vibration fatigue and corrosion are the most common failure mechanisms[4,5].

Traditionally, ship maintenance follows fixed schedules or cycle-based calendars, which may result in premature interventions or late detection of damage. SHM systems address these limitations by continuously tracking structural parameters such as strain and vibration. Through sensor networks and real-time analysis, SHM enables early damage detection and supports predictive maintenance, allowing condition-based interventions instead of rigid scheduling.

In the defense sector, SHM enhances mission readiness, prolongs platform life, and reduces costs, emerging as a strategic enabler for operational flexibility.

This work has been performed under the scope of the dTHOR project (https://dthor.eu/). The objective of the project "Digital Ship Structural Health Monitoring" (dTHOR) is to develop a system based on innovative utilization of large amounts of load and response measurements from robust and advanced sensors, a digital framework complying with recognized open standards for data exchange, and hybrid analysis and modelling which combines physics-based and data-driven models. dTHOR will consolidate end-users military operational requirements based on improved battle damage and structural integrity assessment, reduced hydro-acoustic signatures, and more accurate operation of weapon systems.

STRUCTURAL MONITORING SYSTEMS

Classification Societies (CS) and other agents have developed guidelines to monitor and assess the influence of various types of loads on the structural health of ships, relying on the installation of sensors capable of identifying such effects [6–8]. More recently, the focus has shifted towards advanced SHM systems, which integrate structural diagnostics and prognostics. These systems combine data fusion from diverse sources, both onboard and onshore, and use physics-based models calibrated by sensors and data-driven approaches to provide relevant structural information [9].

A typical configuration for a SHM system is presented in Figure 1 [3]. Here, the Long Base Strain Gauges (LBSG) are placed on the main deck, along its surface, to monitor global longitudinal stresses and bending moments. On the other hand, Accelerometers (ACC) and Pressure Transducers (PT) are placed forward to register different type of loads (low frequency and impact loads).

Table 1, based on the CS rulebooks [6–8], shows different magnitudes for SHM, related to the most suitable sensors to detect them, including strain gauges like LBSG or SBSG (Short-based Strain Gauges), accelerometers, and others.

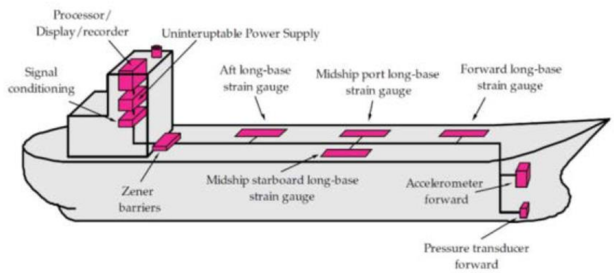

Figure 1. Typical configuration for HSMS [3].

TABLE I. SENSORS USED IN SHM SYSTEMS

Magnitude	Sensors	Location
Global deformations	LBSG / inclinometers	At least four LBSG on the main deck
Local deformations	SBSG / FOS / Relative displacement sensors	Maximum stress locations. Bottom lateral
Rigid body motions	Motion Reference Unit	Near the Centre of Gravity (CdG)
Slamming	ACC / PT / SGSG / FOS	Bottom near forward
Tank sloshing	SBSG / ACC / FOS	Tank walls
Vibrations	ACC	Forward perpendicular
Temperature	Temperature sensor / FOS	At strain gauge locations for temperature compensation
Corrosion	AE / UGW	In the hull plate
Acoustic signature	ACC / Hydrophones / PT	Above the propeller. Areas affected by the vibration of the machinery

In addition to sensors commonly used to monitor the structural behavior of the hull -such as strain gauges (SG) and accelerometers- other technologies are available to assess different aspects of vessel integrity and performance. These include acoustic emission and ultrasonic guided wave techniques for detecting corrosion-related degradation, and systems for capturing the vessel's acoustic signature. While the latter is not directly related to structural health monitoring, it remains important for the design and operational performance of Naval Ships.

TECHNOLOGIES FOR A SHM SYSTEM

Technologies based on accelerometers and strain gauges

Accelerometers and strain gauges are key sensors in Structural Health Monitoring (SHM) systems, providing critical data for assessing ship structural integrity [10].

Strategically placed accelerometers are responsible for monitoring vibrations from machinery, wave impacts, and slamming, with specific locations at the bow, stern, and amidships for vertical bending and roll/sway monitoring [7]. On the other hand, strain gauges measure structural deformation by detecting changes in electrical resistance. LBSG track global deformations, while SBSG measure localized stress (see Table 1).

While significant advancements have been made in sensing technologies, optimizing their placement is crucial for maximizing the effectiveness and cost-efficiency of Hull Structural Health Monitoring (HSHM) systems. Optimal Sensor Placement (OSP) ensures that critical structural modes are accurately captured without redundant data.

Addressing this challenge, Bourikas and Loutas [11] developed a methodology using the Fisher Information Matrix (FIM) specifically for optimizing the placement of strain sensors, focusing on dynamic data acquisition and addressing redundancy. Their work highlighted how damage location significantly influences OSP requirements. Building upon this, within the dTHOR project, a Python-based algorithm was developed by Giannis Stamatelatos [12] to determine optimal locations for multi-dimensional vibration sensors, including accelerometers and Fiber Bragg Gratings (FBGs), further refining OSP techniques for SHM applications.

SHM Box

ISD (https://www.isd.gr/) has developed, in the framework of the EDF dTHOR project, a specific monitoring system composed by one accelerometer and four strain gauges. This system is composed by the SHM box, the mentioned sensors and the embedded software running on the edge.

The sensors are placed forming an L-configuration, with the accelerometer placed in the corner of the L to ensure that strain as a function of acceleration can be identified and correlated. The SHM box, that encapsulates the electronics, batteries and software is presented in Figure 2, left, while the schematic of sensor configuration is show on the left. Here, the red rectangle represents the accelerometer while the blue ones represent the strain gauges.

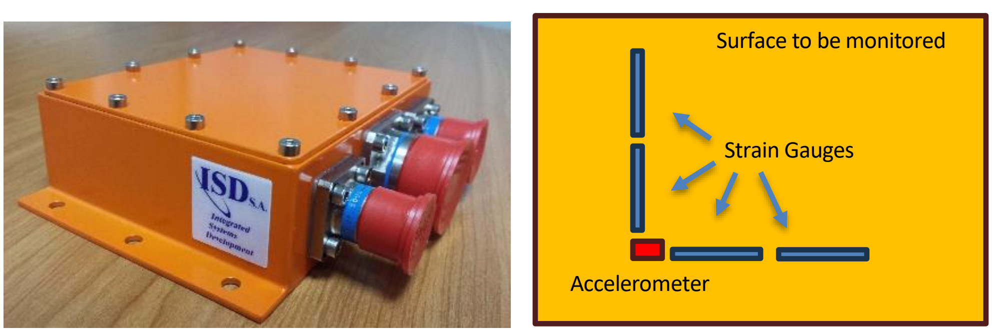

Figure 2. Left: SHM box designed by ISD. Right: Scheme of the sensor configuration.

The SHM system is instrumented by using application software running on a PC. This is a secure application which enables the activation and deactivation of the SHM system, as well as the sampling period and the sampling rate. Decisions on which data analysis is to be done in-situ and the type of data to be saved, etc., are also very powerful features of the ISD SHM box. Using this technology the cumulative stresses in specific areas of the ship that arise from impacts can be monitored in-situ and preventive maintenance interactions can be instigated as appropriate and as a function of measured data and component degradation, once failure criteria have been specified.

Fiber optics sensors

Due to their high-performance characteristics, Fiber Optic Sensors (FOS) are widely used in demanding industries exposed to harsh environments. Their advantages include compactness, low weight, electromagnetic immunity, corrosion and temperature resistance, high sensitivity, and ease of embedment—making them ideal for marine and offshore structures[13]. FOS can be classified according to their spatially resolved measurement type as point sensing, quasi-distributed sensing, and distributed sensing.

Point sensing refers to sensors that measure quantities at discrete locations, including Fiber Bragg Grating (FBG) sensors and interferometric sensors. Although they both rely on the interference of light as a working principle, they use different mechanisms for measuring the physical parameters. FBG sensor technology has been broadly used for simultaneous measurements of strain and temperature in the context of SHM for marine structures, see Figure 3, [13], for easy compensation of the effects of ambient condition changes. They provide high resolution due to their high sampling rate and thus they have been broadly used in SHM application due to the easy embedment into composite hull vessels and their potential for detecting damages in bonded composite structures [14].

Quasi-distributed sensing, refers to a type of fibre optic sensor with multiple sensing elements distributed, not at equal intervals, along the length of the fibre [15]. FBG sensors can also be classified as a quasi-distributed sensing technology in a sense that they can resolve the measuring quantity spatially [13]. FBG sensors, unlike other types of FOS, are intrinsic sensing elements, as the obtained signal is encoded directly in the wavelength form, easing wavelength division multiplexing. They can be easily multiplexed, allowing multiple physical parameters to be measured simultaneously with a single optical fibre, being useful for monitoring complex structures and systems, a technology called Wavelength Division (WDM) -FBG sensing technology [13].

Distributed sensing technologies refer to sensing systems where the entire length of the optical fibre acts as a sensing element, while it also serves as both a transmission fibre and transducer in the sensing system [13]. In distributed sensing, a single optical fibre is used to measure changes in physical parameters such as temperature, strain, pressure, and vibration [16]. Distributed sensors include optical time-domain reflectometry, Raman optical time-domain reflectometry, and Brillouin optical time-domain reflectometry because they are based on Rayleigh, Raman and Brillouin scattering principles, respectively [17]. Distributed sensors measure physical quantities at any location along the fibre length with a spatial resolution in the cm to m range. This allows for large area coverage monitoring-wise while keeping the wiring/cable length low, as opposed to traditional strain gauges or piezoelectric sensors. However, their application requires more complex and expensive interrogator equipment. The advantages of distributed sensing technologies in the context of marine vessels were recently tested and reported in [18], where an Expeditionary Fast Transport vessel of the US Navy was used as a testbed for real-time monitoring of the vessel during normal operation.

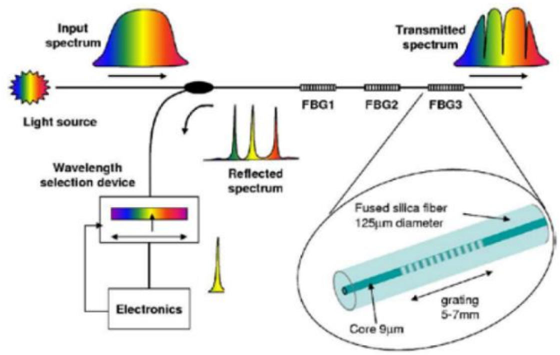

Figure 3. Principle of FBG measurements [13]

Ultrasonic systems for SHM and corrosion monitoring

The evaluation of structural integrity of vessels and the monitoring of active corrosion can involve the use of Acoustic Emission (AE systems). AE systems and testing techniques are based on the use of ultrasonic piezoelectric sensors to ultrasonic waves that are generated inside the material when cracking or other irreversible changes occur [19]. These waves are detected by AE sensors and converted into electrical signals. The signals from the sensors are recorded and analyzed through a data acquisition software.

AE methods are used for the early detection and localization of cracking before failure occurs. An AE methodology has been used to detect corrosion and fatigue crack growth in ship structural elements under different operational conditions, while keeping the environmental noise pick-up at low levels [20] . Effective SHM in ships using AE can be achieved by placing the ultrasonic sensors in a grid arrangement on critical areas of the vessel, to cover large areas with minimal signal loss and to ensure optimal localization of damage-related signals. Another study [21] presented an AE method to monitor hull integrity on a container ship. The AE sensors were placed at critical areas of the vessel, during sea trials. The study demonstrated the AE system's effectiveness in detecting cracking, corrosion, and fretting between crack faces while locating the source of these events. In addition, the background noise was identified and separated from the damage related AE events.

In addition to cracking, structural failure can occur because of corrosion. Corrosion degradation occurs naturally due to exposure to the environment. If unnoticed or ignored, corrosion can lead to failure since cracking can initiate from the affected areas under load. Therefore, corrosion detection is a necessary step to improve the effectiveness of structural integrity monitoring in hulls.

Monitoring of corrosion can be carried out using AE techniques. When corrosion occurs due to the electrochemical reactions involved, hydrogen (H2) is formed on cathode areas producing AE signals. Rapid generation of such signals is associated with accelerated corrosion rates [22].

Loads introduced around corroded sections can produce AE activity related to microcracking and peeling of corrosion layers [23]. Acoustic Emission can be combined with other inspection methods for a comprehensive in-service structural integrity assessment and corrosion detection in various structures [24].

Therefore, real-time ship SHM and corrosion monitoring can be effectively carried out using AE ultrasonic techniques.

ACOUSTIC SIGNATURE ESTIMATION

One of the main concerns of Naval Ships is its acoustic signature, and the efforts to real time monitoring of Underwater Radiated Noise (URN) generated by vessels are becoming more relevant. Three main noise categories are identified: machinery noise, flow noise, and propeller noise. The latter, particularly propeller cavitation, is a dominant noise source and a key research area in underwater noise from shipping.

Sensors for the URN

The acoustic signature management requires the installation of several sensors to monitor the contribution of different sources. The selection of sensors is based on the measurand, range and bandwidth.

Accelerometers are typically used for estimating acoustic signatures in ships, although other sensors like pressure gauges and hydrophones can increase the accuracy of the URN prediction [25], because the measurement of vibration pattern is affected by local contributions, and in some cases, they must be filtered. In the dTHOR project, all these aspects have been investigated to identify the best hardware setup leading to the more accurate predictions. In detail, the study has been structured considering two approaches: the noise radiated by the propeller and by other vibration sources.

From the point of view of the sensor selection, accelerometers have been chosen to monitor both the machinery and the propeller even if the application to the latter has also been investigated using pressure gauges and hydrophones.

Pressure gauges are important to detach the pressure field induced by the propeller because of its hydrodynamic behavior, in cavitating and not cavitating conditions. Although an accelerometer can measure the effect of this pressure field through the vibration pattern induced on the shell plate, the panel itself filters some frequency because of its natural vibration modes. The relationship between pressure and vibration has been investigated through experimental-numerical analysis looking at the effect of the panel dimensioning and the sensor location.

This study led to the definition of specific algorithms aimed at computing the propeller induced pressure field through the measurement of vibration above the propulsor, and then avoiding the needs of a pressure gauge that requires drilling the hull. In Figure 4 the comparison of the URN levels computed through the direct induced pressure pulses and the vibration measurements is shown (Y scale omitted for confidentiality reasons). In this case, the effect of the accelerometer location has been considered and a correction used to fit the gap encountered especially at low frequency has been applied.

In terms of technology, both traditional (current/voltage sensors) and fibre-glass sensors have been considered. Nevertheless, the adoption of fibre-glass technology seems to be the more efficient because of the low number of cables to be laid and the possibility of arranging sensors without current/voltage restrictions, at least over the propeller where tanks are often present. For these reasons, the adoption of fibre-glass sensors can be improved by AI techniques to cover the frequency range beyond the interrogators' constraints through experimental data collection.

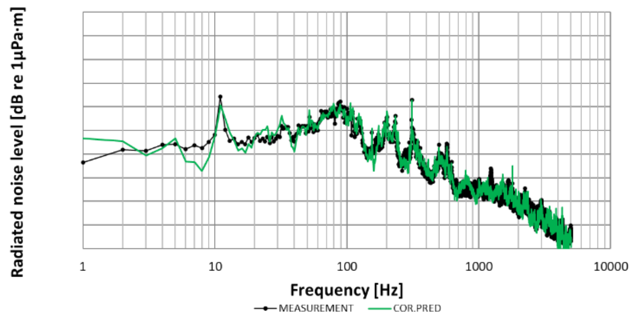

Figure 4. Comparison between the URN level computed through pressure gauges (black lines) and vibration pattern (green lines)

CONCLUSION

The paper highlights advancements in ship Structural Health Monitoring (SHM) under the dTHOR project, emphasizing sensor technologies like accelerometers, strain gauges, and fiber optic sensors for real-time diagnostics and predictive maintenance. It also addresses challenges in acoustic signature management for naval vessels, focusing on sensor optimization and data processing for effective underwater noise monitoring. By integrating innovative sensing systems and hybrid analysis, this work aims to enhance safety, extend ship lifespans, and meet operational demands.

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