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Using Iot Technology For Structural Health Monitoring Applications Of Ships

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ABSTRACT

Structures such as buildings, bridges, and ships have a certain design life. Monitoring the lifetime of these structures, considering damage due to environmental factors, or predicting potential future events is possible by observing changes in the materials of the structures. For this purpose, Structural Health Monitoring (SHM) systems are used. The development of structural health monitoring technology involves observing changes in building materials through periodically sampled response measurements. For data collection and monitoring from these structures at any time and from any location, Internet of Things (IoT) technologies are integrated with the Structural Health Monitoring system. Especially for ships, since ships are more exposed to environmental factors such as wind, waves, and storms, SHM is important to track damages and take necessary actions. This paper provides information about the SHM system on ships, the sensors used for this purpose, IoT technologies for data transmission, and recent advances in how these technologies are integrated and other aspects. SHM implementation is a challenging process owing to the large physical dimensions of ship structures, the variability of environmental factors, and data loss due to damages. In conclusion, information is given on how the SHM system on ships can be improved in the future.

Keywords: Structural Health Monitoring, Internet of Things, Wireless sensors

1. INTRODUCTION

Damage can be defined as the occurrence of a damaging change in any system. It adversely affects its current or future functioning and performance. To detect damage, a comparison can be made between the undamaged initial state and the final state of the system. In structural and mechanical systems, damage will be limited to changes in the durability of structural materials. Changes in materials over time affect the functioning of systems, preventing them from achieving high performance in the future. Usually, damage starts at the material level. Defects or faults, called damage, are present to a certain extent in all materials and systems composed of these materials. Over time, the defects or faults grow to a certain extent under different load scenarios or environmental factors, causing damage at the system level. The initial impact of damage may not be apparent, but accumulated damage over an extended period will eventually lead to the inability of the system to function properly (Farrar et al., 2007). Therefore, timely detection of damage is vital.

For this purpose, SHM systems have been evolved. SHM is the technique of monitoring and predicting damage to the structure by appropriately analyzing data measured by various sensors placed on the structure. This technique is applied in many areas involving various types of structures by detecting damage at earlier stages, identifying its source, and assessing it. Thanks to SHM, it is possible to prevent significant financial losses that may occur in the future due to damage, by detecting them in the early stages (Abdulkarem et al., 2019).

Structural Health Monitoring (SHM) is used not only for structures such as aircraft, bridges, towers, nuclear facilities, and tunnels but also for marine vessels (Brownjohn, 2007). Marine vessels are subjected to dynamic loading from the harsh marine environment. Marine environmental factors can cause damage due to short-term overloading or long-term loading, as well as thickness reduction due to corrosion and erosion. Implementation of SHM systems is essential to guarantee the dependability of ships and other marine vessels, improve human and environmental safety, and reduce maintenance costs. SHM systems are widely used on ships and other marine vessels (Kefal et al., 2015). Ships are more prone to damage due to harsh environmental conditions. In ships, real-time acquisition and monitoring of structural displacements and stresses are realized with the information obtained from stress sensors. Structural Health Monitoring should have functionalities such as real-time damage detection capability with data from stress sensors and the ability to predict the future state of structural properties by receiving data from sensors such as failure modes, fatigue properties, and material corrosion properties (Kefal et al., 2015).

Damage to structures can be detected by evaluating data from integrated sensors that transmit data wirelessly. The collection, cloud storage, and subsequent evaluation of data from remotely located structures is made possible by the recently popularized Internet of Things technology. IoT technologies have emerged as an important technology for monitoring systems as a result of the combination of rapidly evolving sensing technologies such as sensors and wireless communication, and information technologies such as the Internet. IoT is being integrated into SHM systems for robust and reliable monitoring and tracking.

The rest of the study is structured as follows: Information about similar studies on SHM on ships is given in the Literature Review. In the second section, IoT Based SHM Structure Overview, information about SHM structure, structural health monitoring process and damage diagnosis, Sensors, and IoT Technologies are given. In the section SHM and Sensor Locations for Ships; information about SHM applications on ships is given. Finally, in the Conclusion section; conclusions and future applications are given.

2. LITERATURE REVIEW

It is observed that there are many studies in the literature where structural health monitoring systems are integrated into ship structures. Sielski emphasized the importance of a SHM system that can improve the safety of high-speed aluminum ships in particular. The research provides information on fatigue cracking of aluminum structures and focuses on future implications, highlighting the potential impact of this damage on safety and ship integrity. Fatigue strength tests are conducted at the Sea Surface Warfare Center, where the process of beginning crack and growth is monitored. A study has been conducted at the Naval Research Laboratory and the University of Connecticut to evaluate the structural entirety of ships through a semi-analytical assessment of the oscillation of chapped plates. A Bayesian Markov chain Monte Carlo technique was developed to guess parameters. A project at Lehigh University aimed to develop a multi-criteria optimization formulation for the reliability, tracking, and sustaining of ship structural systems in the event of ambiguity. A study at Cornell University centered on developing an adaptable, robust, and general computational framework for model-based hull SHM using CU-BEN finite element software (Sielski, 2012). Okasha et al. argued that assuring the sufficiency of the life span performance of ship structures can effectively contribute to ship safety. The resistances to vertical bending moments at the final failure and initial failure were computed employing an optimization-based approach for the ultimate failure moment and a progressive collapse method for the initial failure moment. The probabilities of failures were calculated with the use of the hybrid Latin hypercube sampling method known as SORM. In their study, they used Bayesian deduction concepts that allow the incorporation of earlier knowledge necessary to update load effects with SHM data. They tested their approach on the Joint High-speed Sealift Ship (JHSS). SHM data from tests on a scale model of the JHSS ship were used to update the life span of ship performance (Okasha, 2010). Kefal et al. developed an intelligent system in their study to determine the ideal location of stress sensors on the ship. They used hydrodynamic, finite element, and iFEM software to create a new system. In their system, hydrodynamic analysis was first carried out to decide the hydrodynamic loading and rigid hull movement of the ship. Then, finite element analysis was carried out to get the simulated sensor stress and structural response data. Finally, iFEM analysis was carried out. iFEM analysis uses simulated stress data acquired from distinct numbers of sensors at different places on the ship. With the system they developed, they tried to decide the optimum points for placing sensors on the ship (Kefal, 2015). Wang and his colleagues conducted a study on the necessity of a ship hull monitoring system and its potential roles at various phases of the life span of the ship. They agreed that fiber optic sensors are highly appropriate for this application. For this purpose, they used Fiber Bragg Grating technology, which involves periodic modulation of the refractive index at the core of the optical fiber. This technology was used in the Composite Hull Embedded Sensor System Project (CHESS). CHESS was set up on a Norwegian Navy ship and the results of systematic sea-keeping tests using this system were demonstrated. With this study, the importance of Fiber Bragg Grating technology in the context of composite hull-embedded sensor systems was emphasized. The results obtained from the CHESS installation on a Norwegian navy ship have shown that it plays a critical role in ship design verification (Wang et al., 2001). Fault detection systems are generally organized independently from SHM systems and added to ship systems. In their work, they created an integrated system that uses Support Vector Machine (SVM) for both fault detection and SHM. They used a combination of model-based and data-driven methods for fault detection. These systems have both advantages and disadvantages in fault detection. They used SVM to attain a numerical trade-off between false alarm rate (FAR) and fault detection rate (FDR), leading to higher fault detection rates. Simulations on a ship propulsion system demonstrate the effectiveness of the developed method. This indicates that this integrated approach using SVM for fault detection and SHM aims to offer a comprehensive solution to improve the performance of ship systems (Zhou et al., 2018). In previous studies, the cross-correlation technique (CAV) between passive sensors of interacting vibrations has been used to predict the impulse response (or Green's function). The cross-correlation technique (CAV) is based on extracting a given time signature from the calculated noise cross-correlation function between passive sensors without using controlled active sources. Assuming that the ambient structural noise field stays the same, the results acquired from CAV can be used for SHM even though they are not the same as the real impulse response amongst passive sensors. Low-frequency random vibration investigation was carried out experimentally by Sabra et al. using data from an aluminum maritime vessel that was operating in high seas (Sabra et al., 2011).

3. IOT BASED SHM SYSTEM OVERVIEW

Structural Health Monitoring (SHM) is performed through damage detection, localization, and assessment of different types of structures at early stages, resulting in increased safety and reduced maintenance costs. Three main parts make up the SHM system: a data processing system, a health assessment system, and a sensor system.

In the initial stage of the sensor system, sensors measure important environmental characteristics including humidity, temperature, and wind speed in addition to structural data parameters like velocity, displacement, and stress. For an evaluation to be accurate, the data must be precise and correct.

The second stage, data processing, includes data collection, transmission, accumulation, processing, and storage. Instead of traditional wired systems, Wireless Sensor Networks (WSN) systems and IoT systems are used as data processing and transmission systems for SHM. The sensor nodes that are placed on a structure make up wireless sensor networks. To send data to a base station over the network, every node works together with other nodes. Sensor nodes can send data packets to the base station or immediately transmit the measured data, depending on the type of transmission network being utilized. Wireless Sensor Networks may communicate thanks to the Internet of Things technology.

In the third stage, data accumulation and processing are performed in the health assessment system. The SHM system using Wireless Sensor Networks is shown in Figure 1 (Abdulkarem et al., 2019).

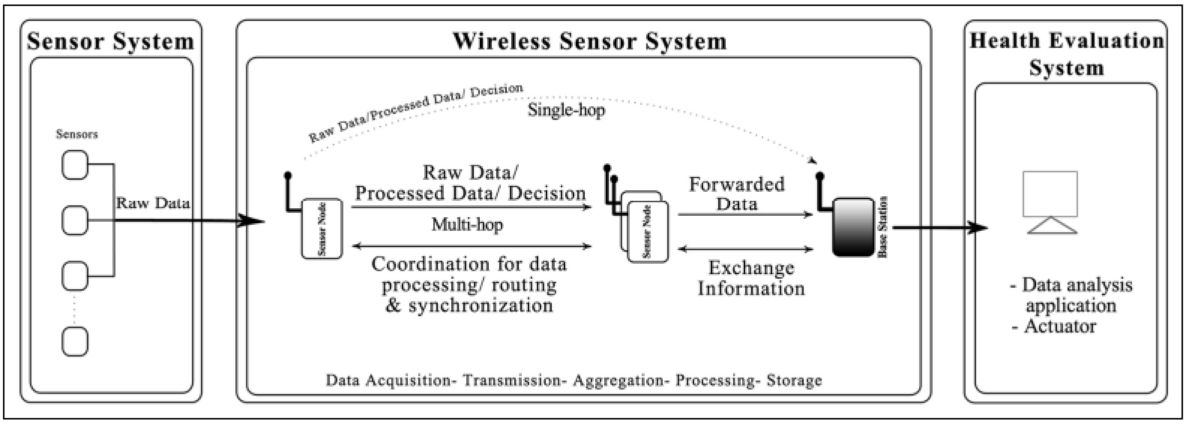

Fig.1. SHM system structure (Abdulkarem et al., 2019).

Structural Health Monitoring Process and Damage Assessment

Damage assessment is carried out based on specific processes within Structural Health Monitoring. Damage assessment is usually carried out in a four-stage process:

1-) Operational Assessment: In this phase, four questions related to the application of the SHM system are attempted to be answered. The first question relates to how the system under observation defines damage. The second question is about the operational and environmental situations of the monitored system. The third question is the constraints related to data collection in the operational environment. The last question is about which technological elements are capable of ensuring the life safety required for monitoring (Farrar et al., 2010).

2-) Data Collection, Aggregation, and Cleaning: During data collection in the SHM process; determining the kinds of sensors that will be employed, determining the locations where the sensors will be installed, and deciding how many sensors to use are carried out. Fiber optic sensors and MEMS sensors are new sensor systems developed for SHM. They are in a key position to receive data on the structure to be monitored. It is necessary to integrate large amounts of incoming data to make it meaningful. Data fusion integrates data from multiple sensors, not from a single sensor, to enable reliable damage detection (Farrar et al., 2010).

3-) Feature Extraction and Information Condensation: Feature Extraction is the ability to distinguish between damaged and undamaged structures with the data obtained from the measured system (Farrar et al., 2010).

4-) Statistical Model Development for Feature Separation: This is the stage where statistical pattern recognition algorithms are applied to the data obtained for damage detection. Algorithms such as supervised learning, unsupervised learning, neural networks, genetic algorithms are used for damage detection (Farrar et al., 2010). This stage consists of four steps: detection, localization, characterization, and prediction (Stull et al., 2011).

Sensors and IoT technologies

To detect and monitor damage to structures through Structural Health Monitoring (SHM), appropriate sensors should be added based on the kind of damage that has to be found. Sensors provide information about the damage occurring inside structures. The more data obtained, the better the damage detection can be performed. For this purpose, actuators are also used together with sensors. The sensor or actuator systems are categorized as active or passive based on the source of the signal and regardless the signals are distributed throughout structures. Passive methods use only sensors. Structure abnormalities like corrosion, deformation, or material perforation can be found using the sensor data. Active methods receive and evaluate data from radiated and external signals (Burgos et al., 2020). Many sensors have been developed for different types of damage such as fiber optic sensors, RFID sensors, Fiber Bragg Gratings (FBG), Microelectromechanical systems (MEMS), Acoustic-Ultrasonic (AU), Comparative Vacuum Monitoring (CV), Acoustic Emission (AE), Sensitive Coatings (SC), Environmental Distortion Monitoring Sensors (EDMS), Microwave sensors (μW), Imaging Ultrasonics (IUs), Foil Eddy Current sensors (ET).

Implementing SHM systems in an IoT environment is possible using a large-scale sensor network. Communication between sensors is facilitated by their unique IPv6 addresses. Sensors and sensor nodes are strategically placed at specific points on the structure to be monitored. Sensors placed on the structure measure the data to be tracked and encapsulate this data into an IPv6 packet. The data is then transmitted to a data collection point, often referred to as a "sink". Communication between sensor nodes requires more energy. Technologies such as ZigBee, LoRaWAN, and Sigfox have been developed to reduce energy consumption (Mouitz et al., 2001).

4. SHM SYSTEM AND SENSOR LOCATIONS ON SHIPS

It is especially important to be able to detect problems with the SHM system so that structures such as ships can be used reliably for many years. With SHM, the location, and magnitude of the fault in the structure become possible with the sensors used. SHM systems are installed by determining the kind of sensor to be employed, the number of sensors, and the location of the sensor. Figure 2 shows how the defect in the hull of the ship is detected using a digital twin system. Digital twinning is the process of creating a virtual simulation of a physical object, emulating its properties, and analyzing them in real-time. Figure 2 shows the digital twin method used to detect damage anywhere on the ship's hull. Fault data was received by the sensors at an unknown location. By creating a digital object of the ship and using different machine-learning models, the actual location of the fault was determined (Anyfantis et al., 2021).

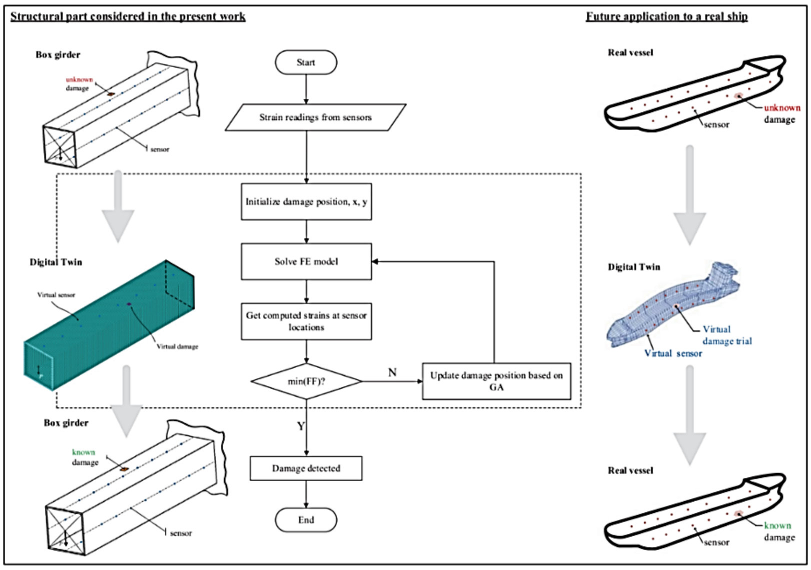

Fig. 2. Using a digital twin system for damage detection (Anyfantis et al., 2021).

The SHM system, together with the sensors used in this system, enables hull monitoring, damage detection, and hull durability assessment. In addition, the SHM system provides the ability to monitor and record operating parameters, ship motion, and sea waves (Torkildsen et al., 2005). Among the many sensors integrated into the SHM system are those measuring air pressure, measuring impact wave profiles, measuring weight distribution, determining the position and speed of the ship. Due to the advantages of composite materials such as design versatility, FGB has a wide range of applications in ships (Mouitz et al., 2001).

Fiber Bragg Grating (FBG) sensors are widely used on ships due to their advantages. The idea of using The original purpose of FBG sensors aboard ships was to track both dynamic and static stresses at crucial points on the hull. The sensors are placed at different points on the hull and measure the forces acting on the hull (Torkildsen et al., 2005). Skjold-class Fast Patrol vessel, the Norwegian HnoMS Skjold is currently the largest all-composite maritime patrol vessel ever built. (Mouitz et al., 2001). HnoMS Skjold was constructed in 1999 (Wang et al., 2001). HnoMS Skiold is a double-hulled Surface Effect Ship (SES) made of fiber-reinforced polymer composite sandwich panels. The SES operates on the principle of an air cushion sandwiched between the hulls through which lifting fans blow air.

A system called CHESS has been installed on the composite hull of HnoMS Skjold for Structural Health Monitoring. This system collects information about the loading of the ship under normal operating conditions. The location of the sensors used on board HnoMS is shown in Figures 3 and 4.

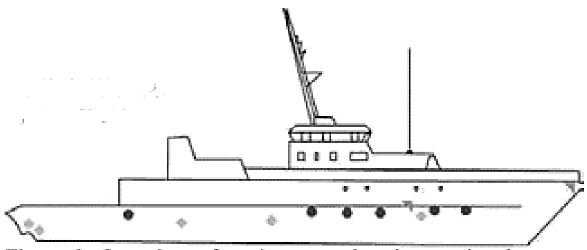

Fig. 3. Sensor locations on the HNoMS Skjold (Torkildsen et al., 2005).

Developing a Finite Element Method (FEM) model that enables the estimation of the stress field in the wave-loaded hull in various sea conditions is the initial stage in the design of the SHM system. The locations of Fiber Bragg Grating (FBG) sensors installed in the HNoMS Skjold's hull were ascertained using the computed stress fields (Wang et al., 2001). The sensors, which are depicted in Figure 3, made it possible to collect and analyze data for the most significant wave loads, including torque (rotational moments), vertical shear force, horizontal bending, vertical hogging/sagging, and longitudinal compressive force (Wang et al., 2001).

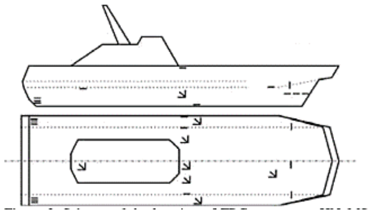

Fig. 4. FGB sensors placement on the HNoMS Skjold (Wang et al., 2001).

In addition to the hull of the ship, the sensors can also be placed on the mast section. Figure 5 shows the FBG and ACC sensors placed on the mast of the Horyzont II. FGB sensors are located at the lowest part of the mast in which the anticipated stress level is maximum. Situated at the base of the mast on the navigation deck is the piezoelectric accelerometer (ACC). The ACC sensor provides a low-frequency recording of the ship's motion in different directions.

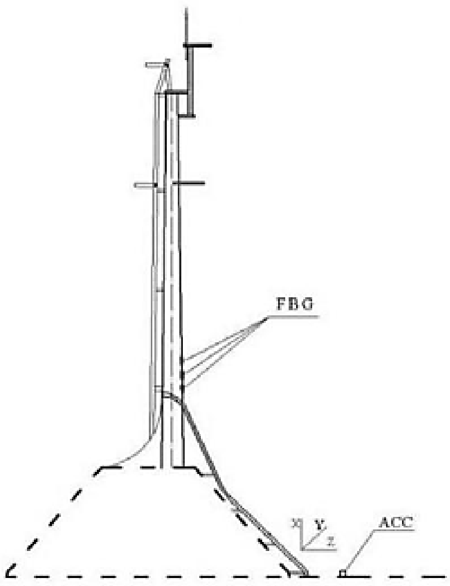

Fig. 5. Sensors locations on Horyzont II ship with FBG and ACC sensors (Murawski et al., 2012).

5. CONCLUSION

SHM system for ship structures is vital. In this study, an overview of the SHM structure, sensors, the importance of sensors in the SHM system, and the Internet of Things (IoT) technologies used in sensors are presented. In the last section, how the sensors are positioned on the ships and how damage detection is performed is explained using the Horyzont II ship and the HNoMS Skjold boat. SHM and sensors play a significant role in quickly detecting damage to ships and preventing potential major accidents and financial losses. Ongoing work is focused on improving SHM and sensor technologies.

REFERENCES

Abdulkarem, M., Samsudin, K., Rokhani, F. Z., & A Rasid, M. F. (2019). Wireless sensor network for structural health monitoring: A contemporary review of technologies, challenges, and future direction. Structural Health Monitoring. doi:10.1177/1475921719854528

Anyfantis, K. N. (2021). An abstract approach toward the structural digital twin of ship hulls: A numerical study applied to a box girder geometry. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 235(3), 718–736. doi:10.1177/1475090221989188

Brownjohn, J. M. W. (2007). Structural health monitoring of civil infrastructure. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 365(1851), 589–622. doi:10.1098/rsta.2006.1925

Burgos, D. A. T., Vargas, R. C. G., Pedraza, C., Agis, D., & Pozo, F. (2020). Damage Identification in Structural Health Monitoring: A Brief Review from its Implementation to the Use of Data-Driven Applications. Sensors, 20(3), 733. doi:10.3390/s20030733

Farrar, C. R., & Worden, K. (2007). An introduction to structural health monitoring. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 365(1851), 303–315. doi:10.1098/rsta.2006.1928

Farrar, C. R., & Worden, K. (2010). An Introduction to Structural Health Monitoring. CISM International Centre for Mechanical Sciences, 1–17. doi:10.1007/978-3-7091-0399-9_1

Kefal A., Hizir O., Oterkus E. (2015). A smart system to determine sensor locations for structural health monitoring of ship structures. Conference: 9th International Workshop on Ship and Marine Hydrodynamics - IWSH 2015At: Glasgow, United Kingdom

Mouitz, A.P., Gellert, E., Burchill P., & Challis, K. (2001). Review of advanced composite structures for naval ships and submarines, Compos. Struct. 53, 21–41.

Murawski L., Opoka S., Majewska K., Mieloszyk M. & Ostachowicz W. (2012). Investigations of Marine Safety Improvements by Structural Health Monitoring Systems, International Journal on Marine Navigation and Safety of Sea Transportation

Okasha, N. M., Frangopol, D. M., & Decò, A. (2010). Integration of structural health monitoring in life-cycle performance assessment of ship structures under uncertainty. Marine Structures, 23(3), 303–321. doi:10.1016/j.marstruc.2010.07.004

Sabra, K. G., & Huston, S. (2011). Passive structural health monitoring of a high-speed naval ship from ambient vibrations. The Journal of the Acoustical Society of America, 129(5), 2991–2999. doi:10.1121/1.3562164

Sielski, R. A. (2012). Ship Structural Health Monitoring Research at the Office of Naval Research. JOM, 64(7), 823–827. doi:10.1007/s11837-012-0361-x

Stull, C. J., Earls, C. J., & Koutsourelakis, P.-S. (2011). Model-based structural health monitoring of naval ship hulls. Computer Methods in Applied Mechanics and Engineering, 200(9-12), 1137–1149. doi:10.1016/j.cma.2010.11.018

Torkildsen, H.E., Grøvlen, A., Skaugen, A., Wang, G., Jensen, A.E., Pran, K., Sagvolden, G. (2005). Development and Applications of Full-Scale Ship Hull Health Monitoring Systems for the Royal Norwegian Navy, Proc. Recent Developments in Non-Intrusive Measurement Technology for Military Application on Model- and Full-Scale Vehicles, Neuilly-sur-Seine, 22-1 – 22-14.

Wang, G., Pran, K., Sagvolden, G., Havsgård, G. B., Jensen, A. E., Johnson, G. A., & Vohra, S. T. (2001). Ship hull structure monitoring using fibre optic sensors. Smart Materials and Structures, 10(3), 472–478. doi:10.1088/0964-1726/10/3/308

Zhou, J., Yang, Y., Ding, S. X., Zi, Y., & Wei, M. (2018). A Fault Detection and Health Monitoring Scheme for Ship Propulsion Systems Using SVM Technique. IEEE Access, 6, 16207–16215. doi:10.1109/access.2018.2812207