Development and Applications of Full-Scale Ship Hull Health Monitoring Systems for the Royal Norwegian Navy

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SUMMARY

FFI has through a number of projects been engaged in the development of ship hull structural health monitoring (SHHM) systems for the Norwegian Navy. Important goals are to increase safety, reduce damage and improve the operational utilization of the ship within the design limits, and reduce cost by condition based maintenance. The development of a practical SHHM system is based on the utilization of modern fiber optic sensor technology, detailed Finite Element Analysis (FEA) of the ship hull, and a modular, scaleable signal processing and data storage computer system. The system gives real-time information on both the global wave load on the hull and the local load in a number of selected critical areas. An Extended SHHM (ESHHM) includes monitoring and recording of the ship motion and operating parameters in order to get a complete picture of the parameters influencing the hull load. Detailed characterization of the sea state is obtained by means of a wave radar and a microwave altimeter mounted in the bow which measure the meeting wave profile. An extended system has been installed on the Royal Norwegian Navy (RNoN) Mine Counter Measure Vessel (MCMV) "HNoMS Otra", and data is recorded and transmitted in batches to FFI for post processing during the test period. The paper presents a thorough introduction to the SHHM system and its applications, in addition to results and analyses of the data recorded onboard RNoN MCMV "HNoMS Otra".

1.0 INTRODUCTION

The Norwegian Defence Research Establishment (FFI) has been involved in the development of a fiber optic Structural Health Monitoring (SHM) system since 1995 ([1]-[2]). The system employs Fiber Bragg Gratings (FBG) and a Fabry Perot filter based interrogation technique ([3]), and the Norwegian company Light Structures AS ([4]) is the commercial supplier of this system.

The FFI activity has recently focused on the design of a full-scale Ship Hull Health Monitoring (SHHM) system for the Royal Norwegian Navy (RNoN) Oksøy/Alta-Class Mine Counter Measure Vessels (MCMV) and the Skjold-Class Fast Patrol Boats (FPB) ([5]). The system is also planned for the Fritjof Nansen-Class Frigates.

The SHHM system calculates the hull loads using a Finite Element Model (FEM) of the ship ([6]) to transform the FBG strain and temperature sensor measurements into corresponding loads. An Extended SHHM (ESHHM) will also include monitoring and recording of the ship motion and operating parameters. Sea waves are characterized by means of the system Wavex ([7]) connected to the navigational radar. The Wavex system provides statistical parameters such as wave direction, wave height

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and wave length from an area in front of the vessel. The profile of the approaching waves in the bow of the vessel is measured using a radar altimeter, and the ship motion is compensated for by data from an Inertial Navigation System (INS).

A distributed signal processing system accumulates and synchronizes the measurements from the different sensor systems. The signal processing system consists of several modules communicating on a TCP/IP socket, which makes the system scalable and adaptive. Real-time processing and Graphical User Interface (GUI) on the bridge, in the machine control and operation room, provides the crew with information on hull loads and sea states. Alarms are activated when the hull loads approach the ship design limits.

A full-scale ESHHM system has been installed on the RNoN MCMV "HNOMS Otra" [8], which is a weight-optimized Surface Effect Ship (SES) built in Fiber Reinforced Plastic (FRP) sandwich composite materials. The system logs all of the essential measurants mentioned above, and the data is sent to FFI for further analyses and filing on a weekly basis during the test periods.

The short-term purpose of the MCMV installation is to establish maneuvering guidelines and operational limits from the measurements of the global and critical local loads of the hull. The primary objectives are increased safety, optimized utilization of the platform and reduced maintenance costs. The installation will form a basis for the further development and installation of SHHM systems on the Oksøy/Alta-class MCMV and Skjold-class FPB series.

The SHHM system has a number of significant applications in addition to the above mentioned, such as; verification of model tank results, condition-based maintenance to reduce cost and non-operative periods, damage detection and evaluation of residual hull strength, monitoring of the acoustic signature and internal noise of the ship, input to the combat system, and the collection of detailed sea state information for use in oceanographic information systems. The methodology may also be easily transferred for use on other platforms (in a dynamic or static environment), such as monitoring of aircrafts and bridges.

This paper will present a thorough introduction to the SHHM system and its applications, in addition to results and analyses of the data recorded on the current installation on RNoN MCMV "HNOMS Otra”.

2.0 FIBEROPTIC SHIP HULL HEALTH MONTORING SYSTEM (SHHM)

The main component in the SHHM system is a network of fiber optic strain and temperature sensors. Static and dynamic strains are measured at critical positions of the hull. A Finite Element Analysis (FEA) of the ship hull is required for optimum location of the fiber optic sensors. The sensors should be located for measurements of global moments and forces acting on the hull and for measurements of local stress at locations critical to the ship design.

2.1 Fiber Optic Sensors

Fiber optic sensors are well suited for structural health monitoring on naval ships, due to their ability to withstand harsh environments, immunity to electromagnetic interference and reduced cabling installation cost when employing wavelength multiplexing and multi-fiber cables. In addition, the reduced noise typically seen in fiber sensor installations, as compared to conventional strain gage techniques, improves the accuracy of advanced SHM data analysis methods.

The SHHM system developed by FFI is based on Fiber Bragg Gratings and a Fabry-Perot filter based interrogation technique [9]. The performance of the system is limited by the interrogation hardware alone, and the performance can therefore be upgraded without altering the sensor network. In addition to high bandwidth measurements, the system also provides static measurements of strain and temperature, which in turn allows for the monitoring of static deformations of the hull.

The integrated sensor packages (Figure 1) facilitate easy installation onboard ships. It consists of fiber Bragg gratings embedded in a sensor film glued directly onto the measurement surface. Since the strain distribution in FRP sandwich composite materials is anisotropic (i.e. non-uniform), it is required to use rosettes in some locations in order to determine the main components in the distribution. A complete strain characterisation is also necessary for detection of local overload (Tsai-Wu last ply failure criteria, [3], [6] and [10]). In addition, the sensor package includes an FBG temperature sensor. FBG sensor strings embedded in the surface are also used. The fiber optic strain sensor system installed onboard RnoN MCMV "HNOMS Otra" consists of 36 strain sensors and 8 temperature sensors. Most sensors are located in an amidships cross-section of the hull, as shown in Figure 2. The sensors are used to estimate the most important global moments and forces acting on the hull, but sensors are also mounted in exposed areas in the forepeak, the superstructure and the wet deck. The string of 6 FBG sensors embedded in the wet deck between the keels provides monitoring of slamming.

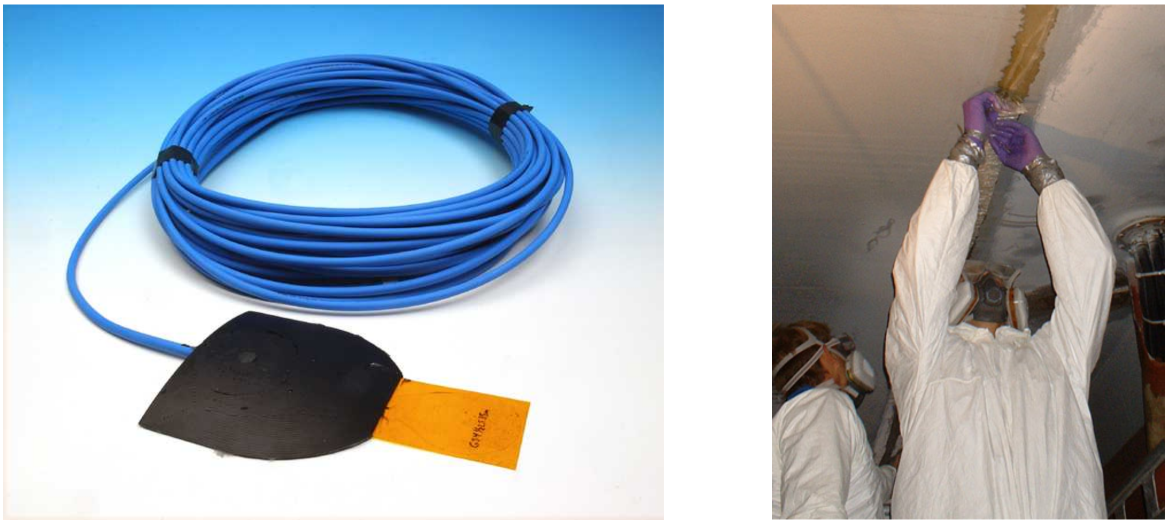


Figure 1 Left) The integrated strain sensor package based on Fiber Bragg gratings. Right) Installation of embedded string of sensors

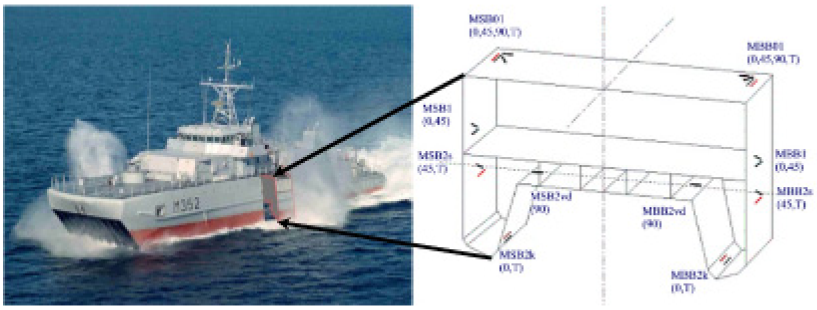


Figure 2 Global moments found from FBG sensors mounted in the amidships section of the hull

2.2 Finite Element Model (FE Model) of Ship Hull Stress and Strain Distributions

The DNV High Speed Light Craft (HSLC) rules [11] specify extreme design values for the sagging moment (a), hogging moment ($-a$), horizontal bending moment (b) and longitudinal twisting moment (c). On a vessel, these extreme loads will appear at a cross section close to amidships (see[6]). In order to be able to measure these extreme values, a cross section close to amidships has been instrumented with fiber optic FBG sensors. Using an FE Model of the ship hull, a “stiffness” matrix $\mathbf{K}$ is determined for the sensor locations amidships. The relation between the global loads $\mathbf{f} = \left[a,b,c,d,e\right]^T$ and the strain $\boldsymbol{\varepsilon}$ is given by

$$\boldsymbol{\varepsilon} = \mathbf{Kf} = \mathbf{K}\left[a,b,c,d,e\right]^T \qquad (1)$$

where d is vertical shear force, and e is longitudinal normal force. Using Singular Value Decomposition (SVD) the pseudo inverse $\mathbf{K}^+$ of the “stiffness” matrix $\mathbf{K}$ can be determined and the global moments represented by **f** can be found from

$$\mathbf{f} = \mathbf{K}^+\boldsymbol{\varepsilon} \qquad (2)$$

The total measured strain $\boldsymbol{\varepsilon}_{MEA}$ is calculated from

$$\boldsymbol{\varepsilon}_{MEA} = \boldsymbol{\varepsilon}_{GLOBAL} + \boldsymbol{\varepsilon}_{LOCAL} \qquad (3)$$

where $\boldsymbol{\varepsilon}_{GLOBAL}$ is the strain originating in the global moments $\mathbf{f}$, and $\boldsymbol{\varepsilon}_{LOCAL}$ is the strain originating in local vibrations. There is no general method to separate global and local strain. If we can assume that the local vibrations are small and uncorrelated, the error using

$$\mathbf{f}=\mathbf{K}^+\boldsymbol{\varepsilon}_{\mathrm{MEA}} \qquad (4)$$

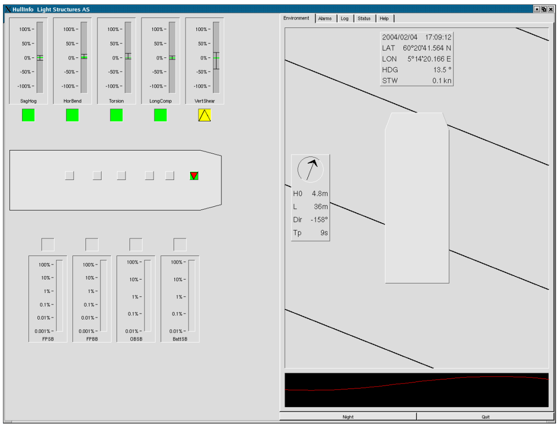
can be reduced by increasing the number of strain sensors as compared with the number of global moments being estimated. The local strain contribution is given by:

$$\boldsymbol{\varepsilon}_{LOCAL} = \boldsymbol{\varepsilon}_{MEA} - \mathbf{KK}^+\boldsymbol{\varepsilon}_{\mathrm{MEA}} \qquad (5)$$

$\boldsymbol{\varepsilon}_{LOCAL} << \boldsymbol{\varepsilon}_{MEA}$ indicates that the error is small.

2.3 Data Processing System

A fiber optic network connects all sensors in the ESHHM System and the distributed network of FBG sensors with a real time distributed data processing system ([12]and [4]). The data processing system is modular, where each module performs a single operation on the data stream such as filtering, transforming, or presentation. The modules in the data-processing system communicate using standard TCP/IP sockets. A communication protocol and data format defined by a common library are used, and may therefore be linked together in any order to meet the signal processing tasks at hand. The inter-module communication protocol is network transparent, which makes the signal processing system easily scalable as computers may be added to meet increased computational demands. Processed data is presented to the crew by means of Graphical User Interfaces (GUI) (Figure 3) on the bridge, in the machine control room, and operational rooms.



2004/02/04 17:09:12
LAT 60°20'41.564 N
LON 5°14'20.166 E
HDG 13.5 °
STW 0.1 kn

H0 4.8m
L 36m
Dir -158°
Tp 9s

Figure 3: GUI presenting real-time loads on the hull, alarms and sea state parameters

The GUI presents the loads on the hull in both real-time and historic views. In addition, the most critical sea state parameters such as significant wave height, wave direction and wavelength are presented. All acquired data are time-tagged and stored on DVD's for shipment and post-processing at FFI.

3.0 EXTENDED SHIP HULL HEALTH MONTORING SYSTEM (ESHHM)

In order to get complete information on the total interaction between sea state, ship movements and speed, operational parameters and fuel weight, and the static and dynamic response of the hull are measured by means of the Extended SHHM system (ESHHM). The data system has been expanded to receive and process information from a number of additional sensor systems, which are either already available onboard or specially installed.

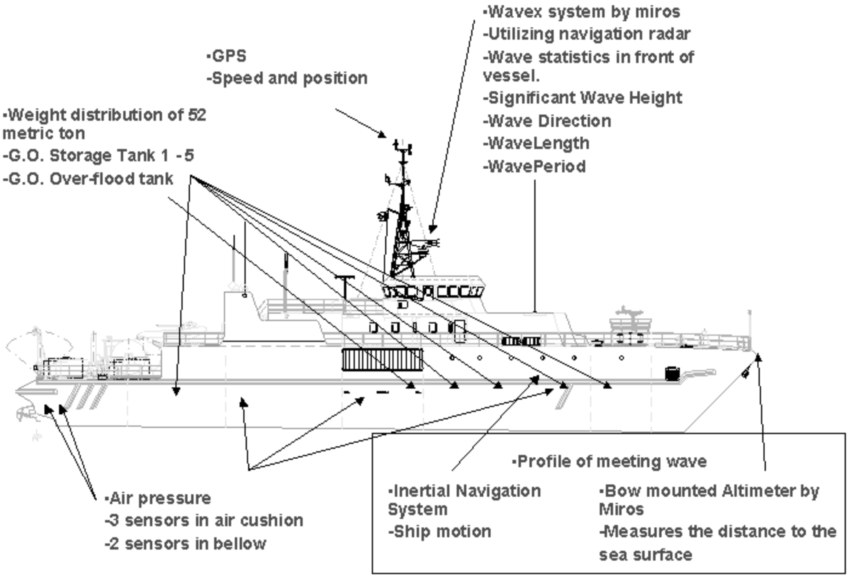


Figure 4: Overview of environmental and operational sensors on RNoN MCMV "HNOMS Otra"

A prototype ESHHM system has been installed on RNoN MCMV "HNOMS Otra" and data are collected during routine operations (see Figure 4). This data will, in addition to data collected during systematic sea trials, be used in a study to establish guidelines for operational limits based on the static and dynamical load on the hull. Depending on the results it is planned to install ESHHM systems on all of the Mine Counter Measure Vessels. This activity represents a step in a long term process which lead to the installation and utilization of SHHM systems on all ships in the Norwegian Navy: mine counter measure vessels, fast patrol boats, frigates and coast guard vessels. The work will comprise of development, procurement and installation of cost effective systems in addition to development of methodology and routines for realization of the various applications of structural health monitoring systems, see Section 4.0.

3.1 Sensor and Control System Integration

Table 1 lists the sensors integrated in ESHHM, and establishes a common set of terms for the different quantities measured (see also [11]).

Condition	Sensors	Measurant
Local hull loads	FBG string on wet deck	Slamming induced strain on wet deck panels
Global hull loads	FBG sensors amidships	Sagging/hogging moment Torsion Horizontal bending moment Vertical shear force Longitudinal normal force Split moment
Sea State	Radar altimeter Wave radar (Wavex [7])	Wave profile at the bow Significant wave height Wavelength Wave direction Wave period
Ship Motion	Inertial Navigation System (INS) Global Positioning System (GPS)	Heave Pitch Roll Yaw Body accelerations Body rotation rates Speed Course Position
Ship State	Fuel tanks Ride controller	Bunker level Air cushion pressure

Table 1: Sensor overview in the Extended SHHM

3.1.1 Sea State

The sea state is characterized by means of an ocean wave measurement system coupled to the navigation radar and a microwave altimeter mounted in the bow measuring the distance to the sea surface. The signal processing system Wavex [7] connected to the X-band navigation radar provides the means for measuring the directional ocean spectra based on analysing sea surface backscatter data. Statistical data such as significant wave height, period and wavelengths for all directions can be calculated by means of the directional spectrum. The wave height in front of the vessel is measured by a wave altimeter mounted in the bow measuring the distance to the surface. Wave monitoring is important in order to establish operation limits for the crew, relating the sea state to the corresponding hull load.

3.1.2 Ship Motion

Ship motion and speed are measured by means of INS and GPS. The wave monitoring will give vital information on the sea state itself while the ship motion sensors will give information on how the sea state actually affects the ship. This again can lead to a more complete picture of the relations between sea state, ship motion and hull loads. Monitoring the ship motion makes it possible to introduce additional parameters that can be of importance for the magnitude of hull loads. Ship motion information is also used to correct the radar altimeter measurements to obtain the wave height in front of the vessel.

3.1.3 Ship State

The system is also connected to the data and control system of the ship in order to receive operational parameters that influence the mechanical load on the hull, for instance, fuel, ballasting, trim and air cushion pressure on SES.

All of the above states and measurants are integrated in ESHHM in order to encounter the significant parameters influencing the hull load and produce a useful and effective tool for ship operation reducing the loads.

4.0 APPLICATION OVERVIEW

The ESHHM system can play an important role in increasing safety, reducing cost, and increasing lifetime of the hull during the total lifespan of a ship. The applications can to some extent be realized by a stand-alone fiber optic sensor system with online presentation of the global loads, but an ESHHM system as described in Section 3.0 is required in order to fully take advantage of the system.

Modern ship design is based on extensive use of FE modelling, which is also required to determine the stiffness matrix $\mathbf{K}$. It would probably be cost saving if the sensor locations were to be determined during the mechanical ship design. At that stage, one should also consider mounting additional sensors in order to verify critical design details, which cannot be modelled with sufficient reliability. Significant cost reductions can be obtained by coordinating the installation of the ESHHM system with the cabling and installation of the other sensors and communication systems on board.

4.1 Verification of Hull Design

A combined verification of the mechanical strength of the hull and the sea keeping properties can be performed by means of a complete ESHHM system. By experience, it is difficult to cover all required well-defined sea states and operational situations during the limited time periods set aside for systematic sea trials. By collecting accurate data during all ship operations, it is possible to build an additional database, which can be analysed as described in Section 5.0. The experimental data contributes valuable additions, verifying the mechanical strength specifications of the ship. In addition, the empirical description of the relations between mechanical loads, wave height for different types of sea state, speed, and heading with respect to wave direction, can be made sufficiently accurate to support the system applications. It is important to identify sea states giving a transition from linear response to non-linear response and rapidly increasing wave loads. For SES vessels, it is especially important to identify situations with slamming and increased probability for damage. It should also be determined if the size of the sensor network can be reduced for future routine operations without reducing the quality of the system. New naval ship designs are verified by means of scale model testing in model tanks. The full-scale test data should be compared with the corresponding sea states simulated in the model tank in order to evaluate the testing as representative for the full-scale application.

4.2 Reduction of Overall Cost

The cost of naval ship operation can be reduced by limiting the aging due to fatiguing effects (increased lifetime), reducing the number of incidents causing damages due to hull overload, and increasing the maintenance efficiency.

4.3 Minimizing Load and Operation within Design Limits

The real-time presentation of the wave loads (see GUI in Section 2.3) can help the crew minimizing the fatigue by proper choice of speed, heading, etc. during routine operations. When exposed to severe sea states, the display can help the crew keeping the load below critical threshold values. During military operations, it is important to utilize the ship's speed potential without exceeding the critical design limits.

4.4 Planning

Today, it is (to a large extent) possible to receive useful forecasts of sea states. Sailing routes and schedules minimizing the hull load, may be planned by combining information on sea states, hull load, and ship manoeuvring capability

4.5 Condition Based Maintenance

Condition based maintenance inspections do not follow a fixed time schedule, but is based on the load recorded and stored by the SHHM system. Inspections are especially important when severe overload has occurred. For some material systems, like steel, it is possible to calculate the fatiguing effects based on accurate records of the strain time series. This makes it possible to make reliable predictions of the remaining life cycle. FE modelling plays an important role here, as a detailed model makes it possible to compare the local strains with the global moments measured by the fiber optic sensor system.

4.6 Damage Detection and Operation of Damaged Ship

During the recent FFI projects, no detailed investigation of damage detection has been performed, but the experience gained so far has identified some promising approaches. Serious structural damages will probably change the stiffness matrix $\mathbf{K}$ discussed in Section 2.2. By running a continuous analysis of the fiber sensor signals, changes in the stiffness matrix may be detected indicating damages. System identification tools may also be used to monitor the sensor signals and indicate changes in its behavior. Naval ships are designed to endure large structural damages. The hull has internal structural elements, which should support the structure when other less protected parts are damaged. It is proposed to instrument the supporting structures so that the rest strength can be monitored.

4.7 Acoustic Signature

The acoustic signatures of ships are partly due to acoustic waves radiated into sea because of mechanical vibrations and noise in the hull. The fiber optic hull monitoring system can detect these vibrations. In order to optimise the system for this application it may be necessary to increase the number of sensors and the bandwidth to match the frequency spectra of the mechanical noise, which normally is larger and reduces system noise. By careful monitoring of the ship noise it is possible to identify the noise sources and issue a warning if there is an increase in ship noise, which can make the ship more vulnerable for detection during underwater warfare.

5.0 FULL-SCALE EXPERIMENTAL RESULTS

The ESHHM system has been in operation since March 9th, 2004. All operations and forces on the vessel including wave conditions have been monitored, and full bandwidth time series of all sensors and measurants have been stored on DVD's. This chapter describes the methodology for the data analysis performed forming a basis for the operator instructions of the Oksøy/Alta-Class MCMV. The analysis associates the sea state and ship state with the corresponding hull loads. Chapter 5.1 and 5.2 describes how ESHHM data from the continuous daily operation of the vessel is employed. Chapter 5.3 presents results from a full-scale sea trial with 20-minute runs where the sea state (waves) and ship state (speed and heading) have been fairly constant.

5.1 Data Analysis of Continuous Monitoring

In order to obtain an accurate measure of the sea state [13], the sea elevation level should be measured over a period of 20 minutes. The Oksøy/Alta-Class primarily operates in sheltered waters, and this type of vessels rarely keeps a steady course for more than a few minutes. Islands, reefs and changing sea depths produce variations in the sea state. The sea and ship state parameters such as speed, heading, wavelengths, and wave heights, etc. needs to be kept stable within the time series in order to associate them with the corresponding hull load level. A time series of 5-minute duration ensures that a major part of the acquired time series contains stable sea and ship state parameters.

The sensor time series of the ESHHM system is re-sampled to a common time grid. The re-sampled data are split into 5-minute time series and stored. Each 5-minute file is then processed in order to create statistical parameters describing the time series of the sensors and calculated measurants. In addition to maximum, minimum, mean value, standard deviation, skewness and kurtosis, parameters describing the data stability of the time-series, transients and data quality are stored in a database.

5.2 Results from Continuous Monitoring

The sagging/hogging moment is plotted vs. the estimated significant wave height in Figure 5. The figure plots 5-minute runs where the ship state parameters such as speed, heading, and air cushion pressure, in addition to sea state parameters such as wavelength, wave height, and wave direction are kept stable. A subset of the time series in Figure 5 with significant wave height between 0.5 and 2 meters are plotted in Figure 6. The left figure indicates that the sagging/hogging moment increases as the wavelength approaches 50 meters. The right figure indicates that the sagging/hogging moment is large when the vessel's heading is directly towards the waves, and at a minimum when the wave direction is 45° to starboard or port (the plot is symmetrical around 0°).

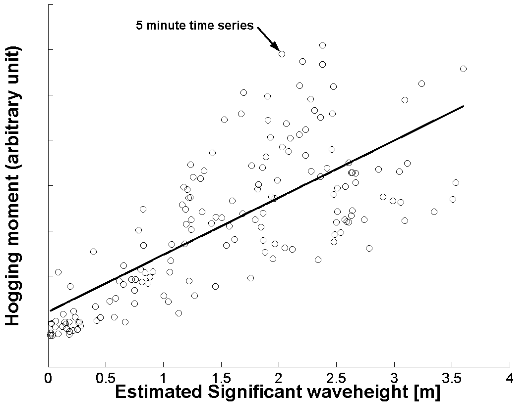


Figure 5 Sagging/hogging moment vs. estimated significant wave height. Every circle represents a 5-minute period

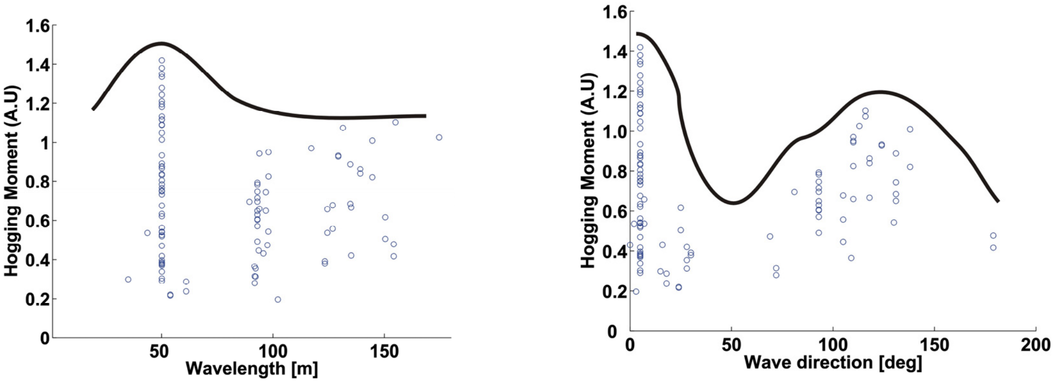


Figure 6 Left) Sagging/hogging moment vs. wavelength. Right) Sagging/hogging moment vs. wave direction. Every circle represents a 5-minute period

5.3 Sea Trials

A full-scale sea trial with the ESHHM system was performed in February 2005 with the RnoN MCMV “HNOMS Otra”. 10 different runs, each of 20 minutes duration were performed. Heading with respect to wave direction, vessel speed, and sea state were systematically varied during the test program. Figure 7 shows the extreme local loads on the wet deck. Normalised loads with head sea (0˚) is given in the left figure. In the right figure, the heading relative to the waves are 45 degrees. The extreme local loads on the wet deck is significant at sea state 5 and above.

The extreme values of the global sagging/hogging moment is given in Figure 8 together with a measure of 4 times the standard deviation. The difference between the standard deviation of the time series, and the extreme values is significant for sea states 5 an above. All the extreme values in the sagging/hogging moment are induced by slamming.

The results from the full scale sea trials indicate that slamming impacts on the wet deck also have a significant influence on the maximum global loads on the hull.

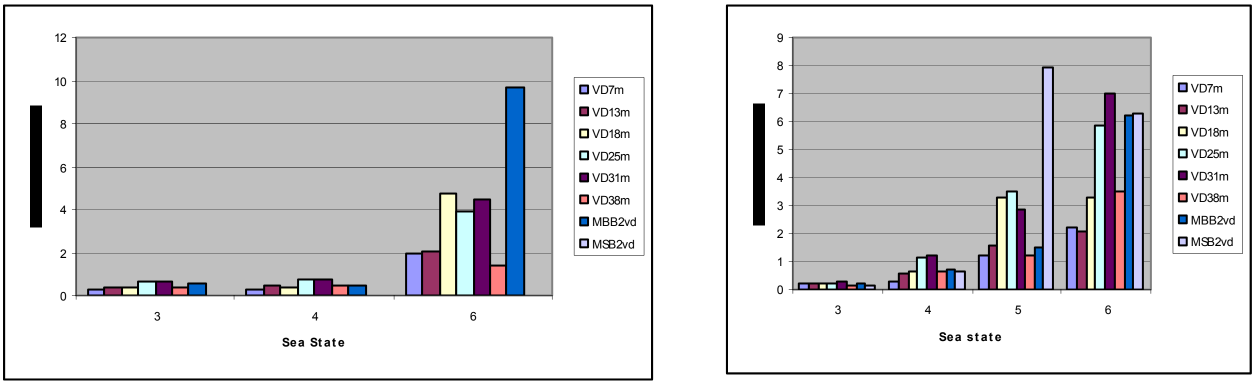


Figure 7 Left) Extreme local load on wet deck panels for head sea (0˚). Right) Extreme local load on wet deck panels for a relative wavedirection of 45˚.

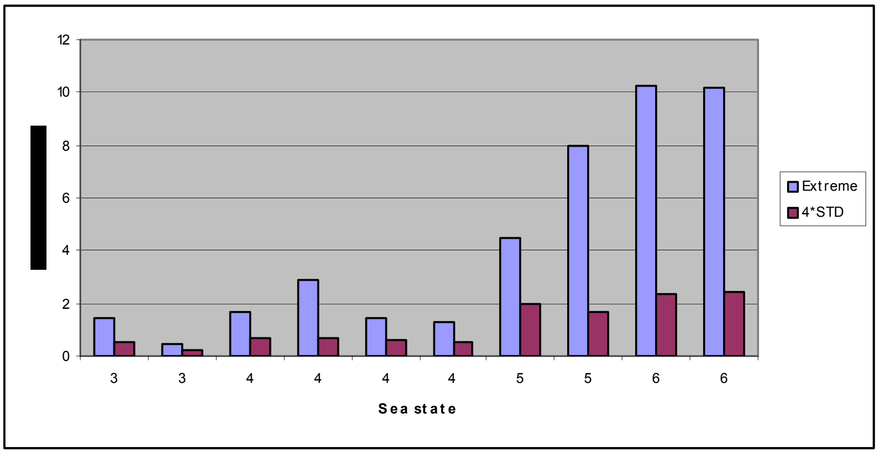


Figure 8 Extreme values of the sagging/hogging moment represented by the blue bars. 4 times the standard deviation of the 20 minute timeseries is given by the red bar.

6.0 CONCLUSIONS

Fiber optic sensors are well suited for structural health monitoring on naval ships, due to their ability to withstand harsh environments, immunity to electromagnetic interference and reduced cabling installation. The sensors are the main component in a Ship Hull Health Monitoring (SHHM) system developed by FFI, and are installed to measure both global hull loads and local stress at locations critical to the ship design.

An Extended Structural Hull Health Monitoring System (ESHHM) has been installed on the MCMV RNoN “HNOMS Otra”. The data collected are analysed and used for the design of operator instructions and sailing restrictions for the Oksøy/Alta-Class aiming to reduce hull loads during operation. The first results from this installation are discussed, showing the importance of understanding the relations between the hull loads, sea state and ship state.

The ESHHM system can play an important role in increasing safety, reducing cost, and increasing lifetime of the hull during the total lifespan of a ship. The system has a wide variety of applications yet to be explored in its full extent.

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SYMPOSIA DISCUSSION

Paper 22 “Development and Applications of Full-Scale Hull Health Monitoring Systems for the Royal Norwegian Navy” presented by H. TORKILDSEN

1. Discussor’s name: B. LOKOS

Q. (1) How were the Bragg grating locations chosen?

(2) What units were used to express Hogging moment?

(3) Did you notice a difference in the load produced by encountering a wave with the wind direction as opposed to against the wind direction?

R. (1) They are located at the cross section of the hull where the highest strains due to global loads were expected. This position was found by means of Finite Element Modeling of the vessel.

(2) The unit used to express the Hogging moment was Nm (Newton meter)

(3) We have not done any experiments in order to investigate the difference in the load produced by encountering a wave with the wind direction as opposed to against the wind direction.