Evaluation and Forecasting of Elapsed Fatigue Life of Ship Structures by Analyzing Data from Full Scale Ship Structural Monitoring

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Abstract: This paper describes the activities carried out by CETENA in collaboration with the Italian Navy to assess the behavior of new FREMM frigates by means of an automatic hull monitoring system and to predict the expected fatigue life of ship structure by analyzing recorded data through a specifically developed post-processing tool.

Key words: Hull monitoring system; fatigue; long-term forecasting; decision support system.

1. Introduction

The actual main targets in designing future-based navy ships are aimed at increasing performances, strength and life and at the same time at decreasing weight, fuel consumption, vulnerability and signature.

Despite the design tools currently available (numerical codes, FEM/BEM models, etc.) constitute a significant help to the designer, allowing to explore a number of alternative solutions with relatively limited effort and time, a prediction of ship behavior in rough seas and in particular of structures fatigue life is not yet reachable with an high level of affordability.

The installation on board of monitoring systems allows to monitor and to log a number of full scale data relevant to the whole ship or to local structures. With this aim in mind the Italian Navy requested the installation of a Hull Monitoring System (HMS) on the new FREMM frigates designed and built by FINCANTIERI: the system described in the present paper has been designed and developed by CETENA in compliance with the additional Class notation RINA MON-HULL+S.

The HMS monitors and records data such as ship rigid body motions, bending moment along the hull girder, local strains in structural details, fatigue cycles experienced by ship structural details, pressures acting on hull, sea state and operative conditions of the ships.

The subsequent data analysis is useful to control and understand ship structural behavior in operating conditions. Having at disposal the actual operating profile of FREMM vessels, the Italian Navy can define realistic design loads for future vessels.

Dedicated tools are required to efficiently post-process a large amount of recorded data. The post-processing tool to analyze the full scale data acquired by HMS has been designed and developed by CETENA under Italian Navy's request.

The present paper reports a description of the tool as well as some preliminary analysis of the data recorded on board the first FREMM frigate. The tool potentialities and the usefulness of the information gathered are shown: the capability of long-term extrapolating the elapsed fatigue life of ship structure allows the Italian Navy to schedule maintenance interventions to extend the vessel life.

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Fig. 1 FREMM frigate.

Another step towards gaining the greatest benefits from full scale data monitoring is constituted by the extension of the HMS capabilities, up to become a decision support system supporting the on board personnel in operating the ship in a safety perspective. An overview of this concept is provided.

Also the design of innovative ship structures can benefit from the availability of full scale data recorded during ship operations. In particular local structures made in lightweight composite materials have often been equipped and monitored by customized CETENA monitoring systems, to assess their design and acquire knowledge on their behavior in operative condition, with the final aim to improve design of future vessels.

2. Targets and Background

Basic and applied research activities as well as development of enhanced and sophisticated design tools always require a validation of the results achieved by theoretical procedures with experimental data.

In early R&D stages using data by model scaled experiments can be acceptable. Anyway, due to complexity of the investigated phenomena, the scale factor can influence the measured values affecting their reliability.

Further, sea spectra can be reproduced only in an approximated way during experimental model tank tests: as a consequence stochastic phenomena occurring during navigation in rough seas and strongly influencing the structural behavior of the ship—such

as slamming events and subsequent whipping vibrations of the hull girder—cannot be exhaustively reproduced.

In such cases a full-scale measurement approach should be applied.

In the same perspective, today ship-owners request ships designed for top performances: high propulsive and energy efficiency to minimize fuel consumption, high reliability of plants and structures for an extended ship life, high structural strength to safely operate in rough seas, low signature and vulnerability levels.

Once a ship is delivered and operative, ship-owners need a continuous feedback on above issues, in order to:

- Assess if the actual operational performance is consistent with the design one;
- Evaluate how ships are managed by on-board personnel and how the ship management could be improved;
- Investigate whether inconsistencies between design and operating performances are due to the ship management or to the ship itself.

While an assessment of ship propulsive performances needs data recorded only during navigation in favorable environmental conditions, an exhaustive investigation of ship structural behavior has to be performed mainly during navigation in rough seas. Hence the data to be collected on board have to include the environmental conditions encountered.

2.1 What a Monitoring System is?

A traditional approach in assessing ship performances and behavior during operations in rough seas is based on observations and manual reporting by on-board personnel.

Despite being economical, this approach is unreliable, inefficient and affected by single person attitude and perception of the surrounding reality. Furthermore it allows only the acquisition of a very limited amount of data (for instance one record every

some hours) and is subjected to loss of records when crew is particularly busy, i.e. in critical conditions when the structural data are of maximum interest for both designers and ship-owners.

The only objective, reliable and undisputable method of detecting and recording ship performance during operational service is by means of an automated, unattended system.

Both designers and ship-owners can thus benefit from the installation and operation of unattended monitoring systems on board, able to continuously record all significant operational and environmental data from dedicated sensors and on-board systems.

2.2 Main Targets of FREMM Monitoring System

Several aspects of the ship operation can be covered by monitoring systems, e.g. propulsive performance and energy efficiency (mainly addressed for fuel saving purposes and only investigated for merchant vessels) and structural behavior.

Based on the above considerations, the main targets for installing on board monitoring systems are:

- Assessment of ship design and plant/structures “as built”;
- Assessment of ship operations and management;
- Surveillance of ship performance and structure;
- Detection of potential risks related to structure and cargo integrity and safety;
- Feedback on innovative/alternative solutions;
- Measurement of data relevant to critical issues and identification of countermeasures;
- Resolution of disputes with suppliers;
- Data collection to improve design of future ships;
- Data collection for basic and applied research;
- Acquisition of additional class notations by Registry.

These topics are addressed by the monitoring systems and by the post-processing tool treated in the present paper. The systems were designed, developed and installed by CETENA on board FREMM frigates designed and built by FINCANTIERI (Fig. 2).

Fig. 2 FREMM frigates in open sea.

In particular the Italian Navy requested to equip the FREMM frigates with the Hull Monitoring System (HMS) in order to:

- Collect real time data to monitor the operational conditions and the actual and design operative profiles of the vessels;
- Define the design loads for future vessels;
- Monitor hull integrity and identify in real-time significant stress situations, for safer ship operations;
- Measure the cumulated fatigue damage of most critical ship structures, forecast the expected fatigue life over selectable time ranges and schedule maintenance interventions;
- Learn the lesson to enhance requirements to next generation vessels;
- Obtain the additional class notation RINA MON-HULL+S.

2.3 Background

CETENA: CETENA has more than twenty years experience in designing, developing, installing and managing monitoring systems on board naval and civil vessels.

The competences acquired during decades of basic and applied research in classic fields of naval architecture and engineering (structures, hydrodynamics, acoustics, etc.) constitute the technological basis onto which the development of monitoring systems is founded. The experience in structural analysis and fatigue life calculations by

means of analytic and finite element methods give CETENA a significant knowledge of methods and techniques to understand, analyse and extrapolate monitored data.

After a number of short-term monitoring systems dedicated to specific structures, the first long-term structural monitoring campaign of a ship was performed by CETENA in the late 1990s applying the in-house developed MOSS (Monitoring of Ship Structure) system[1]: a 146 m long High Speed Craft capable to carry 1,800 passengers and 460 cars navigating at maximum speed of 42 knots was instrumented. Full-scale data were acquired for 1.5 years and subsequently analysed[2,3].

The hardware, software and algorithms of ship monitoring systems developed by CETENA have continuously been improved and new facilities added. The development of the Sh.A.M.An. (**S**hip **A**dvanced **M**onitoring and **A**nalysis) system and the achievement of RINA design assessment certificate constitute the last chapters in CETENA's ship monitoring system history.

Currently the ESNS (Enhanced Safe Navigation System)—including capabilities from both monitoring and active guidance systems—is under development.

A number of dedicated systems for local ship structures have also been developed and used both for research and for engineering services purposes. For example the Sonar Dome acoustic and structural monitoring system, expressly conceived for specific purposes.

Italian Navy: The Italian Navy has been interested for decades in investigating and understanding the behaviour of its ships while navigating in rough seas.

Vessels have been always considered not only as means of transportation or as operating military units, but also as an opportunity to acquire a number of full-scale data and information. The technical staff have thus the possibility to enhance their know-how on naval architecture and design, acquiring the knowledge and the full-scale data needed to optimize

the design and the performances of future Navy ships.

In 2002 the Italian Navy frigate SCIROCCO of “Maestrale” Class (Fig. 3) was equipped with a permanent monitoring system developed and installed by CETENA. This was the first system installed on board an Italian Navy vessel, able to detect local and global structural stresses and to count the loading cycles experienced by the structures at the selected critical spots by means of a rain-flow algorithm. The ship was monitored for a couple of years, but the recorded data had to be manually analysed offline since a dedicated post-processing tool was not available at that time.

A system specifically designed by CETENA was installed for research purposes in November 2007 on board of an Italian Navy Patrol Vessel of “Comandanti” Class[4]. The system was aimed at acquiring data allowing to evaluate and distinguish the wave and whipping contributions to the vertical bending moment on the hull girder. Two bottom panels at bow were instrumented with strain gauges and accelerometers and a transfer function relating the panel deformation and the slamming dynamic pressure on it was derived.

This led to an increased understanding of slamming and whipping phenomena on fast patrol vessels.

When the Italian Navy commissioned to FINCANTIERI the first aircraft carrier of its fleet (Fig. 4), the requirement of an high-performance monitoring system became natural.

The vessel size and being a prototype for the Italian Navy led to the request for an unattended monitoring

Fig. 3 SCIROCCO frigate in open sea.

Fig. 4 CAVOUR aircraft carrier in open sea.

system equipped with a number of sensors distributed along the vessel and a wave radar for the correct determination of the sea state, intended to be operated onboard for the whole ship life. Also in this case the system was designed and developed by CETENA.

Maintaining the same approach to the design and operation of their vessels, the Italian Navy requested for a high-performance monitoring system when launched the ambitious FREMM programme aimed at a strong fleet renewing.

3. The Hull Monitoring System (HMS)

The Hull Monitoring System being installed on the FREMM frigates is based on COTS (Commercial Off-the-Shelf) hard-ware and intended to be operating during for the whole ship life.

The Sh.A.M.An. system previously installed on board the Cavour aircraft carrier constituted the starting basis, but had to be significantly improved—both from a hardware and from a software point of view—to be compliant with the following Class notation:

RINA Rules 2011—Part F “Additional Class Notations”, Chapter 5 “Monitoring Equipment (MON)”, Section 1 “Hull Stress and Motion Monitoring (MON-HULL)”;

RINA Rules for FREMM Frigates—CE 2006—Part F “Additional Class Notations”, Chapter 5 “Monitoring Equipment (MON)”, Section 1 “Hull Stress and Motion Monitoring (MON-HULL)”.

The Design Assessment Certificate referred to the standards “RINA Rules Pt.C-Ch.3-Sec.3;

Pt.C-Ch.3-Sec.6; Pt.F-Ch.5-Sec.1” was obtained on April 6th, 2012.

The HMS is dedicated to the real time acquisition and analysis of data relevant to the ship structure from external hardware communicating with the main computer through serial ports and a TCP/IP connection. The system is conceived as a three-level structure (Fig. 5), of which the first one is constituted by sensors installed on board: long base strain gauges, short base strain gauges, accelerometers, inclinometers and pressure gauges.

Peripheral Processing Units (PPU) is located along the ship to supply power to sensors and acquire real time data.

The third level of the HMS regards the actions performed by the MPU (Main Processing Unit), linked to PPUs by Ethernet connection. It checks the consistency of all data, analyses, displays, stores and compares them with user-defined threshold values, providing users with proper alarms/warnings. It includes also a self-diagnosis tool able to detect malfunctions relevant to sensors and/or to the acquisition system.

The MPU is connected to the WMS (Wave Measurement System), which provides information on the encountered sea spectrum, and to other on-board systems (Table 1).

All acquired data are analyzed providing statistical data (max, min, mean and standard deviation values) with respect to a user-defined time frame.

In addition the data acquired from global and local strain gauges are used to evaluate and count the number and amplitude of stress cycles experienced by the structure: in this manner the complete input data set for fatigue analyses are provided.

Fig. 5 HMS architecture.

Table 1 Interconnections with on-board systems.

<i>Data acquired</i>	<i>On-board system</i>	<i>Acronym</i>
Ship propulsion and operational data	Ship Management System	SMS
Ship position	GPS	GPS
Ship speed	GPS	GPS
Heading	Gyro	Gyro
Wave height	Wave measurement system	WMS
Wave period		
Wave direction		
Wind speed	Anemometer	W
Wind direction		

3.1 Sensors

Based on the design analysis of FREMM vessels and on the requirements by the Class notation, data to be acquired and corresponding sensor types have been established (Table 2).

The position of each sensor has been defined in accordance with the FINCANTIERI and the Italian Navy, to have the most accurate measurement of ship rigid body motions and global loads and the most effective information regarding local loads in the critical structural points of the ship.

While selecting the proper sensor type and model, attention has been paid to sensitivity, accuracy and reliability characteristics. Stating that the system has been designed to operate onboard for a number of years, COTS sensors have been selected, assuring an easy replacement during the system life.

Long Base Strain Gauges: The measure of global longitudinal deformation of the hull girder is performed by Long Base Strain Gauges. In each measurement point, a linear displacement sensor based on strain gauge technology and characterized by infinitesimal resolution has been installed.

A specifically developed mounting solution allows to detecting the hull global deformation free from local strain effects (Fig. 6), in order to compute the hull girder vertical bending moment.

The measured strain ε is in fact related to the vertical bending moment M_f by:

$$\varepsilon = \frac{M_f}{E \cdot W} \quad (1)$$

where: W = section modulus, E = Young modulus.

Table 2 Sensors and data acquired.

<i>Data acquired</i>	<i>Sensor</i>	<i>Acronym</i>
Global hull deformation	Long-Base Strain Gage	LBSG, L
Local strain	Short-Base Strain Gage	SBSG, S
Acceleration	Accelerometer	A
Roll and Pitch	Inclinometer	I
Pressure on hull	Pressure gauge	P

Fig. 6 Typical LBSG installation.

A source of uncertainty when measuring structural deformations is constituted by thermal variations, which are detected by strain gauges as mechanical. A fully active bridge strain-gage configuration has been selected, to compensate any influence of thermal variations on the measured data.

Short Base Strain Gauges: A number of structural details have been instrumented by means of linear strain gauges; in some cases, depending on the expected stress distributions, three of them have been positioned at the same location to detect the full strain status.

FEM analyses of the strain distribution have shown, as expected, that the highest stresses in a fast monohull vessel subjected to heavy navigation conditions are found in the connections between main deck and superstructures. The local stress monitoring was focused on this zone.

Also SBSG sensors may suffer thermal variations during ship operation, even on a daily or hourly basis, depending on sun incidence on ship walls. In order to avoid measurement errors due to thermal variations, each strain gauge has been coupled to a temperature compensator.

Accelerometers and Inclinometers: Ship rigid body motions are measured by means of linear accelerometers and inclinometers, fixed to stiff points of the ship structure.

In correspondence of the ship cog, three accelerometers to measure longitudinal, transversal and vertical accelerations and a bidirectional inclinometer to detect roll and pitch angles have been installed.

Other accelerometers have been installed to measure vertical acceleration at selected locations and to warn the on-board personnel consequently.

Pressure Gauge: The last sensor equipping the FREMM frigates is a pressure gauge, which detects the pressure acting on the hull.

3.2 Acquisition System Architecture

The whole acquisition system of the HMS is based on COTS components, to ensure reliability and easy replacement in case of failure.

The architecture of the PPU is based on a modular system which can be easily extended in case signals from additional sensors would have to be acquired.

The MPU is constituted by an industrial fanless rugged computer equipped with keyboard, monitor and mouse.

All components of the HMS are powered by the ship UPS line allowing safe operation of the system and avoiding loss of data in any condition.

3.3 Wave Measurement System

When performing full scale ship structural monitoring, it is of utmost importance to log data relevant to the sea states the ship is encountering. The motions and stresses recorded by the sensors have to be correlated not only with the ship speed, but also with the actual environmental conditions.

Furthermore the availability of reliable data on sea states and wave characteristics (height, direction, period) encountered by FREMM vessels all along their life allows to define their actual operating profile. The Italian Navy will thus base on those data the definition of design loads to be used for its future ships.

Although a number of relatively cheap devices able

to detect the wave height are available on the market, a system based on wave radar technology has been chosen to have the most accurate measurements of the sea state surrounding the ship.

The WMS installed on FREMM ships is composed by a dedicated x-band short-pulse radiating radar and by a wave measurement subsystem, provided by MIROS or by REMOCEAN companies.

The WMS analyses the sea clutters captured by the radar and calculates the entire set of parameters (height, direction, period) relevant to the sea state and to primary and secondary waves composing it.

A typical view of the WMS interface (Fig. 7) shows the sea clutter surrounding the ship, the wave spectrum and the main sea state parameters calculated: these information are recorded by the HMS as well as the sensors data, to make at the designer disposal all useful information for a fruitful post-processing of full-scale monitoring campaign.

In case of low-quality sea clutter screenings by the x-band radar, the WMS is not able to correctly detect the sea state parameters.

This can basically happen due to unfavorable environmental conditions (low wind, heavy rain) or if the sea state detection area scanned by radar include the coast or other ships.

In such cases an alarm in the HMS occurs.

Fig. 7 Wave Measurement System: SW interface.

3.4 the Sh.A.M.An. Software

The Sh.A.M.An. Software has been developed by CETENA to manage the monitoring system and its processing capabilities. The developer suite LabVIEW 10 provided by National Instruments was selected for the implementation, being specially designed for acquisition and analysis of signals and allowing a flexible allocation of resources for both parallel and concurrent data processing.

An easy to use graphical interface installed on the MPU puts at users' disposal all capabilities needed to set up the system and the interconnections with on board ones, to enable, configure and disable acquisition channels, to perform calibration of installed sensors, and so on.

The main panel of Sh.A.M.An. (Fig. 8) gives an overview of all data acquired by the system.

A table reports and updates the statistics (maximum, minimum, average and standard deviation values) of the acquired signals.

For each sensor, a graphic indicator shows the current value with reference to threshold limits set. The user can thus see the structural and motion status of the ship immediately.

The status of each sensor (normal condition, warning or alarm threshold exceeded, malfunction, not active) is also shown both on the main panel and on a dedicated one: being superimposed to the ship silhouette, it gives the onboard personnel a simple way to identify structure or system related problems.

Alarm management: Automatic routines are implemented in the software to monitor the system and sensor status, generating warning, alarm and malfunction alerts. Such events are recorded in a dedicated file and managed according to Rules standards and to the IMO Alarm code [5].

The interactive link between HMS and SMS gives the possibility to visualize and acknowledge alerts on all shipboard consoles, not only on the HMS computer.

Interface with Loadmaster: A useful interface with

the loadmaster system is provided in the Sh.A.M.An. Software.

The software shows the loading condition in still water indicated by the loadmaster to perform the initial set-up of the system. Afterwards, it allows to compare the actual bending moment in still water experienced by the hull girder with the nominal one: the overall condition of the ship is kept under control.

Short term extrapolation in real time: A short term prediction algorithm has been implemented in the software. For every sensor, the onboard personnel can superimpose in real time the foreseen trend to the time history of data recorded in the last couple of hours (Fig. 9): the behavior of the ship structure in the next incoming hour can be estimated on line.

This extrapolation approach provides a quite reliable short-term indication. As far as long term prediction is concerned, a large amount of recorded

Fig. 8 Sh.A.M.An. Main panel.

Fig. 9 Short term extrapolation in real time.

advanced extrapolation algorithms are needed. For this purpose, a post-processing tool based on Weibull long-term extrapolation technique has been developed, to be used off-line.

Rainflow Module: A dedicated tool logging stress cycles acting on the ship structures is needed to evaluate—and to forecast—the elapsed fatigue life of the monitored details.

In the Sh.A.M.An. Software, a Rainflow module has been included to process data acquired by LBSG and SBSG. It has been implemented according to ASTM standard “E-1049 Standard Practices for Cycle Counting in Fatigue Analysis”.

The Rainflow cycle counting algorithm is a time-domain method to convert an irregular load history into a stress range histogram (load spectrum), by identifying the number of cycles and half-cycles composing the load history for a number of amplitude and mean value classes. The SW shows short term fatigue histograms in real time (Fig. 10).

The complete set of fatigue data are recorded in dedicated files, reporting amplitude and mean value of each cycle and half-cycle experienced by each sensor.

This large amount of information can subsequently be analysed off-line. The post-processing tool for full-scale monitoring data analysis provides panels

dedicated to the evaluation and to the long-term forecasting of the elapsed fatigue life.

4. Post-processing Tool for Full-scale Data Analysis

The availability of structural and operational data recorded on board all FREMM ships constitutes a treasure of information for the Italian Navy: having “learned the lesson” on the FREMM case, the design of future ships can be improved and even more customized to the Italian Navy needs.

A useful exploitation of such amount of data can’t be based on normal techniques like spreadsheets. A device guaranteeing fast and efficient selection, analysis and visualization of data is required. With this aim in mind, a post-processing tool has been developed and implemented by CETENA.

It includes the capability of long-term extrapolating both statistical and fatigue data over configurable time ranges: the maximum expected stresses on ship structure and the long-term expected elapsed fatigue life are evaluated by specifically developed algorithms on the basis of the stress and fatigue cycles experienced during the previous years.

The main purposes of the tool are the management of the ship structures maintenance in a CBM perspective and the assessment of the effective ship behaviour against its design operative profile.

4.1 Main capabilities of the post-processing tool

The post-processing tool is implemented by using the developer suite LabVIEW 10 by National Instruments. It operates linked to a database in which the experimental data (both statistic and fatigue ones) recorded by the HMS system are stored. The tool provides the user with capabilities allowing to:

- Archive the experimental data in a database in a simple and efficient way;
- Display and plot the statistic data recorded. Users can filter them on a time-basis or on an operative condition-basis to focus the analysis on some data

Fig. 10 Fatigue cycle histogram in real time.

sub-sets. Data analysis can be plotted against time or another quantity: ship speed as a function of sea state; structural loads as a function of relevant ship/sea heading; global vs. local structural loads. The max, min, mean, max-mean, min-mean, max-min and standard deviation value of each signal can be jointly or separately displayed;

- Superimpose to the recorded data the corresponding design values. The design operative profile of the ship can be superimposed to ship speed/sea state plot, to verify the effective ship use against the supposed one; the structural design limits can be superimposed to stress/strain data relevant to each LBSG or SBSG;

- Highlight conditions in which recorded stress levels were close to warning/alarm thresholds;

- Long-term extrapolate the statistic data over configurable time-ranges, to estimate the highest expectable loads on the ship structure. The accuracy of the extrapolation increases as the available data set is extended over a long time range and as the operating conditions experienced during the monitoring campaign are representative of the entire operating life of the vessel;

- Evaluate the cumulated fatigue damage on the instrumented structural details of the ship, by analyzing the histogram of the fatigue cycles counted by the HMS;

- Estimate the effect of modifications to structural details geometry or surface finishing (cleaning, welding or post-welding treatments, etc.) on the accumulated fatigue damage;

- Long-term extrapolate the fatigue life data over configurable time-ranges. The accuracy again depends on the quality of the available experimental data set;

- Schedule maintenance tasks on structural details to increase their operating life (CBM approach to ship structures), according to the cumulated or estimated fatigue damage;

- Evaluate the effect of a different use of the vessel

with respect to the actual one on the expected/extrapolated fatigue life of monitored structural details.

4.2 Analysis of Recorded Statistical Data

At the time being the post-processing of the data recorded on the First-of-Class FREMM frigate belonging to the Italian Navy is being performed.

The basic analysis consists in plotting time histories of the statistical data recorded and stored every n minutes by the HMS, by means of the data analysis panel (Fig. 11).

The user can impose and combine a number of filters acting on the data stored in the database: data sub-sets can be obtained for defined ranges of time, latitude and/or longitude, speed, wind and sea state, ship operational parameters and so on.

In this way, the investigation can be focused on specific operational conditions. An analysis focused on the encountered sea state allows to define the actual operating profile and hence the design loads to be used for future vessels.

Time histories: By plotting time histories of data acquired by LBSG during one day navigation in rough sea, information of the global structural loads on the hull girder are highlighted.

Fig. 12 shows the “Maximum-mean” and “minimum-mean” time histories of Vertical Bending Moment measured amidship: strain, stress and VBM

Fig. 11 Plotting recorded statistical data.

Fig. 12 LBSG2 amidship: “M-mean” and “m-mean” VBM.

Fig. 13 Ship speed and Wave height vs. Time.

are linked by (Eq. 1) having inputted in the SW the design structural data of ship sections.

The gap between the two curves represents the VBM variation amplitude experienced by the ship during navigation. As expected, VBM amplitude is correlated to ship speed and the highest VBM occurs when both speed and wave height contemporarily reach significant values (Fig. 13).

Statistical correlations: The already available data are relevant to about one year of continuous monitoring which constitutes a fairly good time basis onto which operate. However during this year the vessel was about 85% docked and 15% navigating in good sea conditions, since it was still involved in the commissioning phase.

Despite the low amount of significant data available, some useful information on the ship structural behaviour arose by analysing the recorded data according to a statistical approach.

Fig. 14 shows the amidship VBM plotted against the pitch, which is strictly correlated to both the ship speed and the wave height: as far as the pitch reaches significant values and grows up, an increasing trend of the VBM is experienced.

Strong correlations have been found, as expected, between global and local deformations experienced by the ship structure.

As the maximum VBM at $\frac{1}{4}$ ship increases, the local strain detected by the SBSG located at the aft interconnection between main deck and superstructures increases (Fig. 15). Measured points are located in the first quadrant: when the vessel is in hogging condition (positive VBM), the monitored structural detail experiences a tensile stress.

Similarly, as the amplitude of the minimum VBM at $\frac{1}{2}$ ship increases, the amplitude of the local strain detected by the SBSG located close to the amidship dilatation joint increases (Fig. 16). The points are located in the third quadrant: when the vessel is in sagging condition (negative VBM), the monitored structural detail is compressed.

Fig. 14 VBM amidship vs. Pitch.

Fig. 15 Maximum VBM vs. local strain at $\frac{1}{4}$ ship.

Fig. 16 Minimum VBM vs. local strain at 1/2 ship.

In both cases some measured points are outside the correlation “cloud”: they are characterised by high values of the local strain and low values of the VBM. Having cross-checked the data time histories, it was found that those points are referred to a period during which the vessel was undergoing dry-dock operations, after which sensors had to be re-calibrated.

Stating that, those data have been excluded by the user for subsequent long-term extrapolations and fatigue analysis.

4.3 Long-term Extrapolation of Recorded Data

The long-term extrapolation of the experimental data acquired over a certain time range is performed according to a basic assumption: the statistical distribution of quantities representing the dynamic response of the ship can be approximated with an high level of accuracy in the long term—i.e. For low values of the exceeding probability, or for high values of the exceeding level—by a three-parameters Weibull distribution.

This approach applies to VBM, local strains, pressures on hull, wave height, ship rigid body motions and so on.

The so-called Weibull asymptotic law of a quantity s is:

$$W(s) = \exp \left[-\frac{(s-\theta)^\alpha}{\gamma} \right] \quad (2)$$

or:

$$\ln(-\ln W) = \alpha \ln(s-\theta) - \ln \gamma \quad (3)$$

and assumes a linear behaviour in a bi-logarithmic

graph.

A proper algorithm has been designed and implemented in the post-processing tool, to automatically find the best set of three parameters θ , α and γ which optimizes the fit of the Weibull law to the measured data set.

This procedure allows to pass from the short term exceeding probability $P(s_i)$ of the measured data to the long term one (Eq. 4).

$$P(s) = \exp \left[-\frac{(s-\Theta)^M}{e^{-Q}} \right] \quad (4)$$

This distribution allows to estimate the maximum expected value of the considered quantity over a selected time range, i.e. In correspondence of the minimum exceeding probability of such quantity.

All intermediate steps performed by the SW to calculate the long term exceeding probability of selected quantities can be plotted. Results relevant to the VBM measure by one LBSG are reported in Figs. 17-21.

The user can select the data set to be used for extrapolation purposes, the time range over which perform it and the so-called “operative coefficient”. This allows to take into account the expected degree

Fig. 17 Measured data time history.

Fig. 18 Sorted measured data.

Fig. 19 Short term exceeding probability.

Fig. 20 Weibull extrapolation and measured data.

Fig. 21 Long-term exceeding probability.

of use of the ship in the future, with respect to the effective use during the monitoring campaign.

By increasing or decreasing this coefficient, a stronger or lighter use of the ship can be simulated and useful consideration can be done on how the ship was and will be operated.

Once having evaluated the long term exceeding probability for two quantities, the post-processing tool correlates them to obtain the long term distribution of r as a function of s (Eq. 5, Fig. 22).

$$r = \Theta_r + \left[(s - \Theta_s)^{M_s} \cdot e^{(Q_s - Q_r)} \right]^{1/M_r} \quad (5)$$

The usefulness of the long-term extrapolation algorithm is related to the possibility to estimate maximum expected loads acting on the structure in the long term, even having at disposal data related to a short or medium term monitoring campaign.

Fig. 22 Long-term correlation of VBM at 1/4 and 1/2 ship.

The designer can thus “tune” the design load selected for the future ships.

4.4 Evaluation of Elapsed Fatigue Life

The evaluation of the elapsed fatigue life relevant to a monitored structural detail is performed by a dedicated section of the post-processing tool.

The software retrieves from database and elaborates the stress cycles, which were counted and recorded in terms of amplitude and mean value by the Rainflow algorithm of Sh.A.M.An. Software. The stress range histograms (load spectra) relevant to a selected detail are built. Both full cycles and half cycles are taken into account (Eq. 6), to provide the full number of cycles experienced by the structure in every stress class $\Delta\sigma_j$.

$$N_j = N_{j-int} + \frac{1}{2} N_{j-half} \quad (6)$$

The number and amplitude of stress classes composing the histogram is self-computed by the tool to comprehend all cycles counted, but can be properly set by the user.

The fatigue damage D_j related to each class is computed by comparing the number of cycles N_{j-tot} with the fatigue limit $N_{j-fatigue}$ of that class, according to the S-N curve referred to the structural detail under investigation (Eq. 7).

$$D_j = \frac{N_j}{N_{j-fatigue}} \quad (7)$$

For each structural detail, the S-N curve can be inputted in the software (Fig. 23) on a point-by-point basis, or by defining the proper set of coefficients C_1 , m_1 , C_2 and m_2 (Eq. 8-9).

$$N = \frac{C_1}{(\Delta\sigma)^{m_1}} \quad \text{if } N \leq N_{CS} \quad (8)$$

$$N = \frac{C_2}{(\Delta\sigma)^{m_2}} \quad \text{if } N > N_{CS} \quad (9)$$

The S-N curve referred to the considered structural detail [6] or the curve referred to the base material[7] can be inputted. In the last case, the software allows to take into account the specific characteristics of the structural detail by a proper set of coefficients:

- K_g structure geometry coefficient;
- K_w weld geometry coefficient;
- K_{te} eccentricity tolerance coefficient;
- K_{ta} angular mismatch coefficient;
- K_a additional coefficient.

According to mentioned fatigue calculation methods, a Palmgren-Miner linear damage hypothesis has been assumed and the fatigue calculation algorithm has been implemented consequently.

The total cumulated damage experienced by a selected structural detail is thus the sum of damages related to each class (Eq. 10).

$$D = \sum_{j=1}^C D_j \quad (10)$$

A first evaluation of the elapsed fatigue life experienced by FREMM structure during the performed monitoring campaign has been performed.

Of course the availability of data relevant to a short time range and moreover the fact that the vessel was docked for the most part of it make this kind of analysis not as significant as it would be in the next years, when she will have been operating in open sea for extended periods. Anyway the potentialities of the post-processing tool and the usefulness of the information gathered can be appreciated.

Fig. 24 shows the performed fatigue analysis for a structural detail instrumented by a three-axial strain

gauge in order to detect all stress components acting on it.

Mirroring the effective use of the ship, most number of cycles are characterised by low stress ranges; in this case the lowest one is null, since the analyst can decide to exclude from the analysis all cycles characterised by amplitude below the so-called cut-off threshold.

The cumulate damage in the considered period ($7.4 \cdot 10^{-4}$) is low and doesn't allow to schedule maintenance interventions yet. This consideration would apply for many years during ship operations, until the cumulated damage will approach significant values, growing towards 1.0.

A tool performing long term extrapolation of fatigue cumulated damage is needed to put the ship manager in the position to schedule maintenance intervention to prolong the ship life.

Fig. 23 Design data input in post-processing tool.

Fig. 24 Elapsed fatigue life of a structural detail.

4.5 Forecasting of Long—Term Fatigue Life

The prediction of long-term elapsed fatigue damage is based on long-term extrapolation of stress range histogram relevant to the each monitored detail.

The statistical distribution of histograms can be approximated with an high level of accuracy by a combination of the two-parameters Rayleigh distribution (Eq. 11) and of the three-parameters Weibull one (Eq. 2).

$$R(s) = \exp \left[-\frac{|s - \theta|^2}{2\sigma^2} \right] \quad (11)$$

A proper algorithm joins Rayleigh and Weibull statistical distributions and builds the long term expected stress range histogram.

For each structural detail, the time range over which perform the extrapolation and the “operative coefficient” can be selected.

In addition an additional Stress Concentration Factor (SCF) can be applied. This allows to estimate the effect of external factors on both elapsed and forecasted fatigue damage: modifications to structural details geometry, surface maintenance, corrosive environments, welding or post-welding treatments and so on.

As shown in Fig. 25, a damage of 0.186 is forecasted for a 30-years period with an operative coefficient of 75%. This low value is due to the short statistical basis onto which the extrapolation is performed and to the fact that it is related to a soft use of the ship, up to now rarely subjected to rough seas during the monitoring campaign.

The possibility to predict the fatigue damage of structural details in the long term is explained by Fig. 26. Several extrapolations have been performed on the same structural detail, based on the same set of experimental data. A 100% operative coefficient and a time range from 15 to 50 years have been considered.

An affordable prediction of how and how much the cumulative expected fatigue damage increases with years is available.

The Italian Navy technical department can decide

Fig. 25 Elapsed and forecasted fatigue life of a structural detail.

Fig. 26 Forecasting fatigue life of a structural detail.

on this basis which maintenance intervention should be done and when.

Weld cleaning, application of anti-corrosion paints or other actions can in fact contribute at fatigue life prolonging. The benefit of such interventions on the expected ship fatigue life can be estimated by performing again the analysis with an SCF lower than 1.0.

If all ships of the same Class are supposed to have almost the same operating profile, the data acquired and the information gathered on the first of Class can be used to improve the design, the use and the maintenance of the sister ships.

5. A Step Forward: The ESNS

A further step is currently being performed in the path towards an efficient monitoring of structures

giving a support in managing ship operation and maintenance.

Like all the monitoring systems, the HMS is characterized by a “passive” attitude towards structural safety in the sense that it may alarm the Ship Officer of a possible risk. However it is not capable of advising him about the effect of a change in ship speed/course given the actual environmental and loading conditions or to predict the ship behavior in case environmental conditions would worsen.

This capabilities are typical of “Operational Guidance Systems” or “Active Guidance Systems”, which can thus actively contribute to the operational decisions by the Officer in view of a safer navigation. They are usually based on an accurate and reliable knowledge of the structural response of the ship to the hydrodynamic loads induced by the waves encountered during the navigation.

A new system under development by CETENA—named ESNS “Enhanced Safe Navigation System”—will join the monitoring and the Active Guidance capabilities: the reliability of structural response prediction for given changes in operating conditions will be strongly enhanced by the real time data acquisition on ship motions and loads coming from the HMS sensors.

6. Conclusions

The present paper reported on the monitoring systems and post-processing tool provided by CETENA to the Italian Navy to support its innovative approach to ship strength and durability assessment and maintenance scheduling.

The main purposes pushing the Italian Navy to install the HMS on FREMM vessels are:

- To verify the operating profile of the vessels, in terms of encountered waves profile, to set realistic design loads for future vessels;
- To monitor and to extrapolate in the long term the elapsed fatigue life of structural details;

- To schedule maintenance interventions to extend vessels operating life.

The capabilities of the HMS and of the post-processing tool allow the Italian Navy to reach those targets. The first post-processing performed shows how measure, log and analyze full scale data can be useful to understand ship behavior in rough seas and to enhance its operation and maintenance during its life.

On the basis of such a successful experience, the HMS system and the post-processing tool are being offered to the market, to improve ship, cargo, passengers and crew safety.

R&D activities are being performed by CETENA to enhance the hull monitoring system performance and capabilities, providing the on board personnel also with Active Guidance capabilities integrated in the ESNS system.

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