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Live reconstruction of global loads on a powerboat using local strain FBG measurements

Pierluigi Fanelli[a], Alessandro Mercuri[a,*], Simone Trupiano[b], Francesco Vivio[b], Giacomo Falcucci[b], Elio Jannelli[c]

[a]*Department of Economics, Engineering, Society and Business Organization, University of Tuscia, Largo dell'Università, 01100 Viterbo, Italy*
[b]*Department of Enterprise Engineering, University of Rome Tor Vergata, Via del Politecnico,1 , 00133 Rome, Italy*
[c]*Department of Engineering, University of Naples Parthenope, Isola C4 Centro Direzionale, 80133 Naples, Italy*

Abstract

Ships often operate under challenging conditions, considering that marine environment can cause failures of the structure related to overloads, fatigue, corrosion and erosion. As a consequence, advanced methods and procedures are under development for the evaluation of the on-site structural performance for both traditionally and newly designed ships. One of the main challenges in this field is the live monitoring of the loads acting on the ship hull; the load data processing can lead, through suited algorithms, to a real-time control of ship trim and, as a consequence, to the development of automatic or semi-automatic trim control systems. The presented procedure for load reconstruction requires a well-suited sensing network. In this kind of application, a high resolution, large sampling frequencies and low sensibility to possible noise factors such as moisture, electromagnetic fields or vibrations are required. These requirements lead to the choice of Fiber Bragg Grating sensors. In this paper, an experimental methodology is proposed to reconstruct the characteristics of loads acting on a fast ship, starting from a finite number of local strain data obtained with FBG sensors. Sensors positions have been defined considering the ship hull as a beam subjected to a set of standard loads acting on a fast ship and taking into account the maximum strain positions. The development of the FE model of the ship hull, obtained from a three-dimensional CAD of a real powerboat obtained with a 3D scan, allows the calculation of the strain field related to a set of standard loads applied on the ship. The above-mentioned data are used as input for a fast-computational algorithm, in which standard and actual strain fields - provided by a network of FBG sensors - are compared to reach the reconstruction of global loads acting on the structure. The algorithm has been effectively applied in sailing condition to the powerboat, detecting the acting loads on the hull in real time.

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Keywords: real-time monitoring; Fiber Bragg Grating; trim control

* Corresponding author. Tel.: +39-0761-357046.
E-mail address: alessandro.mercuri@unitus.it

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1. Introduction

Ships structural failures are often due to overloads, fatigue, corrosion and erosion typical of sailing and may lead to major accidents, which can endanger the crew or the passengers, can pollute the marine environment and can require expensive maintenance or repairs.

In scientific literature, the topic of the calculation of loads acting on ships was faced from different points of view, methods and sensing techniques.

Several works deal with ships loads reconstruction problems, by referring to different procedures, methods and, eventually, sensing techniques. A recurring approach provides for the estimation of ships loads and motion through the Kalman filtering technique (e.g. Triantafyllou and Athans (1981)), which requires the application of the seakeeping theory and proper knowledge of the encountered wave spectrum; this last requirement represents one of the most important limitation of this kind of method (Xu and Haddara (2001)). Furthermore, the problem of the real-time reconstruction on ships has been mainly faced with the aim of evaluating the stress field of hulls; some of the methods which aim at this scope are based on numerical simulations, such as the inverse FEM (iFEM) based techniques (Kefal and Oterkus (2016)).

An experimental methodology to reconstruct the amount of loads acting on a fast ship has been developed (Torkildsen et al. (2005)), starting from a finite number of local strain measurements and giving the technical and economical advantage of providing key information about structure acting loads and sailing conditions using a limited number of sensing devices.

Therefore, on the one hand is interesting a concrete measurement of the global loads, in order to verify the assumptions that formed the basis for the design and dimensioning of ships. On the other hand, measurement of global loads could also satisfy the increasing needs for safety and control of the maritime field. A concrete development of this methodology could lead to the definition of real-time control systems which could give high-accuracy, reliable and noise-independent information about sailing conditions. The here-tested method is based on the exploitation of data from Finite Elements (FE) analysis; these analyses are used to calculate the strain field related to a set of standard loads applied on the ship. The above mentioned data will be used as input for a fast computational algorithm, in which the standard strain field and the real strain field, are compared to reach a real-time global loads reconstruction. The development of this kind of systems has been hampered by many difficulties concerning mounting, protecting and cable shielding of the sensors. Besides, these sensing solutions were external factors sensitive (i.e. moisture, magnetic fields, etc.) and a real-time signal processing were made difficult by available hardware features compared with the large amount of data to be treated and algorithms computational burden. Fiber Bragg Grating (FBG) sensors, used for strain measurements in the proposed method, permit to overall a wide part of these problems; in particular, they are immune from electromagnetic interference, moisture (Yeo et al. (2008)) and corrosion, but also ensure high sensitivity and high frequency response (Li et al. (2005)). They can be incorporated into a single fiber and play a key-role in monitoring systems (Fanelli et al. (2017)), in which also an interrogator must be included. This device is required for FBG sensors data reading, because of its capability in converting sensors light signal in wavelength data. Moreover, suited algorithms, i.e. the one based on the above-mentioned load reconstruction method, could complete monitoring systems which could give high-precision outputs, especially if they are completed with suited wavelet-based denoising (Wang et al. (1997)) and dynamic condensation (Salvini and Vivio (2006), Salvini and Vivio (2007)). Monitoring systems can be applied for both global loads and damage detection (Fanelli et al. (2018a)) on simple and complex systems, on which a proper study of sensors position, with aim of obtaining most suited local strain data, is required (Fanelli et al. (2018b)). This paper main aim is to demonstrate the effectiveness of the proposed method and of the related acquisition and data-processing system in dealing with challenging applications. An experimental study is carried out by simplified towing tests in calm water condition. The hull has been firstly modelled through Finite Element Method in order to simulate its structural response in standard loading conditions. The obtained data have been subsequently used as a base for the global loads reconstruction algorithm, which employed the strain data from an FBG network installed on the ship hull to reconstruct load data. The same data have been compared with reference data obtained from technical literature and ship-building standards.

2. Loads reconstruction method

During navigation the applied forces on the hull of a ship consist of the mass and inertia forces and the distributed water pressure (Jensen et al. (2001)). This kind of load induces a strain response difficult to analyze and foresee in detail. The hull structure behaviour is commonly analyzed as a cantilever beam subjected to concentrated loads. For fastboats, such as the here-tested high-stiffness ship, the most significant global loads considered are:

- longitudinal moments (sagging/hogging);
- horizontal bending moment;
- twisting moment;
- shear force;
- normal force.

In the proposed method, the estimation of global loads is reached by collecting real-time strain measurements using an FBG sensors network mounted inside of the ship hull and accurate Finite Element calculations. Sensors are distributed over the hull cross section at preselected points, with a proper orientation, in order to maximize the measured strain response related to the loads of interest and to minimize interference between the strain signals caused by local effects.

The ship material (in the analysed case aluminium) has to be linear elastic; this leads to a linear dependency between loads to be reconstructed and strain components.

A Finite Element model with standard load cases allows the simulation of the ship mechanical behaviour and provides the local strain values in correspondence with the FBG sensors measurement points. The reconstruction of the real global loads acting on the ship is based on the expression:

$$\boldsymbol{\varepsilon}^T = \boldsymbol{\chi}\boldsymbol{v}^T \tag{1}$$

where:

- $\boldsymbol{\varepsilon}$ collects FBG strain measurements for each timestep;
- $\boldsymbol{\chi}$ is a matrix collecting strain data obtained by Finite Element analysis with standard load cases;
- $\boldsymbol{v}$ is a vector which contains each-timestep scaling factors between real and standard static loads.

By considering the above-mentioned features of the $\boldsymbol{\chi}$-matrix, it can be seen that it could be invertible (i.e. quadratic) only in case of use of a FBG network in which the number of sensors equals the number of considered loads. In order to overcome this limitation and use an higher number of sensors, for the inversion of the $\boldsymbol{\chi}$-matrix, which will be necessary to obtain $\boldsymbol{v}$-vector, a pseudoinversion will be applied, by following the Moore–Penrose inversion. Consequently, vector $\boldsymbol{v}$ is determined by solving the following expression:

$$\boldsymbol{v}^T = \boldsymbol{\chi}^{-1}\boldsymbol{\varepsilon}^T \tag{2}$$

The above considered hypothesis of a linear dependency between applied loads and strain components implies that $(L/\varepsilon)_{Real} = (L/\varepsilon)_{FE}$ where L is the generic load.

This allow the global loads to be calculated considering the loads applied in the different FE analyses (L_{FE}) multiplied by the corresponding factors in $\boldsymbol{v}$-vector. This leads to the calculation of the five global loads for each timestep obtained by the FBG network:

$$\boldsymbol{L}^i_{Real} = \boldsymbol{L}^i_{FE} \cdot v_i \tag{3}$$

The computation time is very low; this is related to the fact that the elements of χ-matrix are known and constant for each calculation timestep, which gives the possibility of inverting the matrix in advance. On the other hand, the FE simulation, which could be considered as the most time-expensive phase of the method, is required once. Consequently, it can be said that this method could become the base of a fast-algorithm for real-time loads calculation; this could lead to the idea of online systems, designed to give real-time information about the acting loads and the trim of the ship.

3. Numerical model of the ship hull

The main goal of this paper is to demonstrate the suitability of the global loads reconstruction method for high-stiffness ship hulls, such as the one typical of powerboats; this leads to the choice, for the experimental tests, of a CUV 40 (Fig.1) powerboat, which can run at 125 km/h during a race, continuously impacting on the free surface of water. For this reason, the aluminum hull is designed to ensure an high stiffness.

Fig. 1. The analyzed CUV 40 powerboat

The boat is made in aluminum with E=70 GPa, ν=0.33 and ρ=2700 kg/m^3. The external geometry of the boat has been initially acquired from a laser scan and then edited to obtain regular surfaces. The superior part of the boat and the stern have been modeled with image recognition techniques and direct measuring on the boat. The internal geometry is very complex and represents the frame of the boat. The aluminum components give stiffness to the boat and are welded together one each other and to the hull. In the model are present 4 different types of components: the longitudinal beams, that run from the stern to the bow directly welded on the hull surface; the transversal ribs, that circumferentially stiffen the boat; the bulkheads, that divide the engine compartment from the cockpit and the latter from the bow compartment; the deck frame, that reinforces the stern and the bow deck. The only structures that have not been completely reconstructed through surface bodies are the longitudinal trusses of the hull and the bow cover. This choice was dictated by the fact that their cross-section was very small compared to the longitudinal development, leading to the decision to represent them as one-dimensional elements (splines), and then modeled with appropriate finite elements (Figure 2). The surface bodies have been meshed with 4 nodes shell elements featuring membrane and bending behavior and 6 DOFs per node, while the longitudinal reinforces have been modelled with beam elements with proper sections. The aluminum sheets for the hull have a thickness of 6 mm, except the very bottom part of the stern that is reinforced presenting a thickness of 8 mm. The engine compartment keel has a T section with dimensions 70 x 70 x 6 mm, the longitudinal beams on the hull at the bow compartment and cockpit have a L section with dimensions 35 x 70 x 6 mm and the longitudinal beams on the hull at the stern and on the deck have a L section with dimensions 38 x 55 x 6 mm. For a detailed description of the FE model, the reader is advised to consult Fanelli et al. (2019).

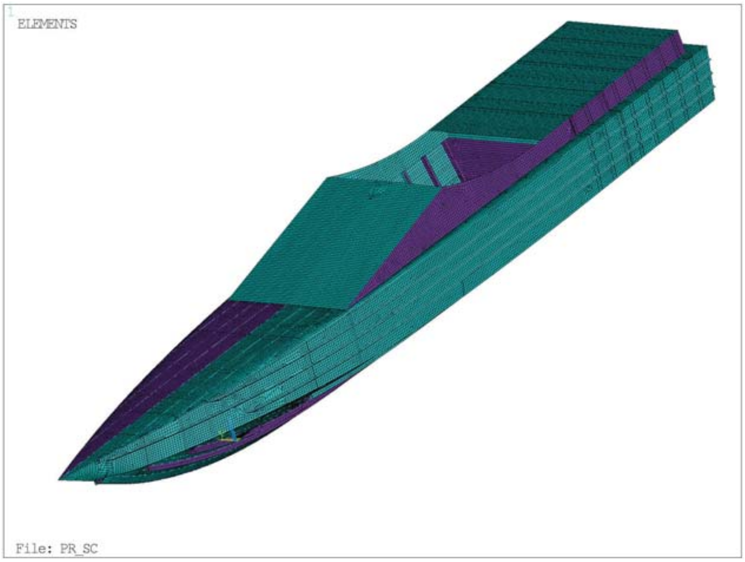

Fig. 2. CUV 40’ FE model mesh.

4. Signal denoising through wavelets method

The estimation of a noise-affected signal is one of the most relevant difficulty in signal processing. Commonly, a signal can be described as follows:

$$y_i = f(t_i) + \xi\delta_i \quad i = 1, ..., n \tag{4}$$

where y_i represent the available noisy data, f is the underlying function which have to be reconstructed through denoising, t_i is time, ξ is the noise level and δ_i are independent variables. In facing up the denoising problem, the f function can be expanded as a generalised Fourier series and then the related coefficients from data can be estimated. The effectiveness of such approach depends on a proper choice of the expansion basis; in fact, a correct choice allows an approximation based on a restricted number of terms of the generalized Fourier expansion. Wavelet series enable an effective Fourier expansion for both homogeneous and not homogeneous functions; for such reason, the wavelet method has been chosen for the here-described application.

Denoising algorithms based on wavelet transforms refer to three fundamental steps, i.e the wavelet transform of the noise-affected signal, followed by the noisy wavelet coefficients modification according to pre-determined rules and then the elaboration of the inverse transform referring on the modified coefficients.

In order to increase estimation precision, the empirical wavelet coefficients can be block-thresholded (Antoniadis et al. (2007)). This implies that in block average empirical wavelet coefficient estimation, informations available from the noisy data will make the threshold decisions more accurate, because they will be larger in number then term-by-term thresholding. A non-overlapping block thresholding estimator has been described by Cai and Brown (1999); this provides for each block estimation of the wavelet coefficients, obtained through the *James-Stein* thresholding rule.

Then, the reconstruction of the unknown function f is obtained through the Inverse Discrete Wavelet Transform (IDWT) to the empirical scaling coefficients and thresholded empirical wavelet coefficients vector.

This kind of threshold has been chosen because of the high quality in function estimation problems; the resulting estimator was called *BlockJS* and has a key-role in denoising the FBG signal within the here-described reconstruction algorithm.

5. Design of the load reconstruction system

5.1. Load reconstruction system workflow

The load reconstruction system workflow is described in Fig.3. The first step is represented by the strain measurements from the FBG network installed onto the ship hull; local strains cause Bragg wavelengths shift on each FBG sensor, the light signal of whom are read by the FBG interrogator and converted to strain data. Then, the strain data are used as input for the load reconstruction algorithm, from whom each timestep-load data are obtained. Considering that these data could be affected by noise, they are filtered by referring to the wavelets method and the *Block James-Stein* thresholding rule.

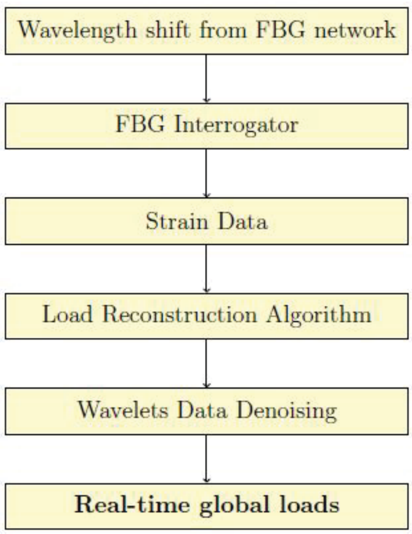

Fig. 3. Global loads reconstruction method workflow.

5.2. FBG interrogator

FBG interrogator plays a key-role in the global loads reconstruction system; it receives a light signal from an FBG array which consists in the reflected Bragg wavelength from each sensor. Interrogator output consists in FBGs Bragg wavelength values for each acquisition timestep, which are passed to external hardware for strain data calculation.

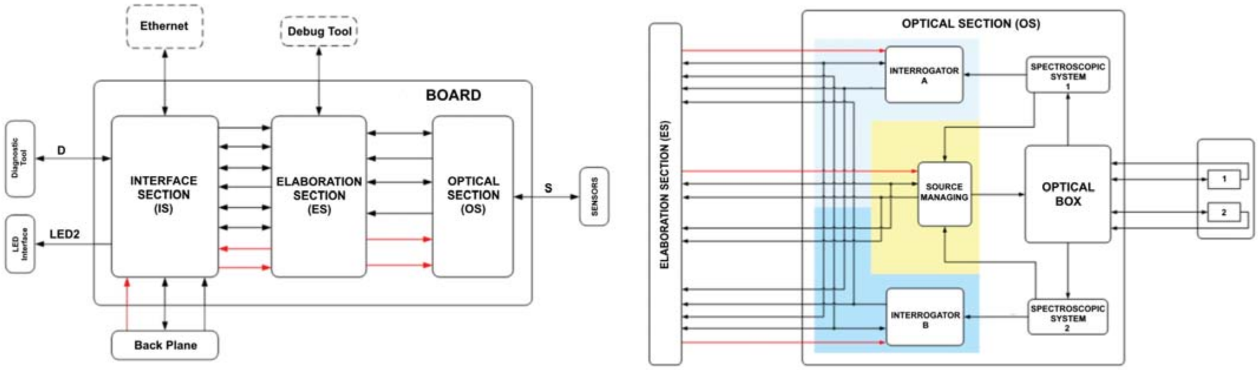

Fig. 4. FBG interrogator technical scheme.

For the here-presented experimental campaign, an high-performance interrogator has been designed and realised (Figure 4); the device can acquire 4 channels of 12 sensors simultaneously with a 5 *pm* accuracy and 1 *pm* resolution. Moreover, the interrogator can acquire sampling frequency up to 3 *kHz*. This allows the recognition of every kind of induced strain, from calm water sailing ones to water impacts ones.

5.3. Reconstruction load system interface

The designed load reconstruction system has also an interface, which consists in a touchscreen monitor, from which each variation of loads value during sailing can be observed (Figure 5). The real-time control is made possible both with color maps, which changes their values depicted on the ship 3D CAD because of loads changes, and by bar plot numerical indicators. Data elaboration is allowed by a dedicated personal computer, on which the before mentioned algorithm are written as source code in real-time acquisitions suited softwares. The system stability from electrical peaks or interruptions is ensured by an UPS (Uninterruptible Power Supply).

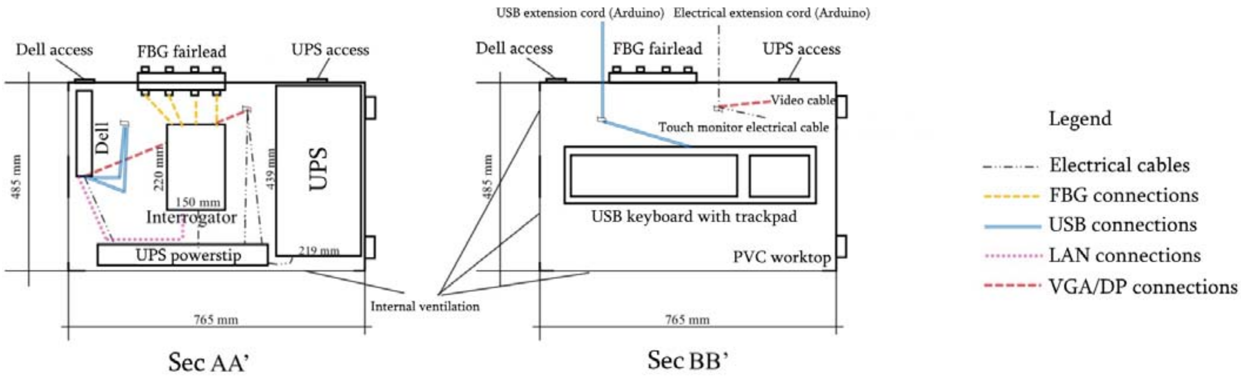

Fig. 5. On board real time reconstruction system technical scheme.

5.4. FBG sensors

Fiber Bragg Grating sensors represent one of the most suited sensing solutions for real time load reconstruction systems; as it was mentioned before, they allow high-frequency measurements in which the output signal is immune from every kind of noise external to the mechanical system (e.g. the hull). Moreover, they have a great resistance and independence from water and moisture, which makes them ideal for naval applications. FBG sensors also have a great strain sensitivity, which guarantees their effectiveness in measuring on every kind of structures, also the high-stiff ones.

Fig. 6. An example of the FBG sensors installation.

5.4.1. *Amidship FBG network*

The amidship FBG network is attached over a cross section approximately 1.0 m in front of the CUV 40 control panel.

Sensors positions have been chosen both considering the need of installing sensors onto reachable places (Figure 6) on the hull and the availability of regular shape zones trying to limit the divergence between the strain field computed through the above described FE model and the measurements operated on the real ship. The sensors were positioned considering where the maximum strains due to every considered load are expected from beam theory.

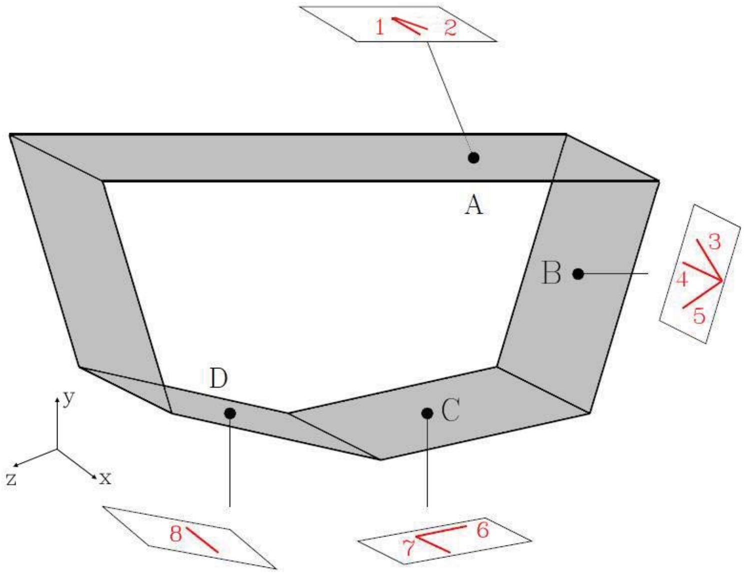

Fig. 7. Scheme of the amidhship FBG newtork.

Idealising the analysed system, the hull was looked upon as a cantilever beam. Considering beam theory, the best strain response from bending moment is located as far from the neutral axis as possible and parallel to the beam. Sensors suited for the measurement the bending moments strains are located in position A, C and D (see Figure 7). Besides two more considerations could be taken into account: vertical sagging/hogging moments and horizontal moment are separated by the sign of the strain values; also the normal force could be measured through these sensors, but also through sensor 4 (pos.B, in Fig7), which is nearer to the neutral axis.

Other four sensors are installed in this network. The positions of three on four of them, considering both the location on the hull structure and the inclination related to hull axis, are designed in order to measure maximum values of strain related to the twisting moment and the transversal shear force acting at the cross section. Sensor located in points A allows the measure of strains related to the twisting moment, while the ones positioned at B could measure strains related both to shear force and to twisting moment in both directions.

The last sensor, which is perpendicular to hull axis and located in point C, has been chosen for circumferential strains measurement, considering shell theory.

6. Experimental validation of global loads measurement method

The experimental validation phase could be ideally divided into two parts; in the first part, the before mentioned FE model of the ship hull has been used in order to simulate the structural response of the ship hull under standard load conditions; this has made possible to collect the χ-matrix values which must be implemented in the load reconstruction algorithm. The second part is the test phase; under predetermined test conditions, the measurement chain has been activated and the global loads data collected in each acquisition timestep. The obtained data have been lately compared with the reference ones, calculated following the most reliable shipbuilding standards (i.e. ITTC, International Towing Tank Conference, and DNV, Det Norske Veritas). In particular, the comparison has been focused on the normal force and sagging/hogging moment values, which were the most indicated in relation to the tests features.

6.1. First part - Computation of the strain field due to standard loads

As it was described above, the first part of the experimental validation of the purposed method is based on the deployment of the FE model of the hull for the computation of the strain fields related to standard loads. The applied loads have been chosen considering the before-mentioned common loads acting on a ship hull during sailing; their standard values (Table 1), which refer to Det Norske Veritas rules for High Speed and Light Crafts, have been chosen considering CUV 40' geometry and standard sailing conditions (Figure 8).

Fig. 8. FE model Loading conditions.

Table 1. Standard loads acting on the hull - FE model.

Standard Load from DNV rules	Reference Symbol	Reference Value	Measurement Unit
Sagging/Hogging moment	$M_{Sagg/Hogg}$	1.00	MN·m
Horizontal bending moment	$M_{H.Bending}$	1.00	MN·m
Twisting moment	$T_{Twisting}$	1.00	MN·m
Vertical shear force	V_{Shear}	0.10	MN
Normal force	N_{Normal}	1.00	MN

These loads allow the gathering of $\boldsymbol{\varepsilon}_{FE}$ vectors for each standard load, in order to collect the χ-matrix; in the next step, using $\boldsymbol{\varepsilon}_{Real}$ values, the $\boldsymbol{v}$-vector of time-depending scale-factors would be assembled, in order to achieve the computation of real-loads vector $\boldsymbol{L}$.

$$\chi = \begin{bmatrix} \varepsilon_{1,HS} & \varepsilon_{1,HM} & \varepsilon_{1,TW} & \varepsilon_{1,SH} & \varepsilon_{1,NO} \\ \gamma_{2,HS} & \gamma_{2,HM} & \gamma_{2,TW} & \gamma_{2,SH} & \gamma_{2,NO} \\ \gamma_{3,HS} & \gamma_{3,HM} & \gamma_{3,TW} & \gamma_{3,SH} & \gamma_{3,NO} \\ \gamma_{4,HS} & \gamma_{4,HM} & \gamma_{4,TW} & \gamma_{4,SH} & \gamma_{4,NO} \\ \varepsilon_{5,HS} & \varepsilon_{5,HM} & \varepsilon_{5,TW} & \varepsilon_{5,SH} & \varepsilon_{5,NO} \\ \varepsilon_{6,HS} & \varepsilon_{6,HM} & \varepsilon_{6,TW} & \varepsilon_{6,SH} & \varepsilon_{6,NO} \\ \gamma_{7,HS} & \gamma_{7,HM} & \gamma_{7,TW} & \gamma_{7,SH} & \gamma_{7,NO} \\ \gamma_{8,HS} & \gamma_{8,HM} & \gamma_{8,TW} & \gamma_{8,SH} & \gamma_{8,NO} \end{bmatrix} \quad (5)$$

6.2. Second part - Measurements and reconstruction on CUV 40’ hull

The testing phase, which has been taken place at ”Cantieri del Mediterraneo” shipyards in Naples, consisted of towing tests, in which CUV 40’ hull has been trailed by another ship, with the aim of simulating an axial load on the hull itself. During the tests, the velocity has been maintained on a constant value of about 10 knots; referring to the sailing conditions, they can be considered of calm sea, both because of the closeness of the test area to the shipyard and for the absence of wind during the test day. Two tests have been performed; a 5 s sampling interval has been chosen, with the aim of acquire in constant speed conditions. Strain data have been acquired under a 2.5 kHz sampling frequency; the collected data have been lately processed through the above described reconstruction algorithm and the output data compared with reference ones.

6.2.1. Normal force

The first part of the analysis concerns the reconstructed value of the normal force acting on the ship hull and its comparison with a reference value, obtained from shipbuilding standards. In particular, the N-force standard value calculation has been obtained by referring to the resistance (which consists of viscous resistance and wave resistance) related to 10 knots towing; the obtained value, with both the ITTC and DNV rules, is of 5 kN.

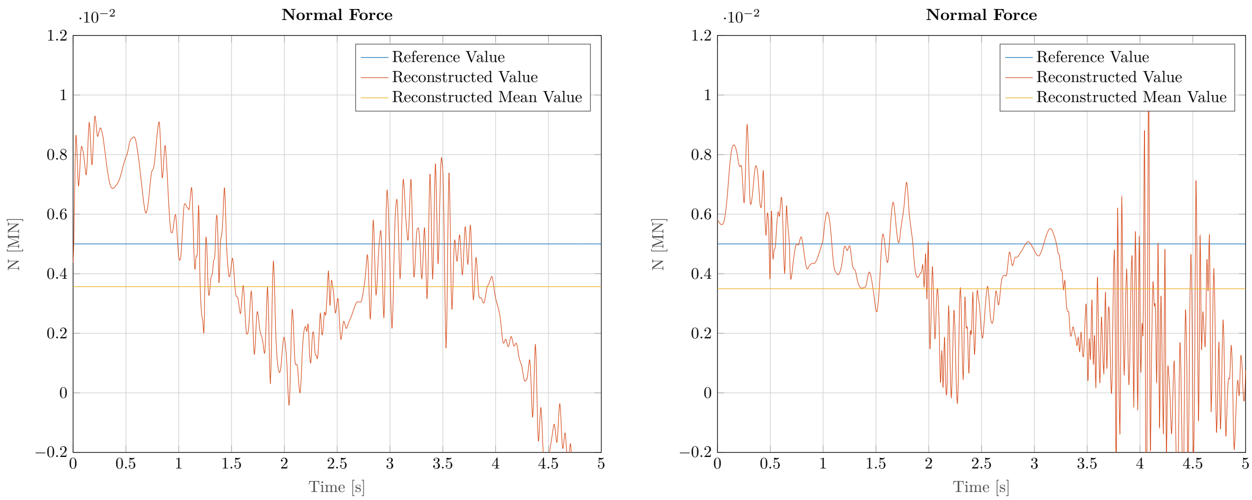

Fig. 9. Normal force reconstructed and reference values comparison (a) First test; (b) Second test.

Fig.9 resumes the obtained results. As it can be seen, the mean reconstructed value of the normal force is comparable to the reference one. The latter is only an approximated esteem of the actual loads as a result of a simplified model corrected by equivalent coefficients interpreting ideal conditions. The result is even more appreciable taking into account the complexity and stiffness of the ship hull considered and the very low number of FBG sensors used for reconstruction. The result deviation goes back to the actual navigation conditions characterized by speed fluctuations and pulling variability. Nevertheless, as a first validation case the load reconstruction shows encouraging results.

6.2.2. Sagging-Hogging Moment

The second part of the analysis concerns the reconstructed value of the longitudinal moments acting on the ship hull, which consists, for fastboats, in sagging and hogging moments, which have opposite directions. These loads are due to two main causes: the combination of on-board weights and buoyancy forces on one hand and wave effects on the other hand. In particular, when the buoyancy forces amid-ship are greater than the internal loads weight, an hogging moment is induced; this causes the keel to be compressed and the deck to be tensioned. Otherwise, if the internal loads weight amid-ship is greater than the buoyancy, an hogging moment is induced; this causes the deck to be placed in compression and the keel to be tensioned.

In waves sagging occurs if wave crests are at the bow and stern, hogging if a wave crest is at mid-ship. Sagging increases in case of large bow flare ship and the ship motions are larger than waves. In case flat bottom stern close to the waterline, the ship stern form can have the same effect.

Taking into account the main features of the test ship and sea conditions, it can be said that the wave-induced longitudinal moments are near-zero. Considering the weight-induced effects, in which the buoyancy-induced effects could be considered, they can be filtered out by taking into account the induced strain in zero-velocity condition. On the other hand, by towing the ship, a longitudinal moment is applied on the whole ship hull. This load value, which will be constant on the whole structure length, is here reconstructed and compared with an expected value, which has been calculated, with DNV rules, taking into account the towing force and the hull geometry and its around 3.5 kN·m.

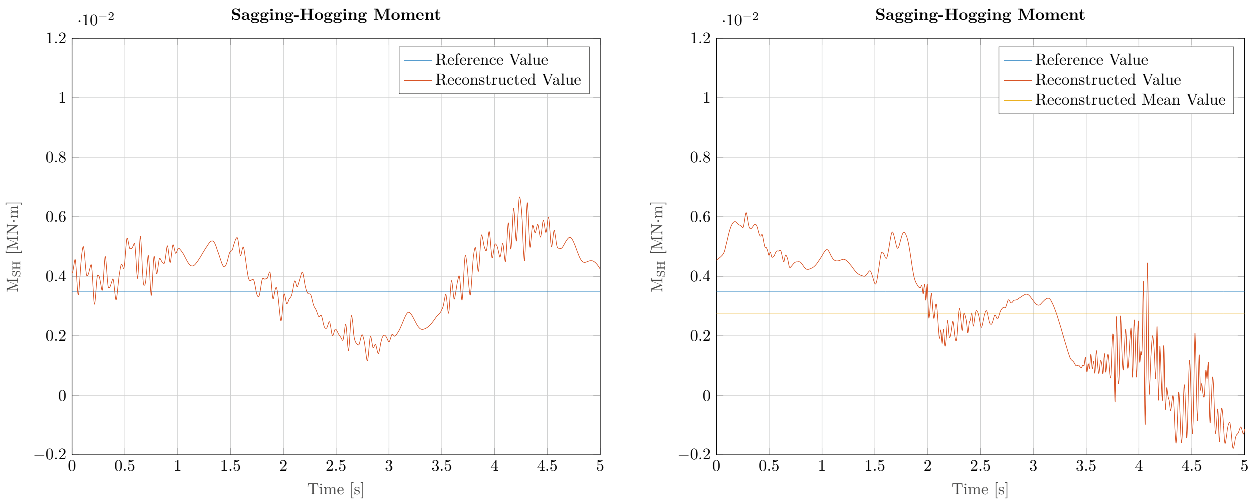

Fig. 10. Sagging/Hogging moment reconstructed and reference values comparison (a) First test; (b) Second test.

Fig.10 resumes the obtained results. The percentage difference between the reference value and the reconstructed mean value is very low in the first test (about 5.7%) and reach an higher value (comparable with the Normal force comparisons) in the second test. The actual test conditions lead to fluctuation in load reconstruction even in this case.

7. Conclusions

This paper aims at demonstrating the suitability of a global loads real-time reconstruction method for applications on powerboats characterised by an high-stiff hull. The procedure, applied for the first time to aluminum race hulls, uses an algorithm that reconstructs the loads on the boat starting from local strain data as input. For the validation of the method, an innovative experimental setup has been set up on the powerboat chosen for the test, a CUV 40. The setup, studied for multiple acquisitions of strain data for different purposes, is composed of multiple chains of FBG sensors (8 for the present application) connected to an FBG interrogator specially design for the case and unique on the market. It is able to collect up to 4 channels simultaneously at 3 kHz. The system is autonomously powered by an uninterruptible power supply and equipped with a screen for on-board consultation. The results presented in this paper are the first validation of the reconstruction system (procedure+instruments) and show a good accuracy in comparison to approximated load esteem and futurity of the approach. Moreover, it must be considered that the here presented tests have been realized in challenging conditions, because of the ship hull high stiffness and the low number of FBG sensors installed, which make the load reconstruction much difficult to achieve. Appreciable results here obtained show this method great potential; besides, the load reconstruction system will allow the application in several kind of naval systems and sailing tests, because of the possibility of increasing sensors number (and, consequently, the precision of reconstructed data) and to adapt the standard load strain matrix (the χ matrix) by referring to a few FEM simulations. Nevertheless, future tests are planned for a more complete evaluation of loads in different navigation conditions.

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References

Antoniadis, A., et al., 2007. Wavelet methods in statistics: Some recent developments and their applications. Statistics Surveys 1, 16–55.

Cai, T.T., Brown, L.D., 1999. Wavelet estimation for samples with random uniform design. Statistics & probability letters 42, 313–321.

Fanelli, P., Biscarini, C., Jannelli, E., Ubertini, F., Ubertini, S., 2017. Structural health monitoring of cylindrical bodies under impulsive hydrodynamic loading by distributed fbg strain measurements. Measurement Science and Technology 28, 024006.

Fanelli, P., Facci, A., Jannelli, E., 2018a. Live crack damage detection with local strain measurement on solid bodies subjected to hydrodynamic loading. Procedia Structural Integrity 8, 539–551.

Fanelli, P., Facci, A.L., Russo, S., 2018b. Influence of sensors layout in damage monitoring of cylindrical bodies under impulsive hydrodynamic loading, in: AIP Conference Proceedings, AIP Publishing. p. 420009.

Fanelli, P., Trupiano, S., Belardi, V.G., Vivio, F., Jannelli, E., 2019. Structural health monitoring algorithm application to a powerboat model impacting on water surface. Procedia Structural Integrity in press.

Jensen, A., Taby, J., Pran, K., Sagvolden, G., Wang, G., 2001. Measurement of global loads on a full-scale ses vessel using networks of fiber optic sensors. Journal of ship research 45, 205–215.

Kefal, A., Oterkus, E., 2016. Displacement and stress monitoring of a panamax containership using inverse finite element method. Ocean Engineering 119, 16–29.

Li, E., Xi, J., Chicharo, J., 2005. Multi-point fiber bragg grating based vibration measurement system with high sensitivity and fast frequency response, in: 2005 IEEE LEOS Annual Meeting Conference Proceedings, IEEE. pp. 820–821.

Salvini, P., Vivio, F., 2006. Master d.o.f.'s choice for new approaches to condense mass matrix, in: Conference Proceedings of the Society for Experimental Mechanics Series, Society for Experimental Mechanics Series.

Salvini, P., Vivio, F., 2007. Dynamic reduction strategies to extend modal analysis approach at higher frequencies. Finite Elements in Analysis and Design 43, 931–940.

Torkildsen, H.E., Grovlen, 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. Technical Report. NORWEGIAN DEFENCE RESEARCH ESTABLISHMENT KJELLER.

Triantafyllou, M., Athans, M., 1981. Real time estimation of the heaving and pitching motions of a ship, using a kalman filter, in: OCEANS 81, IEEE. pp. 1090–1095.

Wang, G., Havsgård, G., Urnes, E., Pran, K., Knudsen, S., Kersey, A., Davis, M., Berkoff, T., Dandridge, A., Jones, R., et al., 1997. Digital demodulation and signal processing applied to fiber bragg grating strain sensor arrays in monitoring transient loading effects on ship hulls, in: Optical Fiber Sensors, Optical Society of America. p. OFA5.

Xu, J., Haddara, M., 2001. Estimation of wave-induced ship hull bending moment from ship motion measurements. Marine structures 14, 593–610.

Yeo, T., Sun, T., Grattan, K., 2008. Fibre-optic sensor technologies for humidity and moisture measurement. Sensors and Actuators A: Physical 144, 280–295.