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Procedia Structural Integrity 24 (2019) 926–938

Structural Integrity Procedia

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AIAS 2019 International Conference on Stress Analysis

Structural health monitoring algorithm application to a powerboat model impacting on water surface

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Abstract

In naval field, live monitoring of local strains and displacements in the hull is the basis for dynamic studies such as checking the design limits, sea-keeping tests in smooth and rough seas, fatigue life estimation and damage detection. Vessels sailing on water are subject to impulsive loadings and local deformations; in these conditions the damage detection in real time becomes crucial. In this paper, a numerical methodology is proposed to measure the deformation of the whole structure of a powerboat entering the water free surface starting from local strain measurements, obtained numerically in a FE simulation. A modal decomposition approach has been used to reconstruct the structural response of the whole boat body. The reconstruction algorithm is calibrated for this study by means of the normalized modal strains matrix obtained through a FEA. A transient FE analysis is implemented to generate local strain signals from virtual sensors. In this analysis hydrodynamic loading resulting from well-known models are applied. The positioning and number of the virtual reference and control sensors are investigated. Virtual control sensors are utilized to compare strains with respect to the reconstructed quantities. Subsequently, the structural health monitoring algorithm has been applied to the powerboat model with a localized damage on the structure. The results reported in the paper reveal the capability of the method to detect the damage in real time.

Keywords: Damage detection; Structural Health Monitoring; Modal Reconstruction

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10.1016/j.prostr.2020.02.081

1. Introduction

The impact of solid bodies on a fluid surface is a complex problem hard to analyze and to completely master. At the same time, many engineering fields present applications of this phenomenon. Just think of: sea loads on ships or offshore structures; return of rockets and spaceships on the earth; energy dissipation or storage; aircraft fuselages in sea landing (Faltinsen (1990); Cavalagli et al. (2017); Cui et al. (1999); Seddon and Moatamedi (2006)).

The case in which the structures interact with a free-surface of water has been studied in many papers in literature, in which, through numerical simulations or analytical simplified models, the authors obtain the hydrodynamic loads on bodies of simple shape impacting the fluid (Moyo and Greenhow (2000); Scolan (2004); De Rosis et al. (2014); Facci et al. (2016); Zarghami et al. (2014)).

Many works had the aim to measure in real time the deflections on flexible bodies impacting the free surface of water (Qin and Batra (2009); Maki et al. (2011)). In Panciroli et al. (2016) the deformed shape of a structure impacting on water has been studied experimentally using localized measurements. The used algorithm reconstructs the strains at desired locations utilizing strain measurements at different positions. The live measurements are guaranteed by fiber optic sensors with Bragg gratings (FBG) easily implementable in case of high humidity (Yeo et al. (2008)). The dynamic response characteristics of these sensors make them eligible for live monitoring implementations (Kuang and Cantwell (2003)).

In large civil structures applications, the use of distributed strain measurements is spreading for real-time Structural Health Monitoring (SHM) studies. The structural behaviour is monitored during operations and the continuous analysis of strain measurements permit to verify the presence of damages that influences the global integrity (Ubertini et al. (2013); Laflamme et al. (2016); Balageas et al. (2006)).

The diagnosis and localization of a damage is of preeminent importance also in case of structures subjected to recursive impact loads. In this case the problem is very challenging because of the complex dynamic behavior of the structure and the fast appearance of large localized deformations.

A SHM approach has been proposed in Fanelli et al. (2017) for fluid-structure interaction of deformable bodies impacting the free surface of the water. In that work the authors present an analytical methodology to detect the presence of a damage in the structure only elaborating the strain measurements during the impact. The distributed strain measurement system has been applied to a curved deformable structure and the algorithm returns the correct diagnosis on the structure integrity. However, the detection and localization of a damage on the structure is partially influenced by the correct disposition of sensing system on the structure (Fanelli et al. (2018a)). In Fanelli et al. (2018a) disposition instructions are obtained through an investigation performed on the case of a polymeric cylinder impulsively loaded axisymmetrically. The impact has been simulated with a FEA generating numerical sensors signals, that have been elaborated by the damage detection algorithm defining which sensors disposition better identifies existence, dimension and localization of the damage.

In Fanelli et al. (2018b) the real-time deformation reconstruction algorithm has been applied to a real case of interest. An FE simulation of a hull structure subjected to impact loads generates virtual strain signals used in place of the real strain measurements of FBG sensors. The study is limited to the 2D analysis of a simplified model of the hull considered in sound and damaged state. The authors proved the potentiality of the damage detection algorithm investigating different sensors layouts in terms of disposition and number.

In this paper the previously presented SHM procedure has been applied to a 3D detailed model of the boat studied in Fanelli et al. (2018b), in order to validate the method when a small damage affects a large stiff structure subjected to impulsive loadings. The authors realized a 3D FE model of the CUV 40 powerboat (chosen for experimental tests presented in Fanelli et al. (2019)) and simulated the vertical impact of the hull on the free surface of the sea. The strain data have been collected as virtual sensors signals and elaborated by the algorithm of reconstruction. The procedure has been applied in case of both sound and damaged state of the hull demonstrating the capability of damage detection of the method.

2. Strain field reconstruction and damage recognition

The structural health monitoring procedure proposed elaborates local strain measurements and reconstructs the global behavior of the structure using the principle of modal decomposition. For reasons of brevity, the strain field reconstruction procedure is here shortly illustrated, but for a detailed explanation of it, the reader is advised to consult Fanelli et al. (2017).

The possibility of a real-time reconstruction of strain values and damage identification is allowed by the simplicity of the analytical frame of the algorithm.

In fact, the dynamic response of a structure loaded beneath the elastic limit is a linear superposition of its modal shapes. The scalar weights that combine the shapes are called modal coordinates *m* and can be applied indifferently to every time-dependent dimension that characterizes the structural response of the structure.

$$\overline{\varepsilon} = \left[R\right]\overline{m} \tag{1}$$

where ε is a vector of strains as functions of time *t*; *R* is the matrix of normalized modal strains at the measuring locations. The terms of this matrix are proper of the structure, they are not time-dependent and do not need to be updated during the monitoring process. If strain values at certain location are known in time, e.g. FBG sensors are mounted on the structure, the modal coordinates can be calculated inverting eq. (1).

The modal shapes can be calculated analytically in case of simple structure with elementary shape. In this case the modal strain values are known not only at the measuring location (the terms of *R* matrix) but everywhere in the structure is desired to reconstruct the deformed entity. *C* is the matrix that contains the modal strains at reconstructed positions. When structures are complex, the *R* and *C* components are calculable with common modal FEA. The time-varying reconstructed value of strain at a desired position can be assessed as:

$$\overline{\varepsilon}_{CP} = \left[C\right]\overline{m} = \left[C\right]\left(\left[R\right]^T\left[R\right]\right)^{-1}\left[R\right]^T\overline{\varepsilon}_{MP} \tag{2}$$

where the subscript MP stands for Measuring Point and CP for Control Point.

If in a Control Point an actual strain signal is available, e.g. from a FBG sensor not used as Measuring Point, the comparison between the reconstructed strain and the actual strain gives information about the health condition of the structure. As a matter of fact, when in sound state, the deviation is small or negligible, it depends on the number of sensors used and their disposition. On the contrary, when the strain values are different, the residual error between them is an index of damaging. In fact, the *C* and *R* matrices are calculated for the structure in undamaged state, so that is impossible for the algorithm to obtain the actual value of the damaged structure. The amplitude of the residual error increases with the severity of the damage because reveals the deviation of the structure stiffness from the sound state.

3. FE model for modal and transient dynamic analyses

In this paper, the structural monitoring procedure has been applied to a race boat that impacts on the water free surface. The boat is a CUV 40 with an aluminum hull highly reinforced with an internal aluminum frame. The structure is very stiff because of the race performances requested. During a race, running at 125 km/h, the hull continuously bumps on the water and loads the frame with high stresses.

A simplified 2D model of the hull was presented in Fanelli et al. (2018b), where the only hull shell was modelled in details, while the internal structure was simplified with equivalent modelling.

The 3D model, here presented, features every structural component of the real boat as the result of a long and complex activity of inverse engineering, since the boat is nearly a prototype designed and handcrafted in a small series. All the geometry are modeled with surfaces because of the characteristics of the structure, i.e. thickness is small compared to other dimensions, and the computational burden to be held.

The external geometry of the boat has been initially acquired from a laser scan and then edited to obtain regular surfaces (Fig. 1). On the main surface of the hull the fluido-dynamic ledges are present too. 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 4 different types of components are present: 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.

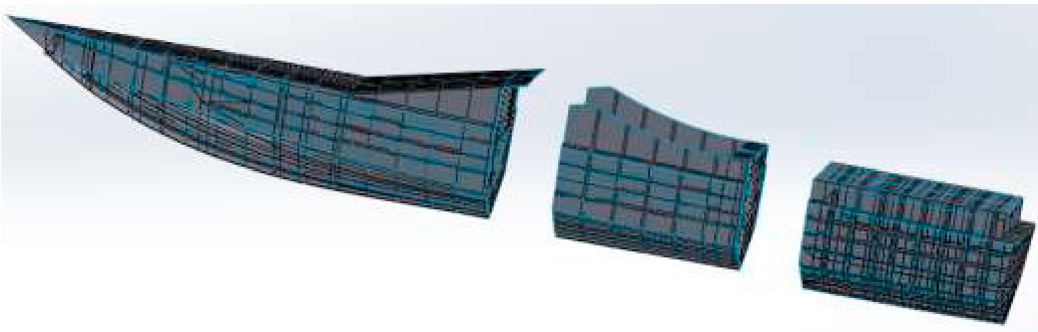

Fig. 1. CUV 40 geometry, exploded view of bow compartment, cockpit and engine compartment.

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. The only exception was made for the trusses of the stern compartment with the function of basis for the two engines of the boat (Fig.s 2 and 3).

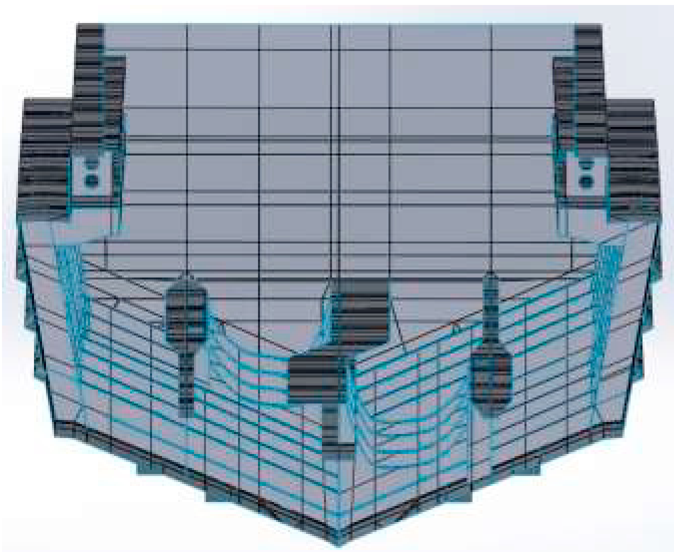

Fig. 2. Particular of engine compartment

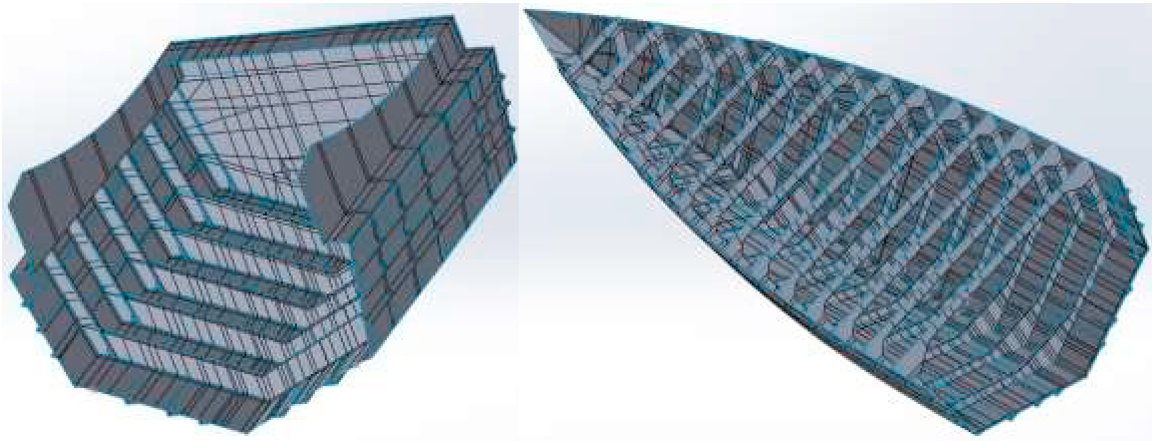

Fig. 3. Particular of cockpit (a) and bow compartment (bow deck hidden) (b)

The hull, the deck and the internal frame are made in aluminum with E=70 GPa, ν=0.33 and ρ=2700 kg/m^3.

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 (Fig. 4).

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. Engine compartment keel has a T section with dimensions 70 x 70 x 6 mm, longitudinal beams on the hull at the bow compartment and cockpit have a L section with dimensions 35 x 70 x 6 mm and longitudinal beams on the hull at the stern and on the deck have a L section with dimensions 38 x 55 x 6 mm.

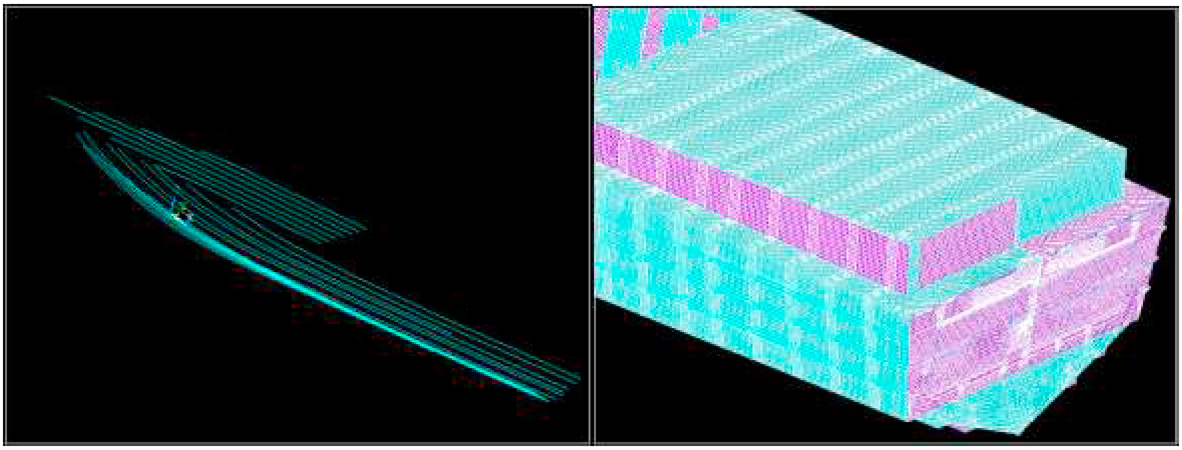

Fig. 4. Mesh of beam elements used for longitudinal reinforces (a) and shell elements (b)

3.1. Modal analysis

The modal analysis of the structure has been performed in ANSYS considering an edited model of the boat. In the case of complex structures with components with very different stiffness, the common problem is the appearance of local mode shapes that interest a very limited amount of mass. These mode shapes have no interest in the health monitoring of the global structure. That is because the modal analysis has been performed on a edited model in which the wind panels of the cockpit, part of the stern deck and the engine cover panels have been neglected.

In Table 2, for reasons of clearness, are reported only the first 50 eigenfrequencies of the boat, but for the modal reconstruction purpose the first 200 modes have been stored.

Table 1. First eigenfrequencies.

Mode number	Frequency [Hz]	Mode number	Frequency [Hz]	Mode number	Frequency [Hz]
1	3.993	21	97.163	41	134.773
2	43.008	22	98.577	42	134.964
3	47.112	23	100.742	43	135.576
4	48.596	24	104.494	44	136.117
5	62.475	25	106.454	45	137.039
6	64.258	26	106.857	46	137.973
7	65.787	27	107.195	47	138.404
8	72.490	28	108.513	48	138.913
9	72.994	29	109.624	49	140.143
10	76.112	30	112.316	50	142.987
11	79.772	31	114.049		
12	82.076	32	118.792		
13	83.392	33	121.203		
14	84.713	34	125.355		
15	85.282	35	125.795		
16	86.655	36	127.825		
17	89.903	37	128.177		
18	92.155	38	129.419		
19	93.159	39	130.870		
20	95.358	40	132.206		

For future applications the authors are considering to implement condensation strategies in order to approach higher frequencies with a reduced computational burden (Salvini and Vivio (2006), Salvini and Vivio (2007)).

No rigid body motions are present in the modal shapes because the analysis has been performed considering the same constraints applied in the transient dynamic analysis, i.e. the nodes of the upper deck on the symmetry plane have vertical displacement constraints and symmetry constraints. The presence of fluid does not affect the eigenfrequencies of the boat as commonly considered as a non-structural added mass that acts as a damping.

3.2. Transient dynamic analysis

The dynamic simulation represents the source of strain data, in place of experimental tests, for SHM procedure validation. It is considered a vertical impact of the boat on the free surface of the water that generates an hydrodynamic loading condition on the hull. The applied pressures are those from the Wagner analytical model, which is based on the potential flow theory. It neglects gravity and is nominally applicable to small deadrise angles. The pressure on the wet part of the hull are obtained as

$$p(x,t)=\rho\left[-a\sqrt{r_w^{\,2}-x^2}+\frac{\pi}{2}\frac{\dot{\imath}}{\tan(\beta)\sqrt{r_w^{\,2}-x^2}}-\frac{1}{2}\frac{\dot{\imath}}{r_w^{\,2}-x^2}\right] \tag{3}$$

where η is the keel penetration with respect to the undisturbed water level, $r_w = \pi\eta/(2tan(\beta))$ is the wet length, a is the keel deceleration, ρ is the water density and a superimposed dot denotes the time derivative (Fig. 5). We consider an initial velocity at the impact instant $\eta'_0 = 5m/s$ and a constant $a = 5g$ and a simulation time of $t = 40ms$ with an integration step of $\Delta t = 0.05ms$.

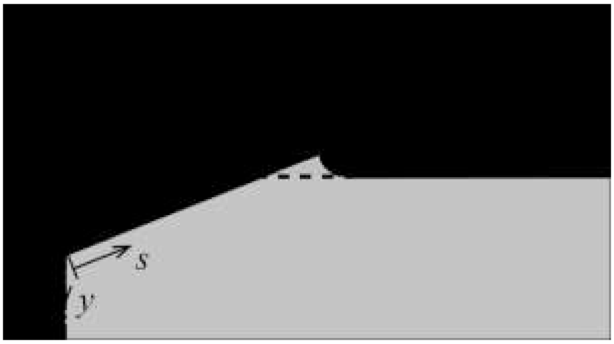

Fig. 5. Scheme of the water entry of the hull.

The hull profile presents a variation of the deadrise angle along the longitudinal direction from the stern to the bow. The time-varying pressure distribution applied in the simulation keeps in consideration this aspect, thanks to a fine discretization of the hull. Obviously the wet part of the hull on which the pressure acts increases during the sinking in longitudinal and transversal direction according to the Wagner model and to the reconstructed vertical motion of the boat.

As previously mentioned the boat is considered constrained at the nodes of the upper deck that lie on the plane that contains the longitudinal and the vertical directions and passes through the keel of the boat. These nodes have vertical constraints and symmetry constraints in respect to the aforementioned plane. As a consequence, without loss of generality we assume the boat still and the volume of water that impacts on the hull moving upwards.

The transient analysis has been done in case of sound state of the boat and in case of damaged hull. The damage introduced in the model is a disconnection of a couple of elements between the rib and a longitudinal reinforce (Fig. 6). It simulates a typical damage on the welding. The anomaly introduced is very small and limited if compared to the dimensions and stiffness of the whole boat.

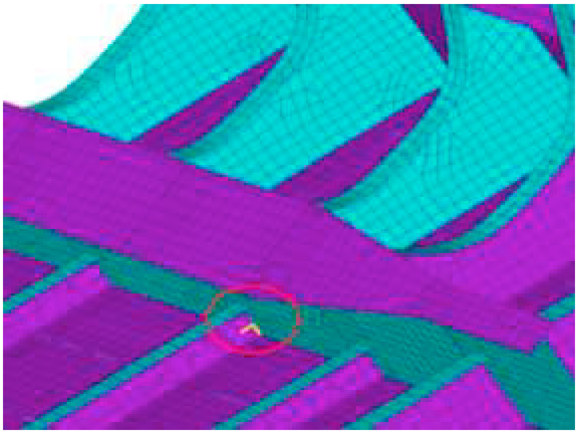

Fig. 6. Welding damage considered between the rib and a longitudinal reinforce.

4. Structural Health Monitoring results

In this paper is tested the capability of the procedure to detect the presence of a damage on the boat during a vertical impact on the water. The challenge of this validation test is in the complexity and stiffness of the structure considered compared to the very localized damage introduced in the model. Considering a future application of the monitoring system on a boat like the one modelled, the author chose to measure the strains on the transversal ribs of the internal frame. The bending due to vertical impact generates circumferential stresses and strains on these frame components.

On the basis of the indications presented in Fanelli et al. (2018a), the sensing system set-up has been chosen. The main parameter in a correct modal reconstruction is the number of modes considered, i.e. the higher the number, the better the result. The number of sensors installed has to be at least equal to the number of modal shapes considered. The spatial distribution has another key role in the reconstruction. In fact, a perfectly evenly spaced distribution not always leads to a good reconstruction, at the contrary sensor positioning where modal displacements show maximum amplitude gives better results.

Combining these indications, it is immediate to understand that the choice of the modal shapes used as modal basis for reconstruction is crucial. A screening of the modes only based on mass participation is not sufficient. The dynamic response of the structure has been elaborated with a Fast Fourier Transform in order to detect in different positions which are the main modal shapes excited.

The procedure has been applied supposing to mount an FBG chain on the third rib from the stern. On the rib, nearby the hull, 21 virtual sensors are considered (Fig. 7). Each sensor measures the strain in the direction parallel to the inclination of the hull. The damage is between sensor 12 and sensor 13.

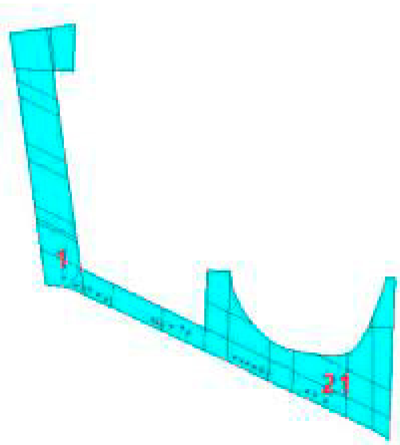

Fig. 7. Half of the third rib from the stern, equipped with 21 virtual sensors.

The results of the transient analysis show a strain evolution in time very similar in case of undamaged and damaged hull. That is because the structure is very stiff and the damage very localized. In Fig. 8 is reported the trend of virtual sensor 12 that is the nearest to the damage.

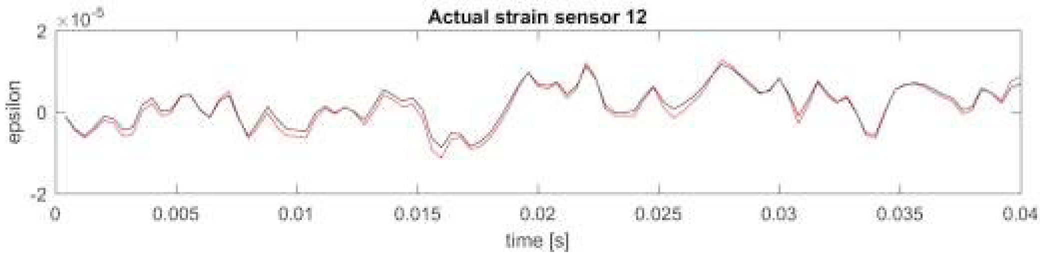

Fig. 8. Actual strain in case of sound state boat (red line) and damaged boat (black line) at control sensor 12

The FFT performed in different points of the rib, revealed that higher eigenfrequencies than the first 50 reported should be considered for the reconstruction. The procedure has been applied using 16 reference sensors (a reasonable number in real sensing systems) with 16 eigenfrequencies from 4 to 400 Hz characterized by an high mass participation index. The sensors 1, 2, 3, 4, 5, 6, 8, 9, 11, 13, 14, 16, 18, 19, 20, 21 were used as reference sensors for the reconstruction, while sensors 7, 10, 12, 15, 17 are considered control sensors for structural health monitoring.

The results reported in Fig. 9 and 10 show the reconstruction of strain values at the control sensors on time. In Fig. 9 the comparison of reconstructed strain signal and actual signal show the effectiveness of the modal algorithm, especially in sensor 10, 12 and 15 where the strain values are maximum.

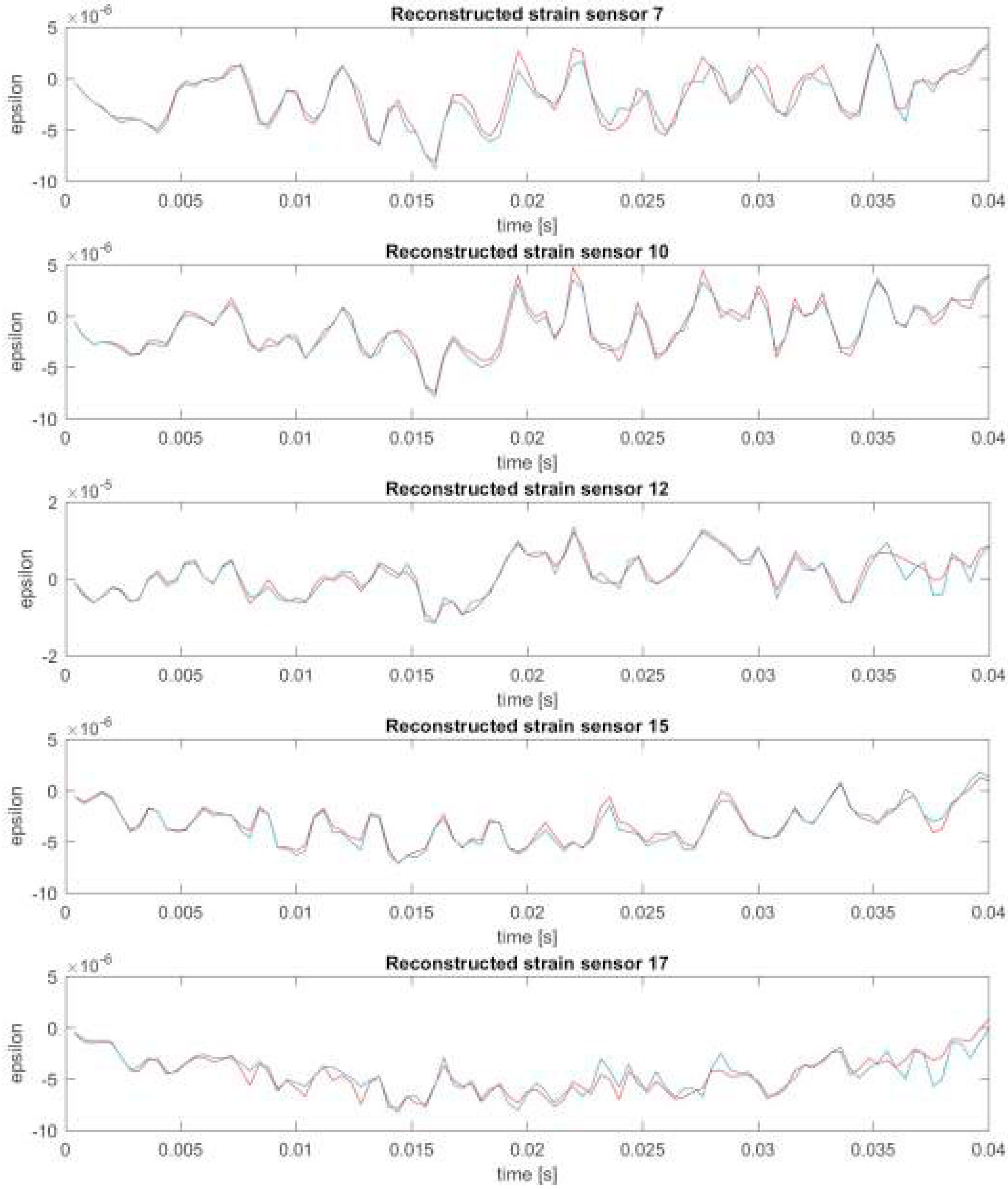

Fig. 9. Reconstructed strain (blue line) and actual strain (red line) at control sensors

When the reconstruction is performed on the strain signal coming from the damaged boat (Fig. 10), the algorithm returns values of strain that present a bigger error. Since the global behaviour is not much affected by the damage, this deviation has to be evaluated through an error index.

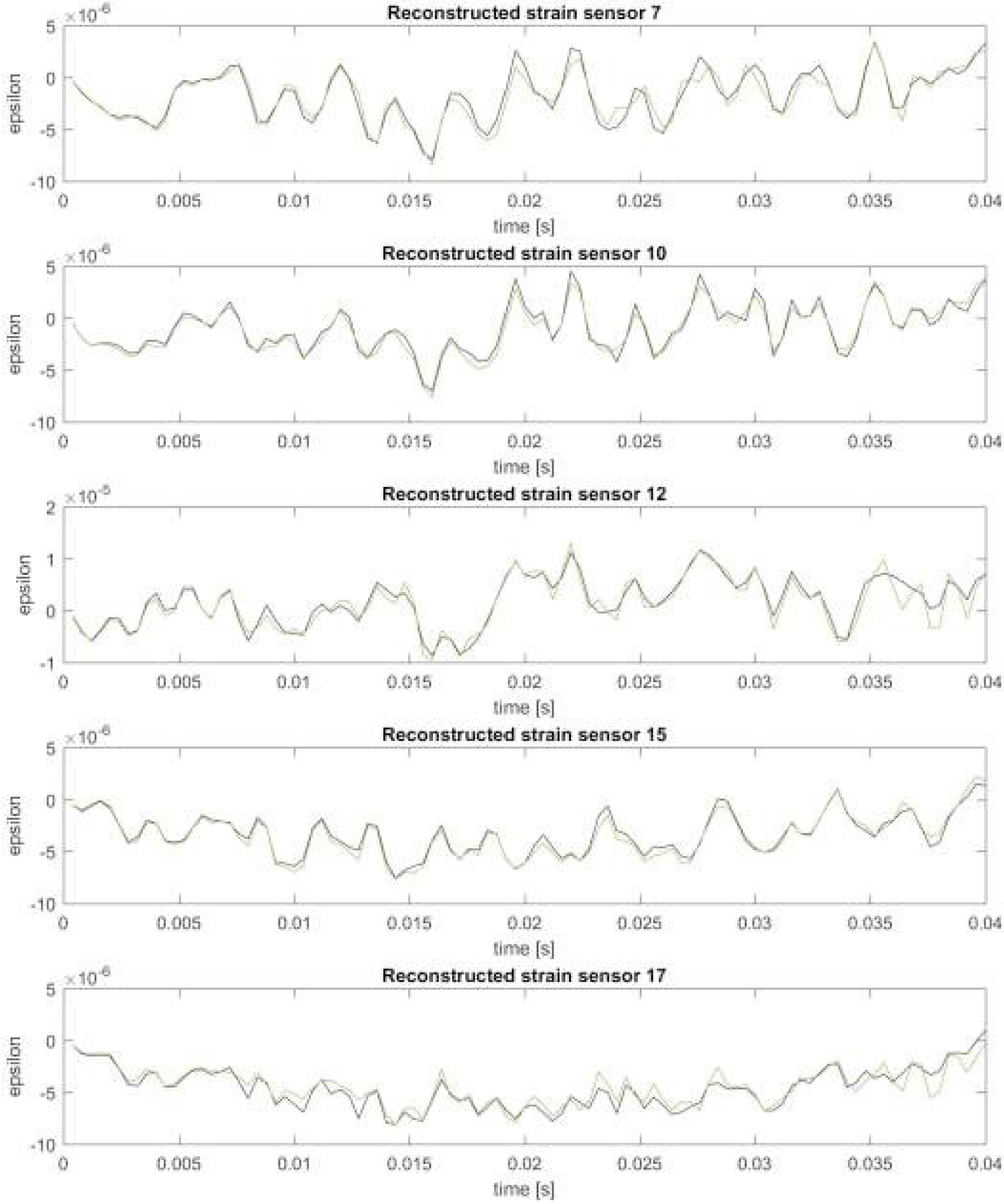

Fig. 10. Reconstructed strain (green line) and actual strain (black line) at control sensors on damaged structure

For the validation of the procedure, a direct comparison between the strain signal reconstructed for undamaged and damaged boat, can be performed using an error function as:

$$I_{\Delta\varepsilon}(s)=\frac{\sqrt{\int_0^t\left|\varepsilon_{CP\_dam}(s,t)-\varepsilon_{CP\_undam}(s,t)\right|^2 dt}}{\sqrt{\int_0^t\left|\varepsilon_{CP\_undam}(s,t)\right|^2 dt}} \quad (4)$$

The index values are reported in Fig. 11, where is evident the trend around the damage. The procedure shows the presence of the damage and the approximated location of it.

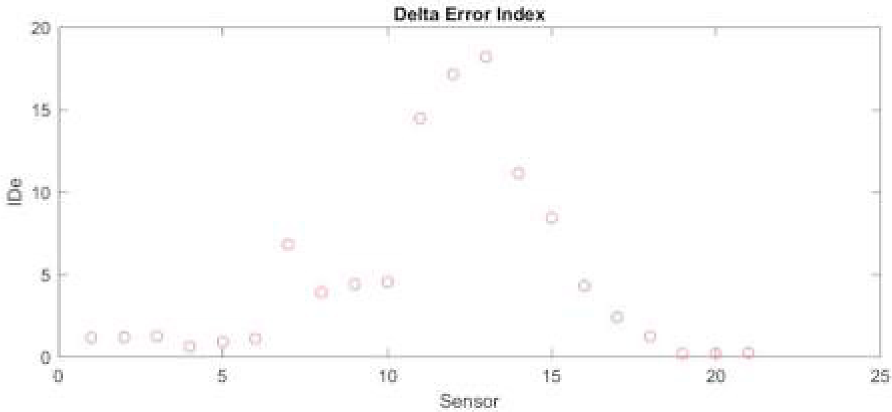

Fig. 11. Error index $I_{\Delta\varepsilon}$

The index used is useful for the procedure validation but it cannot be used for a real time monitoring system. In fact, the reconstructed strain for the sound state is not available in real time conditions when the boat is damaged. At the contrary, Fanelli et al. (2018b) demonstrated that the index I_ε is almost independent from the time sampling interval but is function of the structure, of its health condition and of the sensor system setup.

$$I_{\varepsilon}(s)=\frac{\sqrt{\int_0^t\left|\varepsilon_{CP}(s,t)-\varepsilon_{FEM}(s,t)\right|^2 dt}}{\sqrt{\int_0^t\left|\varepsilon_{FEM}(s,t)\right|^2 dt}} \quad (5)$$

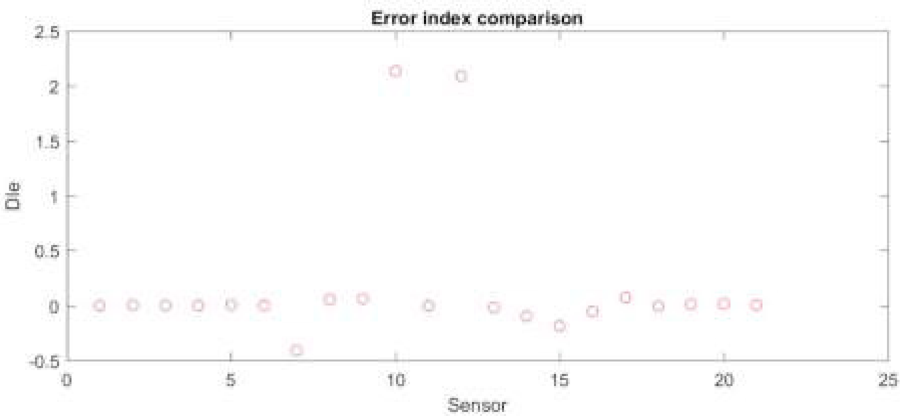

Fig. 12. Difference between index $I\varepsilon$ in sound and damaged condition

The index can be continuously stored by the system and compared with the new calculated value of it. A simple difference between the indexes when the boat is undamaged and after the damaging show clearly the presence and location of the damage (Fig. 12).

5. Conclusions

In this paper the previously presented SHM procedure has been applied to a 3D detailed model of a powerboat CUV 40, in order to validate the method when a small damage affects a large stiff structure subjected to impulsive loadings. The authors realized a 3D FE model of the powerboat and simulated the vertical impact of the hull on the free surface of the sea. The strain data have been collected as virtual sensors signals and elaborated by the algorithm of reconstruction. The procedure has been applied in case of both sound and damaged state of the hull demonstrating the capability of damage detection of the method.

The results are promising for a future implementation in a real sensing system. The algorithm detects the presence of the damage and its location even if the global behavior of the boat is lightly affected by the damage simulated. Nevertheless, the set-up of the sensing system, in terms of sensor positioning and modal shapes choice, still requires an important work, before the real-time monitoring phase, that has to be shortened and developed for future applications.

Acknowledgements

This work was supported by the Italian Ministry of Education, University and Research under PRIN grant No. 20154EHYW9 "Combined numerical and experimental methodology for fluid structure interaction in free surface flows under impulsive loading", with Prof. C. Biscarini as principal investigator; and by the Italian Ministry of Economic Development under "Fondo per la Crescita Sostenibile – Bando "HORIZON 2020" PON I&C 2014-2020 - Sviluppo di tecnologie innovative per la misura, la caratterizzazione e il controllo delle prestazioni degli scafi di navi veloci". The authors want to thank Cantieri del Mediterraneo S.p.A.(Naples) for the support.

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