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Live crack damage detection with local strain measurement on solid bodies subjected to hydrodynamic loading

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Abstract

The interaction of water free surface with solid bodies is object of interest in several mechanical, ocean, aerospace and civil engineering problems. The presence of impulsive loading and large local deformation leads to complex coupled dynamics. The possibility of live monitoring of these body could provide information about damage detection and fatigue life estimation. The definition of appropriate signal processing and modeling tools enabling the extraction of useful information from distributed sensing signals is a relevant scientific challenge. On the basis of previous works by some of the authors, this paper deals with the application of a method for real-time deformed shape reconstruction of solid bodies subjected to impulsive loadings using distributed numerically generated strain measurements signals, such as those produced by Fiber Bragg Grating (FBG) sensors. A numerical study is carried out considering a simplified model of the problem of hull structures subjected to hydrodynamic loading. The hull, analyzed in a simplified section, has been studied both in healthy condition and with the presence of crack damages. The potential for detecting, localizing and quantifying this damage using the reconstruction algorithm is investigated, by leveraging the proposed concept of control sensors, that are FBG sensors used for comparing reconstructed strains and/or displacements with measured quantities. The positioning and number of sensors and the effect of sensor layout on damage detection is investigated, with the aim of developing a real time damage detection methodology.

Keywords: Damage Detection; Structural Health Monitoring; FBG; Modal Reconstruction

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1. Introduction

The wide range of applications in civil, mechanical, ocean and aerospace engineering of the problem of solid bodies impacting the water surface have focused the attention of the scientific literature (Faltinsen (1990); Cavalagli et al. (2017)). The impact of a solid body on the water generates large local strains and displacement and high vibration (Cui et al. (1999)) and needs to be taken into account for the design of marine structures, aircraft fuselages in sea landing, rockets, boosters and other structures interacting with water in the presence of a free-surface, as reported in (Faltinsen (1990); Seddon and Moatamedi (2006). Several works, presented by Moyo and Greenhow (2000); Scolan (2004); De Rosis et al. (2014); Facci et al. (2015); Facci and Ubertini (2015); Facci et al. (2016), deal with the prediction of hydrodynamic loading and related deformation, analytically and numerically. On the other hand, most of the experimental investigations are focused on rigid structures (Garrison (1996); Chu et al. (2005); De Backer et al. (2009)) and rarely address flexible bodies (Qin and Batra (2009); Maki et al. (2011); Stenius et al. (2011); Russo et al. (2017). An experimental methodology to reconstruct the deformed shape of bodies entering the water free surface, starting from a finite number of local strain measurements have been developed in Panciroli et al. (2015) and Panciroli et al. (2016). The methodology uses fiber optic sensors with Bragg gratings (FBG) as sensing devices. FBGs are suitable for high frequency measurements and are practically insensitive to water and moisture, as reported by Yeo et al. (2008) and Majumder et al. (2008). Live measurement of structural deformation (Panciroli et al. (2015); Panciroli et al. (2016); Kuang and Cantwell (2003)) through FBG technology is possible thanks to its characteristics such as high resolution, lightness, flexibility, small size and response speed. The enhancement of this methodology could lead to the definition of real-time Structural Health Monitoring (SHM) systems to track the evolution in structural performance during operation and to verify the integrity of the system time wise. With the development of new sensing technologies, the increasing availability of high computational capacities and the steady improvement of signal processing algorithms, the use of distributed strain measurements is becoming popular for real time analysis and SHM of large structures and surfaces (Ubertini et al. (2013); Laflamme et al. (2016); Balageas et al. (2006); Materazzi and Ubertini (2011)). The structural monitoring of bodies subjected to fluid-structure interaction due to impulsive loading is still to be developed in depth. A further development of the deformed shape reconstruction method for curved structures is presented in Fanelli et al. (2017), where a novel methodology for damage detection is proposed. The main challenge is performing damage diagnosis, localization, and prognosis on structures where traditional sensing solutions can be used with difficulty because of technical limitations. The use of advanced sensing solutions, capable of performing distributed strain monitoring, is a fruitful research direction to achieve an effective SHM. In Fanelli et al. (2018) the sensors layout is investigated in order to detect design instruction for monitoring systems implementation. FE models of cylindrical bodies subjected to impulsive loads are realized and sensors signals generated numerically and processed to detect damage presence, extension and position.

This paper deals with the application of the method for real-time deformed shape reconstruction of solid bodies subjected to impulsive loadings using distributed numerically generated strain measurements signals. Such signals may represent those produced by Fiber Bragg Grating (FBG) sensors and the proposed procedure may be applied for structural health monitoring.

A numerical study is carried out considering a simplified model of the problem of hull structures subjected to hydrodynamic loading. The hull, analyzed in a simplified section, has been studied both in healthy condition and with the presence of crack damages. The potential for detecting, localizing and quantifying this damage using the reconstruction algorithm is investigated, by leveraging the proposed concept of control sensors, that are FBG sensors used for comparing reconstructed strains and/or displacements with measured quantities. The positioning and number of sensors and the effect of sensor layout on damage detection is investigated, with the aim of developing a real time damage detection methodology.

2. Real-time damage detection

The real time monitoring of the structure is based on the processing of the FBG signals performed through a modal decomposition method. The analytical procedure, presented in Panciroli et al. (2015) and enhanced for curved bodies in Fanelli et al. (2017), is here briefly reported.

The elastic response of a structure can be reconstructed on the basis of a finite number of mode shapes of it. The time-varying displacement and deformation at reference points of the structure is expressed in terms of modal coordinates *m(t)* :

$$\begin{aligned} v_R(t) &= [\Phi]\, m(t) \\ \varepsilon_R(t) &= [\Psi]\, m(t) \end{aligned} \tag{1}$$

where $v_R(t)$ and $\varepsilon_R(t)$ are vectors containing displacements and strains as functions of time t at the measurement location; Φ and Ψ are N x M matrices with N number of measurement points and M number of mode shapes, with $M \leq N$. The matrices terms are the normalized modal displacement and modal strain component at the measuring locations, respectively. The matrices Φ and Ψ are characteristics of the investigated structure and can be obtained analytically, numerically or experimentally, before monitoring and without requiring any further updating.
Since the vector $\varepsilon_R(t)$ collects the signal coming from sensing system, the modal coordinates $m(t)$ are known.

$$m(t) = \left([\Psi]^T [\Psi]\right)^{-1} [\Psi]^T \varepsilon_R(t) \tag{2}$$

In simple shape structures, where the modal shapes are known in every point, the Φ and Ψ matrices can be rewritten as ϕ and ψ matrices containing modal components at every requested position and it is possible to reconstruct the entire deformed shape. Likewise, for more complex structures the matrices ϕ and ψ can be obtained with a FE modal analysis.

For damage detection purposes, we consider a set of virtual FBG sensors deployed along the structure. Some of these sensors are used for reconstruction purposes, and are called reference sensors, while the remaining ones, called control sensors, are used for monitoring purposes to measure the deviation between the reconstructed deformation and the actual deformation.

At the control sensors positions the time-varying reconstructed displacements and strains are:

$$\begin{aligned} v_C(t) &= [\phi]\left([\Psi]^T [\Psi]\right)^{-1} [\Psi]^T \varepsilon_R(t) \\ \varepsilon_C(t) &= [\psi]\left([\Psi]^T [\Psi]\right)^{-1} [\Psi]^T \varepsilon_R(t) \end{aligned} \tag{3}$$

By denoting Ψ and ψ with the matrices containing modal strain components at the locations of the reference and control sensors, respectively, a residual error can be computed between measured signal and reconstructed one. Considering that both Ψ and ψ matrices are obtained for the structure in undamaged conditions, the residuals are expected to be relatively small only if the structure remains in its sound state. On the contrary, when the structure is damaged, the reconstruction algorithm fails to provide the strain field, because it relies on the wrong mode shapes, being those affected by damage. It follows that residuals are expected to become relatively large as damage increases and are therefore used as damage sensitive features for damage detection.

3. Numerical model

In previous works the damage monitoring procedure has been tested for simple structures damaged with a delamination that affects a relatively extended zone of the body.

In this paper the method has been applied to a more complex structure with a very localized damage such as a crack with a small penetration. The structure considered is the aluminum hull of a powerboat CUV 40’ that runs at 125 km/h of mean velocity during a race, continuously impacting on the free surface of water.

The hull geometry (Fig.1) has been acquired with a 3D laser scan and managed to determine a 2D transversal section at 4.2 m from the stern of the boat, where the impacts are relevant. In the neighborhood of this location the sections are almost constant. On the hull there are ledges made in aluminum for boat stability.

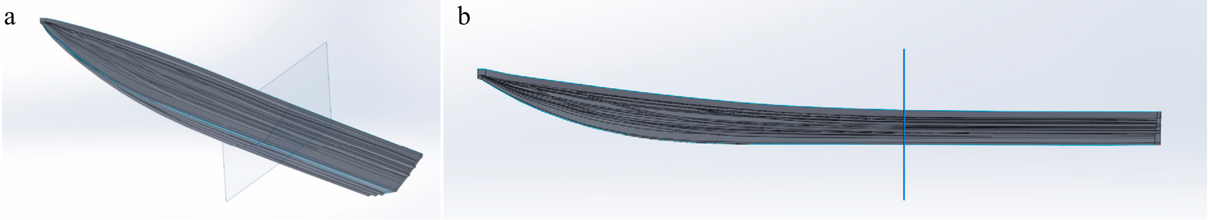

Fig. 1. Hull geometry: (a) 3d view; (b) longitudinal view.

The hull has a thickness of 6 mm and is made in aluminum with E=70 GPa, ν=0.33 and ρ=2700 kg/m^3. The FE model of the hull section is made of solid plane elements with plain strain state condition and exploiting the symmetry (Fig.2a).

Inside the hull, the powerboat is reinforced with a rigid keel at the bottom extremity connected with ribs to longitudinal reinforcements positioned at the end of the immersed hull (Fig.2b). Given that the goal of this work is defining the applicability of the method to a complex geometry, some modelling approximations have been introduced, sacrificing the exact reproduction of the actual conditions. Because of the high stiffness of the reinforcement, compared to the thin hull, no relative displacements are permitted between the extremity of the hull connected to keel and the longitudinal reinforcement. For the same reason the remaining part of the hull above the reinforcement and the upper deck have been ignored. We considered a section positioned longitudinally in the middle between two subsequent ribs. In this way we neglect the effect of the ribs on the hull bending in the section plane. The hull has a deadrise angle β of 21.7° and the width in *x-direction* is 1.4 m (Fig. 3).

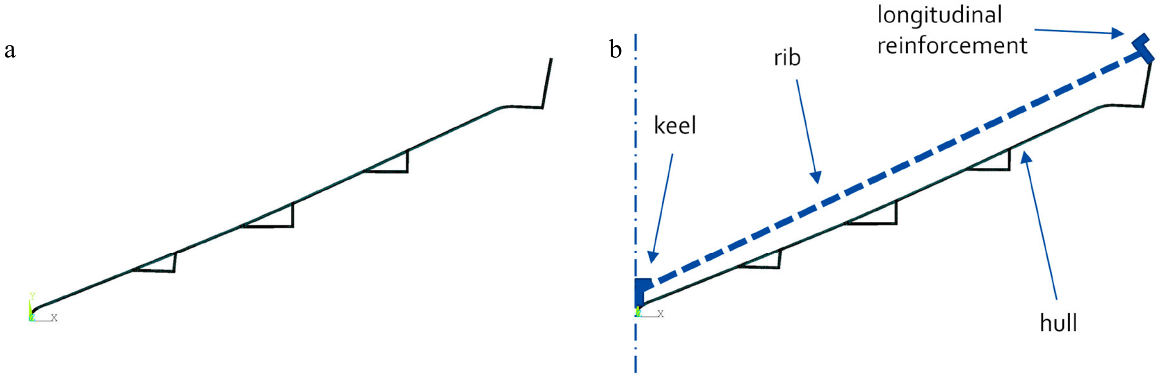

Fig. 2. (a) 2D model of the symmetric portion of the hull section; (b) symbolic positioning of internal reinforcements.

A modal analysis of the structure has been performed and the first 8 modal shapes have been extracted, characterized by natural frequencies of 18.7 Hz, 49.3 Hz, 86.1 Hz, 115.5 Hz, 203.5 Hz, 282.1 Hz, 419.0 Hz and 527.4 Hz. With an approximation, the presence of fluid can be considered as a non-structural added mass that acts as a damping, lowering the amplitude of the oscillations without affecting natural frequencies values. These modal shapes are characterized almost exclusively by a flexural behavior. For this reason the matrices Φ, Ψ, ϕ and ψ collect only displacements v, orthogonal to hull abscissa s and relative to keel position, and in plane deformation ε in s direction (Fig.3).

An hydrodynamic loading condition is considered due to the vertical impact of the hull on the free surface of the water. In order to determine the applied loads we use the Wagner analytical model, which is based on the potential flow theory, neglects gravity, and is nominally applicable to small deadrise angles. In particular, according to the Wagner solution, the pressure coefficient on the wet side of the wedge can be computed as

$$p(x,t) = \rho\left[-a\sqrt{r_w^{\,2}-x^2} + \frac{\pi}{2}\frac{\dot{\eta}^2 r_w}{\tan(\beta)\sqrt{r_w^{\,2}-x^2}} - \frac{1}{2}\frac{\dot{\eta}^2 x^2}{r_w^{\,2}-x^2}\right] \tag{4}$$

where η is the keel penetration with respect to the undisturbed water level, $r_w = \pi\eta/(2\tan(\beta))$ is the wet length, a is the keel deceleration, ρ is the water density and a superimposed dot denotes the time derivative. We consider an initial velocity at the impact instant $\dot{\eta}_0 = 5m/s$ and a constant $a = 5g$ and a simulation time of $t = 80ms$ with an integration step of $\Delta t = 5\cdot 10^{-2} ms$.

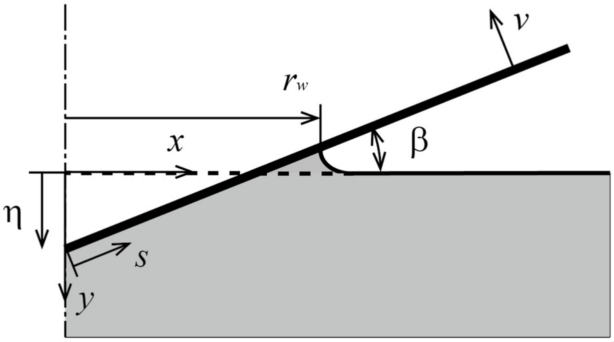

Fig. 3. Schematic of the water entry of the hull and relevant geometrical parameters.

The modal shape matrices are defined for 24 potential positions for virtual sensors at the inner side of the hull (Fig.4). These points represent the potential positioning of the FBG sensors in the experimental setup. In order to define a correct setup for the experimental campaign we want to define how many reference sensors are needed for displacements reconstruction and where to set the control ones for damage monitoring.

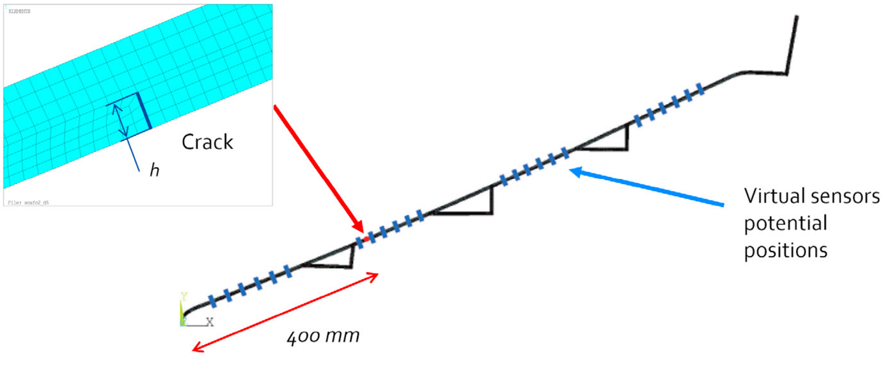

Fig. 4. Schematic of virtual sensors and crack positions.

A crack is present on the external surface of the hull, at a distance of 400 mm from the keel. Five different crack depths h are considered (0.5 – 1 – 1.5 – 2 – 2.5 mm) in the simulations.

4. Monitoring results

As previously mentioned, the intent of this work is testing the monitoring procedure on this particular geometry where a very localized damage is present. In previous works, we denoted that the sensors lay-out has a reliable role in the correct detection of the damage position, while a lay-out that can reconstruct the undamaged structure behavior can always detect the presence of a damage. The condition for a good modal reconstruction is obviously the almost uniform distribution of reference sensor on the entire structure. When this is not possible, because of the dimension of the structure or the difficult access to part of it, good results can be achieved positioning the sensors nearby loading zones and, in general, where the principal modal shapes have the higher amplitudes.

A series of 5 sensors set-up has been analyzed in order to foresee the future implementation of FBG sensors on the CUV hull in the experimental campaign. Obviously an higher number of mode shapes considered leads to a better accuracy in reconstruction results, but on the other hand the number of reference sensors must be at least equal to the number of mode shapes considered. The implementation of an high number of sensors leads to a sensible increasing of experimental set-up cost. For this reason it should be preferable to define a lay-out that minimizes the number of sensors implemented guaranteeing at the same time the correct monitoring.

We considered a set with a total of 4 reference sensors (Set 1), 2 sets with two different dispositions of 6 sensors (Set 2 and Set 3) and 2 sets with two different dispositions of 8 sensors (Set 4 and Set 5) (Fig. 5). In case of Set 2 and 4, a reference sensor is very close to the crack (about 5 mm far), while in Set 1,3 and 5 all reference sensors are far from crack position (at least 90 mm far).

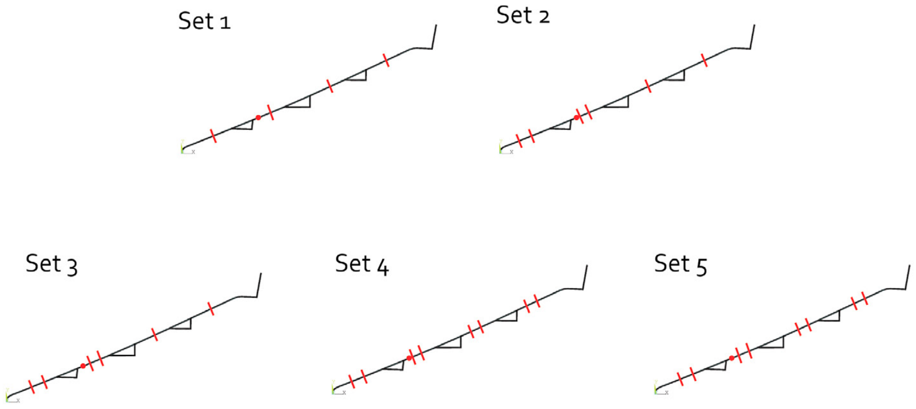

Fig. 5. Reference sensors lay-out.

Firstly we analyzed the capability of the selected sets of reconstructing the behavior of the undamaged hull during 80 ms of impact on water. In order to quantify the informative content of reconstructed strains and displacements, we computed the deviation between measured from FEA and reconstructed strain at control sensors, as well as the deviation between measured and reconstructed displacement, as

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

$$I_v\left(s\right)=\frac{\sqrt{\int_0^t \left|v_C\left(s,t\right)-v_{FEM}\left(s,t\right)\right|^2 dt}}{\sqrt{\int_0^t \left|v_{FEM}\left(s,t\right)\right|^2 dt}} \tag{6}$$

In Fig. 6 and 7 are reported the deviations for the five sets in case of undamaged structure. The accuracy on strain reconstruction is very high and almost everywhere under 10%, excluding some points in Set 1 and Set 3. At the contrary, the reconstruction of displacements present some critical issues nearby the keel for every sensors set. The error comes from a bad reconstruction of displacements in the first 20 ms of impact, when the loads are very high and concentrated near the keel, that cause very local deformations. This kind of deformed shape is not easily reconstructed with the modal shapes considered. For a better reconstruction it should be introduced more modal shapes with very local displacement distributions characterized by very high natural frequencies. However this effect is present only very close to the keel and rapidly decreases, obtaining a good accuracy everywhere else. As it can be predicted, sensors sets with more reference sensors present lower deviations and almost constant values whatever control sensor considered.

It is very interesting that the error is almost independent from the time interval considered for its evaluation (Fig. 8). This implies that the deviation between measured strain and reconstructed strain is characteristic of the modal reconstruction parameters, such as geometry, modal shapes considered, reference sensors distribution and number, but it is almost independent from the loading applied.

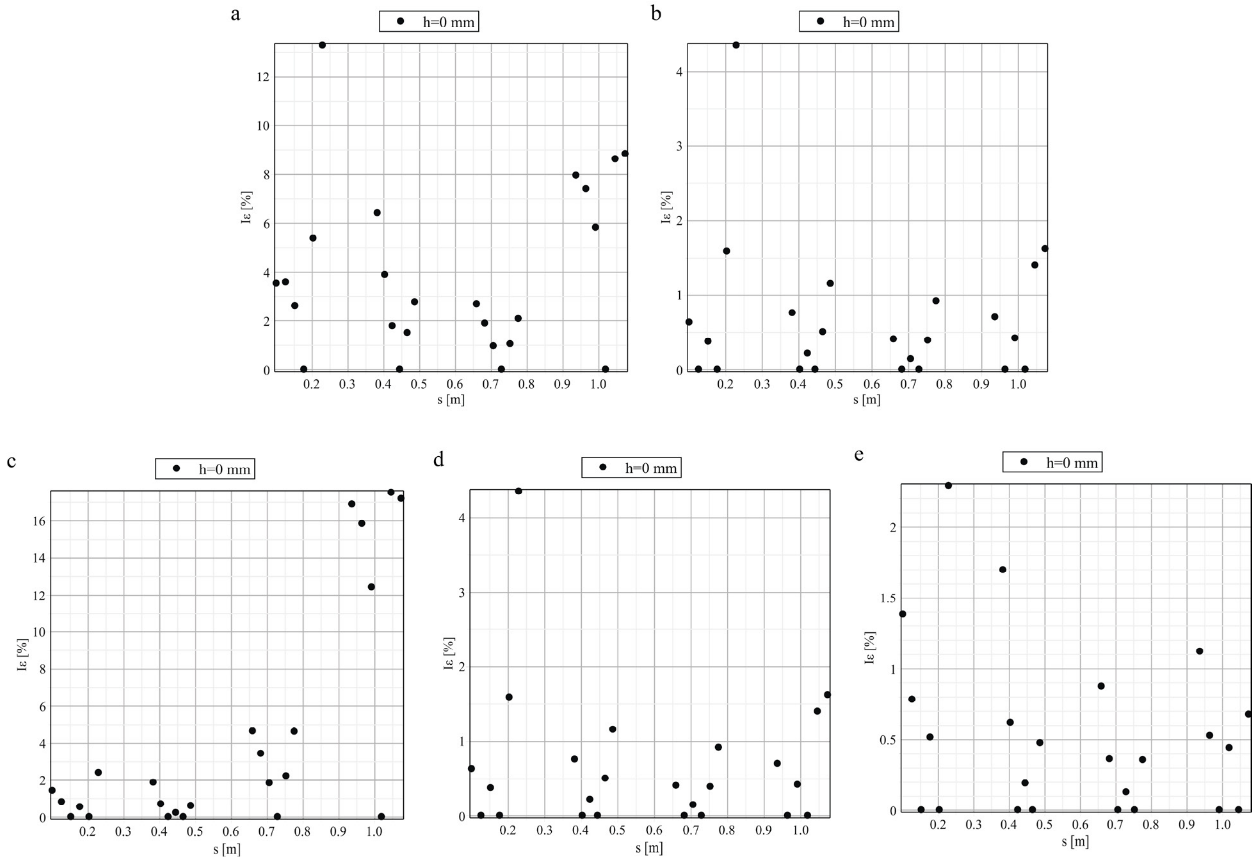

Fig. 6. Strain reconstruction error at different control sensors in case of undamaged hull: (a) Set 1; (b) Set 2; (c) Set 3; (d) Set 4; (e) Set 5.

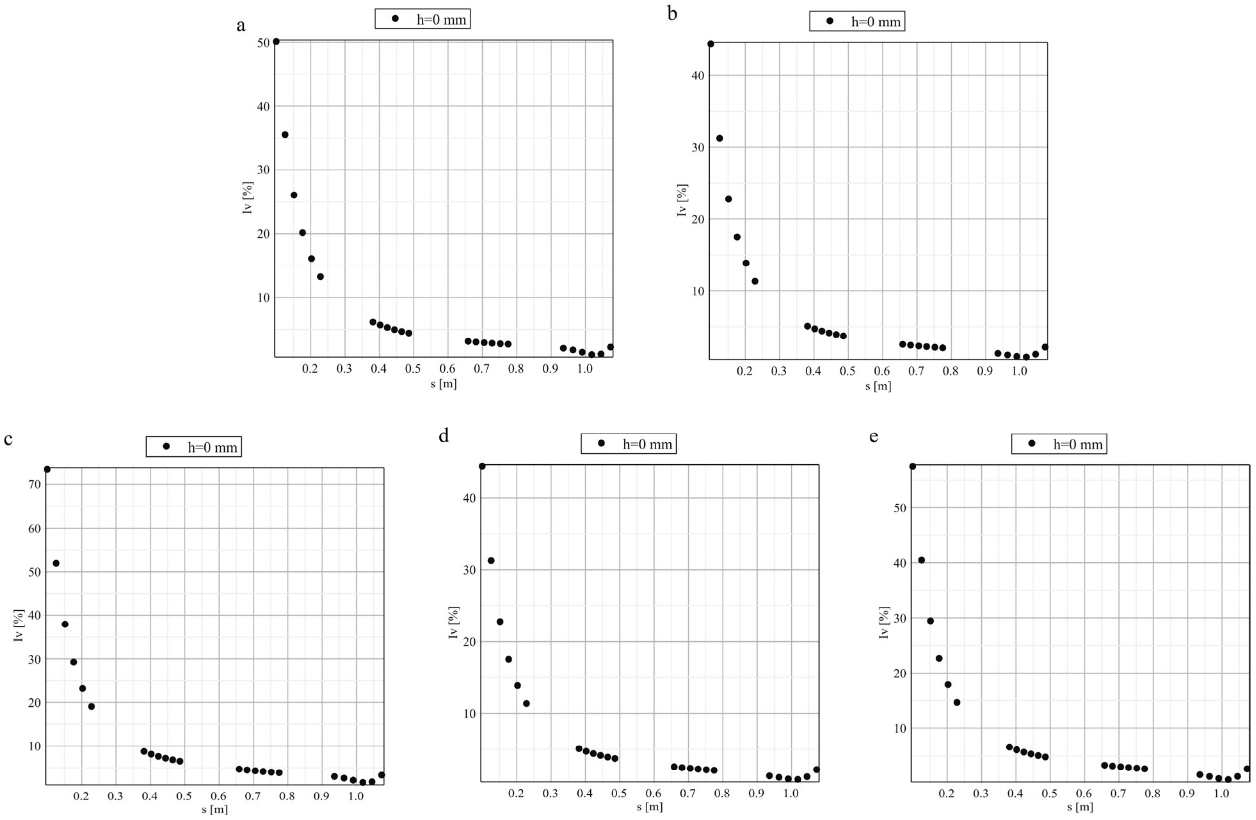

Fig. 7. Displacement reconstruction error at different control sensors in case of undamaged hull: (a) Set 1; (b) Set 2; (c) Set 3; (d) Set 4; (e) Set 5.

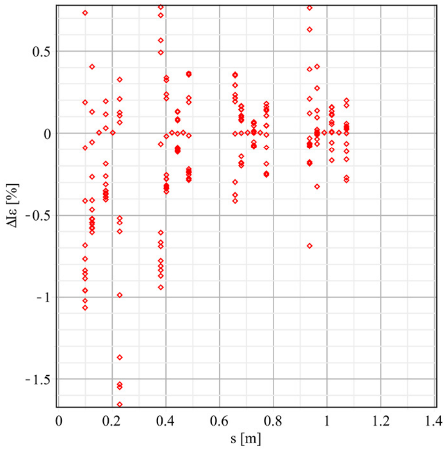

Fig. 8. Strain reconstruction error at different control sensors in case of undamaged calculated on different time interval on Set 5.

Reporting strain and displacements evolution on time, it can be seen a different behavior for those sets that present a reference sensor nearby the crack (Set 2 and 4) and for those that have all reference sensors far from it (Set 1,3,5). For reasons of brevity we report the diagrams for one set for each behavior and in particular Set 4 (Fig.9) and Set 5 (Fig.10). In Figure 9a and 9b are reported the results obtained with set 4, that presents a reference sensor close to the crack. It is evident the very good accuracy of the reconstruction. When the hull is damaged (in Fig.9c and 9d are reported the results for *h*=2, in case of set 4), the strain reconstruction fails for many control sensors positioned in the proximity of the crack, revealing the presence and position of the damage. At the contrary, the displacement reconstruction fails for almost every control sensors, revealing the presence but not the position of the damage.

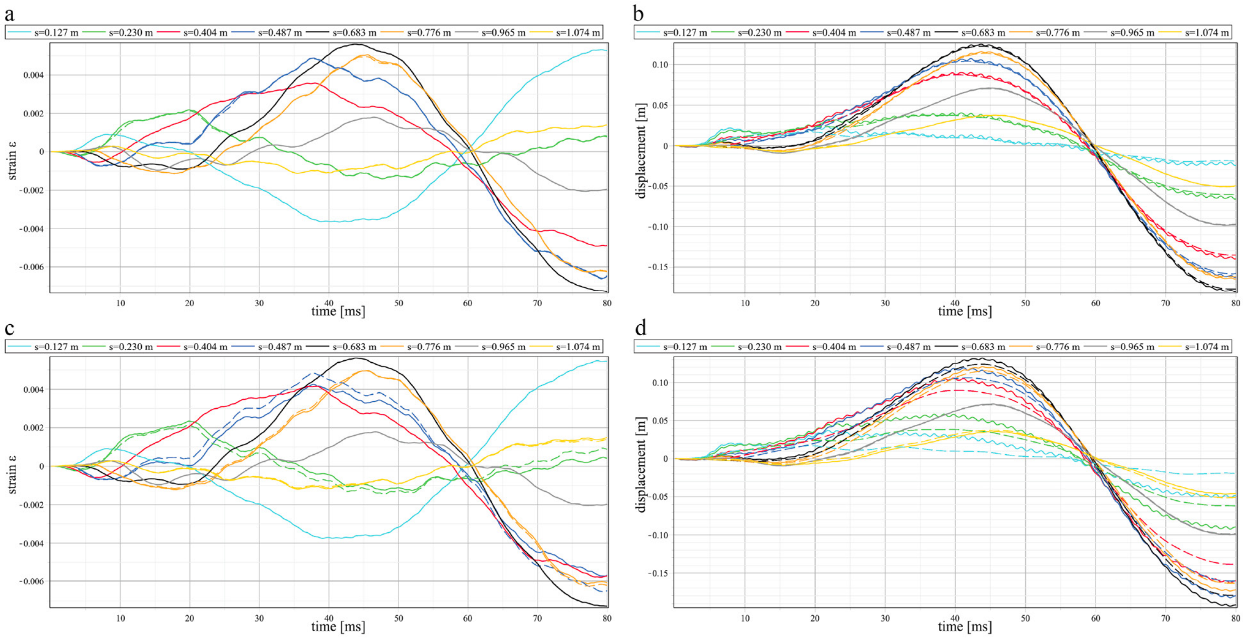

Fig. 9. Reconstructed strain for undamaged hull (a) and damaged with h=2 (c); reconstructed displacement for undamaged hull (b) and damaged with h=2 (d). Case of sensors set 4.

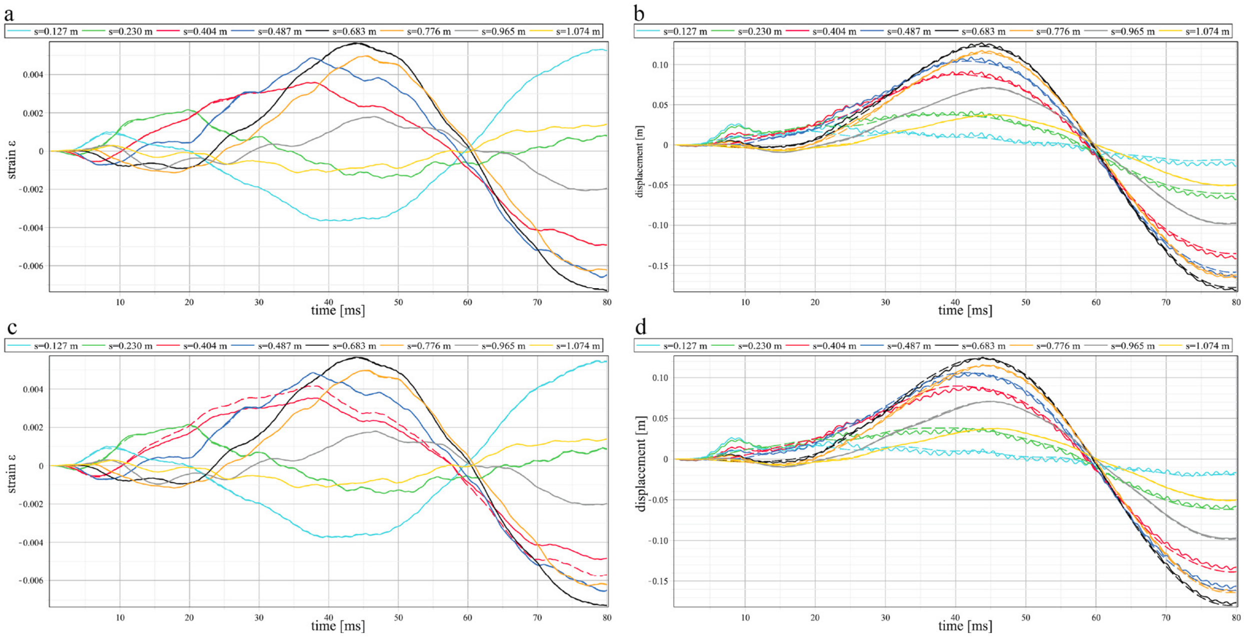

Fig. 10. Reconstructed strain for undamaged hull (a) and damaged with h=2 (c); reconstructed displacement for undamaged hull (b) and damaged with h=2 (d). Case of sensors set 5.

When all the reference sensors are far from the crack (set 5) the strain and displacement reconstruction for the undamaged hull is still reliable (Fig.10a and 10b). When the hull is damaged (in Fig.10c and 10d are reported the results for *h*=2, in case of set 5), the strain reconstruction fails only for the closest control sensors to the crack. When the crack appears far from reference sensors, the damage is detected only if there is a control sensor very close to the crack. With this sensor distribution, the displacement reconstruction fails for almost every control sensors, but with a very small deviation, revealing the presence but not the position of the damage.

These observations are more evident if we consider the difference between the reconstruction error on the damaged and undamaged hull, for each reference sensor set and at every control sensor potential position:

$$\begin{aligned} \Delta I_\varepsilon(s) &= I_\varepsilon(s)_{h=i} - I_\varepsilon(s)_{h=0} \\ \Delta I_v(s) &= I_v(s)_{h=i} - I_v(s)_{h=0} \end{aligned} \tag{6}$$

The monitoring procedure is able to detect a crack damage that is at least 1 mm depth, while it fails when the damage is smaller (Fig. 11 and 12). The strain reconstruction is able to detect the presence and position of the damage if it appears in proximity of a reference sensor. When the crack is far from reference sensors, it is possible to define presence and position only if a control sensor is close to the damage. On the other hand, the displacements reconstruction shows always a distributed error, that permits to reveal the damage presence (but not the position) for every reference sensor at every control sensor position. In every case the error is proportional with the damage entity.

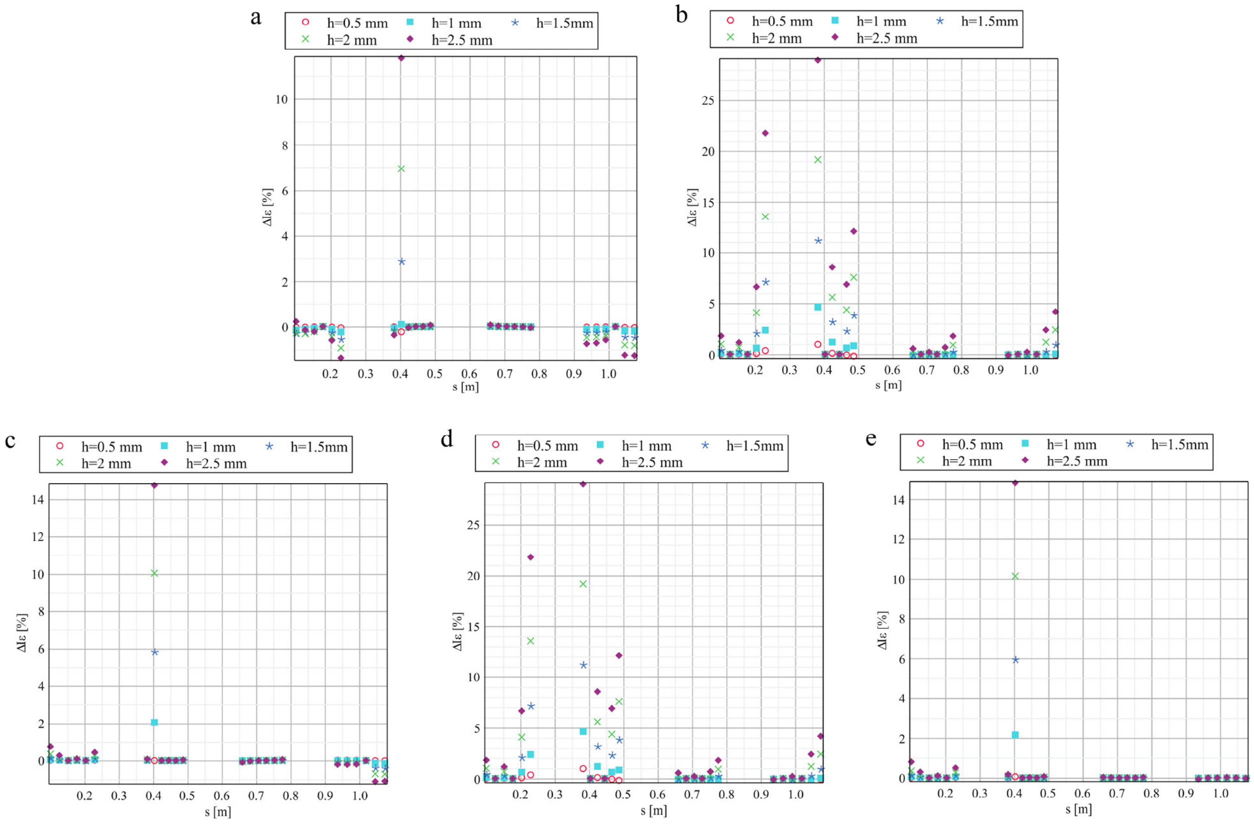

Fig. 11. Strain reconstruction error $\Delta I\varepsilon$ at different control sensors: (a) Set 1; (b) Set 2; (c) Set 3; (d) Set 4; (e) Set 5.

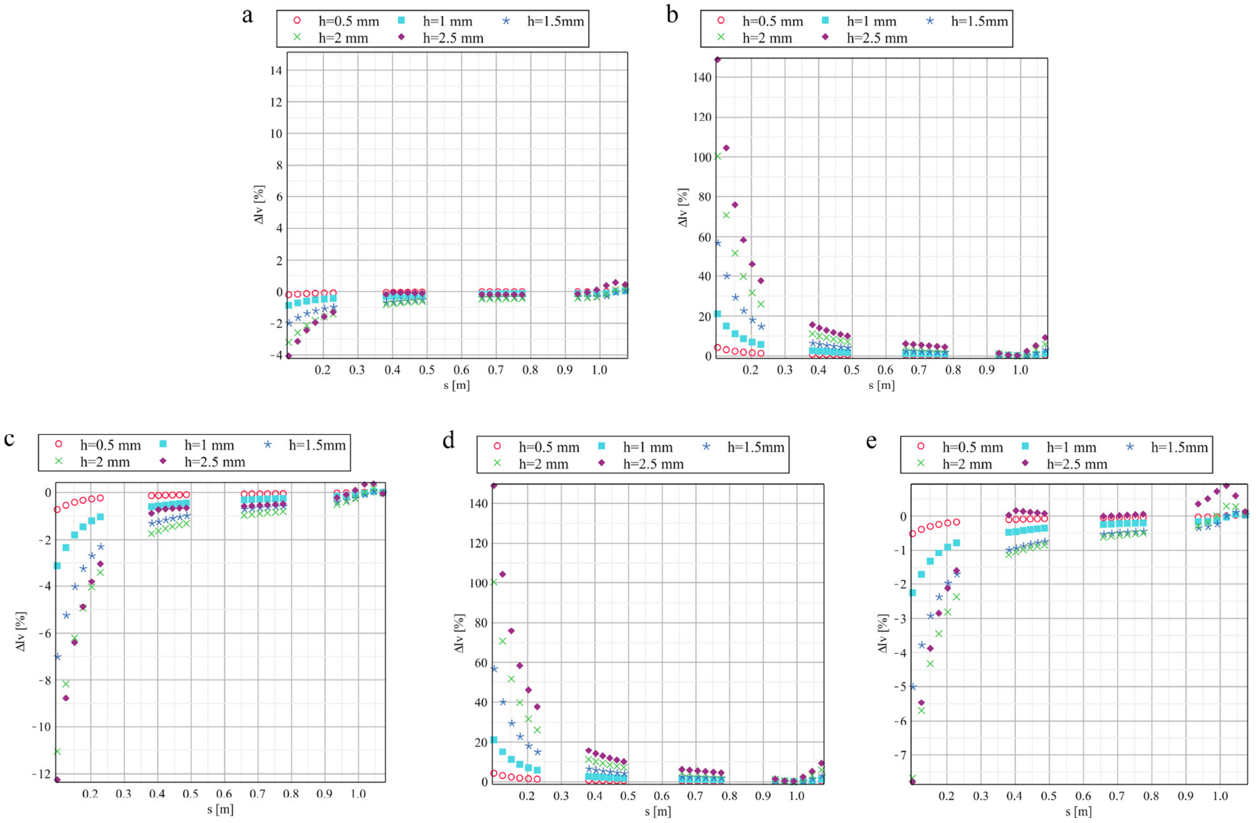

Fig. 12. Strain reconstruction error *Δlv* at different control sensors: (a) Set 1; (b) Set 2; (c) Set 3; (d) Set 4; (e) Set 5.

5. Conclusions

This paper deals with the application of the method for real-time deformed shape reconstruction of solid bodies subjected to impulsive loadings using distributed numerically generated strain measurements signals. Such signals may represent those produced by Fiber Bragg Grating (FBG) sensors and the proposed procedure may be applied for structural health monitoring.

A numerical study is carried out considering a simplified model of the problem of hull structures subjected to hydrodynamic loading. The hull, analyzed in a simplified section, has been studied both in healthy condition and with the presence of crack damages. The potential for detecting, localizing and quantifying this damage using the reconstruction algorithm is investigated, by leveraging the proposed concept of control sensors, that are FBG sensors used for comparing reconstructed strains and/or displacements with measured quantities. The positioning and number of sensors and the effect of sensor layout on damage detection is investigated, with the aim of developing a real time damage detection methodology.

The results reveal that the procedure is able to detect crack damages with a depth of at least 1 mm in respect of a hull thickness of 6 mm. The combined analysis of strain reconstruction and displacement reconstruction permits to detect the presence of the damage whatever reference sensor distribution is considered. For particular reference sensors distributions, i.e. the case in which a reference sensor is close to the crack, the methodology is able to define the crack position even if the control sensor is far from the crack.

The authors feel that the study presented in this paper is preparatory and preliminary to an experimental validation, that will allow to account for several aspects not considered in the numerical benchmark, such as tridimensional effects and noise in the measurements.

Acknowledgements

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