Journal of Fluids and Structures 61 (2016) 60–75

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Live monitoring of the distributed strain field in impulsive events through fiber Bragg gratings

R. Panciroli [a,*], C. Biscarini [b], G. Falcucci [c], E. Jannelli [c], S. Ubertini [d]

[a] Niccolò Cusano University, Rome, Italy
[b] Unesco Chair "Water Resources Management and Culture", University for Foreigners of Perugia, Italy
[c] University of Naples "Parthenope", Naples, Italy
[d] DEIM - Engineering School, University Of Tuscia, Viterbo, Italy

ARTICLE INFO

Article history:
Received 2 July 2015
Accepted 29 October 2015
Available online 21 December 2015

Keywords:
FBG
SHM
High speed imaging
Modal decomposition
Hydroelasticity
Water entry

ABSTRACT

In this paper, we propose a measurement technique based on local strain measurements to perform real-time reconstruction of the overall structural deformation and the distributed stress field produced by the impact of a body on a water free surface. In particular, we seek establishing a measurement chain capable of acquiring and elaborating the signals at high frequency, so that it can be utilized to study rapidly varying strain fields, such as those occurring in impulsive events. Fiber Bragg gratings are utilized to sense the local structural deformation. Experiments are conducted on flexible plastic wedges with variable deadrise angles impacting on a quiescent fluid surface. The experimental tests are performed in free fall and we explore variations of the entry velocity by varying the drop height. The structural deformation is reconstructed from point-wise strain measurements utilizing a modal reconstruction methodology. The impact dynamics are analysed through accelerometers and linear position sensors. Results show that the impact behaviour of the flexible body is characterized by a main overall deformation where the structure is distorted in the direction of the loading, whereby marked vibrations, whose amplitude increase with the entry velocity, dominate the dynamic response. The influence of the mode shapes considered in the present analysis on the accuracy of the results is also observed. The proposed methodology allows for a fairly high acquisition frequency, which translates into a real-time structural reconstruction technique. Results show that the proposed methodology can be a valuable tool for the live monitoring of structures undergoing impact events.

1. Introduction

The water entry of wedge-shaped bodies has received considerable attention in the recent years, as it allows reproducing the non-linear dynamics of hull slamming problems, which is to say the impact between ship hulls and the water surface. Such events generally produce large impulsive loadings, which in turn induce vibrations and local structural damages. Therefore, the development of experimental techniques to characterize such impulsive loading is crucial for the design of

* Corresponding author.
E-mail addresses: riccardo.panciroli@unicusano.it (R. Panciroli), chiara.biscarini@unistrapg.it (C. Biscarini), giacomo.falcucci@uniparthenope.it (G. Falcucci), elio.jannelli@uniparthenope.it (E. Jannelli), stefano.ubertini@unitus.it (S. Ubertini).

http://dx.doi.org/10.1016/j.jfluidstructs.2015.10.013
0889-9746/

marine vessels (Faltinsen, 1990, 2006). Objective of this work is to propose an FBG sensing technology for the live monitoring of structures undergoing impact events. This problem is of particular interest for naval and aerospace applications (Seddon and Moatamedi, 2006; Abrate, 2013).

Water impacts are characterized by a distributed hydrodynamic pressure which might generate large deformations, introducing complicating factors, such as fluid-structure interaction phenomena (Faltinsen, 2000; Scolan, 2004; Carcaterra and Ciappi, 2004; Panciroli, 2012) or structural instability (Cui et al., 1999). Notwithstanding the large amount of experimental works, data are mostly available for rigid bodies (Wu et al., 2004; Lewis et al., 2010; El Malki Alaoui et al., 2015; Panciroli et al., 2015a; Shams et al., 2015), while data on flexible bodies is limited (Stenius et al., 2011; Panciroli et al., 2013; Panciroli and Porfiri, 2014, 2015). The main advance of the present article with respect to previous articles by the authors on a similar topic (Panciroli et al., 2013; Panciroli and Porfiri, 2014, 2015) is that we here develop a technique capable of reconstructing the strain and displacement fields in the whole structure. Previous work allowed an analytical prediction of the deformation (Panciroli and Porfiri, 2015), or measured a single point-wise deformation (Panciroli et al., 2013; Panciroli and Porfiri, 2014), or mainly focused on the fluid response rather than the structure (Panciroli and Porfiri, 2013; Jalalisendi et al., 2015). An experimental methodology capable of measuring the whole structural deformation is instead lacking. We here try filling this gap.

In this paper, we propose an experimental methodology to measure the structural deformation of compliant bodies entering the water free surface starting from local strain measurements. Specifically, we utilize fiber optic strain sensors with Bragg gratings (FBG) and we propose utilizing a modal decomposition approach to reconstruct the structural response of the whole body in real time starting from the local strain measurements. As the proposed methodology allows for a fairly high acquisition frequency, such a methodology could be applied for real-time structural health monitoring (SHM).

A detailed knowledge of the structural health is of great interest in many engineering fields. Consequently, the development of experimental methods for investigating the behaviour and improving the safety and reliability of critical structures is in constant demand. In particular, the development of live SHM techniques represents a very challenging task in current sensing technology research (Balageas et al., 2006; Farrar and Worden, 2007; Johnson et al., 2011; Minak et al., 2010; Trendafilova et al., 2014). SHM can aid recognizing the ability of the structure to perform its duty while screening the integrity of the system. The correct evaluation of the stress field in the whole structure is crucial for the proper implementation of a SHM technique. However, sensing the stress field of an entire structure is hardly feasible in practice. Therefore, SHM must rely on a finite number of measurement locations, as an example through local strain measurements.

Optical sensors, such as fiber optic sensors with Bragg gratings (FBG) (Rao, 1999; Grattan and Sun, 2000; Lee, 2003; Yeo et al., 2008), are one of the most promising strain sensing technologies and their applications and reliability are growing fast (Tennyson et al., 2001; Li et al., 2004; Majumder et al., 2008; Torres et al., 2011). Multiple sensors can be installed over a single optic fibre at arbitrarily locations. Data from the whole set of sensors are synchronously acquired by a single interrogator, whereby the same accuracy is assured at each sensing location. FBG sensors are light, flexible, and their size is minimal, thus not affecting the structural mass, stiffness, and strength. One of the most promising applications of FBG sensors is the structural deformation reconstruction from point-wise strain data (Kim and Cho, 2004; Chang and Kim, 2011; Yi et al., 2012; Webb et al., 2012). Recently, some researchers proposed to utilize FBG sensors for the live monitoring of marine structures (Silva-Muñoz and Lopez-Anido, 2009) made on composite and smart materials (Kuang et al., 2001; Guemes and Menéndez, 2002; Kuang and Cantwell, 2003). In fact, a unique property of this technology with respect to conventional electric sensors is the possibility of performing measurements during the production stage, with the FBG sensors embedded into composite structures (Leng and Asundi, 2003). Moreover, their insensitivity to water and moisture make them ideal candidates for measurements in water entry problems.

A well-suited SHM technology should incorporate a data analysis algorithm capable of dealing with complex morphologies and boundary conditions, whereby being robust, stable, and reliable under a wide range of loading conditions. A particularly challenging application of SHM technologies is the live monitoring of impulsive events because of two complicating factors. First, high interrogation frequencies are needed, involving both the measuring system and the data analysis algorithm. Second, the high energy content often related to impulsive events might lead to complex structural responses. Reconstructing the deformed structural shape from local strain measurements is a so-called inverse problem. Several authors solved similar problems through the implementation of an inverse finite element method (iFEM) (Tessler and Spangler, 2005; Nishio et al., 2010; Gherlone et al., 2012; Maincon and Barnardo-Viljoen, 2013). In these models, the introduction of even small measurement errors might lead to severe overestimation of the load estimate. It is common in the literature to reduce this effect by performing a singular value decomposition (SVD) (Golub and Reinsch, 1970) of the stiffness matrix. This method suppresses the small singular values that would otherwise become very large after the matrix inversion. However, to date, notwithstanding the great accuracy and potentiality, such iFEM models are too heavy to be implemented in a real-time sensing technology. Instead, modal decomposition (Chang and Kim, 2011; Kang et al., 2007) can be utilized for this purpose. Within this approach, modal amplitudes are computed from strain-displacement relationships.

In this work, the proposed methodology is employed to study the water impact of V-shaped flexible bodies, for which we explore variations in the entry velocity. Results focus on the overall acceleration of the body, local deformations at characteristics locations, and the overall structural deformation reconstructed from high speed images recordings. The rest of the paper is organized as follows. First, in Section 2 we describe the inverse reconstruction methodology. Then, in Section 3 we detail the experimental setup and the data acquisition process. In Sections 4 and 5 we utilize the proposed deformation reconstruction methodology to study the problem of a flexible wedge entering the water in free fall, and we assess the