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Displacement and stress monitoring of a Panamax containership using inverse finite element method

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ABSTRACT

The inverse Finite Element Method (iFEM) is a revolutionary methodology for real-time reconstruction of full-field structural displacements and stresses in plate and shell structures that are instrumented by strain sensors. This inverse problem is essential for structural health monitoring systems and commonly referred as 'displacement and stress monitoring' or 'shape- and stress-sensing'. In this study, displacement and stress monitoring of a Panamax containership is performed based on the iFEM methodology. A simple, efficient, and practically useful four-node quadrilateral inverse-shell element, iQS4, is used for the numerical implementation of the iFEM algorithm. Hydrodynamic analysis of the containership is performed for beam sea waves in order to calculate vertical and horizontal wave bending moments, and torsional wave moments acting on parallel mid-body of the containership. Several direct FEM analyses of the parallel mid-body are performed using the hydrodynamic wave bending and torsion moments. Then, experimentally measured strains are simulated by strains obtained from high-fidelity finite element solutions. After that, three different iFEM case studies of the parallel mid-body are performed utilising the simulated sensor strains. Finally, the effect of sensor locations and number of sensors are assessed with respect to the solution accuracy.

1. Introduction

Vessels are operated under challenging conditions because marine environment can cause failure of the structure due to extreme or cyclic loadings, corrosion, and erosion. Structural failure may lead to major accidents that may result in crew or passenger life loses, pollution of the marine environment, and very expensive maintenance/repair costs. Therefore, it is necessary to ensure safety, reliability, and integrity of ship structures for avoiding major accidents. Moreover, the number of new vessels is increasing day-to-day. Therefore, new structural designs, new construction techniques, and new materials are progressively being used in the shipbuilding industry. As a result, it is necessary to increase knowledge about the on-site structural performance not only for traditionally designed ships, but also for newly designed ships.

Structural Health Monitoring (SHM) is an interdisciplinary procedure that (1) integrates sensing systems to the structure, (2) processes the data collected from the sensing systems in real-time, and (3) provides decisive real-time information from the structure about its global and/or local structural state. Therefore, the necessities mentioned earlier and detailed structural management of the ships including inspection, maintenance, and repair plans can only be successfully accomplished if an application of SHM system is installed into the ships. In 1994, the International Maritime Organisation (IMO) originally recommended the utilisation of hull stress monitoring systems to facilitate the safe operation of ships. Then, the requirements for a typical hull structural monitoring system are regulated by class societies including American Bureau of Shipping (1995), Lloyds Register (2004), Det Norske Veritas (2011). Recently, American Bureau of Shipping (2015) has published a guide that discusses the need for fitting of hull condition monitoring systems on all types and sizes of merchant vessels. Besides, plenty of researchers considered the hull structural monitoring as an important case study. For example, different types of hull structural monitoring systems are investigated for various ship types (Van der Cammen, 2008, Torkildsen et al., 2005, Andersson et al., 2011, Sielski, 2012, Zhu and Frangopol, 2013, Hageman et al., 2013, and Majewska et al., 2014). In particular, Phelps and Morris (2013) presented a general review regarding the technical aspects of available hull structural monitoring systems. However, most of the aforementioned SHM approaches don't take into account the advanced structural topologies and boundary conditions. Moreover, they mostly require sufficiently accurate loading information even though it is not easy to estimate dynamic loads of waves and winds due to the complexity and statistical feature of oceanographic phenomena.

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Furthermore, some of them are not appropriate for use in real-time due to the time-consuming analysis.

Real-time processing of the data obtained from a system composed of a network of strain sensors is the key component of the SHM procedure for supplying trustworthy information about the structural condition. In other words, real-time reconstruction of three-dimensional structural displacements and stresses by utilising discrete on-board strain measurements, known as 'displacement and stress monitoring' or 'shape- and stress-sensing', is the primary technology for performing an accurate SHM. Apart from the SHM systems mentioned earlier, Tessler and Spangler (2003, 2005) developed a powerful algorithm called inverse Finite Element Method (iFEM) for the purpose of displacement and stress monitoring of engineering structures. In contrast to other developed SHM methods, iFEM framework has a general applicability to any type of structural topology and boundary conditions because using inverse beam, frame, plate, and shell elements enables an effective discretization of the physical domain. The iFEM algorithm minimises a weighted-least-squares functional with respect to nodal displacements in order to perform the shape-sensing of the structure. Since the iFEM weighted-least-squares functional is defined by using only strain-displacement relationship, the iFEM methodology can reconstruct the structural deformed shapes of the structure without prior knowledge of material properties and loading information. Therefore, unlike other proposed SHM systems, stability and accuracy of the shape-sensing results obtained through iFEM methodology is independent from material properties of the structure and any type of static or dynamic loadings acting on the structure. In fact, this special feature makes the iFEM methodology much more powerful than the other SHM systems. Once the structural deformed shape is obtained, the full field strains can be calculated from strain-displacement relationship. Then, full field stresses of the structure can be evaluated by using full field strains and material properties of the structure. This stress calculation not only allows iFEM methodology to perform stress-sensing of the structure, but also allows real-time damage predictions if the full field structural stresses are converted to an equivalent stress by using an appropriate failure criterion such as von Mises yield criterion.

Many different numerical and experimental iFEM studies have proved that the iFEM framework is an accurate, robust, and fast shape- and stress-sensing algorithm. For example, Tessler and Spangler (2004) developed a three-node inverse shell element (iMIN3) by using lowest-order anisoparametric C° continuous functions and adopting kinematic assumptions of the first-order and shear-deformation theory. Tessler and Spangler (2004) numerically verified the precision of iMIN3 element for performing iFEM analysis of plate/shell structures. Also, Quach et al. (2005) and Vazquez et al. (2005) confirmed the robustness of the iMIN3 element by conducting laboratory tests that uses experimentally measured real-time strain data. Moreover, Tessler et al. (2012) enhanced iMIN3 element for displacement and stress monitoring of plate and shell structures undergoing large displacements. Apart from iMIN3, Kefal et al. (2016) have recently formulated a four-node quadrilateral inverse-shell element, iQS4, utilising the kinematic assumptions of the first-order and transverse-shear deformation theory. This new element includes hierarchical drilling rotation degrees-of-freedom (DOF) and further extends the practical usefulness of iFEM for shape-sensing analysis of large-scale structures. Kefal et al. (2016) numerically verified the precision of the iQS4 element by the analysis of several validation and demonstration problems. Furthermore, Cerracchio et al. (2010) and Gherlone et al. (2011, 2012, 2014) formulated a robust inverse frame element that uses kinematic assumptions of Timoshenko beam theory including stretching, bending, transverse-shear and torsion deformation modes. They numerically and experimentally validated capability of their inverse frame element by conducting several shape-sensing analyses of three-dimensional frame structures undergoing static and/or damped harmonic excitations. Moreover, Cerracchio et al. (2013, 2015a) has recently improved the original iFEM formulation of Tessler and Spangler (2003, 2005) by adding the kinematic assumptions of recently developed Refined Zigzag Theory (Tessler et al., 2009, 2010) in order to perform SHM of multi-layered composite and sandwich structures. The application of iFEM methodology for SHM of future aerospace vehicles is discussed by Tessler (2007) and Tessler et al. (2011). Likewise, another application of iFEM algorithm to real-time displacement monitoring of a composite stiffened panel is presented by Cerracchio et al. (2015b). Apart from the aerospace applications, Kefal and Oterkus (2015) performed shape-sensing of a longitudinally and transversely stiffened plate as a fundamental application of the iFEM framework to SHM of marine structures. Similarly, Kefal and Oterkus (2016) presented a more sophisticated application of iFEM to marine structures namely displacement and stress monitoring of a chemical tanker based on iFEM algorithm. They performed iFEM case studies when the chemical tanker is subjected to the head sea waves because this phenomenon of ship advancing in waves can be very crucial for closed-decked ships such as chemical tanker. However, for open-decked ships such as containerships, head sea wave loads may be less important than beam sea wave loads due to torsional and warping stresses induced by torsional moments. Since hull girder torsion loading on containerships represent a major loading quantity particularly when combined with hull girder vertical and horizontal bending loads, displacement and stresses monitoring of a containership floating in beam sea waves should be investigated in addition to all proposed iFEM marine structure applications.

Hence, the main focus of this study is to demonstrate the application of the iFEM methodology for monitoring multi-axial deformations and stresses of a Panamax containership for the first time in the literature. For this purpose, the numerical implementation of the iFEM algorithm is done using the simple, efficient, and practically useful iQS4 element developed by Kefal et al. (2016). Hull form of a Panamax containership is designed performing several hull surface transformations of S175 containership. A typical mid-ship section is designed for the Panamax containership and the parallel mid-body of the containership is modelled using the iQS4 element. The 'smart methodology' proposed by Kefal et al. (2015) is followed to determine the optimum sensor locations for performing iFEM analyses of the parallel mid-body. First of all, hydrodynamic analysis of the containership is performed for beam sea waves. As an output, oscillatory pressures acting on the hydrodynamic panels, rigid body motions of the containership, and hydrodynamic section forces including vertical and horizontal bending moments and torsional moments are obtained. Secondly, several direct FEM analyses of the parallel mid-body are performed using the hydrodynamic wave bending and torsion moments. Then, experimentally measured strains are simulated by strains obtained from high-fidelity finite element solutions. Thirdly, three different iFEM analyses of the parallel mid-body are performed utilising the simulated sensor strains obtained for three different cases. These are (1) pure vertical bending case, (2) pure horizontal bending case and (3) pure torsion case. Finally, the effect of sensor locations and number of sensors are assessed with respect to the solution accuracy of each iFEM analysis.

2. Inverse finite element formulation for shells (Kefal et al., 2016)

2.1. Quadrilateral inverse-shell element

The four-node quadrilateral inverse-shell element (iQS4), developed by Kefal et al. (2016), is adopted to demonstrate the iFEM