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Measurement of ship hydroelastic response using multiple wireless sensor nodes

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ABSTRACT

A measurement system is required for the assessment of the structural and kinematic response of a free-running model, either at model or full scale. Tethered and optical measurements systems used in towing tanks and wave basins are unsuited to this application. A system of wireless sensor nodes with synchronised video capability has been developed which allows rigid body motions and three-axis accelerations to be obtained by a single nine degree of freedom sensor node whilst the structural deformation of the hull girder can be obtained from a minimum of three nodes in parallel. The system performance was assessed in a controlled towing tank environment in comparison to a tethered system, using three nodes mounted on a flexible, four segment model hull. Measurements from the wireless system were comparable to the tethered results with the same degree of accuracy. Further tests showed a single node to produce comparable measurements to an optical system. The additional synchronised video capability allows a visual image of an extreme wave encounter to be correlated to the magnitude of the responses experienced. Practical advantages of the wireless system demonstrate its viability for acquiring high quality model data; further development should allow its application to full scale.

1. Introduction

A key challenge for the naval architect is to be able to measure the response, including hydroelastic, of ships and floating offshore structures at model and full scale, in particular for design purposes. Conventionally predictions of ship responses (motions, accelerations and global loads) are made from measurements at model scale using a tethered (wired) instrumentation system or optical measurements in a towing tank, with the model restrained in yaw attached to a towing carriage. Typical instrumentation abilities for each of these systems are given in Table 1.

The systems detailed in Table 1 have a number of disadvantages associated with them. Firstly, by nature of towing tank geometry experiments involving forward speed are limited to unidirectional waves and head seas, a restricted number of degrees of freedom (usually just heave and pitch) with a wave basin being required to measure additional degrees of freedom (Wellicome et al., 1999; Molland et al., 2001). With a tethered system the range of instrumentation required that can measure the complete dynamic response of a ship structure (including motions, accelerations, structural deflection and loads) leads to a data acquisition and infrastructure intensive system (requiring amplifiers, cables and data acquisition equipment for instance) with the additional problem of waterproofing the instrumentation and infrastructure. The accuracy of optical systems relies on the use of a large number of cameras (Vicon, 2012) resulting in a high-cost system where it is difficult to use enough markers on the ship to ascertain relative motions. Furthermore, such systems only measure motions with additional sensors (and therefore infrastructure) being required to determine loads and accelerations.

A more comprehensive set of data can be obtained by measuring the response of either a free-running model or a full-scale ship (through in-situ monitoring). Based on the previous discussion any measurement system used for such measurements should have minimal infrastructure and be capable of measuring the complete dynamic response with a limited number of sensors, therefore measuring the ship response in an efficient and accurate way. Tethered systems are unsuited due to the aforementioned infrastructure required which is impractical for both a free-running model and full scale vessel, and the interaction of a tether with a free-running model. Optical systems require a shore-based platform for cameras to be mounted on which is impractical for full scale monitoring. Instead, a system of wireless sensor nodes has been identified as a potential measurement technique.

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Table 1
Summary of typical measurement system capabilities.

System	Instrumentation	Measurement	Uses
Tethered	Potentiometers Accelerometers Strain gauges	Motions (heave and pitch) Accelerations Strain (global loads)	• Standard seakeeping experiments in a towing tank (e.g. Drummen et al., 2009; McTaggart et al., 2003) • Extreme ship responses in a towing tank (e.g. Bennett et al., 2013a; Bennett et al., 2013b)
Optical (Qualisys, 2012; Vicon, 2012)	System of multiple static cameras with markers on the moving object	Motions	• Standard seakeeping experiments in a towing tank (e.g. Broglia et al., 2011) • Extreme ship responses in a towing tank (e.g. Ge et al., 2005) • Six degree of freedom motions in a wave basin (e.g. Wang et al., 2012) • Measurements of wave profile (e.g. Benetazzo, 2011)

Full-scale monitoring of ship structures can be done for a variety of purposes with a number of benefits. These include the potential improvements to ship safety through, for example, the monitoring of slamming loads. Such a system is applicable to both smaller, high speed craft and larger ocean going vessels. Development of such systems will require assessment of the trade-off of wireless transmission distance against power consumption, the alignment of sensors installed in the ship and local effects of steel structures on magnetometer readings.

The rapid reduction in the cost of low power, low mass wireless sensors primarily driven by production scale applications such as car airbags, mobile phones and games consoles allows access to this measurement technology. Wireless sensor solutions have been widely applied in the civil engineering industry (e.g. Lynch and Loh, 2006; Mascarenas et al., 2008) and to biomedical applications (e.g. Patel et al., 2007; O′Donovan et al., 2009). They have been less widely used in the marine industry with current applications being, for example, underwater measurement of the torque of a self-pitching propeller (la Gala et al., 2011) and in a proof-of-concept study for applications in marine sports (ESPRIT, 2011). By taking measurements with multiple sensor nodes an accurate picture of the response of the ship, global and local, could be obtained with ease. However there still remains the question as to whether measurements with wireless sensors can be made to a sufficient level of absolute accuracy to be of use to the naval architect. If the accuracy level proves sufficient then such sensors have the capability to be developed into a system that can take all the required response measurements in a synchronised manner using individual measurement nodes on the model or ship.

The purpose of this research was to develop and test a low-cost, low-mass measurement system that is capable of measuring the six degree of freedom translational (surge, sway and heave) and rotational (pitch, roll and yaw) motions as well as accelerations and the structural deformation of a free-running model or full scale vessel, addressing the deficiencies identified with tethered and optical systems for this purpose. It should have the ability to be extended to measure global and local loads in the future. The measurement technique investigated was a system of multiple wireless sensor nodes. Testing and validation took place in a towing tank (considered to be the most efficient method of evaluating its performance) in comparison to a typical tethered system. The benefits and accuracy of the system are discussed as is the versatility of the system with reference to real-world application.

2. Experimental set-up

To assess the capabilities of the wireless sensor technology, experiments were undertaken in unidirectional waves in a towing tank 60 m long, 3.7 m wide and 1.86 m deep. The maximum carriage speed was 4.5 ms^{-1}. The tank was equipped with a single, motor-driven wavemaker paddle. Measurements using the technique of Isaacson (1991) showed that reflections from the wave absorption beach were less than 10%.

Table 2
Principal particulars of naval frigate hull (model scale).

Length overall (m)	2.60
Length between perpendiculars (m)	2.52
Breadth (m)	0.29
Draught at amidships (m)	0.096
Displacement (Kg)	29.40
LCG aft amidships (m)	0.091
Service speed (ms^{-1})	1.40
Pitch gyradius (%LOA)	25.26
2-node natural frequency (rads^{-1})	94.30

Table 2 gives the principal particulars of the segmented, flexible backbone naval frigate hull (scale 1:43.62) which was tested as a representative ship hull. Further details of the model are given in Denchfield (2011). A flexible model was used in order to show the ability of the wireless sensor technology to measure structural deformation as well as motions and accelerations (which could not be obtained from a rigid model hull) using the technique described in Section 3.4.4. The model was tested at its service speed of 1.4 ms^{-1} (corresponding to 18 knots at full scale). A rendered model of the hull is shown in Fig. 1(a) whilst the experimental hull is shown in situ in the towing tank in Fig. 1(b).

Table 3 provides details of the wireless sensor node instrumentation system under test (further details of which are given in Section 3) whilst Table 4 provides details of the tethered instrumentation system used to validate the wireless sensor results. In addition a wave probe was positioned level with amidships to measure the encountered wave profile. Test runs were of 80 s duration. Fig. 2 is a schematic of the instrumentation set-up.

The abilities of the wireless sensor system were tested using seakeeping experiments in regular waves. Wave frequencies were between 3.49 rads^{-1} and 6.28 rads^{-1} (equivalent to 0.529 rads^{-1} and 0.951 rads^{-1} at full scale). Wave heights corresponded to $H/L_{OA}=0.02$, 0.04 and 0.05 giving wave heights of 52 mm, 104 mm and 130 mm at model scale (2.27 m, 4.54 m and 5.67 m at full scale).

3. Evaluating ship response from a system of wireless sensor nodes

3.1. Sensor hardware

The Shimmer (Burns et al., 2010) wireless sensor platform was used to collect inertial and magnetic data. The Shimmer wireless