Ocean Engineering 129 (2017) 352–362

Contents lists available at ScienceDirect

Ocean Engineering

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

A concise account of techniques available for shipboard sea state estimation

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ARTICLE INFO

Keywords:
Sea state estimation
Wave buoy analogy
Vessel responses
Frequency domain
Time domain

ABSTRACT

This article gives a review of techniques applied to make sea state estimation on the basis of measured responses on a ship. The general concept of the procedures is similar to that of a classical wave buoy, which exploits a linear assumption between waves and the associated motions. In the frequency domain, this assumption yields the mathematical relation between the measured motion spectra and the directional wave spectrum. The analogy between a buoy and a ship is clear, and the author has worked on this *wave buoy analogy* for about fifteen years. In the article, available techniques for shipboard sea state estimation are addressed, but with a focus on only the wave buoy analogy. Most of the existing work is based on methods established in the frequency domain but, to counteract disadvantages of the frequency-domain procedures, newer studies are working also on procedures formulated directly in the time domain. Sample results from several studies are included, and the main findings from these are mentioned.

1. Introduction

In today's maritime world, the operation of ships requires careful monitoring of the related costs while, at the same time, ensuring a high level of safety. Shipboard decision support systems may enable a ship's crew to reduce costs and minimise risks while sailing, so that the performance is optimised. A ship's performance with respect to safety and fuel efficiency is in general negatively influenced by the encountered waves. Consequently, it is of particular importance to estimate the surrounding sea state, and any shipboard decision support system needs to have information about the encountered waves as input for the system to be the most accurate and reliable.

Trustful means for sea state estimation include floating wave buoys, which are primary tools used to collect statistical ocean wave data. However, wave buoys are not practical for a sailing ship requiring (precise) sea state information in real-time and at its actual geographical position. On the other hand, the analogy between a ship and a floating buoy naturally suggests to using the ship itself as a kind of wave buoy. Thus, a number of research studies have explored this 'wave buoy analogy' in the past, and the author of the present paper has worked extensively on the topic for about the last fifteen years.

This paper presents a concise account of techniques for shipboard sea state estimation using measured vessel responses, resembling the concept of a traditional wave buoy. Moreover, newly developed ideas for shipboard sea state estimation are introduced. The account, or review, is not necessarily complete, as it primarily reflects the author's personal experience and background; obtained alone and together with national as well as international colleagues. However, it is believed that the author has come across most of the work carried out within the particular field, so other fundamental studies, not related to the present author, will also be cited; without the ambition to list every single reference from the literature.

Although other means for shipboard sea state estimation exist, based on, e.g., the use of X-band navigational radars or over-the-bow looking devices, those means will not be mentioned herein and, hence, shipboard sea state estimation refers in the following to only the wave buoy analogy, where sea state estimation is conducted on the basis of measured vessel responses. Onwards, *sea state estimation* will at most places be shortened by SSE.

1.1. Past work and literature

Until the 1970s, little work on shipboard SSE had been done, but early researches (e.g. Lindemann and Nordenstrøm, 1975; Lindemann et al., 1977; Robinson, 1990; Debord and Hennessy, 1990; Francescutto, 1993) on in-service monitoring systems combined with decision support tools emphasised the need for estimates of the on-site sea state; at the actual position of the advancing vessel. Some of the initial studies on shipboard SSE (Takekuma and Takahashi, 1973; Pinkster, 1978) did not consider ships with forward speed, and although attempts were made to introduce forward speed in shipboard SSE, notably by Japanese studies (Isobe et al., 1984; Kobune and

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http://dx.doi.org/10.1016/j.oceaneng.2016.11.035
Received 21 October 2016; Received in revised form 23 November 2016; Accepted 23 November 2016
Available online 01 December 2016
0029-8018/

Hashimoto, 1986; Hirayama, 1987; Iseki et al., 1992; Saito et al., 2000; Maeda et al., 2001), the first study to strictly consider the Doppler shift, implying a 1-to-3 relationship between encounter frequency and wave frequency for certain conditions in following sea, was made by Iseki and Ohtsu (2000). Since then several studies with good results have been published for ships with forward speed (Iseki and Terada, 2002; Iseki, 2004; Nielsen, 2006; Nielsen and Stredulinksy, 2012; Nielsen and Iseki, 2012; Nielsen et al., 2013; Montazeri et al., 2016a; Montazeri, 2016); all considering full-scale data of different vessels. A number of studies have also been made in relation to station keeping and dynamic positioning, where shipboard SSE has been made with success for ships without forward speed (Waals et al., 2002; Tannuri et al., 2003; Pascoal et al., 2007; Simos et al., 2007; Sparano et al., 2008; Pascoal and Soares, 2009).

1.2. Content and composition of paper

Different mathematical models exist for the wave buoy analogy, and the main principles will be outlined in Section 2. It is shown that shipboard SSE can be carried out either in the frequency domain or in the time domain, and, based on the setting, Sections 3 and 4 provide summaries of the fundamental assumptions and the different mathematical models which are applied depending on the particular domain, being it time or frequency. Sample results taken from several of the author's previous application studies, relating to both frequency and time domain calculations, are included in Section 5. Finally, concluding remarks are given in Section 6.

2. Wave buoy analogy

Most of today's marine vessels are instrumented with sensors to record, e.g., global motion components such as heave, pitch, and vertical acceleration at specific position(s) relative to the centre of gravity. In this sense, vessels resemble classical wave buoys; although the latter typically have much simpler geometrical forms compared to the hull of a ship. Anyhow, the response recordings from marine vessels can be processed to facilitate estimation of the on-site sea state, making the analogy to floating wave buoys by relating the measurements and the sea state through a mathematical model, see Fig. 1.

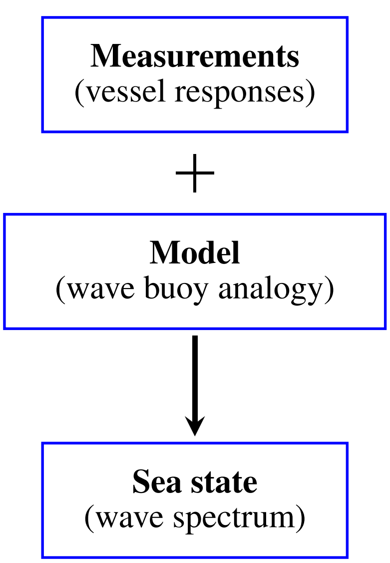

Fig. 1. Combination of wave-induced response measurements and a mathematical model can be used to deduce information about the on-site sea state (Nielsen et al., 2016).

2.1. Main assumption

In mild and moderate wave climate, the wave-induced six degrees-of-freedom motion of a ship and associated structural loads are often assumed to be linear with the incident waves, meaning that the amplitudes of those responses are proportional to the wave amplitudes in regular waves. Consequently, the responses can be quantified in irregular waves by adding together results from regular waves with different amplitudes, wavelengths and propagation directions.

The linear assumption between waves and associated responses facilitates the use of transfer functions, or response amplitude operators (RAOs), that express how waves are *transferred* into responses. State-of-the-art techniques for calculation of RAOs include 3-dimensional panel codes considering potential wave theory; sometimes supplemented with CFD based on the full set of Navier–Stoke's equations and/or considering other nonlinear effects. Nonetheless, strip theory calculations are still widely used, due to their adequate degree of approximation, and often they provide good results.

In theory, RAOs are not necessarily accurate in severe waves, where a nonlinear relationship between waves and responses would/could occur. In practice, however, many studies have shown that even in severer wave conditions, RAOs can be still used to calculate responses of ships.

2.2. Frequency and time domain approaches

The majority of previous work on the wave buoy analogy (e.g. Hua and Palmquist, 1994; Iseki and Ohtsu, 2000; Tannuri et al., 2003; Nielsen, 2006, 2008b; Pascoal et al., 2007; Montazeri et al., 2016a) is based on a solution formulated entirely in the frequency domain. This is illustrated in Fig. 2, where a response spectrum is combined with RAOs, using spectral analysis, so that an estimate of the sea state is given in terms of a wave (energy) spectrum. Studies have shown that, in practice, wave estimation is improved by (optimally) selecting a set of three simultaneous vessel responses (Nielsen, 2006).

Instead of a solution formulated in the frequency domain, derived by use of spectral analysis and with possible disadvantages, it has been suggested by Nielsen et al. (2015, 2016) to make the fitting of the *measured* response and the corresponding *theoretically* calculated one directly in the time domain (Fig. 3). In this sense, the approach is similar to a previous work by Pascoal and Soares (2009) that also formulate the governing equation directly in the time domain. However, the latter method (Pascoal and Soares, 2009), based on Kalman filtering, relies completely on availability of accurate RAOs, which is the main difference to the former works (Nielsen et al., 2015, 2016) as will be outlined in Section 4.

In the next two sections, 3 and 4, the fundamentals of the techniques used for, respectively, frequency domain and time domain shipboard SSE are briefly described. As such, the sections can be read separately and have to some extent been formulated as stand-alone sections, which means that repetitions of fundamental assumptions and background occur.

3. Frequency domain approaches for SSE

Shipboard SSE is often considered in the frequency domain. Strictly speaking, the linear assumption about waves and associated responses needs, in this case, to be supplemented with additional assumptions: Firstly, the ocean waves and associated responses represent ergodic random processes (e.g. Ochi, 1990), so that stationarity, in a stochastic sense, applies within a certain period of response records at each estimation sequence. Secondly, the speed and the course of the ship (relative to waves) are constant in that period. Thus, response measurements from the particular period can be processed by spectral analysis using standard Fast Fourier Transformation (FFT) or multi-variate autoregressive procedures (Nielsen, 2005, 2006), where the