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Estimation of directional sea spectra from ship motions in sea trials

R. Pascoal, L.P. Perera, C. Guedes Soares*

Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Tecnico, Universidade de Lisboa, Lisbon, Portugal

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ABSTRACT

This paper compares the skill of two algorithms that enable real-time estimation of the directional wave spectra exciting a ship from its measured motions. One algorithm consists of a nonlinear optimization of a parametric or non-parametric spectral model and the other is a Kalman filter based observer. Sea trials have been conducted on an oceanographic vessel that was instrumented with a six degree of freedom fiber optic gyro, complemented with a rate gyro, several accelerometers, a dedicated GPS receiver and a bow mounted down-looking wave radar with motion compensation. The two algorithms are applied to the measured data and a discussion is provided on their skill to recover the properties of existing sea states.

1. Introduction

This paper concerns procedures that enable real-time estimation of the wave spectra exciting a ship by measuring its motions, in an extension of the principles that govern the use of wave-rider buoys to record sea surface height and derive wave spectra. The wave climate greatly influences marine operations and, therefore, this topic has deserved the attention of researchers and the maritime community. Improvements to vessel performance, the avoidance of dangerous loading and stability conditions and minimizing seasickness and other health conditions related to the crew or passengers, can all benefit from on-board estimation of the wave conditions.

The research efforts specifically focused on the estimation of sea spectra from ship motions has extended for several decades, since the first post-WWII deployments to estimate the scalar spectrum with data recovered from moored ships, instrumented with accelerometers and pressure transducers (Darbyshire, 1961; Tucker and Pitt, 2001), to the more recent procedures enabling estimation of the directional spectrum under non-negligible speed of advance and in real-time. The estimation procedure has shifted from direct methods in the frequency domain to nonlinear optimizations or time domain procedures that require higher computational resources, which in the meanwhile have become available.

Estimation of sea spectrum from ship motions, with the explicit account for wave direction and ship speed of advance, appears to have been first presented in Japan during the 1970's, with well-structured published research produced by Takekuma and Takahashi (1973), as a result of work started in 1971 by the 108th Research Committee of the Ship-building Research Association of Japan. At the time they coined the procedure as a “Reverse Operational Method of Sea Spectrum” and were not focused on determining the directional spectrum but rather on taking into account the fact that ship response changes with incoming wave direction.

In the late 1970's, Pinkster (1978) proposed that the wave feedforward information could be used to achieve better performance in dynamically positioned vessels. During the 1980's there appears to be reduced interest in spectral estimation from ship motions, but Pinkster's work, though he did not go as far as to actually demonstrate the hypothesis on a real ship, seems to have motivated several proposals and experiments on spectral estimation that appeared in 1990's and early 2000's. In these publications there was a small detour from using ship motions alone to estimate directional wave spectra and wave staffs or laser probes around the hull were proposed as a means to measure relative elevations (Drennan and Donelan et al., 1994; Linfoot and Wright, 1995; Waals et al., 2002).

In the early XXI century there was a renewed interest on estimation of the directional spectrum from ship motions, with several publications addressing the problem from diverse perspectives. It is probably at this time that most of the proposals appear and that researchers start to worry more explicitly about strategic positioning of the onboard sensors, mathematical details, real-time algorithms and speed of advance.

Focusing on the available methods to estimate wave spectra from ship responses, one will find, as with generic procedures designed for spectral estimation given the responses of an excited medium, that there exist parametric and non-parametric formulations, depending on whether or not an analytical shape is made available. There are many features in common with generic spectral estimation procedures

* Corresponding author.
E-mail address: c.guedes.soares@centec.tecnico.ulisboa.pt (C. Guedes Soares).

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designed to determine spectra, however, the single most important aspect, correctly emphasized back in 1970, is the fact that the predictions of full sensor dynamics (i.e. ship) are not negligible, requiring state of the art hydrodynamic calculations, and that, unlike the response of a spherical wave buoy, the response of a vessel is also a function of wave direction and not just of frequency.

Similar work has been published on wave spectrum estimation using parametric and nonparametric representations. The parametric formulation consists on giving a spectral shape with mathematical representation and unknown coefficients, such as the JONSWAP, while the nonparametric is a minimization where only a non-negativity constraint on the spectral amplitude is mandatory but the form is otherwise not specified (this is sometimes called hyperparametric representation) (Pascoal et al., 2007).

Iseki and Ohtsu (2000), Iseki and Terada (2001), Iseki and Daisuke (2002), and Iseki (2004) proposed a non-parametric Bayesian formulation for estimating the directional sea spectrum. The Bayesian formulation is a formal path to obtain a constrained non-linear optimization problem. In the respective publications, he incrementally improves or at least suggests different procedures to estimate the motion cross-spectra, needed for the final step of the estimation of the wave spectrum. Iseki is probably the first, in this setting, to propose the use of multivariate autoregressive moving average filters in order to provide real-time cross-spectral estimates, but his contribution felt short, since real-time cross-spectra of ship motions did not result in real-time wave spectral estimation due to the computational bottleneck of the non-linear optimization that was still necessary to recover the wave spectrum.

Tannuri et al. (2001, 2003) proposed both parametric and non-parametric procedures for stationary vessels. After several numerical and physical experiments, Tannuri favoured the non-parametric formulation, which was written as a Bayesian problem, and explicitly arrived at a non-linear programming problem to optimize for the spectral ordinates. The computationally demanding procedure was signalled to be a problem and there was great care in justifying which motions should be chosen for the optimization, as well as to why hydrodynamic calculations need to be carried out carefully.

Saito et al. (2000), Maeda et al. (2001), Masuda et al. (2001), also proposed non-parametric methods, formulated as non-linear programming problem, and suggested that results from the procedure could be used to provide guidance for ocean going ships.

Nielsen (2005, 2007, 2008) worked extensively on the Bayesian formulation of the same problem, reinstated the need to carefully handle the non-bijective nature of the encounter frequency, identified the need to carefully calculate ship responses and the need to refine the way that the tuning parameters are found, as they influence the shape of the estimated spectra. Furthermore, the proposed approaches were confronted with spectral estimation from radar backscatter images from full scale trials.

Pascoal et al. (2007, 2008, 2009) worked on several aspects of spectral estimation and proposed several alternatives of non-parametric and parametric formulations. In these publications, it was clearly stated that the computational bottleneck is at the final step of optimization, with execution times given for comparison, and therefore conditioning factors and ways to quickly find robust initial estimates were proposed. It was probably the first time, in this setting, that genetic algorithms were used to provide global search in the parametric formulation and that the Kalman filter was used to obtain estimates of the actual wave elevations in real time and without requiring any cross-spectral calculations. Those algorithms were verified only with numerical simulations and in this paper they are compared with experimental results obtained in sea trials conducted in 2009. It is interesting to note that around the same time the works of Tannuri and co-workers and of Nielsen have been validated with full scale motion data (Simos et al., 2010; Nielsen and Stredulinsky, 2012). A recent limited validation has also been made of the parametric approach of Pascoal and Guedes Soares (2009) using a small patrol boat (Hinostroza and Guedes Soares, 2016a, 2016b).

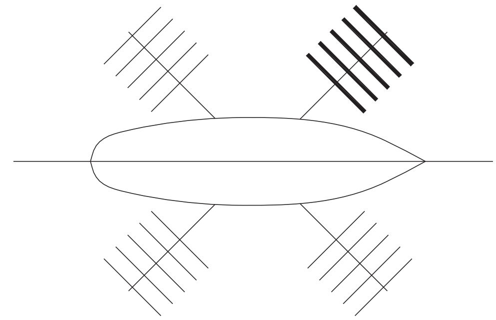

Fig. 1. Waves that induce practically the same amplitude of the response but different phases.

Fig. 2. Fiber optic gyro with rate gyro and heave accelerometer.

Fig. 3. Bow mounted down-looking wave radar with vertical accelerometer for motion compensation.

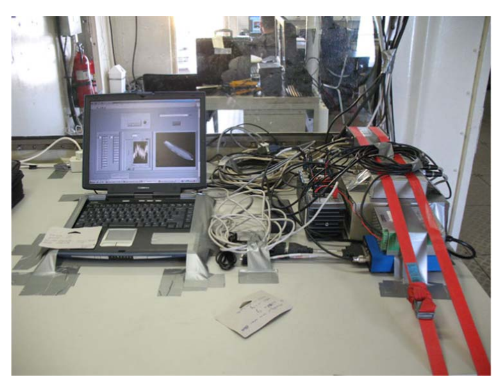

Fig. 4. Data acquisition equipment, wave radar processor and GPS.

In the sections to follow, the formulations adopted in this study are briefly described and the results of a full scale experimental campaign are shown and compared with the estimates of the two main alternative methods, allowing conclusions about their relative capabilities.