Applied Ocean Research xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Applied Ocean Research

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

Sea state estimation using vessel response in dynamic positioning

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ARTICLE INFO

Article history:
Received 5 May 2017
Received in revised form 17 August 2017
Accepted 13 September 2017
Available online xxx

Keywords:
Sea state estimation
Vessel response
Dynamic positioning
Closed-form expressions

ABSTRACT

This paper presents a novel method for estimating the sea state parameters based on the heave, roll and pitch response of a vessel conducting station keeping automatically by a dynamic positioning (DP) system, i.e., without forward speed. The proposed algorithm finds the wave spectrum estimate from the response measurements by iteratively solving a set of linear equations, and it is computationally efficient. The main vessel parameters are required as input. Apart from this the method is signal-based, with no assumptions on the wave spectrum shape. Performance of the proposed algorithm is demonstrated on full-scale experimental DP data of a vessel in three different sea states at head, bow quartering, beam, stern quartering and following sea waves, respectively.

1. Introduction

Complex marine operations are moving further from shore, into deeper waters, and harsher environments, see Sørensen [1]. The operating hours of a vessel are weather dependent, and good knowledge of the prevailing weather conditions may ensure cost-efficient and safe operations. In addition, the performance of the DP operation will be improved by fast dynamic tracking of the first order wave induced motions used as input to the wave filter in the DP system. Recently, there has been a lot of focus on increasing the level of autonomy in marine operations, see Ludvigsen and Sørensen [2], and having a fast and reliable method for obtaining a sea state estimate is useful both in the control and in decision support systems to aid the decision making process, with or without the operator onboard the vessel.

Several methods exist for obtaining information about the sea state. Wave rider buoys are present at fixed locations, usually near the coast, providing accurate measurements for specific sites. Some vessels have installed wave radar, see Clauss et al. [3], but these systems may be expensive to install, require frequent calibration [4,5], and in the case of large vessel motion the measurement quality is degraded. The satellite image quality may be affected if the cloud cover is low, and in general, weather data may lag up to six hours.

Today, the majority of marine vessels are equipped with sensors that gather vast amounts of data regarding the operational state, fuel consumption, hull girder stresses, acceleration, attitude and position, to name a few. In this sense, many marine vessels are inherently equipped with sea state measuring systems, since the sensor measurements can be used to infer about the on-site sea state, in a similar way as is done with traditional wave rider buoys. Estimating the sea state based on vessel motions has been explored extensively over the last 10–15 years, e.g., [6–9], see Nielsen [10] for an overview of the different methods. One proposed method is called the *wave buoy analogy*, where the ship motions in 6 degrees of freedom, or other global ship responses such as hull girder stresses, are transformed into the frequency domain, and an estimate of the wave spectrum is obtained by means of parametric or Bayesian modeling. The vessel is implicitly assumed to be in stationary conditions if not elaborate procedures are applied [11,12].

For advanced controller schemes, e.g., hybrid or switching control, sea state parameters estimated using computationally efficient algorithms are sought. In steady state DP operations, reliable and accurate estimates of the sea state are more important than frequent updates, while in transient operations (i.e., start up, change of heading and similar) fast updates even at the expense of accuracy are favoured. *Online* sea state estimates from rapid schemes, can be used to manipulate parameters in the control law directly [13], or be input to performance monitoring functions and risk assessment models that choose the best algorithms available. There are many computationally efficient schemes for estimating the peak frequency of the waves, however, algorithms for estimating the wave height and direction are rare. Belleter et al. [14] present a time-

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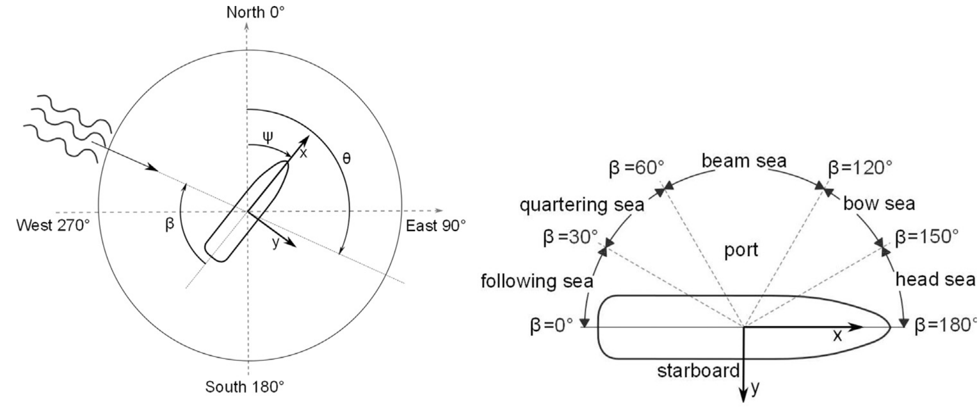
https://doi.org/10.1016/j.apor.2017.09.005
0141-1187/



(a) Global wave propagation direction Θ (b) Relative wave direction β

Fig. 1. Definition of the wave propagation direction $\Theta \in [0, 360)^\circ$, heading of the vessel ψ, and relative wave direction β. Starboard incident waves have $\beta \in (-180, 0]^\circ$, and port incident waves have $\beta \in [0, 180]^\circ$. The coordinate system x–y represents the *body*-frame with the z-axis pointing down (into the page), and the dashed coordinate frame in (a) is the North-East-Down (NED)-frame, also with the down-axis pointing downward (into the page). Notice that the vessel is symmetric about the x-axis.

domain method for estimating the peak frequency of encounter in order to detect parametric rolling, and Brodtkorb et al. [15] use the response spectra in heave and pitch to estimate the peak frequency of the sea state for use in controllers. Nielsen et al. [16] estimate the amplitude, phase and frequency of a regular wave, making a step towards a sea state estimation algorithm that is computationally efficient, *and* provides the wave height and direction estimate, in addition to the peak frequency. On a related note, the vessel response history itself may also be used for predicting the vessel response deterministically up to 30-60 seconds ahead of time using the correlation structure in the time history process, see Nielsen et al. [17].

This paper proposes a computationally efficient and robust sea state estimation algorithm that provides an estimate of the wave spectrum, from which sea state parameters such as the significant wave height H_s, peak period T_p (or other characteristic periods), and the relative wave direction β can be derived. The sea state estimation algorithm is non-parametric, i.e., there are no assumptions on the shape of the wave spectrum, and so the sea state estimate is obtained through solving a set of linear equations relating the wave spectrum to the response measurements via (motion) transfer functions. In this initial study, the transfer functions of a barge (box-shaped vessel) called closed-form expressions, see Jensen et al. [18], with the same main parameters as the actual vessel are used in the estimation procedure. The main reason for this is to make the procedure as simple as possible, so it can be used for vessels where the detailed hull geometry is unknown or unavailable due to non-disclosure issues. For DP vendors, this will be an advantage for i.e., efficient tuning of the DP control system. If the actual transfer functions of the vessel are pre-calculated by advanced computational tools, e.g., by panel codes or strip theory, the approach will just require interpolation in a hyper-dimensional matrix, which is done in other sea state estimation algorithms. The sea state estimation algorithm is demonstrated on the heave, roll and pitch response measurements of the NTNU-owned and operated research vessel (R/V) Gunnerus during DP tests in three different sea states with head, bow quartering, beam, stern quartering and following sea waves.

The paper is organized as follows: an introduction to wave spectra, response spectra, cross spectra and closed-form expressions is given in Section 2, and Section 3 presents the sea state estimation algorithm. In Section 4 the collection and validation of the response measurements, wave elevation measurements, and tuning of the closed-form expressions is discussed, before the estimation results are presented. Section 5 concludes the paper.

2. Vessel modeling

2.1. Vessel response in irregular waves

For control design purposes, the vessel motion is usually modeled as a mass-damper-restoring system subject to the loads from current, wind, and waves. For ships in DP the thrusters will produce mean and slowly varying generalized forces in the horizontal plane to cancel those from the environment. Therefore the DP control system influences the surge, sway and yaw motion of ships, and the *heave (z)*, *roll* (ϕ) and *pitch* (θ) motions are more suited for sea state estimation. The measurements of heave, roll and pitch are recorded in the *body*-frame, which is defined with positive x-axis pointing towards the bow, positive y-axis pointing towards starboard, and with positive z-axis pointing down, see Fig. 1b. In DP the vessel has zero or low forward speed, so that the frequency of encounter is assumed to be the same as the incident wave frequency.

In this paper, fully developed wind-generated sea states are considered. It is also assumed that the sea state is stationary in the statistical sense (statistical properties are constant), and that the waves are long-crested, with propagation direction Θ, as defined in Fig. 1a. The wave direction relative to the vessel heading is β, with $\beta = 180^\circ$ being head sea, and $\beta = 0^\circ$ being following sea, see Fig. 1b.

The relationship between the wave amplitude and the vessel response amplitude (here only heave, roll and pitch are considered) is given by the complex-valued (motion) transfer functions $X_i(\omega, \beta)$, which can be calculated using hydrodynamic software codes. The complex-valued cross-spectra $R_{ij}(\omega)$ can be calculated as:

$$R_{ij}(\omega) = X_i(\omega, \beta)\bar{X}_j(\omega, \beta)S(\omega), \quad (1)$$

where $R_{ij}(\omega)$, $i, j = \{z, \phi, \theta\}$ are the heave, roll, and pitch response spectra, $\bar{X}_j(\omega, \beta)$ is the complex conjugate of the transfer functions in heave, roll and pitch for relative wave direction β, and $S(\omega)$ is the wave spectrum. When $i = j$, $X_i(\omega, \beta)\bar{X}_i(\omega, \beta) = |X_i(\omega, \beta)|^2$, which is the amplitude of the transfer function squared. The cross spectra $R_{ij}(\omega)$ calculated from measured responses for a data set from Run 3 are shown in Fig. 2. When $i \neq j$, $R_{ij}(\omega)$ is complex-valued, and when $i = j$ the imaginary part is zero, $\mathcal{I}m(R_{ii}) = 0$. The imaginary parts of the cross spectra pairs have opposite signs, i.e., $\mathcal{I}m(R_{ij}) < 0 \Leftrightarrow \mathcal{I}m(R_{ji}) > 0$, that are dependent on the incident wave direction. This is used later to determine β.

The vessel will act as a *low-pass filter* such that small wave length λ compared to the ship length will hardly result in any response. Hence, limited information about the waves can be obtained from