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Selection of the optimum combination of responses for Wave Buoy Analogy—
An approach based on local sensitivity analysis

Najmeh Montazeri¹, Ulrik Dam Nielsen²,³, and Jørgen Juncher Jensen²

¹Vessel Performance Solutions, SCION DTU, Denmark
²DTU Mechanical Engineering, Technical University of Denmark
³Centre for Autonomous Marine Operations (AMOS), NTNU, Trondheim, Norway

Abstract

One method to estimate the wave spectrum onboard ships is to use measured ship responses. In this method, known also as Wave Buoy Analogy, amongst various responses that are available from sensor measurements, a couple of responses (at least three) are usually utilized. Selection of the best combination of ship responses is important. Optimally, this selection should not be implemented manually in onboard applications. Therefore, availability of an automatic response selection procedure would be a great advantage for decision support. In this paper, a local sensitivity analysis is applied to evaluate the importance of individual responses in sea state estimation. The sensitivity factor is defined by calculation of the partial derivatives of wave parameters with respect to the variance of individual responses.

Keywords

Wave Buoy Analogy; Response selection; Sensitivity analysis; Derivatives; Sensitivity Factors.

Introduction

Operational performance management of ships is one of the main concerns in the shipping industry. Many newly-built vessels and marine structures are equipped with data collection systems for monitoring purpose. Decision support systems are nowadays available to provide optimal ship operational performance and route optimisation.

The effect of waves degrade a ship’s operational efficiency to some extent. Added resistance due to waves enforce additional trust to achieve the desired speed. In order to implement performance analysis, this wave induced added resistance should be estimated. Moreover, accidents occur due to unexpected and dangerous sea states, which can make the crew unable to keep the ship under proper control. For these reasons, estimation of sea state onboard ships is very important for performance analysis and operational guidance. On the other hand, the wave estimates in those applications deal with uncertainties. Therefore, it is beneficial to develop more reliable methods for onboard wave estimations.

Different methods have been used so far for onboard wave estimation. One method, which is called Wave Buoy Analogy, WBA, considers the ship as a wave buoy. So, the measured responses of the ship and their transfer functions are used to estimate the encounter waves. Different approaches in this field can be found in the literature e.g. (Tannuri et al., 2003; Pascoal and Guedes Soares, 2009; Nielsen and Stredulinsky, 2012; Nielsen, 2008). Selection of the optimum combination of ship responses for wave estimation is an important issue in the WBA. Depending on the dimensions and also the loading conditions of a ship, the values of individual wave-induced responses and, consequently, the usefulness of them in wave estimation varies from one case to another. Therefore, this choice should be made based on prior knowledge about the transfer functions of a particular ship in different operational conditions.

In (Andersen and Storhaug, 2012) and (Lajic, 2010) studies on automatic selection of responses have been initiated, where sea state estimation is carried out using individual responses separately. Then, a proper combination of responses are those, for which the wave parameters or the wave spectral moments are closest to each other. In this paper, a more systematic and mathematically advanced method based on a local sensitivity analysis is applied to quantify the importance of different responses for wave estimation.

Basic formulation

The theoretical relationship between the cross-spectral density of the $i^{th}$ and $j^{th}$ responses, $\Phi_{ij}(\omega)$, and the directional wave spectrum is given by:

$$\Phi_{ij}(\omega_c) = \int_{-\pi}^{\pi} H_i(\omega, \theta) H_j^*(\omega, \theta) S(\omega, \theta) d\theta,$$

where $\omega$ is frequency, $\omega_c$ is encounter frequency and $\theta$ is relative wave direction. $S$ is the directional wave spectrum, $H$ denotes the complex-valued transfer function.
and * is the conjugate notation. The responses are measured with respect to the moving reference frame of the ship and, hence, they are considered in the encounter-frequency domain. In other words, the left- and right-hand sides of Eq. (1) are the measured and the calculated cross-spectral density of responses, respectively.

In the wave buoy analogy, this equation can be considered as a cost function relating the measured and calculated responses. Another cost function that could be implemented is formed using the equivalence of the amount of variance between the measured and the theoretical responses. This equation can be derived by integration of the two sides of Eq. (1) with respect to frequency. Thus, the variance of individual responses, \( R \), can be written as:

\[
R_i = \int_0^\infty \int_{-\pi}^{\pi} H_i^2(\omega, \theta) S(\omega, \theta) \, d\theta d\omega, \tag{2}
\]

Eq. (2) is used in (Montazeri et al., 2016) for estimation of parametric wave spectrum.

**Sensitivity measure**

The method used here is adopted from (Brun et al., 2002), where a sensitivity analysis is used for importance ranking of the parameters to be estimated. Assuming that the estimated quantity, \( f \), is a function of \( n \) input variables, i.e., \( f = f(x_1, x_2, \ldots, x_n) \), the sensitivity of \( f \) to individual variables can be calculated using the derivatives:

\[
sf_j = \frac{\partial f}{\partial x_j}, \quad j = 1, 2, \ldots, n \tag{3}
\]

where the derivative of \( f \) with respect to the parameter \( x_j \) is evaluated at a point in the parameter space, where the sensitivity analysis is carried out. \( sf_j \) represent the sensitivity factors, which form the sensitivity vector \( SF = \{sf_j\} \).

In the parametric estimation, the wave spectrum is represented in terms of integrated wave parameters, \( p \). Those parameters are considered as \( f \) in Eq. (3). The variance of the \( j \)th response, \( R_j \) in Eq. (2), is used as \( x_j \). Therefore, Eq. (3) can be rewritten as

\[
sf_{pj} = \frac{\partial p}{\partial R_j} \tag{4}
\]

For the sake of comparability between the different responses, the sensitivity factor should be scaled and non-dimensionalised. Therefore, this quantity is multiplied by \( R_j \), so that the scaled sensitivity factor is given by

\[
sf_{pj} = \frac{\partial p}{\partial R_j} \frac{R_j}{p}. \tag{5}
\]

Eq. (5) expresses the sensitivity of a wave parameter to a change in the variance of the measured \( j \)th response. A high \( sf_{pj} \) means that the magnitude of the \( j \)th response has an important influence on the wave parameter estimate and vice versa. \( \frac{\partial p}{\partial R_j} \) in Eq. (5) can be evaluated as outlined in the following section.

**Table 1. Ship characteristics**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Length [m]</td>
<td>349.0</td>
</tr>
<tr>
<td>Beam [m]</td>
<td>42.8</td>
</tr>
<tr>
<td>Design Draft [m]</td>
<td>14.5</td>
</tr>
<tr>
<td>Speed [kn]</td>
<td>20</td>
</tr>
</tbody>
</table>

**Influence of wave parameters on the response spectra**

The transfer function of a particular response exhibits properties that typically change as the wave parameters (particularly the wave period and the wave direction) change. This means that spectral calculations, where transfer functions are combined with a wave spectrum, in general, lead to different outcomes depending on the wave parameters. In other words, the impact of varying one parameter of the wave spectrum, keeping the other parameters fixed, on the standard deviation of individual responses of a ship is usually notable (Nielsen, 2010).

A 9400 TEU container ship is studied in this paper as a case study. The main characteristics of the vessel are given in Table 1. The amplitudes of the transfer functions for the particular operational condition in Table 1 are shown in the appendix.

As an example, Figures 1 and 2 show the influence of the peak period and the mean wave direction, respectively, on the response spectra, \( \Phi \), of pitch motion for this ship. A long-crested JONSWAP spectrum is used for these illustrations. Similar plots have been presented in (Nielsen, 2010). It can be seen in Figure 1 that the standard deviation of pitch motion, i.e. the square root of the area under the spectrum, has a very small magnitude if the wave energy is concentrated at high frequencies (low peak periods). This is due to the large ship size relative to the wave length. As the peak period increases, this motion becomes considerable. Figure 2 shows that a shift of 90 degrees in wave direction from head/following sea towards beam sea results in a very small amplitudes of the pitch transfer function and, consequently, a small standard deviation in this motion.

Using Eq. (2) the partial derivative of the variance with respect to a wave parameter, \( p \), is achieved by

\[
\frac{\partial R}{\partial p} = \int_0^\infty \int_{-\pi}^{\pi} \frac{\partial S}{\partial p} H^2(\omega, \theta) d\theta d\omega, \tag{6}
\]

where \( \frac{\partial S}{\partial p} \) can be obtained analytically or numerically. \( S \) is considered as a single short-crested unimodal wave modelled by the JONSWAP and a "cos" model spreading factor. The significant wave height, \( H_s \), the peak period, \( T_p \), and the mean wave direction, \( \mu \), are considered as the main parameters of the wave spectrum. Substituting \( H_s \) for \( p \) and calculating the derivative, Eq. (6) can be written
This constant value of $\frac{\partial R}{\partial H_s}$, regardless of the value of the significant wave height, all responses have the same importance in estimation of the significant wave height. This is quite reasonable because the transfer function, by definition, does not depend on the wave height. Therefore, $H_s$ is neglected in the sensitivity analysis here.

The derivative of the response variance with respect to the peak period is calculated by

$$
\frac{\partial R}{\partial T_p} = \int_0^\infty \int_{-\pi}^\pi \frac{1}{T_p^4} \left[ \frac{5}{4} \left( \frac{2\pi}{\omega T_p} \right)^4 \gamma \exp\left\{ -\frac{\omega^2 T_p^2}{2\sigma^2} \right\} \right] S(\omega, \theta) H^2(\omega, \theta) \sin(\theta - \mu) d\theta d\omega,
$$

and, the sensitivity factor for $T_p$ is:

$$
\frac{s f_{T_p}}{T_p} = \left( \frac{\partial R}{\partial T_p} \right)^{-1} \frac{R}{T_p}.
$$

Finally, the derivative of the response variance with respect to the relative wave direction is calculated by

$$
\frac{\partial R}{\partial \mu} = \int_0^\infty \int_{-\pi}^\pi \frac{1}{T_p^4} \left[ -\frac{4}{T_p} + \frac{5}{T_p^5} \left( \frac{2\pi}{\omega T_p} \right)^4 - \frac{\omega}{2\pi^2 \sigma^2} (\omega T_p - 1) \right] S(\omega, \theta) H^2(\omega, \theta) \sin(\theta - \mu) d\theta d\omega,
$$

and, the sensitivity factor for $\mu$ is:

$$
\frac{s f_{\mu}}{\mu} = \left( \frac{\partial R}{\partial \mu} \right)^{-1} \frac{R}{\mu}.
$$
The sensitivity of variations are relatively high, the sensitivity of almost all wave conditions and since the inverse of steepness of these curves with respect to the mean wave direction is

\[
\begin{align*}
\frac{\partial R}{\partial \mu} &= 2s \times 5.061 \frac{H_s}{T_p^2} \left[1 - 0.287 \ln(\gamma)\right] \times \\
& \int_0^\infty \int_0^\pi \frac{g^2}{\omega^2} \exp[- \frac{5}{4} \left(\frac{2 \pi}{\omega T_p}\right)^4] \gamma \exp[- \frac{\omega T_p}{2 \pi} \gamma^2] \times \\
& H^2(\omega, \theta) N(s) \cos^2(\frac{\theta - \mu}{2}) \tan(\frac{\theta - \mu}{2}) d\theta d\omega,
\end{align*}
\]

where \(\mu\) is in rad. The sensitivity factor for \(\mu\) is normalised by \(2\pi\):

\[
\frac{s_{J\mu}}{s_{\mu}} = \left(\frac{\partial R}{\partial \mu}\right)^{-1} \frac{R}{2\pi}.
\]

In order to get a visual understanding of the importance of individual responses, the variances of responses can be plotted for different wave periods and directions. Figures 3 to 7 show the variations of heave, pitch, vertical bending moment at midship section, sway and roll at \(V=20\) kn and \(D=14.5\) m. The steepness of these curves with respect to periods and directions represents the quantities of Eqs. (9) and (11), respectively.

It can be realized from Figures 3 and 4 that in head sea and following sea conditions, the energies of heave and pitch are negligible when the peak period falls in the wind sea range (e.g. \(T_p < 10\) s). Therefore, in such conditions, other responses should be used for wave estimation. As seen in Figure 5 the wave bending moment responds to almost all wave conditions and since the inverse of steepness of variations are relatively high, the sensitivity of \(T_p\) and \(\mu\) to this response is considerable for a large range of \(T_p\) and \(\mu\). The non-zero variances of pitch and bending moment in beam sea condition are due to the asymmetric geometry of the ship with respect to midship section. Sway motion is also useful in many wave conditions as shown in Figure 6. However, as expected, the variance of this response is very small in head sea and following sea. It can be seen in Figure 7 that the energy of roll motion is highly dependent on the wave condition. As inferred from Figures 3 to 7, the most critical condition for wave estimation is following sea condition, where all responses have small magnitudes.

**Results and discussion**

In the following, the sensitivity analysis is implemented for various waves with peak periods between 7 and 17 seconds, and mean wave directions from following sea to
head sea. The loading condition of the ship is the same as the previous section. The significant wave height is fixed at 4 meters. $\gamma$ and $s$ are also fixed at 3.3 and 25, respectively.

The sensitivity factors based on Eqs. (10) and (12) are calculated for heave, pitch, sway, roll and vertical bending moment at the midship section. It is assumed for calculation of the derivatives that the wave parameters are known. In practice, in order to perform the sensitivity analysis, the predicted wave parameters obtained, for instance, from the trend analysis in (Montazeri et al., 2015) can be used. The sensitivity factors can be calculated in real-time. As an alternative, for a specific ship, the procedure can be also pre-analysed at different loading and wave conditions so that the optimum combination of responses are determined over a range of probable conditions, and can be utilized during the operations. The latter approach is beneficial in the interest of time saving for real-time decision support applications.
When the peak period is long, e.g. $T_p > 14$ s, the sensitivity factor of the wave direction, as seen in Figure 8, the impact of different responses on the peak period is similar to $\mu = 130^\circ$. The sensitivity factor of the wave direction, on the other hand, depends very much on the value of the peak period (Figure 9). Bending moment, pitch, roll and heave could be useful in this case. As the sensitivity factor and the amount of energy of sway motion is almost zero, using this response in head sea condition is inefficient.

All in all, it can be inferred from this paper that the wave bending moment is generally the most effective response for estimation of both the wave period and the wave direction for the specific ship. It is notable that the sensitivity analysis should be provided in different loading conditions in terms of speeds and drafts. However, the sensitivity factors are not expected to be subject to major changes since the magnitudes and the trends of transfer functions do not differ considerably. It can also be expected that the importance of the responses are somewhat similar for other vessels of similar size and with a similar range of operational conditions.

It is noteworthy that the method in this paper assumes the accuracy of different transfer functions to be in the same level. However, hydrodynamic models and numerical calculations of transfer functions are exposed to uncertainties, which may vary from one response to another. Therefore, beside the sensitivity analysis, the responses can be weighted based on knowledge about the accuracy of transfer functions calculations. For example roll would be given less weight that heave and pitch, since the uncertainty of this motion is believed to be higher.

**Figure 9. Normalised sensitivity factor for $\mu$, (The legends are identical in all plots)**

### Conclusion

In this paper, identification of an optimum combination of ship responses for state estimation is carried out. The method is based on the sensitivity of the major wave parameters in a standard spectrum (JONSWAP) to the magnitudes of individual response variances. Those sensitivity calculations are simply obtained using first order derivatives of response variances with respect to the wave parameters. It is believed that choosing the responses with higher importance at typical conditions can make the outcome of the WBA more efficient and reliable. It should be noted that this method can be used as a prior input to any response-based wave estimation method including parametric and non-parametric methods such as [Nielsen, 2007] [Tannuri et al., 2003] [Pascoal and Guedes Soares, 2008]. The method helps to make onboard wave estimates more accurate, which can improve the efficiency of performance management and decision making.
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References


Appendix

Figure 10. Amplitudes of RAO for heave

Figure 11. Amplitudes of RAO for pitch

Figure 12. Amplitudes of RAO for sway
Figure 13. Amplitudes of RAO for roll

Figure 14. Amplitudes of RAO for vertical bending moment at midship section