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Wave Bimodal Spectrum based on Swell and Wind-sea Components

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Abstract: This paper addresses the problem of how to estimate a ocean wave spectrum using standard meteorological information provided by weather forecast companies. A method is proposed for calculating a wave bimodal spectrum using the wind-sea and the swell components, also a description of the commonly used spectrum models are presented. The spectral models are evaluated using real buoy data obtained from the National Data Buoy Center of National Oceanic and Atmospheric Administration. The three most frequently used spectral models were considered for comparison, two of them, Pierson-Moskowitz and JONSWAP produce single-peaked spectra while Torsethaugen produces double-peaked spectra. The proposed method showed an improvement in the accuracy of the spectra when independent components for wind-sea and swell were used for estimating the buoy spectra. The accuracy of the spectral estimation is evaluated using a similarity index.

Keywords: Ocean waves, wave spectra, bimodal spectra, wind-generated waves, swell waves.

1. INTRODUCTION

Wave spectra give the distribution of the wave energy in a particular point and time on the sea surface as function of the frequency. They represent the different wave components that is determined by the sea conditions. A developing sea condition produced by a local storm in the early stages generates peak values of energy at high frequencies. On the other hand, a fully developing sea conditions produced by a storm that has lasted for a long time over a large area generates peak values of energy at low frequencies. All this information is summarized in the wave spectrum. The main importance of the wave spectrum is that, it can be used to obtain interaction forces against human-made structures on the ocean. For example, the wave resistance force acting on the ship or on a marine structure like offshore platforms.

Spectra based on buoy measures are not available for each single point on the oceans. Therefore spectra are estimated at any point on the sea using models based on few parameters, typically the significant wave height and peak period. The forecast of these parameters are calculated using weather models by meteorological companies or agencies. They provide latitude-longitude grids with the forecast of these parameters. In these maps can be examined the extension of the sea that has the similar parameters and how they will change in the next future.

A classification of the wave spectral models can be done using the number of peaks in the spectral density function. According to this classification Pierson-Moskowitz spectrum (Pierson and Moskowitz, 1964) and Joint North Sea Wave Project (JONSWAP) spectrum (Hasselmann et al., 1973) represent the sea state with a single-peaked spectrum. On the other hand, Torsethaugen (Torsethaugen, 1993) represents the sea state with a double-peaked spectrum, which includes the effects of wind-sea and swell components. However, the Torsethaugen spectrum uses the dominant values of the sea state which means that the input parameters of the model are the same two parameters than Pierson-Moskowitz and JONSWAP. Torsethaugen spectrum models a double-peaked spectrum through a method of partitioning the wave spectrum into two frequency bands: the swell component is obtained using the low frequency band and the wind-sea component is obtained using the high frequency band.

This idea of decomposing the wave spectrum in two frequency bands to analyse wave spectra was proposed originally in (Strekalov et al., 1972). The authors use a high frequency spectrum for describing the wind-sea component and a Gaussian shaped spectrum for describing the swell component. A six parameter spectrum is proposed in (Ochi and Hubble, 1976). The spectrum is decomposed into two parts, each one has three parameters, which are the significant wave hight, the modal frequency and the shape factor. Then, the total spectrum is the summation of both parts, one which includes the low frequency components and the second which covers the high frequency components of the wave spectrum. The Ochi-Hubble model uses two JONSWAP spectra for describing the wind-sea and swell components. The statistical analysis for fitting the parameters using the data of the JONSWAP project can be read in (Ochi and Hubble, 1976). Other double-peaked spectrum obtained as a summation of two spectra is proposed in (Guedes Soares, 1984). The model represents both wind-sea and swell components by two JONSWAP spectra at different peak frequencies. The spectral model has four input parameters, the significant wave height, the peak period, the ratio of the spectral peaks and the ratio of the peak frequencies. Torsethaugen spectrum is commonly used for representing bimodal sea states. It uses

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also two JONSWAP spectra to represent bimodal sea conditions, however it does not use the standard JONSWAP model parameters as was done in (Guedes Soares, 1984). Torsethaugen spectrum used more constants in the model for fitting the double-peaked spectra, however as input, it uses the dominant values of significant wave height and average wave period.

This paper proposes a spectral model for representing wave systems, which incorporates wind-sea and swell sea states. The model has 4 input parameters for both the wind-sea component and the swell component, then each component is represented with 2 parameters the significant wave height and the average wave period. All this information is available in the meteorological databases and is used to estimate the wave spectra as from the weather forecast maps. The model estimations are evaluated using real buoy data, which is considered as ground truth data, obtained from the National Data Buoy Center of National Oceanic and Atmospheric Administration (NOAA, 2015).

The paper has the following structure: This section has presented the introduction and relevant previous bimodal spectral models. Section 2 describes the basic elements in spectral wave models and their scopes. Section 3 explains the formulation of the bimodal spectrum based on wind-sea and swell components. The comparison with measured wave spectra is illustrated in Section 4. Finally, conclusions are summarized in section 5.

2. SPECTRAL MODELS

Sea conditions can be influenced by several factors like fetch, breaking waves, wave refractions and reflections, local currents and more than one swell. Spectral models are approximations limited to some conditions, these are, for example, deep-water waves on the open ocean, fully developed sea conditions [1], wind-generated sea, ignoring other influences. Spectral models are used to estimate the expected spectral shape for a given combination of significant wave height (H_s) and peak period (T_p) and are validated for specific sea conditions. Spectral models assume that ocean waves at a location can be influenced mainly by wind or swell or a combination of both of them. In the first case, waves are generated by the local wind and in the second one, waves are entering into the location from other areas. Thus, each spectral model has specific conditions where it can be used for fitting real spectra.

2.1 Pierson-Moskowitz spectrum

Pierson-Moskowitz spectral model was developed for fully developed wind-generated seas from analysis of wave spectra of the North Atlantic Ocean under the assumption of infinite water depth and infinite fetch. It produces one peak spectra. The model equation (Moskowitz et al., 1963; Pierson and Moskowitz, 1964), is shown below

$$S(\omega) = A\omega^{-5} e^{-B\omega^{-4}} \tag{1}$$

[1] In fully developed sea conditions the waves have the maximum height possible for a given wind speed, and it is produced when wind blows for a sufficient period of time across the open ocean.

where

$$A = \frac{4\pi^3 H_s^2}{T_p^4},\ B = \frac{16\pi^3}{T_p^4}$$

Note that, the spectral model is function of the significant wave height (H_s) and the peak period (T_p).

2.2 JONSWAP Spectrum

Joint North Sea Wave Project (JONSWAP) spectrum was developed for non-fully developed wind seas using North Sea data between the Sylt Island and Iceland. The spectral density function is more peaked than Pierson-Moskowitz spectrum because it represents non-fully developed seas under the assumption of finite water depth and limited fetch. The spectral density function (Hasselmann et al., 1973; Fossen, 2011) is as follows

$$S(\omega) = A\omega^{-5} e^{-B\omega^{-4}} \gamma^{\alpha} \tag{2}$$

where the peak enhancement factor γ^{α} was introduced to represent fetch limited wind sea. The γ values depend on wind speed, fetch and time duration. Hasselmann et al. (1973) suggest

$$A = \frac{4\pi^3 H_s^2}{T_p^4},\ B = \frac{23\pi^3}{T_p^4},\ \gamma = 3.3,\ \alpha = e^{-\left(\frac{0.2049 T_p \omega - 1}{\sqrt{2}\sigma}\right)^2}$$

where

$$\sigma = \begin{cases} 0.07 \text{ for } \omega \leq \dfrac{4.88}{T_p} \\ 0.09 \text{ for } \omega > \dfrac{4.88}{T_p} \end{cases}$$

The JONSWAP spectrum will be more peaked when γ value is increased. Also, γ can be expressed as function of H_s and the peak period T_p according to the sea conditions, as can be seen in (Torsethaugen and Haver, 2004).

2.3 Torsethaugen spectrum

This spectral model represents wave conditions in open ocean areas where the waves are dominated by local wind (high frequency components), but also exposed to swell (low frequency components). The spectrum was developed using curve fitting of experimental data from the North Sea in Norwegian waters. In this model (Torsethaugen, 1993), the sea states are classified into two types depending on the origin of the highest spectral peak. Thus, the spectrum has one peak or two peaks, according to the value of the peak period T_p. The distinction between wind dominated (non-fully developed waves) and swell dominated (fully developed waves) sea states is determined by the fully developed sea condition given by

$$T_{pf} = a_f H_s^{1/3}$$

where $a_f = 6.6$. If $T_p < T_{pf}$, the primary spectral peak corresponds to a local wind system. If $T_p > T_{pf}$, the primary spectral peak corresponds to a swell system. Values of T_p around T_{pf} will produce single-peaked spectra. This behaviour can be seen in Fig. 1. The Torsethaugen spectra have two peaks when the primary spectral correspond to low frequencies (marker +) and high frequencies