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Development of a bi-modal directional wave spectrum

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ABSTRACT

Addressing sea state in a coastal region of Gulf of Oman by a directional wave spectrum for the very first time is the main focus of this study. The region encounters wind-sea as well as swell. So, proper modeling of the sea state requires in general a double peak spectral model.

The research is firstly conducted to calibrate nondirectional Torsethaugen double peak spectrum for the region by entering the separation frequency; a frequency in which wind-sea and swell parts could be divided. This novel calibration procedure is simple while results in much better outcome. Besides, one has to decide about an appropriate Directional Spreading Function (DSF) for the wind-sea and swell components. Then, nine possible combinations of three well-known DSFs have been investigated and calibrated to provide maximum conformity between observed and modeled directional wave spectra.

1. Introduction

A trustworthy statistical modeling of wave directional properties at a specific location is a necessary prerequisite to ensure design precision and accuracy in coastal and offshore regions. Here, the spectral formulation, stemming from the early work of Phillips (Phillips, 1958), is among practical tools in ocean engineering. For the case of directional spectral formulation it actually addresses wave energy and its distribution over different wave frequencies and directions.

Various methods like maximum entropy method, maximum likelihood method and Bayesian method have been developed over years to estimate a directional spectrum from measurements (Longuet-Higgins et al., 1963; Borgman, 1969; Isobe et al., 1984; Kobune and Hashimoto, 1986; Kuik et al., 1988). Such methods have been reviewed and categorized by Benoit et al. (1997). Among them is a common practical approach in which a directional spectrum $S(f,\theta)$ is expressed as follows:

$$S(f,\theta)=S(f)D(f,\theta) \tag{1}$$

in which $S(f)$ is nondirectional spectrum and $D(f,\theta)$ is Directional Spreading Function (DSF).

Now, for coexistence of local wind generated wave and distant swell wave; from now on we briefly call them wind-sea and swell, respectively; one expects at least a double peak nondirectional spectrum. It is commonly assumed that nondirectional wave spectrum is of a single mode form, and can be well modeled by a well-known standard spectrum such as JONSWAP or Pierson–Moskowitz spectrum. This approach is totally reasonable for severe sea states. However, moderated and low sea states; as one encounters in most Iranian coastal regions at Gulf of Oman; are often of a mixed nature, consisting of wind-sea as well as swell. Then, such sea states should be addressed by a double peak nondirectional spectrum. To characterize this issue, an approach was pioneered by Strekalov and Massel (1971) to sum two individual spectra as follows:

$$S(f)=\sum_{i=wind-sea,\ swell} S_i(f)=S_W(f)+S_S(f) \tag{2}$$

here, $S_W(f)$ and $S_S(f)$ stand for wind-sea and swell components of the spectrum, respectively.

This approach was used later by researchers to combine and modify available standard nondirectional spectra e.g. Pierson–Moskowitz or JONSWAP resulting in the well-known double peak spectra like Ochi–Hubble model and Torsethaugen model (Ochi and Hubble, 1976; Guedes Soares, 1984; Torsethaugen, 1993; Moon and Oh, 1998; Violante-Carvalho et al., 2004; Torsethaugen and Haver, 2004; Mackay, 2011).

For DSF, there are some standard uni-modal forms as cosine-power distribution (Longuet-Higgins et al., 1963; Mitsuyasu et al., 1975; Hasselmann et al., 1980), wrapped normal distribution (Borgman, 1969; Briggs et al., 1995), wrapped-around Gaussian distribution (Mardia, 1972), hyperbolic distribution (Donelan et al., 1985), von Mises distribution (Abramowitz and Stegun, 1975; Hashimoto and Konube, 1986), Poisson distribution (Lygre and Krogstad, 1986) and Boxcar or Steklov distribution (Venugopal et al., 2005) which have been checked occasionally by other researchers based on observations (Ewans, 1998). However, no single model is universally accepted due to site specificity associated with particular formulations. In order to distribute a nondirectional spectrum over directions, it has been a common

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practice to use distinct DSFs for distribution of wind-sea and swell parts as also recommended by rules and regulations (EM 1110-2-1100, 2006; DNV-RP-C205, 2010). So, for this situation it would be appropriate to rewrite Eq. (1) as follows:

$$S(f,\theta) = \underbrace{S_W(f)D_W(f,\theta)}_{Wind\ \ part} + \underbrace{S_S(f)D_S(f,\theta)}_{Swell\ \ part} \tag{3}$$

To this end, the paper aims at developing a directional spectrum $S(f,\theta)$ for Chabahar coastal regions together with an introduction to a general practical approach for calibration of double peak spectra. Measured wave data in Chabahar bay in the northern coasts of Gulf of Oman are used to verify the proposed approach. The area is experiencing both wind-sea and swell regimes throughout the year especially in Monsoon seasons (Rashmi et al., 2013). As the border of Indian Ocean and Gulf of Oman, it is under construction and development activities and its field observations are recently released.

Available data are briefly reviewed in the next section. Based on field observed spectra, nondirectional Torsethaugen double peak spectrum is firstly calibrated in Section 3 using a simple novel approach. Assessing some standard DSFs in Section 4 together with their calibration to maximize conformity, they finally resulted in developing a calibrated directional spectrum for the region.

2. Local measurements

In order to monitor regional coastal waters a mega project had been initiated by Port and Maritime Organization of Iran since 2006. Fig. 1 shows the focal point of this paper together with measurement stations as stars for the Chabahar bay, also called Khalij-e Chabahar, which is around 25°20′53″N and 60°30′40″E in DMS (Degrees Minutes Seconds). Nortek Acoustic Wave and Current profiler (AWAC) had been used to gather such directional field data. Stations specifications are summarized in Table 1. Such raw data are processed using Nortek STORM software to recognize extreme events. The raw data come from direct measurements with no filter for anomalies e.g. gaps or spikes. Therefore, a simple code is developed to reject any records which do not pass certain quality requirements.

3. Calibration of the nondirectional spectrum

Nondirectional spectrum has always its own importance and application irrespective of its distribution over different angles. This motivated the authors to firstly focus on calibration of nondirectional spectrum as the sum of $S_W(f)$ and $S_S(f)$ based on the form introduced by Eq. (2). Then, the directional spectrum is

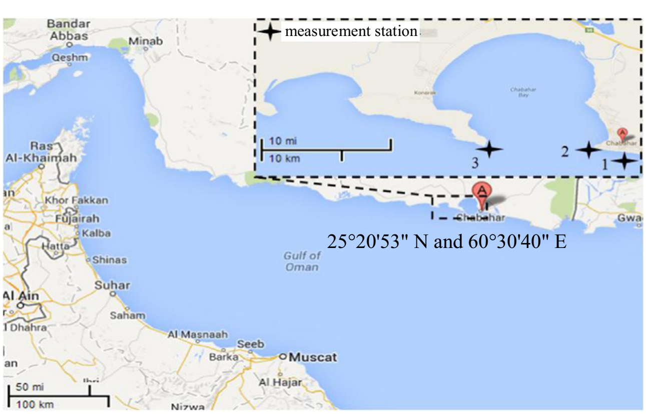

Fig. 1. Chabahr bay in Gulf of Oman and measurement stations.

calibrated by finding and tuning appropriate DSFs as presented in Section 4.

For the purpose, Torsethaugen spectrum is nominated as the most recent well-known attempt to deal with double peak spectral presentation as $S_T(f) = S_{T\ W}(f) + S_{T\ S}(f)$ in which T stands for Torsethaugen (Torsethaugen, 1993).

Torsethaugen spectrum originally developed by combining two JONSWAP spectra. The spectrum is presented as a sum of wind-sea and swell components for j = 1, 2 as follows (Torsethaugen, 1993):

$$S(f) = \sum_{j=1}^{2} E_j S_{nj}(f \cdot T_{Pj}) = \sum_{j=1}^{2} E_j S_{nj}(f_{nj}) \tag{4}$$

where:

$$E_j = \frac{1}{16} H_{Sj}^2 \cdot T_{Pj} \tag{5}$$

$$S_{nj} = G_0 A_{\gamma j} \Gamma_{Sj} \gamma_{Fj} \tag{6}$$

here, it should be noted that Torsethaugen only requires that the user provides two input parameters H_s and T_p. Its other main parameters are all expressed in terms of the significant wave height (H_s) and spectral peak period (T_p). At first, $T_f = a_f H_s^{1/3}$ should be calculated as the peak period in a fully developed sea in which a_f is slightly sensitive to the fetch length. Then, one could decide if the sea state is wind-sea dominated $(T_P < T_f)$ or swell dominated $(T_P > T_f)$.

It was shown later by Torsethaugen and Haver (2004) that some of the parameters for the general form of Torsethaugen spectrum, considering its complex formulation, are of marginal importance for design purpose. So, they introduced the simplified form as presented in Tables 2 and 3 for wind-sea dominated and swell dominated sea states. Here, bold parameters are those empirical coefficients tuned in this research together with a_f as it has the main rule in switching between formulations.

Besides, in Eq. (6) G_0 = 3.26, $\Gamma_{Sj} = f_{nj}^{-4} \exp[-f_{nj}^{-4}]$ and $A_{\gamma j}$ as well as γ_{Fj} are functions of peak enhancement factor γ as follows:

$$\gamma_{F1} = \gamma^{\exp\left[1/2\sigma^2 (f_{n1}-1)^2\right]} \tag{7}$$

$$\gamma_{F2} = 1 \tag{8}$$

$$\sigma = \begin{cases} 0.07 & f_{nj} < 1 \\ 0.09 & f_{nj} \geq 1 \end{cases} \tag{9}$$

$$A_{\gamma 1} = \left(1 + 1.1\left[\ln(\gamma)\right]^{1.19}\right)/\gamma \tag{10}$$

$$A_{\gamma 2} = 1 \tag{11}$$

here, γ is calculated using Tables 2 and 3.

However, such a comprehensive parameterization of the spectrum has been originally shaped based on measurements at deep sea; Statfjord field in Norwegian waters (Torsethaugen, 1993); and later supported by other data close to that location (Ewans et al., 2006; Bitner-Gregersen and Toffoli, 2009). So, it has to be implemented for other locations like Gulf of Oman with care.

Here, the spectrum is examined in three forms of standard version $(S_T(f))$, calibrated version $(S_{Cal\ T}(f))$ and Separation Frequency Implemented (SFI) calibrated version $(S_{SFI\ \ Cal\ \ T}(f))$ in order to model the sea states at the region. For $S_T(f)$, original values have been exactly used as the coefficients (Torsethaugen, 1993). To catch $S_{Cal\ T}(f)$ coefficients, minimizing Root Mean Square Error (RMSE) of modeled spectrum values, $\Delta A/A$ and $\Delta f_p/f_p$ have been set as calibration targets using nonlinear Generalized Reduced Gradient (GRG) algorithm (Lasdon et al., 1973). Here, A and f_p are the area under the spectrum and its peak frequency, while Δ