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Parameter Identification of JONSWAP Spectrum Acquired by Airborne LIDAR

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Abstract In this study, we developed the first linear Joint North Sea Wave Project (JONSWAP) spectrum (JS), which involves a transformation from the JS solution to the natural logarithmic scale. This transformation is convenient for defining the least squares function in terms of the scale and shape parameters. We identified these two wind-dependent parameters to better understand the wind effect on surface waves. Due to its efficiency and high-resolution, we employed the airborne Light Detection and Ranging (LIDAR) system for our measurements. Due to the lack of actual data, we simulated ocean waves in the MATLAB environment, which can be easily translated into industrial programming language. We utilized the Longuet-Higgin (LH) random-phase method to generate the time series of wave records and used the fast Fourier transform (FFT) technique to compute the power spectra density. After validating these procedures, we identified the JS parameters by minimizing the mean-square error of the target spectrum to that of the estimated spectrum obtained by FFT. We determined that the estimation error is relative to the amount of available wave record data. Finally, we found the inverse computation of wind factors (wind speed and wind fetch length) to be robust and sufficiently precise for wave forecasting.

Key words JONSWAP spectrum; parameter identification; least square method; airborne LIDAR

1 Introduction

Identifying the parameters of the power spectrum density function is a critical aspect of the analysis of the dynamical process of wind waves, because the temporal variation of the wind field is embodied in the spectrum. Particularly for the Joint North Sea Wave Project (JONSWAP) spectrum (JS), which was first introduced by Hasselmann (1973), three of four parameters depend on the wind speed and wind fetch length. In the aircraft monitoring system, the wind factor is regarded as a perturbation effect during the scanning process for ocean surface waves when using airborne Light Detection and Ranging (LIDAR). Although the accuracy of the measurements is slightly disturbed by the wind effect, the feedback regulation of the aircraft, including its robustness, flying path, and so forth, greatly depend on wind perturbation. Therefore, a fast and precise parametric extraction algorithm for the ocean wave power spectrum is an essential aspect of wind factor estimation.

The surface elevation of ocean waves measured by airborne LIDAR comes directly from the simple geometrical relationship between the altitude of the aircraft, the

scanning angle, the laser pulse speed, and the elapsed time. The measurement points travel in zigzag fashion along the flying path and, as indicated in Bermont *et al.* (2006), the density of these measurement points gradually decreases with their distance from the camera. Even so, the airborne LIDAR provides a high-resolution (1 mm for 8-m height with a 5-mm statistical error) and cost-effective (16 km² h⁻¹) survey tool for topographic mapping and coastal region surveying (Irish and Lillycrop, 1999; Turner *et al.*, 2016; Blenkinsopp *et al.*, 2012; Wang and Phipot, 2006).

The JS is a fetch-limited wind wave spectrum with four parameters, which are, respectively, a Philips constant α , peak spectrum angular frequency ω_p , peak enhancement factor γ , and constant factor σ . In spectrum analysis, which corresponds to an FFT operation from the discrete wave elevation records to the power spectrum, the ω_p can be read directly from the estimated spectrum. The factor σ can be considered to be constant, which is equal to 0.07 for $\omega \leq \omega_p$ or equal to 0.09 if not. In Mitsuyasu *et al.* (1979), Synder (1974), and Hasselmann *et al.* (1976), the authors gave analytical expressions, which had been obtained in different seas, to compute the other two parameters of the JS, α and γ . Hasselmann *et al.* (1976), for instance, expressed the scale parameter by the integral form of the spectrum data and established a relation between the shape and scale parameters. Mitsuyasu *et al.*

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(1979) represented these two parameters in dimensionless fetch form. Although these estimation approaches were verified in a practical manner by error analysis, their procedures require cooperation between diverse sensors, buoys, anemographs, and so forth. Furthermore, the integral operator is much more complicated to realize than that of linear system in this paper.

The least squares method (LSM) is currently extensively used in engineering analysis and regression analysis for statistical formulation, to name two examples. The application of LSM in ocean wave prediction has been discussed by Nougier *et al.* (2014) (for amplitude coefficient identification), Nadri and Patzold (2015) (for angle frequency and amplitude determination), and Huang *et al.* (2016) (for surface current determination). Once we established a cost function for the undetermined parameters, we developed equation sets by the partial differential of the cost function of each parameter. The idea of LSM is to set these linear equations to zero to find the minimum error between the model and unestablished function by identifying the most suitable parameters.

We have organized this paper as follows: in Section 2, we describe ocean waves at a fixed location based on the random-phase method and deduce the identification algorithm by minimizing the mean-square error of the target JS for the estimated spectrum. In Section 3, we simulate the algorithm in the MATLAB environment and compare the results using different constraints. We draw our conclusions and offer a future perspective in Section 4.

2 Ocean Wave Representation and Algorithm

The vertical displacement of wind waves at a fixed location ($x=0$) was discussed by Dean and Dalrymple (1984), whereby the surface elevation of small amplitude waves can be obtained by the assumption of linearization. Thus, the superposition principle can be naturally applied to establish the surface elevation model, known as the Longuet-Higgins (LH) model, with a sum-of-sinusoid expression as follows:

$$\eta(t) = \sum_{m=1}^M A_m \cos(\omega_m t + \varphi_m), \quad (1)$$

where A_m , ω_m are the amplitude and the angle frequency of harmonics waves, respectively. φ_m is a uniformly distributed random phase, defined as $[0, 2\pi]$.

In the ocean, we assume that the wave amplitude of each component can be found in JS ($S(\omega)$), and the relation between these two quantities is as follows:

$$A_m = \sqrt{2S(\omega_m)\Delta\omega}. \quad (2)$$

In the following applications, due to the lack of actual data, we generate the elevation of (linear) fully developed open seas by the JS as follows:

$$S(\omega) = \alpha \frac{g^2}{\omega^5} \exp\left[-\frac{5}{4}\left(\frac{\omega_p}{\omega}\right)^4\right] \gamma^r, \quad (3)$$

where,

$$r = \exp\left[-\frac{(\omega - \omega_p)^2}{2\sigma^2\omega_p^2}\right].$$

Above, we introduced the nature of four visible JS parameters. Next, we emphasize that the JS could be determined using a two-parameter spectrum, including wind speed at 10-m height over the mean water level, U_{10} and the wind fetch length F . We can develop the Philips constant α and peak spectrum angular frequency ω_p according to Hasselman's parametrization:

$$\alpha = 0.076 \left(\frac{U_{10}^2}{gF}\right)^{0.22}, \quad \omega_p = 22 \left(\frac{g^2}{U_{10}F}\right)^{0.33}. \quad (4)$$

Using a floating buoy, Mitsuyasu *et al.* (1979) determined that the peak enhancement factor could also be represented by wind speed and fetch, as follows:

$$\gamma = 7.0 \left(\frac{gF}{U_{10}^2}\right)^{\frac{1}{7}}. \quad (5)$$

Fig.1 shows some examples of the JS by the application of Eq. (4), with $U_{10}=10, 15$ and 20 ms^{-1} , and $F=100$ km. We chose a mean value of $\gamma=3.3$. We can see that the peak spectrum angular frequency shifts to the left with an increase in wind speed, as does the augmented extremum with an increase in wind speed. These problems respect the facts set forth in Eq. (4). Furthermore, the steepness of the three curves is reflected in the shape parameters, and this phenomenon is demonstrated in Eq. (5). Thus, the four JS parameters can be reduced to a two-parameter spectrum by introducing wind speed and fetch.

Fig.1 JS for $U_{10}=10, 15$, and 20 ms^{-1} . $F=100$ km.

For the identification algorithm, we transform the non-linear JS (3) into linear form in a natural logarithmic scale as follows:

$$y = \beta_0 + \beta_1 x + D, \quad (6)$$

where