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Spectral Characterisation of Bonny Offshore Water Wave in Nigeria

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Abstract

This paper presents detailed information on ocean wave spectral characteristics of Bonny offshore, a fast growing and one of the busiest Nigerian offshore locations. The data obtained from Bonny shallow water offshore are discretized into 31 frequencies and 72 directions. Wave energies are concentrated within wave periods between range of 1.0 sec and 1.5 sec. The wave spectra are found to be mono-modal and this is against the general belief that West African offshore locations are bi-modal in spectral characterization. Estimation of spectra zeroth moment (m_o) is used to verify the accuracy of the spectral plot. It is found that the developed spectral plot provided sufficient accuracy of the value of m_o. The consequence of spectral estimation inadequacies can reflect on offshore facilities' over-design or under-design of structures required for installation and use in the area. Optimal design could save large cost especially in this era of low cost oil.

Keywords: *Wave Spectra, Amplitudes, Sea State, Nigerian Offshore, Bonny Offshore, Wave load*

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1. Introduction

The continually increasing Nigerian population is mounting great pressure on major roads in the coastal states of the country. Presently, an attempt to design and build special passenger boats to help decongest the busy roads by opening up safe maritime transport is being researched on by the Centre for Maritime and Offshore Studies, Federal University of Petroleum Resources Effurun; a research targeted at defining the best hull with respect to the sea states of the operational location. This can easily be achieved if detailed and precise wave spectra reports of key areas/routes in Nigerian offshore waters are made available. It is also noted that wave spectra are very vital in ascertaining responses of offshore structures and floating bodies.

The wave spectrum itself is the energy content per given frequency value. In Front End Engineering Design (FEED) that involves design concept selection and development, the natural frequency of the structure must be assessed Vis-a'-Vis the frequency of wave conditions with large energies. This is crucial to avoid resonance and to ensure minimum wave loading. Wave spectra of a given location also provide a definition of the significant wave height (Hs) obtainable in that location through the spectra zeroth moment.

Primarily, in getting the wave spectra also referred to as energy spectra, one must first obtain the sea state that describes the amplitude and frequencies in the appropriate directions (Wyatt, 1997; Vugts et al., 2007). It is important that waves coming in the same direction be treated as a unit during spectra analysis, as it is a key factor behind quality of results. Aside the quality of results, the directions are vital during computations for structural response (Chakrabarti, 1987). Though, there is a variety of approaches that can be used in determining structural responses such as the use of roll tanks as described by Jensen et al. (2004), use of industrial software, direct measurements, response amplitude operator (RAO) and analytical method as presented by Abam and Akaawase (2018). However, the RAO approach, which involves the use of wave spectra, has proven over the years to be better than the others.

It is noted that the sea presents a random pattern of wave travelling from different directions. To handle this real situation, frequency spectra are usually multiplied with a spreading function to obtain the directional wave spectrum in the case of parametric models (Olagnon et al., 2013). This is in fact the complete description of the wave spectrum for qualitative purposes (Lars, 2003).

The method adopted for computations in this work is based on wave amplitudes and direction (a, θ) for the corresponding frequency. Thus, ensuring complete energy distribution to relate a wave model to marine structure's (floating or fixed) responses. The consequence would be an improved result in the computation of the frequency spectra.

2. Materials and methods

2.1. Data source/study area

A 3-year data acquired from Bonny shallow offshore location in Nigeria through Shell Nigeria is utilized in the work. Bonny is located in the East of the mouth of River Niger, at a shallow depth of about 19.0m off the coast of the Atlantic Ocean. It is one of the busiest offshore locations in Nigeria due to the oil and gas exploration, existence of local ports and Islands and availability of Nigeria Liquefied Natural Gas Company (LNG) in the zone. Bonny location in West Africa and Nigeria is shown in Fig. 1.

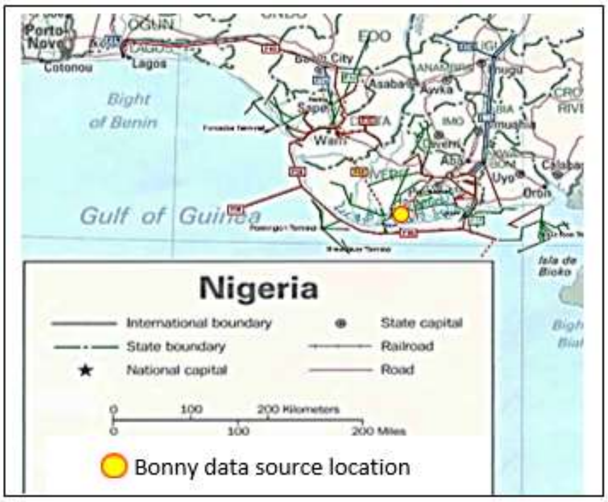

Fig. 1: Map showing bonny offshore

2.2 The approach

The data provided by SHELL Nigeria (from Bonny offshore location, see Figure 1) contained time series. This is vital when handling discrete frequencies in an attempt to ascertain the energies. The Fourier expansion of the spreading function is often limited to second order (Ewans, 2013). That is to say, Fourier expansion (n) can only be equal to a maximum of two (2).

$$D(\theta) = \frac{1}{2\pi}\left(1+\sum_{n=1}^{n=2} r_n \cos\left(n(\theta-\theta_n)\right)\right) \qquad (1)$$

where r_n is the directional spreading index, θ_n is the mean wave angle, D(θ) is the directional distribution and θ is the instantaneous wave direction. This can only be ascertained according to Olagnon et al. (2013) when the first and second directional spreading are given:

$$\sigma_1 = \sqrt{2(1-r_n)} \qquad (2)$$

$$\sigma_2 = \sqrt{(1-r_n)/2} \qquad (3)$$

σ_2 and σ_1 are the directional standard deviation of ocean waves.

For engineering purpose, directions are not usually distinguished within the range of 10 - 14 degrees, this is simply because σ_1 and σ_2 are almost the same at this range. Practically, this means that at much concentrated swell, the exact spread is of reduced importance (Ewans et al., 2013). This work presents a detailed approach from first principle how wave spectra computations are done considering wave angular distributions and frequencies. The product of this method can easily be integrated into Response Amplitude Operator to derive the response spectra of any floating or installed structures offshore with improved accuracy.

In defining a spectra shape, many challenges are often encountered. This may include but not limited to short duration measurements from the area of interest. Conventionally, a parametric model is chosen from the available spectrum then fitted to the principal wave characteristics. The present work involves computing wave spectra from records of sea surface elevation taking into consideration the wave travelling direction. This ensures addition of energies in a given direction. To achieve this, a 3-year wave data collected at the Bonny offshore was analyzed using wave analysis toolbox of MATLAB governed by Equations (7) to (15).

First, the entire data was imported into MATLAB and as recommended by Akinsanya et al. (2017), peak period (T_p) equivalents were obtained from the zero crossing periods (T_z).

$$T_p = 1.3 \times T_z \qquad (4)$$

Then peak frequencies (f_p)

$$f_p = \frac{1}{T_p} \qquad (5)$$

Next, the entire data was sorted with reference to f_p values in an increasing order. Then, class intervals were established to reach 31 groups of f_p values. To reach this decision, the maximum and minimum values of f_p were extracted from the data using the

MATLAB max, min commands. Then this statistical approach was applied:

$$Interval = \frac{Highest\ Value - Lowest\ Value}{Number\ of\ desired\ classes} \tag{6}$$

At this stage, the data have been prepared for analysis. Thus, Equations (11) to (15) were utilized in the computations. The surface elevation as described by Torsethaugen (1993) is represented as:

$$\xi(t) = \sum_{i=1}^{N} a_i \cos\left(2\pi f_i + \alpha_i\right) \tag{7}$$

where N is the number of frequency, a_i is the wave amplitude, α_i is the phase angle and f_i is the discrete frequency. With this, the records have been presented in such a way that those with same phase angle are together. This process is repeated for N>30 instances. From these groupings, a uniform phase distribution for the individual f_i is gotten. A Raleigh distribution is expected for each of the frequency distribution plots. The expected values of amplitudes are found from separate frequency distribution. The amplitude spectrum is generated from expected values of the amplitude for each frequency plot. That is,

$$\mu_1 = E\{a_i\}$$

$$\mu_2 = E\{a_2\}$$

$$\mu_n = E\{a_n\} \tag{8}$$

where μ_n is the expected value of the amplitude. Thus, a Raleigh distribution can be computed for all values of a > 0 in the relationship:

$$P(a_i) = \frac{\pi}{2}\frac{a_i}{\mu_i} \exp\left(-\frac{\pi}{4}\frac{{a_i}^2}{{\mu_i}^2}\right) \tag{9}$$

For the directional spectrum discretization from first principle, the spectra are discretized in 31 frequencies and 72 directions and the variance density spectrum $S(f_i)$ is gotten from the amplitude in a relationship:

$$S(f_i) = \frac{1}{\Delta f_i} E\left\{\frac{1}{2}{a_i}^2\right\} \tag{10}$$

where Δf_i is the gap between the discrete frequencies. The frequency direction spectra can be actualized by deploying the work of Hason (2001):

$$S(\omega, \theta) = \lim_{\Delta f_i \to 0} \lim_{\Delta\theta \to 0} \frac{1}{\Delta\omega\Delta\theta} E\left\{\frac{1}{2}a^2\right\} \tag{11}$$

where f is the frequency in cycles/sec (Hz). Which implies that:

$$S(\omega, \theta) = \lim_{\Delta\omega \to 0} \lim_{\Delta\theta \to 0} \frac{1}{\Delta\omega\Delta\theta} E\left\{\frac{1}{2}a^2\right\} \tag{12}$$

$$S(\omega, \theta) = \frac{1}{2\pi} E(f, \theta) \tag{13}$$

where ω is the angular frequency, and is expressed as:

$$\omega = 2\pi f \tag{14}$$

The continuous curve known as the volume element becomes:

$$\Delta Var = \int_{\Delta f}^{0} \int_{\Delta\theta}^{0} E(f, \theta) d\theta d\omega \tag{15}$$

The zeroth moment, m_o is expressed as:

$$H_s = 4\sqrt{m_o} \tag{16}$$

where H_s is the significant wave height and m_o is the zeroth moment.

3. Results

3.1 Measured wave directions

Taking all measurements in the clockwise direction, plots are made for mean wave direction against peak frequency and wave amplitude for Bonny offshore available data (see Fig. 2 and 3, respectively). A good concentration of wave is found around South-West direction.

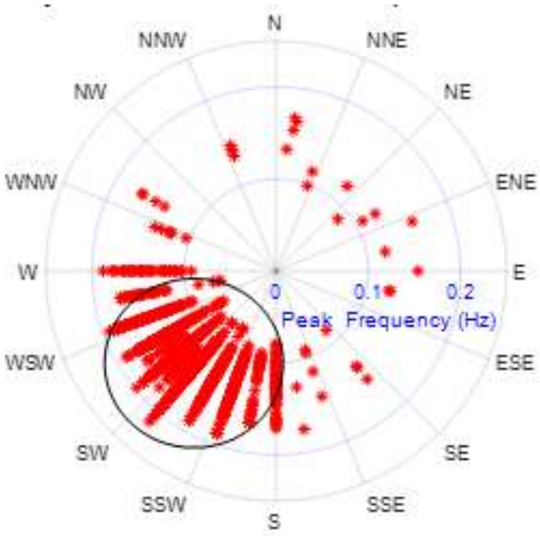

Fig. 2: Bonny wave direction against peak frequency.

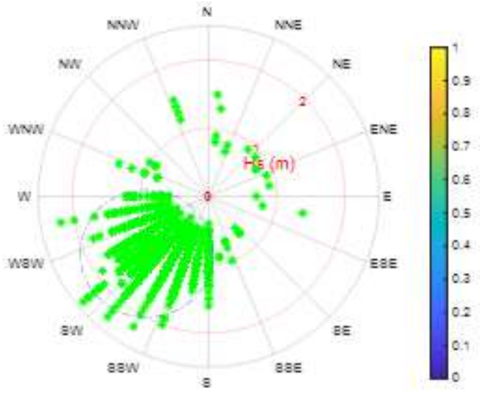

Fig. 3: Bonny offshore amplitudes and direction

3.2 Directional Spectrum

Utilising Equations (4) to (15), plots were made for the wave spectral (Fig. 4) and the directional spectrum (Fig. 5).

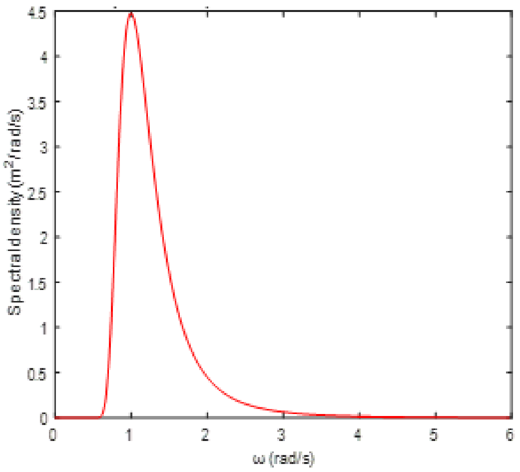

Fig. 4: The Bonny offshore wave spectral representation.

Using polar plots, the Bonny sea states with waves coming from the various directions is visualized in Fig. 5, the plan view of the detailed approach of section 2.2 complimenting Fig. 4 (frequency spectrum). The main direction was found to be 225 degrees.

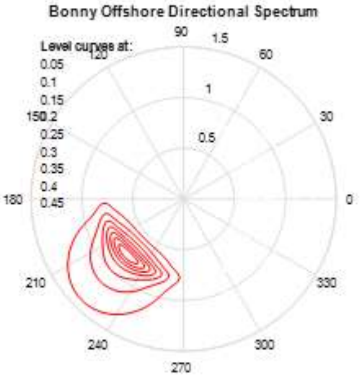

Fig. 5: Bonny directional spectrum

4. Discussion

To verify the reliability of this result, the wave spectra zeroth moment (m_o) is computed from the wave spectra (see Table 1) in order to derive the measured significant wave height numerically. The m_o denotes the energy content of the Bonny offshore wave. The measured Bonny offshore average significant wave height within the period of record is noted as 1.2 m.

Table 1: Zeroth moment values (m_o) computed from the plot.

Description	Zeroth moment value, m_o
Bonny spectra	0.09615

The result of the spectra computations shows high degree of accuracy as shown in Table 2 with an actual measured H_s adequately estimated at an absolute error of only 3.3%.

Table 2: Estimated Hs from Bonny computed spectra

Spectra Used	Wave spectra zeroth moment, m_o	Estimated significant wave height from spectra, $Hs=4\sqrt{m_o}$	Absolute Error in Hs determination
Bonny spectra	0.09615	1.240322539	0.033

This shallow water region of the Nigerian offshore is mono-modal spectra as shown in the plot of Figure 4. This is not surprising observing from the very short wave period that is not near the usual West African swell wave period. Unlike influential locations such as Bonga, the Bonny location is perhaps hidden and shielded from the direct effect of swell just as observed in Asabo work (Agbakwuru et al., 2020). Figure 4 also sees a huge energy concentration between 1.0 rad/s (wave period of 6.3 sec) and 1.5 rad/sec (wave period of 4.2 sec). The consequence is that structures and floating vessels with natural frequencies in this range may heavily be impacted on by the water waves of Bonny offshore. Therefore, it is important and indeed necessary for marine and offshore designers and engineers to verify models with actual data at locations putting into consideration directions of incidental waves. In this era of low oil prices, this will save costs and minimize risks of failed structures due to waves.

5. Conclusions

The need for detailed and quality computation of wave spectra (considering both the wave directions and wave frequencies) cannot be overemphasized. This is simply because the definition of the significant wave height attained by a statistical wave is related to the wave spectra moment (m_o). Generally speaking, m_o is the area enclosed by the wave spectra and in fact the energy content of the wave itself. Large errors in computation can lead to serious issues of design inadequacy, thus, impacting on costs and safety.

Acknowledgement

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Nomenclature

Symbol	**Description**
a_i	Wave amplitude
r_n	Directional spreading index
θ_n	Mean wave angle.
σ_n	Directional standard deviation of ocean waves.
α_i	Phase angle
f_i	Discrete frequency.
$\xi(t)$	Surface elevation
fp	Peak frequency
N	Number of frequencies
μ_n	Expected value of the amplitude.
$P(a_i)$	Raleigh distribution
$S(\omega,\theta)$	Frequency direction spectra
H_s	Significant wave height
m_o	Zeroth moment.