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Time Domain and Frequency Domain Analyses of Measured Metocean Data for Malaysian Waters

Duong Vannak, Mohd Shahir Liew, and Guo Zheng Yew

Abstract**—**Data of wave height and wind speed were collected from three existing oil fields in South China Sea – offshore Peninsular Malaysia, Sarawak and Sabah regions. Extreme values and other significant data were employed for analysis. The data were recorded from 1999 until 2008. The results show that offshore structures are susceptible to unacceptable motions initiated by wind and waves with worst structural impacts caused by extreme wave heights. To protect offshore structures from damage, there is a need to quantify descriptive statistics and determine spectra envelope of wind speed and wave height, and to ascertain the frequency content of each spectrum for offshore structures in the South China Sea shallow waters using measured time series. The results indicate that the process is nonstationary; it is converted to stationary process by first differencing the time series. For descriptive statistical analysis, both wind speed and wave height have significant influence on the offshore structure during the northeast monsoon with high mean wind speed of 13.5195 knots (σ = 6.3566 knots) and the high mean wave height of 2.3597m (σ = 0.8690m). Through observation of the spectra, there is no clear dominant peak and the peaks fluctuate randomly. Each wind speed spectrum and wave height spectrum has its individual identifiable pattern. The wind speed spectrum tends to grow gradually at the lower frequency range and increasing till it doubles at the higher frequency range with the mean peak frequency range of 0.4104 Hz to 0.4721 Hz, while the wave height tends to grow drastically at the low frequency range, which then fluctuates and decreases slightly at the high frequency range with the mean peak frequency range of 0.2911 Hz to 0.3425 Hz.

Keywords**—**Metocean, Offshore Engineering, Time Series, Descriptive Statistics, Autospectral Density Function, Wind, Wave.

I. Introduction

At present, there are more than 10,000 offshore production structures worldwide and more than 250 fixed platforms located in offshore Peninsular Malaysia, Sarawak and Sabah regions. The numbers will increase with world energy demand. The design life of a platform is 25 years; the majority of the structures are going to exceed the designed life period.

With increasing energy demand, oil-and-gas companies are eager to explore other areas for a new source of hydrocarbons. To determine the sites for exploratory drilling, regional sea state condition surveys are done to ensure that operations will have no disruption from any extreme event and the design of offshore platform will be scrutinized for its design efficiency and economics due to escalating material costs.

In deepwater regions, offshore structures are often exposed to critical states due to severe metocean conditions. Damage has been reported on offshore drilling platforms due to wave forces. The periodicity of loads has two phases on structural damage, the first being the dynamic resonance of the structure and the other is the fatigue failure of the material [1]. Generally, the overall design of the offshore structure depends on the environmental loads, with wind speed and wave height being the most critical loads considered, which are applied to the structure from various directions. The environmental load data are obtained from a hindcast database which provides significant wave heights, wave directions, spectral information, current amplitude and direction, and wind speed and direction over a long time period. Hindcast data are far more comprehensive than any measured time history [2]. If there is insufficient or missing measured data for the location, the standard practice is to use hindcast data to derive metocean design criteria [3].

II. Metocean

Responses of selected offshore structures, due to metocean forces, are monitored in real-time and full scale, providing essential information and knowledge for the design of offshore structures and offshore installations. Measured metocean data is used to produce customized domains to get high resolution prediction of ocean and coastal conditions, and also can be configured to whatever scale required – for instance to resolve the wave energy gradients behind an island, throughout an oil field or along a shipping channel and into a harbor entrance [4]. Metocean data help to reduce construction costs with accurate and less conservative design conditions besides avoiding high costs for installation and operation. It is necessary to support offshore operational planning for the optimal design of offshore installations and to ensure offshore safety and environmental protection as there is no universal wave spectral model which can be applied to all storms in the world. The environmental study at the exposed installation area is important and is required for all stages of offshore oil-and-gas exploration and production [5]. However, other parameters must also be considered at some locations and specific types of operations, such as sea temperature, visibility and ice conditions [6]. The response or resistance of offshore structural facilities to environmental loads is usually dependent on the load application, which is critical to ensure reliability of offshore structures. The use of wind and wave statistics in the design and operation of offshore facilities provides the engineer with a source of information on output or response statistics for key design parameters, rather than only single-value input statistics. Although it is not practical to analyze each and every facility exposure event during its

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lifetime, simplified statistical models can account for the environmental exposure and its effect on response parameters [7].

III. Autospectral Density Function

In analysis of metocean data, random sea state maintains certain identifiable statistical properties on a short term basis [8]. The sea state intensity is characterized by its total energy which is distributed according to the frequencies of the various wave components - length, period or frequency [9]. The energy of the sea is usually expressed in terms of its autospectral density function; it is given as local energy spectrum, and it describes the energy distribution over different wave frequencies at a fixed point [10], providing a more comprehensive description of the environmental load conditions defined for a single position, with specified surface characteristics (height, period, direction, etc.) [5].

A. Fourier Transform and Autocorrelation

The most common way of generating the autospectral density function is by applying the Fourier transform on the autocorrelation function R(τ) for weakly stationary random processes as shown in Fig. 1 [11]. The autocorrelation function will be transformed from the time domain into the frequency domain to ascertain the energy content associated with the structure [4]. The autocorrelation is the correlation of a function with a lagged version of itself. It is an even function and is unity at zero time lag [12] and the autocorrelation function tells us something about how rapidly the time series can be expected to change as a function of time. If the autocorrelation function decays rapidly, it indicates that the process changes rapidly. The autocorrelation function also contains information about the expected frequency content of the time series. If the autocorrelation function has periodic components, then the corresponding process also will have periodic components [13]. Informally, autocorrelation is employed to observe repeating patterns, such as the presence of periodic data which are buried under noise, or identifying the missing fundamental frequency in a signal implied by its harmonic frequencies [14]. The time series values should be considered stationary if the sample autocorrelation function of the times series values either cuts off fairly quickly or dies down fairly quickly, but if it dies down extremely slowly, then the time series values should be considered nonstationary and it must be converted into a series of stationary time histories [15].

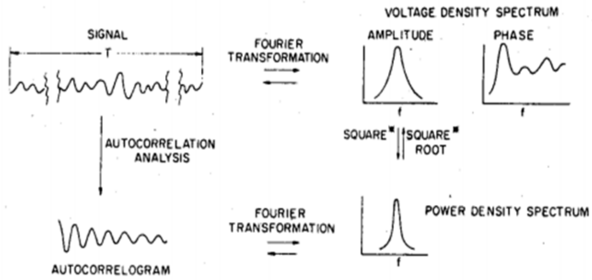

Fig. 1 Relationships between a signal and its analyses

B. Spectral Analysis

At present, spectral analysis is important in time series analysis as it produces the density distribution of wave frequencies which is representative of the actual conditions [16] and it is the best method to describe random sea states. From the resulting response spectrum, the significant and the maximum expected responses can be easily obtained for any given time interval [17]. It is a technique applied to real wave measurements to estimate the amplitude of each oscillatory component from the first low frequency wave to its high frequency component [5]. If the signal varies slowly, then its power will be concentrated at low frequencies; if the signal tends to be periodic, then its power will be concentrated at the fundamental frequency of the rhythm, perhaps at its harmonic frequencies; if the signal lacks periodicity, then its power will be distributed over a broad range of frequencies. It is important to avoid aliasing errors so that an accurate estimate of the power spectrum can be obtained [16]. The middle frequencies carried the most energy in the sea during the time interval of the measurement. It can be seen that in any particular sea, there is very little energy associated with low-frequency waves and also little energy associated with high-frequency waves. Most of the energy is concentrated in the middle band of frequency, e.g. the PM Spectrum (describes 'fully developed' sea states at Gulf of Mexico) and the JONSWAP spectrum (describes 'fetch-limited' sea states in the North Sea region) [18].

For a real-valued random process, the autocorrelation function is even, and the autospectral density function is given by

$$S(f) = \int_{-\infty}^{\infty} R(\tau)\cos(\omega\tau)\,d\tau \qquad (1)$$

where *S(f)* is the wave energy density spectrum. It is a real and even function of frequency *f*, and the autospectral density function yields no phase information [11].

As the data, *x(t)*, is nonstationary based on the results of the autocorrelation results, the first difference method, as shown in (2), is used to convert data into stationary process for calculating the power spectral density together with the Tukey smoothing window, *w(k),* to remove white noise. *k* is time lag. $M \leq N$-1and it is usually restricted to $M \leq N/10$ [11].

$$z_t = x_t - x_{t-1} \quad \text{where } t = 2, \ldots, N \tag{2}$$

$$S(f) = \sum_{k=-M}^{M} w(k)R(k)e^{-j2\pi fk} \tag{3}$$

Two different autospectra can be observed:

1) A spectrum is defined to be a low-frequency spectrum if its energy content tends to be higher at low frequencies rather than at high frequencies
2) A spectrum is defined to be a high-frequency spectrum if its energy content tends to be higher at high frequencies rather than at low frequencies.

C. Normalized Power Spectral Density Function

Normalization is the process of regularizing data with respect to variations in sample preparation, sample thickness and amplifier settings, in addition to any other aspects of the measurement; it also tends to produce values that compares well across different laboratories, research studies, and spectral analysis algorithms [19], [20]. Normalization of spectra is the application of similarity analysis to correlate spectra with generation factors. The analysis establishes the dependence between various normalized nondimensional parameters and thereby leads to a possible universal function [18].

Normalized autospectral density function compensates for large values in the spectrum that may have been brought about not by an increase in the coupling between the processes at frequency *f,* but by an inherently large concentration of power at that frequency during the process [16].

There are two commonly used methods to normalize spectral data: the dot product normalization, which essentially normalizes the spectrum based on the total area under the curve and the scaling normalization, which normalizes the spectrum based on the height of the strongest peak [21]. One of the many schemes used effectively in studying the similarity characteristics of wind wave spectra obtained from a wide variety of sea conditions is the dot product normalization and the results can be described by a universal spectral form [18].

$$\frac{S(f)f}{\sigma^2} = F(f) \tag{4}$$

where $S(f)$ is a frequency spectrum of the water surface displacements at a fixed location with respect to the frequency f. $F(f)$ is a dimensionless function that is universal for the spectrum of energy. σ^2 is the variance of the water surface displacements which is related to the spectrum function by

$$\sigma^2 = \int_0^\infty S(f)df \tag{5}$$

IV. Environmental Loads

A. Significant Wave Height

The surface characteristics of the real sea are extremely complex and variable [5]. In the design of offshore structures, the primary objective is to ensure maximum safety and reliability at an acceptable cost, taking into account both extreme loads as well as fatigue loads [22]. The forces on the structure are caused by the motion of the water due to waves (generated by wind) on the surface of the sea. In most aspects of offshore engineering design, wave load is usually the most important environmental load and has substantial forces much higher than the other environmental factors (wind, current etc.) [17].

Waves are characterized by wave height, wavelength, period and wave direction (with respect to north) with discrete time lags [3], [22]. Wave height is measured as the elevation of the water level at a point close to the platform [17] and is generally quoted as significant wave height, Hs, which is defined as the average of the largest one-third of all waves in a particular sea state [9].

Significant wave height is given by the following expression:

$$H_s = \frac{1}{N/3}\sum_{i=1}^{N/3} H_i \tag{6}$$

where N is the number of individual wave heights; H_i is a record ranked highest to lowest.

In spectral analysis, significant wave height is related to the total energy content of the wave spectrum:

$$H_s = 4\sqrt{m_o} \tag{7}$$

where $m_o = \int_0^\infty S(f)df$ is the total area under the wave energy spectrum [9].

B. Wind Speed

As wind passes over the surface of the water, small ripples are formed. These ripples grow exponentially and form fully developed waves [17]. Wind is caused by differences in atmospheric pressure as air moves from higher to lower pressure regions, resulting in winds of various speeds [23].

Wind is an important process in most aspects of metocean engineering besides being a major structural load. Therefore, its load contribution is always considered in the design of offshore structures. It acts on the portion of the platform above the water level as well as on any equipment, housing, derrick, etc. located on the deck and has direct influence on sea state and current circulation, and also drives a significant element of non-tidal surge elevation. Wind conditions are also considered in determining the orientation and design strength of facilities (flare booms), offshore operational planning (crane and helicopter operations) and in process engineering related to the offshore industry (e.g. dispersion of airborne pollutants) [5], [17].

An important parameter pertaining to wind data is the time interval over which wind speeds are averaged. For averaging intervals less than one minute, wind speeds are classified as gusts. For averaging intervals of one minute or longer they are classified as sustained wind speeds [17].

C. Wave and Wind Statistics

For any given location and period, wind records are segmented by speed and direction, and expressed as percentage occurrences within a given speed/direction category [5]. Using such trace records, two types of analysis may be performed: the time domain analysis and the frequency domain analysis. Both methods assume stationarity (i.e. sea state does not vary with time). Time domain analysis employs mathematical functions, physical signals or time series of environmental data with respect to time while frequency domain analysis involves those with respect to frequency [3]. For wave records, two assumptions are made, namely the wave field is described as the summation of sine waves of varying frequency, amplitude and direction. Secondly, the field is assumed to be statistically stationary – which means that the statistical description of the waves at a given time is essentially the same description that would be obtained at a slightly different time [24].

In the South China Sea, waves are primarily driven by monsoon winds, with the roughest weather arriving from the North-Northeast during the Northeast monsoon. In addition, tropical storms and typhoons can also produce severe weather, although they are much less predictable. Typhoons are rare in Sabah waters and relatively mild in strength, but still strong enough to skew long-term wind and wave distributions, though less likely to affect extremes in current speeds. Operational statistics are required for many offshore activities i.e. monthly, seasonal and directional statistics (maximum, mean and standard deviation).

There are four seasons of the year, defined as follows:

1) Northeast Monsoon (November to March) characterized by predominantly northeasterly winds, increased cloudiness with the heaviest rainfall of the year. Regular 'surges' in the Monsoon winds increase the wind speeds and raise the wave heights.
2) Transition I (April and May) is the time when winds are light (except during occasional squalls) and variable in direction.
3) Southwest Monsoon (June to September) is dominated by southwesterly winds, which occasionally increase due to approaching typhoons east of the Philippines, thus raising the waves. Nonetheless, the duration, wind speed and wave heights are lower than those experienced during the Northeast Monsoon.
4) Transition II (October and November) sees variable wind direction with an increase in wind speed and frequency squalls. It is also the time of the year when the risk of typhoons affecting the area is the greatest [3].

V. Methodology

This study is conducted by analyzing the measured data of wave and wind speed on the following fields located in the South China Sea:

1) Platform A – offshore Peninsular Malaysia,
2) Platform B – offshore Sarawak
3) Platform C – offshore Sabah.

The interval between each consecutive measurement is ten minutes. Errors were observed in the measured data. Bad data points were marked and removed. Each bad value is filled by interpolation of adjacent data points. Hence, the calculation of mean and standard deviation are not corrupted by the removed bad data. If more than 20 % of the data has to be removed in this manner, the entire time series is marked bad [24].

For descriptive statistical analysis, the calculation of mean and standard derivation for all data in the above three locations is based on monthly, seasonally and yearly basis. Power spectral analysis, on the other hand, focuses on different months in each year, each month in different years for northeast and southwest monsoons respectively, by calculating the normalized autospectral density envelope.

VI. Results and Discussion

A. Descriptive Statistics Analysis Results

The figures below show the average and standard deviation of wind speed and wave height in South China Sea – offshore Peninsular Malaysia, Sarawak and Sabah regions.

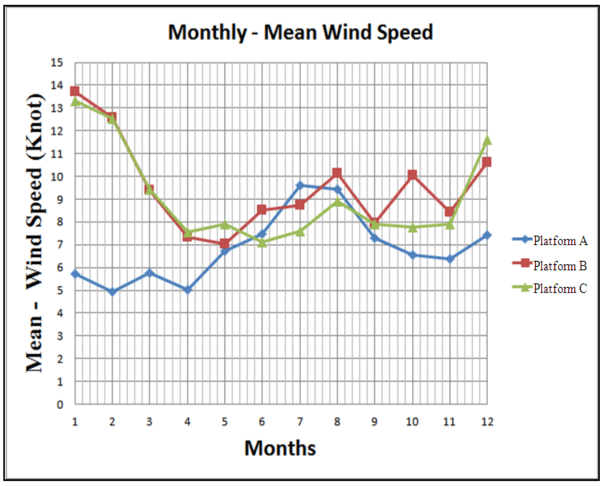

Fig. 2 Monthly – Mean Wind Speed for Platform A, Platform B and Platform C

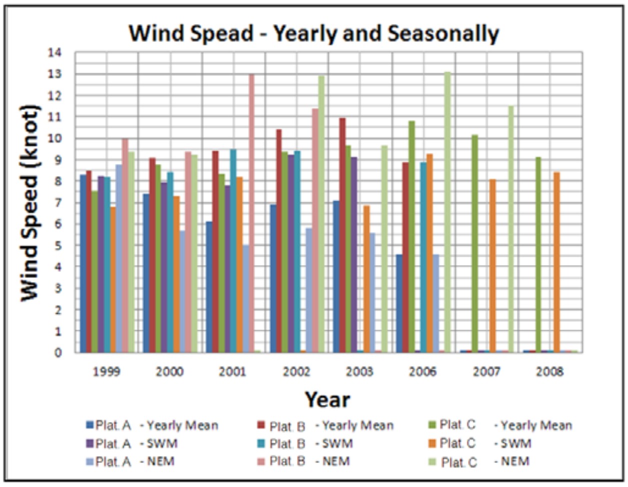

Fig. 3 Wind Speed – Yearly and Seasonally For Platform A, Platform B and Platform C

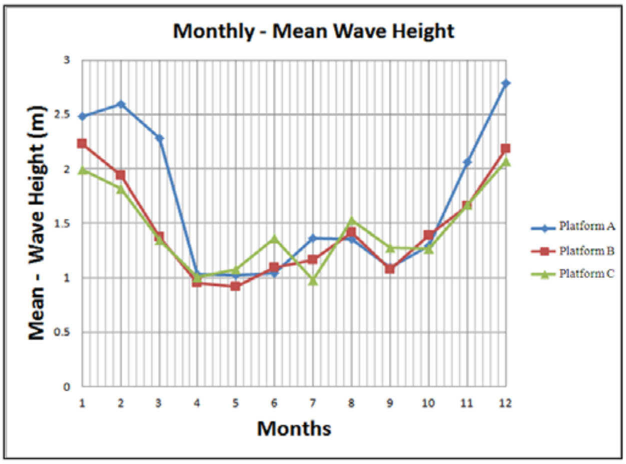

Fig. 4 Monthly – Mean Wave Height for Platform A, Platform B and Platform C

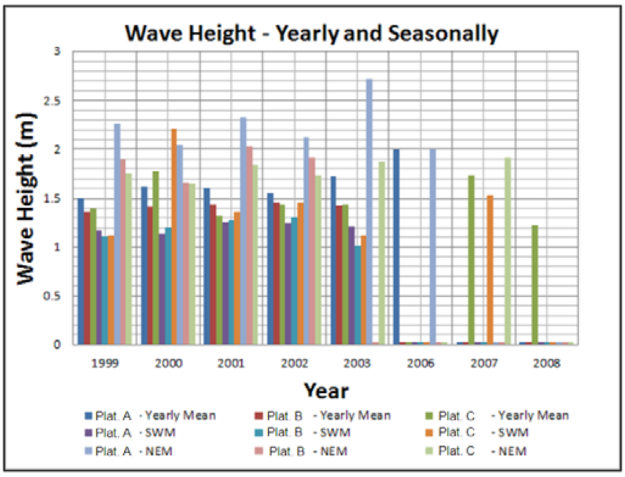

Fig. 5 Wave Height – Yearly and Seasonally For Platform A, Platform B and Platform C

The results confirm that the process is nonstationary (which is converted to stationary process using first difference method) and white noise is removed through the Tukey smoothing window for developing power spectral density.

The results show that the maximum wind speed was recorded during the Southwest monsoon for Platform A, the Northeast monsoon for both Platform B and Platform C with maximum values at ($\bar{x}$ =9.2406 knots, σ =4.7506 knots) for Platform A, ($\bar{x}$=12.9636 knots, σ =6.1407 knots) for Platform B and ($\bar{x}$ =13.1300 knots, σ =6.3346 knots) for Platform C. These three regions have high mean wind speed of ($\bar{x}$ =13.5195 knots, σ =6.3566 knots).

The maximum wave height was recorded during Northeast monsoon for all the three locations with maximum values of ($\bar{x}$ =2.7163m, σ =1.1108m) for Platform A, ($\bar{x}$ =2.0316m, σ =0.8135m) for Platform B and ($\bar{x}$ =1.9100m, σ =0.6868m) for Platform C. These three regions have high mean wave height of ($\bar{x}$ =2.3597m, σ =0.8690m).

B. Spectral Density Analysis Results

The figures below show the normalized power spectral density envelope of wind speed and wave height in South China Sea – offshore Peninsular Malaysia, Sarawak and Sabah regions.

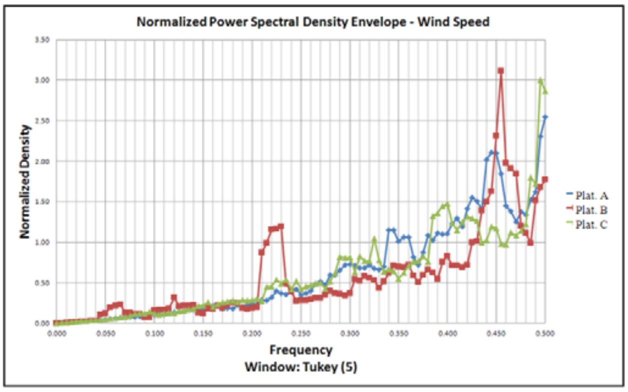

Fig. 6 Normalized Power Spectral Density Envelope – Wind Speed For Platform A, Platform B and Platform C

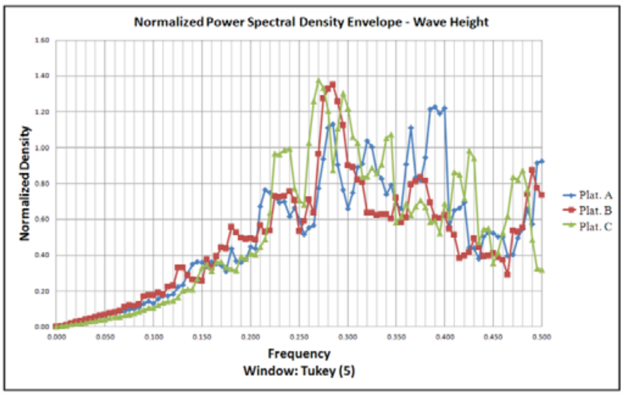

Fig. 7 Normalized Power Spectral Density Envelope – Wave Height For Platform A, Platform B and Platform C

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From the results, although there is no clear dominant peak and the spectra seem to fluctuate randomly, there are two different identifiable patterns for wind speed spectrum and wave height spectrum in shallow waters.

For wind speed spectrum, the appearance of the spectral plot indicates that it tends to grow gradually at lower frequencies and increase until it doubles at higher frequencies with the significant peak frequency ranging from 0.455 Hz to 0.5 Hz, the overall peak frequency ranging from 0.23 Hz to 0.5 Hz, and the mean peak frequency ranging from 0.4104 Hz to 0.4721 Hz.

For wave height spectrum, the spectral plot indicates that it tends to grow drastically at low frequencies, then fluctuates and decreases slightly at high frequencies with the significant peak frequency ranging from 0.27 Hz to 0.295 Hz, the overall peak frequency ranging from 0.235 Hz to 0.49 Hz, and the mean peak frequency ranging from 0.2911 Hz to 0.3425 Hz.

VII. Conclusion

Both wind speed and wave height have significant influence to offshore structures during the Northeast monsoon with high mean wind speeds of 13.5195 knots (σ = 6.3566 knots) and mean wave height of 2.3597m (σ = 0.8690m). There is an individual identifiable pattern for wind speed spectrum and wave height spectrum with the mean peak frequency ranging from 0.4104 Hz to 0.4721 Hz for wind speed spectrum, and 0.2911 Hz to 0.3425 Hz for wave height spectrum.

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