Spectral Analyses of Sea-State Wave Data for the Development of a Regional-Sensitive Spectral Model

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ABSTRACT: Spectral analysis is seen as an integral part of the design and operation of offshore structures/vessels as they are tools used in understanding the fundamental values that are used in the codes of design and operation. Conventionally in the Malaysian region, spectral models used in the analyses process are based on the JONSWAP and Pierson-Moskowitz spectrum which are empirical models based on values of the North Sea and North Atlantic respectively. As such, the lack of a regional spectral model indicates that the values used are not regionally sensitive to the inherently calmer waters of the Malaysian basins. As a result, Malaysian basins has seen the use of more conservative values in the design and operation process as well as fatigue issues associated with the differing peak frequencies of wave spectrums in the region. To address this, this paper will discuss the derivation process of the spectral model that is required to cater to the Malaysian region for application in the offshore design process which from hereon shall be known as the Zul-Liew-Lim-Carigali (ZLLC) spectrum

1 INTRODUCTION

Traditionally, the determination of wave criteria for an offshore structure is determined by two distinct methods, a) spectral analysis of measured data unique to region of interest and, b) the utilization of prescribed design values of significant wave height (i.e. PTS, API and DNV). To each method of approach, there are their advantages and disadvantages. In the case of using design values, the design process is far more simplified than performing spectral analysis but has to take into account varying wave periods along with the selected wave height to analyze the worst case loading that could develop. This will resultantly lead to more conservative values than spectral analysis as the consideration of preclusion of extreme values based on a pre-selected return period is utilized during design; for instance, wind and wave conditions are based on an arbitrarily selected extreme loading value of a 100-year storm period. On the other hand, spectral analysis of measured data on site of interest will produce the density distribution of wave periods which is far more representative of the actual conditions. Conventionally, it would be favourable to select a theoretical spectrum or envelope to fit the measured spectrum developed although that is seldom possible especially in regions which are outside the North Sea and the Gulf of Mexico. It would therefore be more accurate to describe the regional sea wave distribution through the development of a regional-sensitive spectrum similar to ones that have been developed for the North Sea (JONSWAP spectrum) and North Atlantic (Pierson-Moskowitz spectrum).

Spectral analysis can be described as a representation of a time series or mathematical functions in the frequency domain. Spectral analysis differs from time domain analysis in a sense that it can clearly identify the content of energy over a range of particular frequencies. This technique is commonplace in the area of control systems, sound engineering and statistics. The analysis is achieved through a set of mathematical operators that are applied upon the time series such as Fourier Transform which decomposes the finite signal of sinusoidal waves into frequency components. As it is suitably applied in the analysis of time series of any form, spectral analysis applications can be extended into the area of offshore engineering in the form of spectral analysis of metocean loads. In offshore conditions, the dominating environmental criterion used in the design of offshore structures is the sea wave component (especially for Malaysian waters which have a large amount of fixed offshore structures). The ability to analyze sea waves as a time series will allow the dissecting of waves by energy content in the spectrum, which in turn enables the identification of, a) critical/peak wave frequencies in a particular sea, b) the energy content associated with each particular frequency range and, c) spectrum which can be applied in the development of transfer functions to describe the characteristic of movement in offshore structures and vessels.

2 DEVELOPMENTAL & LIMITATION OF SEA SPECTRAL MODELS

Spectral analysis while more accurate in obtaining results far more representative of a regions' metocean conditions, are not always attainable due to shortcomings such as the lack of workable measured data which hampers the accuracy of the envelope. The empirical equations do however provide a relatively good approximate of the actual conditions and are able to replicate sea states of a particular region at a given wave design criteria and thus could save significant analysis time for design and operations. The drawback to existing spectral models is that they particularly cater to fully developed seas existent in the North Sea and North Atlantic, i.e. JONSWAP (1973), Pierson-Moskowitz (1964) and Bretschneider (1969) spectrum and as such, represents different peak frequency and energy content compared to Malaysian waters. Empirical spectrums do however come along with drawbacks that affect the accuracy of the envelope, a) highly restrictive to fully developed seas, b) assumption of unlimited fetch length, c) does not consider effect of squalls, d) considers waves as uni-directional, e) seafloor topography (critical in nearshore conditions), f) possible limitations of workable data during development of previous spectrums.

Current practice in the Malaysian waters dictates the usage of JONSWAP and Pierson-Moskowitz spectrums which are highly conservative and non-reflective of the region's sea state which can be seen in Figure 1. Further analysis and decomposition of the localized spectrum will be discussed in the following section.

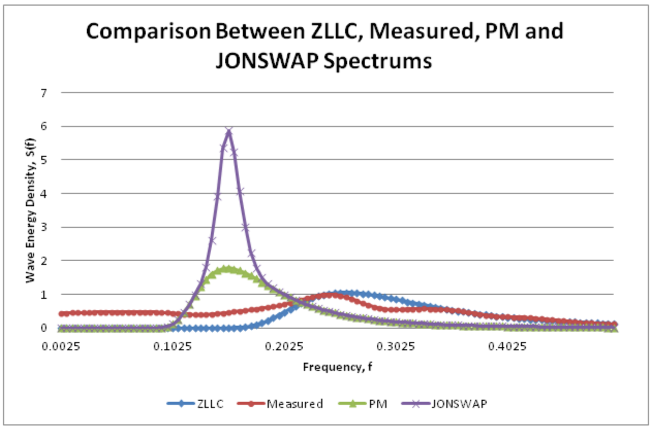

Figure 1: Comparison between Measured, ZLLC, Pierson-Moskowitz and JONSWAP

However, the development of the ZLLC spectrum which is the inherent point of discussion throughout this paper will surpass certain limitations that previous empirical models could not account for. For example, the availability of workable data to produce the measured spectrum is far more accurate than 50 years ago, which is the time most of the established spectrums have been based upon. This is due to the ability to use corrected hindcast data (SEAFINE for the South China Sea region in which Malaysian waters rest upon) through a set of corrective algorithms developed for the region of concern. This thus replicates the consistency of hindcast data and accuracy of measured data in the production of measured spectrums. However, due to complexity of modeling the various components in each unique sea, certain variables have to be excluded from the formulation of the empirical equation to produce a best approximate of the sea state based on dominating variables, i.e. squall incidents and uni-directionality assumption of waves.

3 ZLLC SPECTRAL MODEL DEVELOPMENT

As discussed earlier, JONSWAP and P-M spectrum models are the current references for the behavior of sea state wave of the Malaysian basin. However, the initial finding indicates that the P-M spectrum model is more identical or representative on the actual sea state wave of the Malaysian basin than the JONSWAP spectrum due to relatively closer energy densities. This situation coupled with associated statistical tests enables us to conclude that the reference on JONSWAP spectrum for the characteristics of localized sea state wave is unsuitable. The summary on the characteristics of P-M spectrum models is as shown in the following Table 1.

Table 1: Summary of characteristics of P-M Spectrum Model.

	Pierson-Moskowitz
Parameters	1 (H_s)
Swell Consideration	No
Direction	Uni-direction
Sea State	Developed
Fetch Limited	No

Based on the initial findings, adoption of the P-M spectrum in order to match and characterize the measured spectrum is preferred through an introduction of a modification factor. However, the linearity of the P-M spectrum formula which is dependent on one variable limits the modification approach. The introduction of this modification is intended to shift the critical frequency of the spectrum to that which is more representative of the measured spectrum. As such, the Modified P-M spectrum is seen as a suitable substitute for the P-M spectrum as it is a two-parameter spectrum which is necessary to facilitate the peak shift. The following summarizes the Modified P-M spectrum.

Table 2: Summary of Modified P-M spectrum characteristics

	Modified P-M
Parameters	2 (H_s & T_p)
Swell Consideration	No
Direction	Uni-direction
Sea State	Developed
Fetch Limited	No

The characteristics of the Modified P-M spectrum are quite similar to those of P-M spectrum except the Modified P-M spectrum is dependent on two variables. The basis for this modification goes back to the relationship factor which the P-M spectrum has established between the significant wave height and the peak period which is not representative of localized effects.

An earlier observation was that the critical frequency of the measured spectrum is higher than the critical frequencies of the JONSWAP and P-M spectrums, while the energy content of the measured spectrum is slightly less than the energy content of the P-M spectrum and significantly less than the energy content of JONSWAP spectrum. These conditions led to the possible assumption that the sea state of the area where the measurement took place could possibly still be in the state of a 'developing sea'. This argument is founded on the basis that the ZLLC spectrum displays similar characteristics as illustrated in Figure 2, whereby the wind that generates the waves in the equatorially located Malaysian waters is milder than those at the North Atlantic Ocean and North Sea. The illustration of how the sea states affect the critical frequency of the wave spectrum is exemplified by the following Figure 2

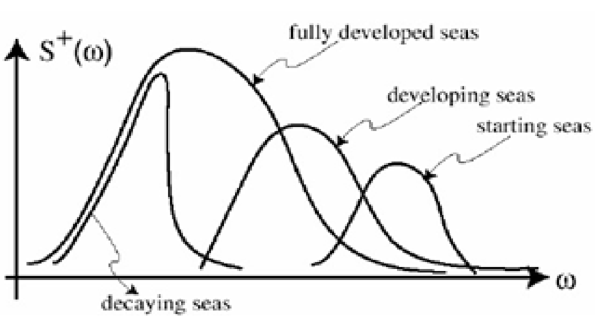

Figure 2: The influence of sea states on the behavior of the wave spectrum.

The low energy wave spectrum indicates the energy transferred from the wind to the wave was small possibly due to fetch limitations and this gives us a possible explanation of the spectral phenomenon of the ZLLC spectrum. The position of the Malaysian basins at the equatorial line of the earth where the climate is more stable than other regions is possibly the contributing factor in the calmer wind and wave conditions of the area.

In continuation, the formula of Modified P-M spectrum is as shown below.

$$S(\omega) = \frac{5}{16} H_s \frac{\omega_0^4}{\omega^5} \exp(-1.25[\omega/\omega_0]^{-4}) \quad (1)$$

From the formula above, the controlling variables on the shape of the spectrum are H_s and ω_0. The relationship between the ω_0 and the peak wave period, T_p may be obtained from

$$T_p = (2\pi/\omega_0) \quad (2)$$

Sensitivity tests on the effect of the variables have been performed and the results of the tests indicate that the adjustment on the value of T_p will help in shifting the critical frequency towards the higher frequency as shown in Figure 3, which is far more representative of localized conditions. Meanwhile, Figure 4 shows that the adjustment of the H_s value will only affect the amplitude of the energy density of the spectrum and not in the shift of the critical frequency.

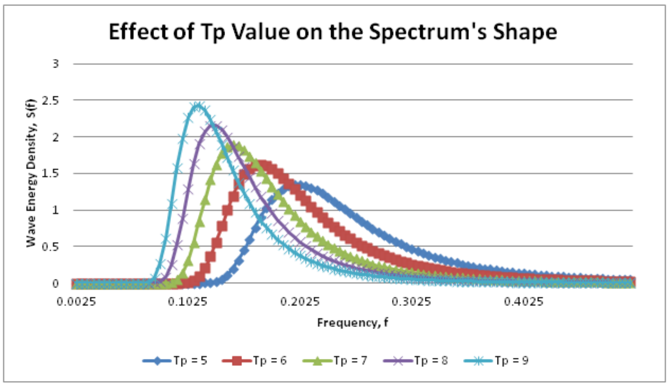

Figure 3: The effect of T_p value on the spectrum's shape.

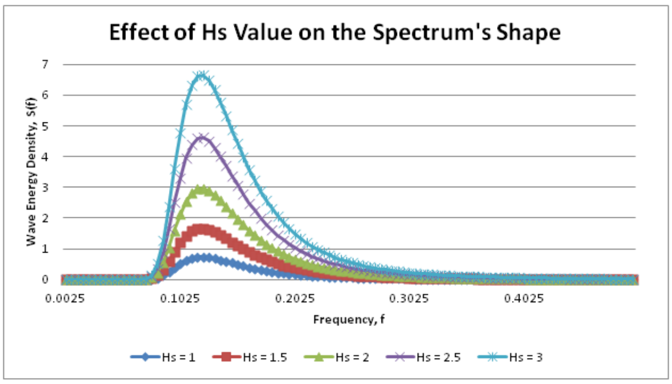

Figure 4: The effect of H_s value on the spectrum's shape.

The results indicate that the modification on the T_p value of the Modified P-M spectrum would be sufficient in order to produce a spectrum model that counterparts the measured spectrum in terms of the critical frequency and energy density. The modification on the T_p value was done by introducing a regionally sensitive factor (from here on labeled 'x_R') to the T_p value and this alteration produces the following ZLLC spectrum model.

$$S(\omega) = \frac{5}{16} H_s \frac{(x\omega_0)^4}{\omega^5} \exp(-1.25[\omega / x\omega_0]^{-4}) \qquad (3)$$

The empirical formula was then applied data 10 years' worth of data sets of H_s and T_p but with varying x_R values to produce spectrums that match the respective measured spectrums. Subsequently, statistical analysis was performed on the x_R values to conclude the envelope value that would represent the Malaysian basins. From the analysis, the x_R values seem to follow a normal probability distribution as shown in the Figure 5 and the ultimate x_R value for Malaysian basin is 2.26.

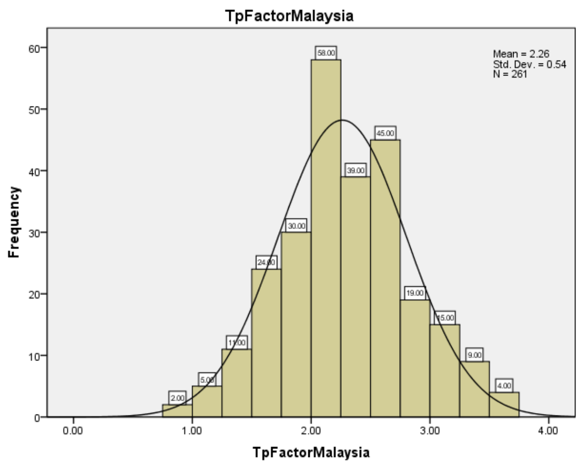

Figure 5: Histogram and derived probability distribution of x_R values.

4 CONCLUSION AND RECOMMENDATION

The introduction of the x_R factor into the Modified P-M spectrum has shown that it can create an envelope filter that depicts the energy densities and peak frequencies that are existent in the Malaysian waters as compared to previous methods of utilizing the JONSWAP and P-M spectrum which cater to the North Sea and North Atlantic respectively. The results are testament to a range of extensive tests conducted based on data from platforms located within the vicinity such as the Malay Basin, Sarawak Basin and Sabah Basin. The results presented herein will be able to drastically alter the existing design and operating standards of oil operators in the region. They will encompass platform design, fatigue analysis, operability of vessels and associated maintenance. The way forward on this research would be to include measured data from more platforms from various other basins in the Malaysian basins to test for consistency of the x_R factor in creating the envelope filter, the ZLLC spectrum

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