Spectral Analyses of Sea-State Wave Data for the Development of Offshore Metocean Applications: A Malaysian Case Study

M.S.Liew[1], E.S.Lim[2]& T.N.Tengku Shahdan[3]
[1]UniversitiTeknologi PETRONAS, Perak, Malaysia
shahir_liew@petronas.com.my
[2]UniversitiTeknologi PETRONAS, Perak, Malaysia
lim.eu.shawn@gmail.com
[3]University of Management & Technology, Selangor, Malaysia
noorainun@umtech.edu.my

Abstract– Spectral analysis has been a traditional and fundamental tool used by a multitude of disciplines in data analysis by creating comprehensible and interpretable information in the frequency domain. In recent times, this analytical tool has extended itself to applications in offshore engineering in the form of metocean analysis. Metocean analysis is defined as the understanding of meteorological and oceanographic effects on offshore installations. These environmental loads tend to manifest themselves in wave-like forms that allow spectral analysis to be applicable in analysis. These analyses are however unique to regions in which they are analyzed for. Traditionally, Malaysian waters have been basing itself on codes and standards that dictate the use of empirical spectrums such as JONSWAP and Pierson-Moskowitz which is based upon measure data in the North Atlantic Ocean. These conditions present itself in far more conservative values than the inherently calmer Malaysian waters. As such, optimization is seen as an avenue that can add value to the offshore engineering activities of the Malaysian waters. The paper herein will discuss the analytical and engineering processes that are involved in the development of this regionally-sensitive empirical spectral model. The discussion will encompass on the optimal use of autocorrelation lags as well as smoothing functions used to reproduce the characteristics of Malaysian waters as well as the empirical coefficient used to develop the model based on existing models. The spectral model from hereon will be referred to by its' patent pending name, Zul-Liew-Lim-Carigali (ZLLC) spectrum.

Keywords: Spectral analysis; Autocovariance; Smoothing Parameter; Noise; Empirical coefficient; optimization; Offshore Engineering, Metocean

1.0 Introduction

Wave spectrum is an important consideration in the design of offshore facilities. From the wave spectrum, imperative information such as the critical frequency of the wave and the energy distribution of the wave across various frequencies can be obtained. Such information is called as design wave environment and it is very critical in the offshore engineering field especially in the design of ships, vessels and offshore structures. Conventionally, to obtain the design wave environment of an area for an offshore development activity, two distinct methods are available, 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. However, until now, this approach is seldom utilized in the offshore engineering application because of some drawbacks expected owned by the approach, a) time specific by which may exclude the eagerly concerned extreme conditions, b) the requirement of large amount of data which considerably costly and time consuming activity. Because of those drawbacks, it would befavourable to utilize a theoretical spectrum or envelope to fit the measured spectrum developed.

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 off-shore 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.

2.0 Requirement for Regional Sensitive Spectrum

The development of mathematical or theoretical spectrum models was at its peak in 1950s as many crucial discoveries were made. Begun with Neuman spectrum model in 1953, the development continued with the introduction of many more spectrum models including the most referred spectrum models in offshore engineering application, Pierson-Moskowitz (P-M) spectrum (1964) and JONSWAP spectrum (1973) (Chakrabarti, 1987). In fact, the development of offshore engineering in the Malaysian waters region also is vastly relying on the P-M and JONSWAP spectrum models. The empirical equations given by those mathematical spectrum models do however provide a relatively good approximate of the actual conditions of the sea state wave. Indeed, historically speaking, the utilization of P-M and JONSWAP in obtaining the design wave environment of an area in the Malaysian waters region has proven to be safe and sound as there is no platform reported collapse due to environmental loading yet.

Nevertheless, the safe condition in our region provided by the design wave environment obtained from P-M or JONSWAP spectrum not necessarily the optimum condition as it could be way greater than the optimum condition. Originally, P-M and JONSWAP spectrum models were developed based on measurement performed at regions outside of Malaysian waters namely North Atlantic Ocean and North Sea respectively (PM, 1964; Hesselmann, 1973). As a result of that, it is unattainable for the sea state wave in our region similar to those at the North Atlantic Ocean and North Sea, so thus the spectrum. This is because, the characteristics of a spectrum is highly influenced by, a) fetch length which may limit the wave development, b) whether the seas are developing or decaying, c) seafloor topography as deep water wave spectra are invalid in shallow waters, and vice versa, and d) local currents because strong currents may significantly impact the wave spectrum. These factors indicate that the development of empirical models is highly regionally-dependent and as such, 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).

3.0 Local Measured Spectrum

In order to facilitate the development of the spectral model, it is imperative that local spectral conditions are identified. As discussed in the previous secion, this is achieved via the fast fourier transform (FFT) of the raw wave data that has been procured from the vicinity of the Malaysian waters. In this study, six (6) different platforms located in three (3) different operating regions in Malaysia have been selected, namely Peninsular Malaysia, Sarawak and Sabah Operations.As FFT has the initial assumption that the input data has to be stationary in nature, the wave data needed to be tested for stationarity.If a time series is nonstationary, then the sample auto-correlation function will neither cut off nor die down quickly, but rather will reduce at a much slower rate compared to the lag number (Bowerman and O'Connell 1979) and (Box, 1976).However, it is detected that during the course of the study, the number of lags using in the autocorrelation of the raw data affected the reproduction of the measured spectrum. As such, it become key to assess the value of autocorrelation lags that will yield a spectrum that possessed significant detail while being able to reduce the visibility random errors that presented itself in the raw data. It was also noted that the smoothing function utilized in the final production of the measured spectrum did significantly affect the level of detail in the spectrum and its' ability to filter out random errors that present itself in the raw data. As such, the parameters that were looked into the optimization process were autocorrelation lag or the normalized version of autocovariance and the smoothing parameter which in particular is the smoothing function's span number. This optimization step is essential as it will give the reference spectrum which has an interpretable and comprehensible formthat possesses significant content of information while precluding the effects of random errors by a certain degree. The reference spectrum will be the medium to compare and justify the development of the regional sensitive spectrum model to be developed here after.

Conventionally, there is no absolute reference numbers for the autocorrelation lag and smoothing function's span for performing spectral analysis. For autocorrelation lag, Box & Jenkins (1994) states that the useful estimate of the autocorrelation function would be less than N/4 where N is the observation size, while for the smoothing parameter, no distinctive number was specified. As a result of that, most practices tend to gravitate around the prescribed thumb of rule with qualitative judgment on the spectral form. It is anticipated that the utilizing maximum lag number is not the optimum condition for spectral analysis as increasing autocorrelation lag number beyond the optimal value will increase the white noises and excessive smoothing applied to the spectrum will produce a spectrum that has greatly reduce detail which could not characterize the actual condition of the sea state wave.

The optimization was done by performing sensitivity test on the parameters mentioned above. Associated numbers for both parameters were varied in order to get the optimum numbers. The outcome of the test is presented in Figure 1.

Figure 1shows the spectral plot when the autocorrelation lag number is set at 999 and the span number is at default value, 5. The spectrum possesses many instantaneous peaks and it becomes difficult to identify the actual critical frequency content of the waves. In this case, some of the peaks are difficult to define whether they are due to the white noises or form part and parcel of the wave content. Figure 2 shows the spectral plot when both of the parameters are set to 999 for autocorrelation lag and 99 for span number.

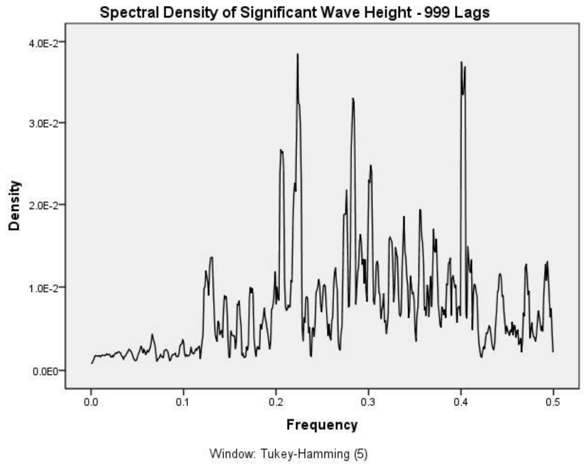

Figure 1: Spectral Plot of Field A for January 2000 at Autocorrelation Lag Number 999 and Span Number 5.

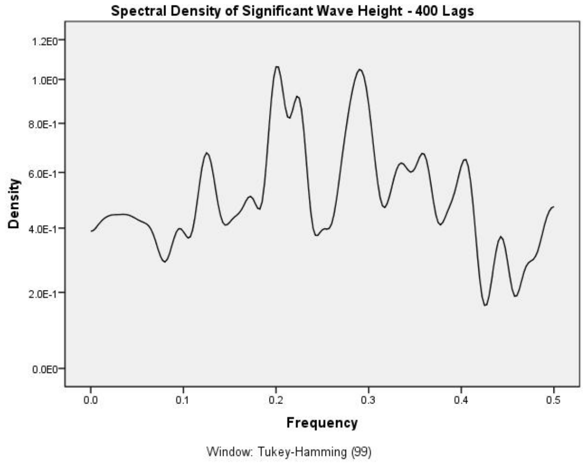

Figure 2: Spectral Plot of Field A for January 2000 at Autocorrelation Lag Number 999 and Span Number 99.

At the specified autocorrelation lag and smoothing function's span numbers in Figure 2, the shape of the spectrum has removed significant detail but however is still unable to identify the significant peaks that exist in the raw data.Through the sensitivity test for both parameters, we found out that there is a condition where the spectral plot converges in its variance values. Figure 3 shows the spectral plot at the optimum numbers for autocorrelation lag and smoothing function's span.

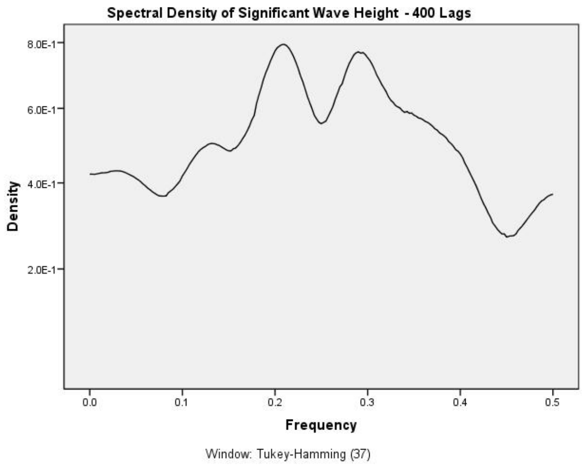

Figure 3: Spectral Plot of Field A for January 2000 at Autocorrelation Lag Number 400 and Span Number 37.

In making the decision for the optimum conditions for spectral analysis, the main properties of the spectrum such as the critical frequency and the energy content of the spectrum, represented by the area under the spectrum, is ensured to be different by a small difference. For the sensitivity test on the autocorrelation lag number, the variation on the number does not affect the critical frequency as well as the energy content; consolidated and meaningful peak spectral envelopes begin to develop in the plots.However, for the test on smoothing function’s span number, only the energy content is affected; in which at this point is not significantly important as spectral utilization in offshore design gravitates its concern more towards the peak spectral values. Excessive smoothing function span number will also result in significant loss of detail. The following Figure 4 shows the effect of variation on the span number on the energy content of the spectrum.

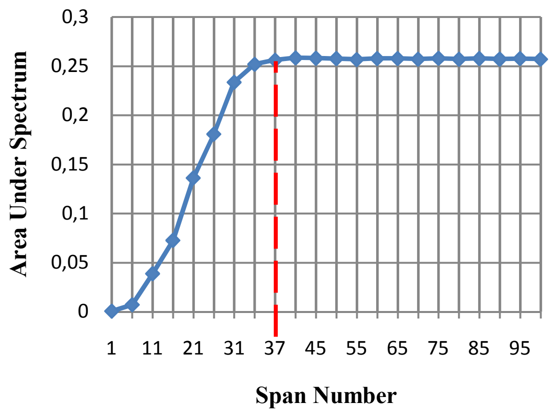

Figure 4: Comparison of Area under Spectrum at Different Smoothing Function’s Span Number.

The percentage difference between area under spectrum at span 37 and span 99 for the data is used only 0.42%.This finding justifies the decision to adopt span number 37 as the final smoothing function’s span number for the spectral analysis because of the significance that the spectral plot produces.

The following Figure 5 and Figure 6 show other examples of the end result of the spectral analysis performed at the same parameters for different monitored time data samples. All of them are able to reproduce plots that clearly define the spectral peak of the wave data.

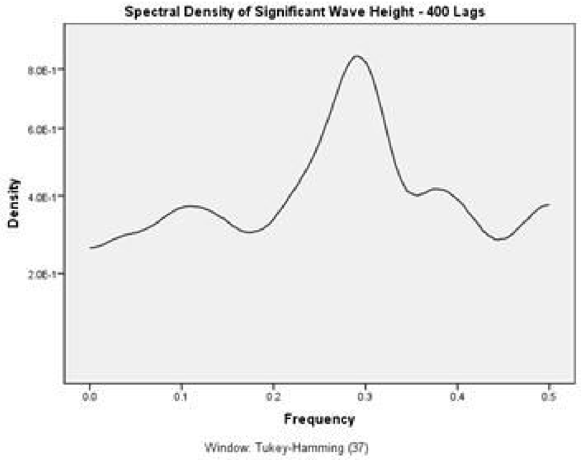

Figure 5: Spectral Plot of Field A for June 2000 at Autocorrelation Lag Number 400 and Span Number 37.

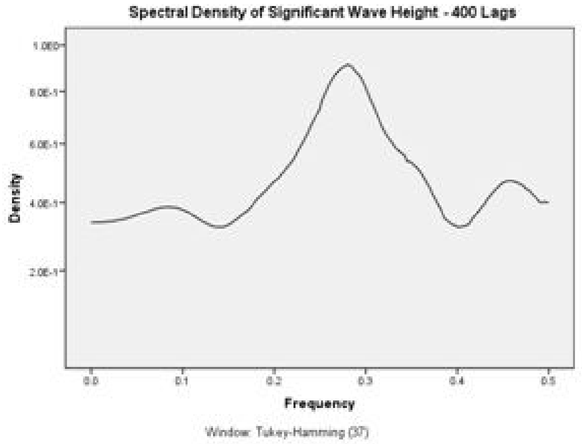

Figure 6: Spectral Plot of Field B for April 2003 at Autocorrelation Lag Number 400 and Span Number 37.

4.0 Development & Limitation of Existing Sea Spectral Models

In hindsight of existing practices, the current Malaysian environment dictates the usage of P-M and JONWAP spectrums for the application in South China Sea waters in which Malaysian operations are nested in (PTS, 2010) (API, 2010). As a result of a lack of spectral studies in the region, major oil operators in the region still have to prescribe to values less optimized for the Malaysian region. Wave scatter plots were developed from measured data during the development of both P-M and JONSWAP spectrums in the 1970s.The statistical distribution from these regions indicates that there is a significant difference from the metocean conditions in South China Sea (IMAREST, 2011). Table 1 shows the distribution of waves by wave height in the North Sea.

Table 1: Scatter plot of wave height in the Barents Sea (North Atlantic)

Occurrence	Peak Period (s)								
Significant Wave Height (m)	0 - 2.9	3 - 5.9	6 – 8.9	9 – 11.9	12 – 4.9	15 –17.9	18 – 20.9	21 – 23.9	TOTAL
0.0 – 2.9				0.01	0.05				0.06
3.0 – 5.9		0.02	0.97	0.45	0.03				1.5
6.0 – 8.9		<0.01	8	6.8	1.9	0.08	<0.01		16.7
9.0 – 11.9		15.2	48.5	13.5	8.4	0.94	0.12	0.09	81.7
TOTAL	0	15.3	.51.5	21.3	10.7	1.1	0.13	0.09	100

Based onTable 1, it is noticed that 81.7% of waves are within the region of 9.0m to 11.9m significant wave height. This marks a significant difference from Malaysian waters whereby significant wave heights vary along the range of 1.0m to 3.0m for operating conditions (PETRONAS, 1999). Due to the fact that wave spectral development is dependent on the wave height input, this will result in spectrum differences in terms of, i) spectral energy density and, b) spectral peak frequency. This leads to the understanding that spectral models should cater to regional metocean conditions and thus forms the basis for the development of the spectrum.

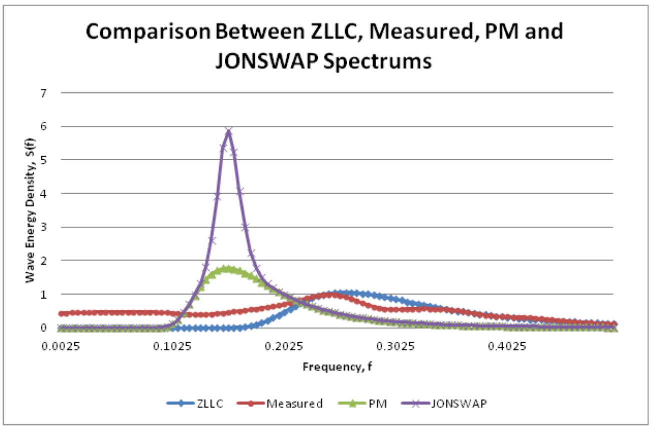

Figure 7: Comparison between Measured, ZLLC, Pierson-Moskowitz and JONSWAP

However, the development of theZul-Liew-Lim-Carigali(ZLLC) spectrum which is the inherent point of discussion throughout this paper will address 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 (Mayeetae, 2011). This thus replicates the consistency of hindcast data and accuracy of measured data in the production of measured spectrums. This analysis was based upon the assumption made in hindcast data whereby it was found that hindcast values possess a mean absolute error of approximately 1.0m with a 0.5m bias which is equated to approximately scatter index of 10-15% (Reece &Cardone, 1982). This scatter index is expected to be far larger in South China Sea as the average wave heights possess a much lower value, thus dictating the need for this study to be particularly sensitive to excessively large bias and mean absolute errors.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.

5.0 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 waters. 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 conservative in comparison. The summary on the characteristics of P-M spectrum models is as shown in the following Table 2.

Table 2: Summary of P-M Spectrum characteristics

	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. In this empirical model, the peak period component is incorporated into the model via a correlation factor that relates the significant wave height value to peak period (Chakrabarti, 1987). During the course of the study, it was found that the relationship between significant wave height and peak period possess a difference in correlation values for Malaysian waters. The introduction of an empirical factor is thus required to adjust the spectral model to mimic measured conditions.The introduction of this factor 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 looked into compared to the P-M spectrum as it is a two-parameter spectrum which is necessary to facilitate the inclusion of the factor. The following Table 3 summarizes the Modified P-M spectrum.

Table 3: 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. The JONSWAP spectrum is not discussed in the study herein as this spectrum is similar in characteristics with the P-M spectrum with the exception that it caters to significantly larger peak enhancement factors. As such, this would further preclude the possibility of modeling the Malaysian waters by adopting the JONSWAP spectrum. The modified P-M spectrum will utilized as the model in which the empirical factor is to be incorporated.

An earlier observation based on Figure 7was that the critical frequency of the measured spectrum is in the higher range than the critical frequencies of the JONSWAP and P-M spectrums. The opposite is true for the energy density of the spectrum as the measured spectrum exhibits far smaller variances compared to P-M and 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 starting seas rather than swells or fully developed states.Figure 8 shows the relationship between the spectral density content and peak frequencies in relation to the present sea state in the region. Compared to fully developed seas and swells, starting seas tend to be irregular and have shorter crests, resulting in broader spectrums (Holthuijsen, 2007). The spectrums of starting seas also tends to be lower in value as fetch lengths and sufficient duration of wind blow have not been achieved as that of fully developed seas. Figure 9 further illustrates that wind seas tend to have broader peaks which is the case of Malaysian waters. Cross checks with measured spectrum in Figure 7 concurs with such literature review.

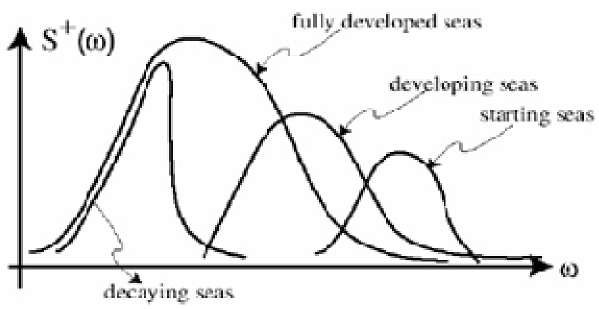

Figure 8: The influence of sea states on the behavior of the wave spectrum.

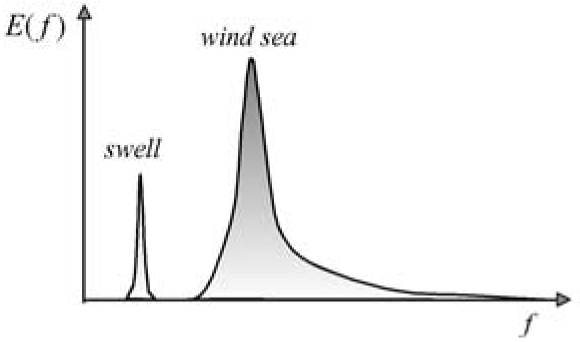

Figure 9: The spectral energy representation of wind sea and swell sea states

The low energy wave spectrum indicates the energy transferred from the wind to the wave was small possibly due to fetch limitations or insufficient wind blowing duration and this gives us a possible explanation of the spectral shape 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.

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

From the Equation 1 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 Equation 2

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

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. Studies were carried out to identify the parameter that contributed to the peak frequency shift in Malaysian waters. Figure 10 illustrates the effect of varying peak period, T_p*to* the spectrum. This is followed by a test on the change in significant wave height, H_s on the modified P-M spectrum in Figure 11.

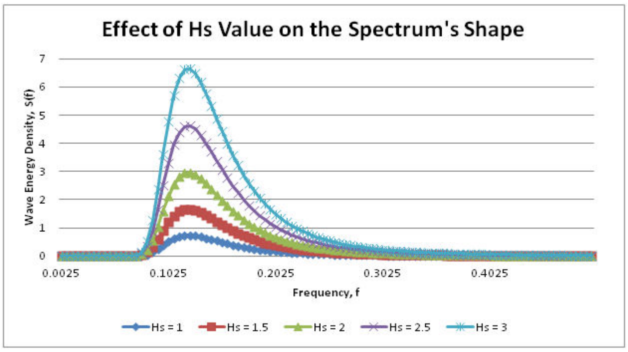

Figure 10: The effect of T_p value on the spectrum's shape.

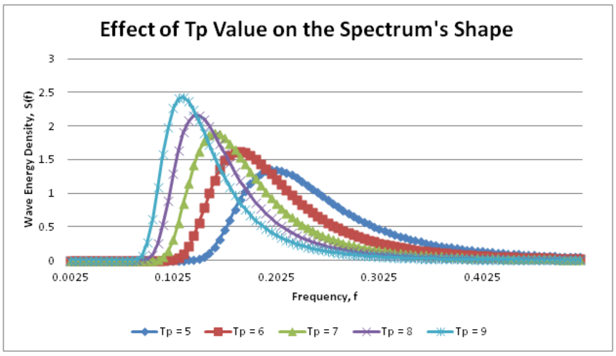

Figure 11: The effect of H_s value on the spectrum's shape.

The results indicate that the modification on the T_p value of the Modified P-M spectrum would facilitate a shift in the 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 defined as 'x_R') to the T_p value and this alteration produces the following ZLLC spectrum model.

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

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 12 and the ultimate x_R value for Malaysian waters is 2.26. At the point in time of this study, the data sets were collected from six (6) platforms located in three (3) major operating fields in Malaysian waters. This empirical modification introduced into the spectral model could lead to the potential conclusion that the wind waves that develop in Malaysian waters are likely to be that of starting seas and possess a lower periodicity than previously anticipated.

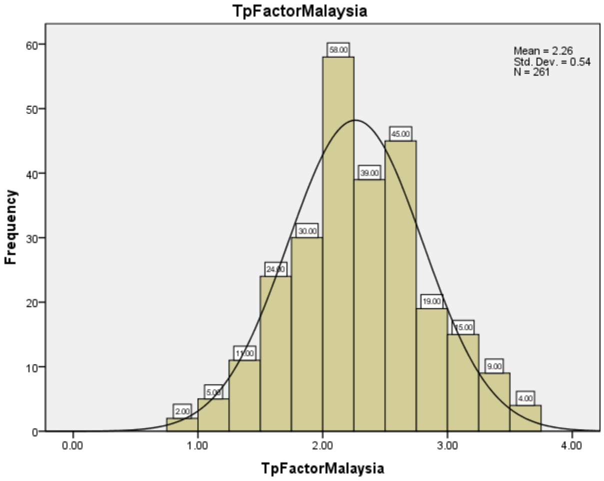

Figure 12: Histogram and derived probability distribution of x_R values.

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