

Spectral analysis of wind waves using field data in Strait of Hormuz

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Present study consists the analysis of extreme wind wave spectrum in Strait of Hormuz. Data was measured by Port and Maritime organization from 2009 to 2011 in “Monitoring and Modeling Study of Coastal Zone of Persian Gulf” project framework. Wave measurement instrument type was AWAC under sea equipment which has been implanted at 25m depth. Data records analyzed by computer program in STORM, MATLAB and SPSS environments for quality controlling and identifying wave spectrum characteristics like spectrum dispersal, directional spectrum, multi peak spectrum, spectrum shape, parameters of spectrum and spectral classification. Model parameters of JONSWAP and PM spectra were estimated for the observed spectra by using the least square error method

[Key words: Wind generated wave, Extreme water wave, Spectral analysis, Persian Gulf, Strait of Hormuz]

Introduction

There are two ways to study the nature of wind waves; spectral analysis and wave by wave (wave train) analysis¹. The more powerful and popular of these two approaches is the spectral analysis. A wave spectrum contains important information on a wave sample which can be given by conditions of seas and oceans. For example, the overall shape of a wave spectrum can show whether the local waves or swells are dominant^{2, 3}. It can also determine the number of swells⁴. In this study, conventional methods and superior spectral analysis are used to discuss water waves generated by the wind in the Strait of Hormuz. Strait of Hormuz is located in the eastern part of Persian Gulf and joints it to Oman Sea⁵. The narrowest width of the Persian Gulf is located in Strait of Hormuz is approximately 56 km.

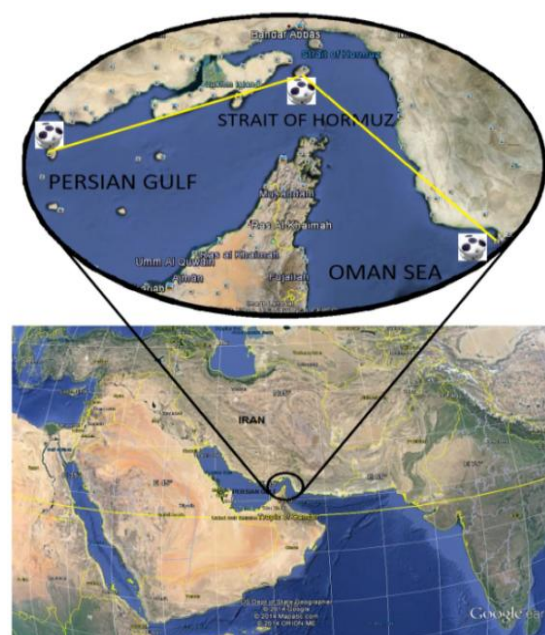


Fig 1 Schematic map of study area

Materials and Methods

The area that was considered for this study located between 52.5° and 57.5° east. This area is schematically shown in the figure 1.

One of the objectives of Iranian coastal monitoring and modeling project which is being carried by Port and Maritime Organization is to measure marine parameters such as water waves and winds⁶. In this study, wave measurement stations in three subsurface stations Larak, Faroor and Jask are used (Table 1). Measuring device in these stations is AWAC (Acoustic Wave And Current)⁷. Table 2 shows Characteristics of this wave recorder. Also figure 2 shows AWAC wave measurement instrument and its base frame.

Table 1 Primary Profiles of selected wave and wind stations

Station Name	Location		Measurement Date	
	X	Y	Start	End
Faroor	250901	2905642	2009/10/9	2010/12/10
Larak	430486	2966586	2009/6/10	2011/18/10
Jask	575653	2832497	2010/4/9	2011/27/4

Table 2 Characteristics of AWAC wave measurement system

Effective depth	35m
Acoustic frequency	1MHz
Sampling Rate	2Hz
Wave measurement Rate	-15m to +15m
Accuracy	2°
Resolution	0.1°
Period Range	0.5s to 100s



Fig 2 Photos of the AWAC instruments

Spectral analysis assumes that the sea state can be considered as a combination of a large number of regular sinusoidal wave components with different frequencies, heights and directions as given by Equation^{1, 8, 9}:

$$\eta(t) = \sum_{n=1}^N a_n \sin(2\pi f_n t + \phi_n).$$

where;

$\eta(t)$: Surface elevation at time t in fixed point

a_n : The amplitude of the n^{th} sinusoidal component

f_n : The frequency of the n^{th} sinusoidal component

ϕ_n : Phase angle of the n^{th} sinusoidal component

To determine wave spectrum, mathematical tools known as Fast Fourier Transform (FFT) has been used. As the result of FFT the energy density of wave component with frequency f_n in the frequency interval Δf_n is^{4, 8}:

$$S(f_n)\Delta f_n = \frac{1}{2}a_n^2$$

That $S(f)$ versus f graph is called the wave frequency spectrum. The general shape of the plotted spectrum can reveal a great deal information about wave sample. From wave spectrum several characteristic parameters to describe sea state can be defined in terms of moment. The n^{th} moment of the spectrum is given by^{1, 10, 11}:

$$m_n = \int_0^\infty f^n S(f) df$$

Spectral wave height parameter is related to m_0 as:

$$H_{m_0} = 4\sqrt{m_0}$$

There are two approximate spectral wave period parameters to estimating the average wave period.

$$T_{01} = \frac{m_0}{m_1}, \quad T_{02} = \frac{m_0}{m_2}$$

The width of spectrum is an indicator of whether the waves are regular or not. One more robust definition of spectral width parameter (Q_p) is given by Goda as¹²:

$$Q_p = \frac{2}{m_0^2} \int_0^\infty f[S(f)]^2 df$$

To describe energy distribution over the direction, directional wave spectrum ($S(f, \theta)$) is used^{1, 13}:

$$S(f, \theta) = S(f)G(\theta|f)$$

Where; θ is the angle from the principal direction of wave propagation.

For identification of Multi Peaked Spectra the adopted Violante-Carvalhouses conditions as follows^{4, 14}:

- Each peak must be separated by two times frequency resolution.
- The ratio between the two spectra must be less than 15.
- The ordinate of lower limit of the 90 percent confidence interval of the greater peak is higher than the ordinate of the upper limit of 90 percent confidence interval of the trough the peak.

Model spectrum is an empirical formula to describe spectrum shape. Two famous model spectrums, Pierson Moskowitz (PM) for fully developed wind wave system and JONSWAP for young and developing wave system are used^{15, 16}.

Pierson Moskowitz (PM) spectrum calculated by:

$$S(f) = 8.1 \times 10^{-3} g^2 (2\pi)^{-4} f^{-5} \exp\left[-\frac{5}{4} \left(\frac{f}{f_p}\right)^{-4}\right]$$

Where, f_p is peak frequency (the frequency at the maximum spectral density of the spectrum).

JONSWAP spectrum calculated by Violante-Carvalho formula by using five parameters ($\alpha, f_p, \gamma, \sigma_a, \sigma_b$) as¹⁴:

$$S(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp\left[-\frac{5}{4} \left(\frac{f}{f_p}\right)^{-4}\right] \gamma \exp\left[-\frac{(f-f_p)^2}{2\sigma^2 f_p^2}\right]$$

$$\text{Where; } \sigma = \begin{cases} \sigma_a & \text{for } f \leq f_p \\ \sigma_b & \text{for } f > f_p \end{cases}$$

In order to assess how well the fitting is, the scatter index, RMSE defined as given below;

$$\text{RMSE} = \sqrt{\sum_{i=1}^N \frac{1}{N} (S(f_i) - S_j(f_i))^2}$$

Where; $S(f_i)$ denotes observed spectra and $S_j(f_i)$ denotes the model spectrum.

Results and Discussions

There are various softwares that would give us real spectrum. As AWAC wave measuring devices were installed and discharged by STORM software, the same software was used for spectrum derivation. MATLAB and SPSS softwares were also used for analysis. As distribution of energy spectrum can be used to extract the status of storms and major events, therefore it was first calculated. In Figure 3 an example of the distribution of the energy spectrum in one measured time period is given.

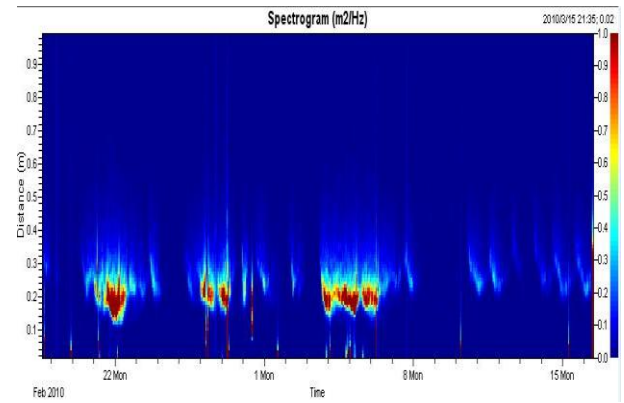


Fig 3 Larak wave spectrogram (from 2010/18/2 to 2010/16/3)

Important parameters derived from wave spectrum are calculated. Because of the peak period and significant wave height importance, in Table 3 classification of waves based on these two parameters for Larak station (central station) are prepared.

To understand the extreme events, Waves with a significant height over 1 meter with wind speed over than $10 \frac{m}{s}$, average and maximum spectrum, mean direction and spreading direction was calculated.

Another wave spectrum classification is based on a number of peaks. In this study the multi-peak spectrums were observed just in Jask station. For this station the portion of one and two-peak waves with more than 1m significant wave height, is provided in table 4. Also figure 5 shows an example of two-peak wave spectrum in Jask.

Spectrum width is calculated with Goda Peakedness Parameter formula as mentioned in materials and methods section of this paper. This parameter for Larak stations is as follows at figure9.

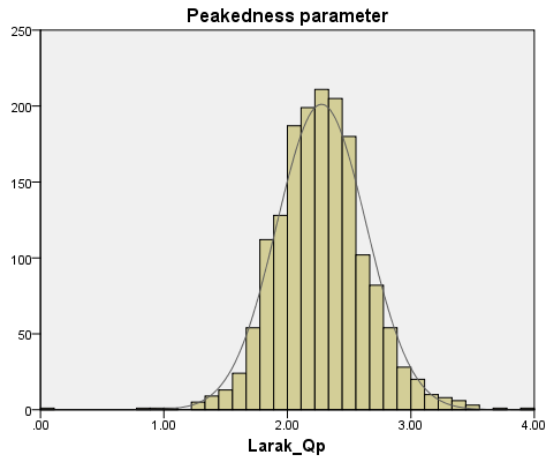


Fig 9 Larak Peakedness Parameters

The results of fitting measured wave spectrum with model spectrum are calculated with MATLAB. In the tables 5 fitting coefficient for Larak extreme waves are given. Also the maximum wave spectrum fitted with model spectrum for central station is in figure 10. It should be noted, instead of α and γ , respectively, a and g_a marks are used.

The values of the fitting coefficients and its goodness related to Larak maximum measured spectrum fitted with JONSWAP model is as follows:

Coefficients (with 95% confidence bounds):

$a=0.01425$ (0.01335, 0.01515)

$b=0.1693$ (0.1685, 0.17)

$c=2.67$ (2.451, 2.888)

Goodness of fit:

RMSE: 0.1176

Table 5 Larak JONSWAP model fitting coefficient

	AVE(a)	MIN(a)	MAX(a)	AVE(fp)	MIN(fp)	MAX(fp)	AVE(ga)	MIN(ga)	MAX(ga)	R-square:	RMSE:
Monthly Max.	0.0095	0.0058	0.0161	0.1833	0.16	0.2171	2.8103	1.746	5.775	0.9725	0.0679
Monthly Ave.	0.0096	0.0059	0.0121	0.1976	0.1731	0.2203	1.5403	1.051	2.665	0.9911	0.0171
$H_{ms} > 2m$	0.0108	0.0072	0.0163	0.1663	0.1494	0.1859	2.3014	0.6365	3.717	0.0961	0.0961
Ave.	0.0099	0.0058	0.0183	0.1773	0.1512	0.2295	2.3855	0.7938	5.775	0.9761	0.0652

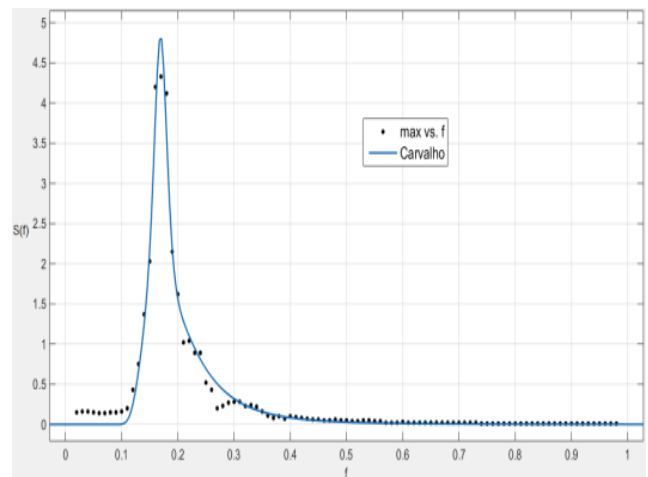


Fig 10 Larak JONSWAP model (Carvalho) fitted plot to the maximum measured spectrum

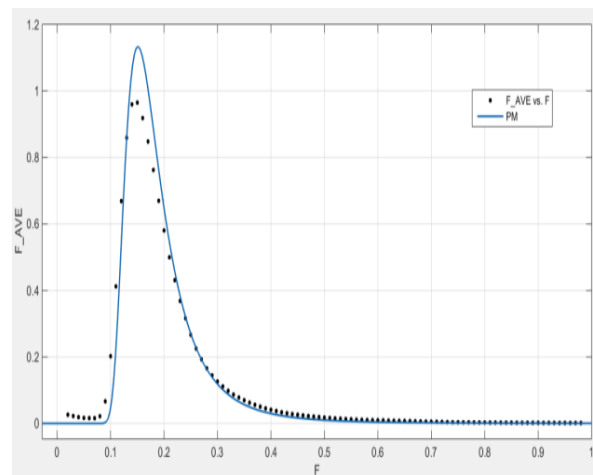


Fig 11 Farooq PM model fitted plot to the measured average spectrum

Coefficients (with 95% confidence bounds):

$H_s= 1.404$ (1.398, 1.409)

$T_s= 6.307$ (6.291, 6.322)

Goodness of fit:

RMSE: 0.01081

It should be noted, instead of symbols α , f_p and γ respectively a, b and c are used.

To have an overview about the wind and its resulting waves, wind speed and wave spectrum correlation diagram is given in Figure 12.

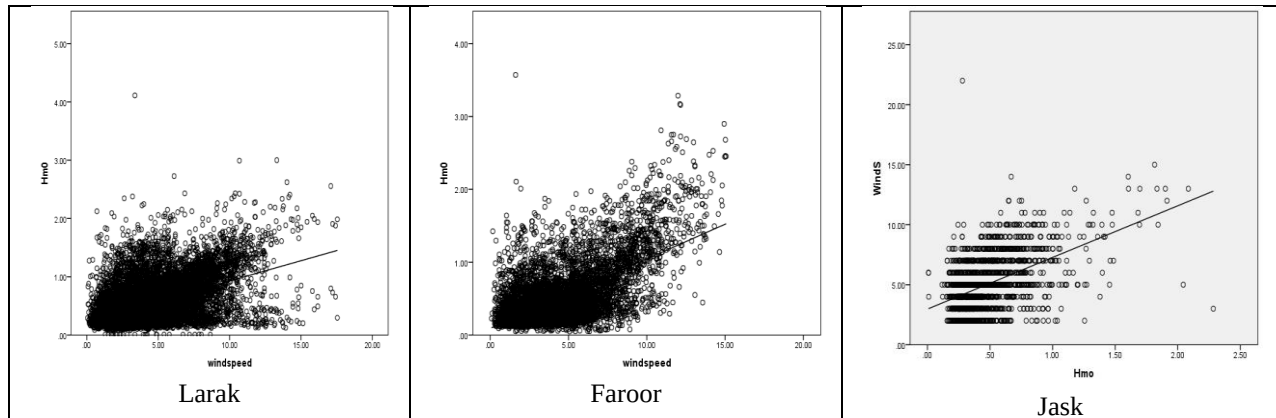


Fig 12 Wind speed and wave spectrum correlation

Conclusion

The summary of the key results obtained from the study of some sixty-three million samples of three stations; Larak, Faroor and jask respectively us:

The maximum extreme observed energy spectrum has been to the amount of $5.98 \text{ m}^2/\text{Hz}$ in Faroor station. Stations mean wave spectral direction was 185, 253 and 153 degree from the north. Biggest maximum wave height was 6.86m, 5.96m and 3.57m. Biggest stations wave spectrum peak period was 16.23s, 9.28s and 16.35s. Two peak spectrums was significant just in Jask with quota of 21%.

Mean periods of two peak waves for seas were 5.5s and for swell were 10s in Jask station. The difference frequency for two peak spectrum was about 0.08Hz. Godapeakedness parameter for stations were 2.27, 2.1 and 1.64.

For all 3 stations the narrowest wave spectrum was related to low frequencies. Important storms in terms of speed and continuity to generate waves with the significant wave height over 1 meter in Larak were southwest direction, in Faroor were from northwest to the north and south east and in Jask were east and west directions. With the increasing power of storm, more narrow and single-peaks pectrum occurred. Biggest mean values of α , γ and f_p related to JONSWAP modeling parameter were 0.0099, 2.39, 0.177Hz,

that occurred in Larak station. Goodness of fitting for both JASWAP and PM spectrum models were more than 96%.

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