Malaysian Journal Of Civil Engineering

Full Paper

WAVE SPECTRUM ANALYSIS FOR OPERATIONAL OFFSHORE PLATFORM IN MALAYSIA WATER

Article history
Received
11 May 2024
Received in revised form
27 July 2024
Accepted
28 July 2024
Published online
01 August 2024

Syamil Aziem Ahmad Saharuddin[a], Nur Fatin Maisarah Dzulkifli[b], Nurul 'Azizah Mukhlas[a]*, Mohd Khairi Abu Husain[b], Noor Irza Mohd Zaki[b], Mohamad Shazwan Ahmad Shah[a], Sarehati Umar[a],Ng Chiew Teng[a], Sayyid Zainal Abidin Syed Ahmad[c]

[a]Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia.
[b]Faculty of Artificial Intelligence, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia.
[c]Faculty of Ocean Engineering Technology, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia.

*Corresponding author
nurulazizah@utm.my

Graphical abstract

Abstract

As an ageing platform has passed its design life of 20 to 30 years, it is crucial to identify wether it is still fit for operation based on the current environmental behaviour, particularly due to the wave impact. Hence, an analytical approach of wave spectrum analysis between the wave behaviour and offshore structural response will be conducted. The aim is to verify the stability and safety of ageing offshore platforms with the current wave behaviour based on identifying wave characteristics, developing a normalized wave energy spectral density, and analyzing the natural frequency of offshore structural response. The methodology includes data collection from structural dynamic monitoring assessments, wave spectrum development using empirical models, and evaluation of offshore platform stability. The results will provide insights into platform stability, resonance risks, and safety assessment of ageing offshore platforms in Malaysian waters. The findings will contribute to recommendations for modifications or improvements to ensure the safety and integrity of offshore platforms in the specific region.

Keywords: wave spectrum, natural frequency, resonance, structural dynamic monitoring, offshore structure

1.0 INTRODUCTION

Malaysia ranks as the second largest oil and gas producer in Southeast Asia. Fixed offshore platforms are widely used in oil and gas production in Malaysia's marginal fields with shallow water depths. The contribution of the oil and gas industry to the national economy is well known. However, as of early 2017, 40% of PETRONAS's ageing offshore platforms and pipelines were older than 30 years [1]. As an ageing platform has passed its design life of 20 to 30 years, it is anticipated that the dynamic response, determined by the structure's natural frequency, would differ from its excitation frequency, preventing frequency resonance. Given various environmental excitations on offshore platforms [2], estimating the frequency of incoming random excitations, particularly the wave effect, is necessary to ensure optimal functionality during usage. With the changing behaviour of the current environment, this study tends to develop a frequency band based on the natural frequency of the structural response and normalized wave power spectra for early detection of resonance phenomena.

2.0 WAVE EXCITATION FREQUENCY

The behaviour of offshore structures subject to dynamic stresses like waves and wind is described using two main concepts: the natural frequency and the excitation frequency. An offshore structure's natural frequency is the frequency at which it oscillates in response to a disturbance or outside stimulus.

According to Chopra [3], the natural frequency is determined by the structure's mass, stiffness, and damping properties. The natural frequency is generally measured in hertz (Hz) and varies by the dynamic properties of the structure and the surrounding environment. On the other hand, the excitation frequency of an offshore structure is the frequency of the external force acting on the structure, such as waves, wind, currents, and earthquakes. These forces can cause the structure to vibrate or oscillate at a corresponding frequency.

When designing offshore structures, it is crucial to consider the excitation wave frequency. The frequency at which waves exert the highest force on the structure is the excitation frequency. The structure's position, the water's depth, and the wave's nature can all affect this frequency [4]. The excitation wave frequency is also crucial for offshore structure maintenance and safety evaluations in addition to design issues. It is anticipated that the excitation frequency of the structure, would differ from its natural frequency, preventing frequency resonance. Given various environmental excitations on offshore platforms[2], estimating the frequency of incoming random excitations, particularly the wave effect, is necessary to ensure optimal functionality during usage.

Changes in wave spectra over time are essential to study because they allow the determination of the excitation frequency of an ocean wave that keeps evolving and affects the stability of offshore structures. It can be analyzed using the analytical approach involving mathematical and statistical techniques to identify the wave energy distribution across different frequencies and determine the dominant wave excitation frequency. The Pierson-Moskowitz (P-M) spectrum, the JONSWAP spectrum, and a modified spectrum named the ZulLiew-Lim-Carigali (ZLLC) spectrum are all examples of empirical spectra used in the analysis. The application depends on the location and condition of the structure.

3.0 NATURAL FREQUENCY OF OFFSHORE STRUCTURES

Offshore platforms are vulnerable to various environmental loads and dynamic forces, causing complex structural responses. Natural frequency refers to the range of frequencies present in a signal or system. In the context of offshore platforms, natural frequency plays a critical role in analyzing the dynamic behaviour of structures subjected to wave loads [5]. It is essential for developing and safely operating offshore structures in Malaysia, as it helps detect resonance and fatigue issues. Analyzing natural frequency in vibration data is a common practice among engineers and structural health monitoring experts. Techniques like accelerometers, wave radar, and strain gauges can be used to evaluate the natural frequency of a platform's response. Resonance is a physical phenomenon where an external force matches a system's natural frequency. Offshore oil and gas exploration platforms are exposed to various environmental forces, such as waves, wind, and currents. Resonance can occur when the frequency of wave excitation matches or approximates the platform's natural frequency, leading to increased vibrations and structural integrity concerns. To ensure stability and safety, engineers must analyze and compare the structures' natural frequency to the wave excitation frequency. Ishida and Tanaka [6] describe the use of damping devices to suppress resonance in offshore platforms

3.1 Data-based Structural Dynamic Monitoring Approach

The data-based structural dynamic monitoring (SDM) approach uses a statistical model rather than physics law-based [7]. Data-based SDM employs pattern recognition and machine learning to infer structural states from measured and processed data [8]. These methods are practical when there are sufficient sensors, SDM computational procedures are expensive, and the structure's physical attributes are either unknown or challenging to predict [9]. Moreover, SDM systems typically include sensors, data transmission systems, and health evaluation components. Sensors are installed on structures to collect data, which is then transmitted for processing, assessing damage, localization, and type [10].

In offshore platform operations, mechanical vibrations are generated by waves, wind, adverse weather, helicopter landings and boat impacts [11], subjecting the structures to continuous forces [12]. These vibrations, caused by random excitations, are monitored by vibration sensors. These sensors measure vibration parameters and process the signal to determine vibration characteristics, including amplitude, frequency, displacement, velocity, acceleration, phase, and period [13]. Chandrasekaran et al. [14] developed a power spectral density using wired and wireless sensors to determine the peak frequency and validate accelerometer data across the two networks. Furthermore, Chandrasekaran and Chithambaram [15] employed a fast Fourier transform (FFT) to decompose the signal into different frequencies, illustrating the power spectral density and utilizing short-time Fourier (STFT) to identify frequency localization. The accuracy and reliability of evaluations heavily depend on the type, quantity, and quality of sensor data.

In brief, the vibration-based method plays a crucial role in monitoring the structural health of offshore structures. Unlike most large-scale structures, offshore structures are subjected to various periodic excitation cycles during their operational life. As highlighted by Han et al.[5], the predominant load on offshore platforms is waves, and determining the structural response of the jacket due to random waves in the frequency domain using power spectral densities provides valuable insights. The stability and effectiveness of frequency-domain techniques in characterizing structural traits make them particularly relevant for offshore structural health monitoring [16].

4.0 CASE STUDY: SPECTRAL ANALYSIS ON OFFSHORE STRUCTURES

The study's coverage area includes the three regions of Malaysia water, namely Peninsular Malaysia Asset (PMA), Sabah Asset (SBA) and Sarawak Operation (SKO). For this research, the data obtained from Tarpon monopod platforms will be used to explore the wave excitation behaviour towards offshore platforms. The focus is to get insights into the properties and behaviours of wave excitation in a particular environment. The analytical approach of analyzing wave energy distribution and determining the dominant wave excitation frequency for offshore structures in Malaysian waters will be based on ZLLC spectrum [17].

The ZLLC spectrum's spectral structure can be explained by the low-energy wave spectrum, which shows that the energy transferred from the wind to the wave was low, either because of fetch restrictions or an inadequate wind-blowing period. It was formed by considering calmer wind and wave conditions in Malaysian water, which are more likely to be those of starting seas and have a lower frequency than first anticipated. The empirical formulation is as follows:

$$S(F) = \frac{5}{16} H_s \frac{(x_R f_m)^4}{f^5} \exp\left(-\frac{5}{4}\left(\frac{f}{x_R f_m}\right)^{-4}\right) \quad (1)$$

where H_s is the significant wave height, $f_m = 1/T_p$, in which T_p is the peak period and x_R is the sensitivity factor [17].

From the third party, the natural frequency of the platform is obtained based on the data-based approach in structural dynamic monitoring (SDM) assessment. The assessment is conducted on each platform located in PMA, SKO and SBA offshore regions, using wave propagation-based and vibration-based techniques to analyze environmental loads and structural responses. SDM incorporates sensors to monitor environmental conditions, including wave height, and capture dynamic responses, such as displacements, accelerations, and operating frequency in the platform's response. By employing various sensing technologies and data acquisition systems, SDM enables continuous monitoring and evaluation of structural integrity.

4.1 Wave Characteristics of Malaysia Water

This section analyses and discusses the wave characteristics, specifically the wave height. The data used for analysis includes information from literature reviews and data collected from SDM assessment, as shown in Table 1.

Table 1 Comparison of wave height over the years in different region

Data	Previous Study		Data Collection (2021)		
	1985-2000	1999-2008	PMA	SKO	SBA
Range wave height (m)	0.7-3.0	-	0.5-3.9	0.4-3.7	0.8-2.4
Maximum wave height (m)	3.0	PMA: 2.7 SKO: 2.0 SBA: 1.9	3.9	3.7	2.4

Based on the data obtained, there is an increasing pattern in the magnitude of wave characteristics from the previous year received in the literature [18-19] and the current (2021) data collection. According to the literature review conducted between 1985 and 2000, the wave height range in Malaysian waters was reported to be between 0.7m and 3.0m. Additionally, another literature review provided maximum wave height data for the period between 1999 and 2008, with PMA recording a maximum of 2.7m, SKO recording 2.0m, and SBA recording 1.9m. Based on a recent SDM assessment taken in 2021, the wave height data obtained were as follows: PMA recorded a range of 0.5m - 3.9m, SKO recorded a range of 0.4m - 3.7m, and SBA recorded a range of 0.8m - 2.4m. These differences can be attributed to climate patterns, sea conditions, and measurement techniques. Monsoon seasons, wind patterns, and storms significantly impact wave heights. Climate variability, long-term climate trends, and human activities influence wave height.

These differences affect the wave spectrum and its role in offshore operations. Table 2 lists important wave parameters for wave energy spectra using ZLLC according to the region. Higher wave heights indicate more severe sea conditions, which can challenge offshore platforms' structural integrity and safety. Hence, understanding these differences is crucial for assessing offshore platforms' design, stability, and safety in Malaysian waters.

Table 2 Wave Parameter for Each Region

Parameter	PMA	SKO	SBA
H_s (m)	2.0812	1.9937	1.2908
T_z (s)	5.1213	5.0126	4.0332

Hence, the empirical wave spectrum approach is employed to generate the wave spectra for each region. Figure 1 showcases the wave spectra from all three regions are combined in a single graph to facilitate a comprehensive comparison and observation of their differences. As for the PMA region, the maximum energy is obtained at $1.2363\mathrm{m}^2/\mathrm{Hz}$. The corresponding frequency at maximum energy is found to be 0.3125Hz. Meanwhile, SKO shows a maximum energy value of $1.1104\mathrm{m}^2/\mathrm{Hz}$ at a frequency of 0.3190Hz, and SBA reveals a maximum energy of $0.3745\mathrm{m}^2/\mathrm{Hz}$ at 0.3971Hz.

The analysis of wave spectra in Malaysian waters reveals significant variations due to geographical location, local bathymetry, and weather conditions. These factors influence wave propagation, resulting in wave height and period variations. These differences highlight unique wave characteristics and energy distribution. Analyzing the energy spectral density of wave excitation provides valuable insights for evaluating wave conditions in the studied regions, enhancing offshore platform safety and stability. The findings also help design and maintain offshore structures, highlighting the importance of considering region-specific conditions in offshore platform evaluation.

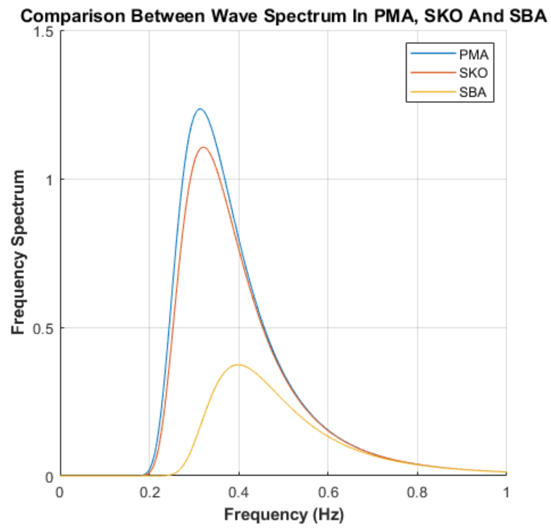

Figure 1 Wave Spectra Model According to The Region

4.2 Effect of Wave Excitation Frequency on Offshore Structure's Natural Frequency

Based on the SDM assessment conducted at three different locations, Table 3 summarizes the minimum and maximum value of the platform's natural frequency considering the East-West and North-South directions.

Table 3 Summary of Natural Frequency

Region	Natural Frequency (Hz)	
	Minimum	Maximum
PMA	0.1957	0.2248
SKO	0.2905	0.3442
SBA	0.2962	0.3499

In this intriguing section, the crucial task is to develop the frequency band by merging the wave spectral density and the natural frequency limit within the platform's response. By integrating the range of natural frequency with the wave spectrum developed from the acquired wave data, invaluable insights into the safety and resonance potential of the offshore platforms are gained.

Figure 2 presents the frequency band showcasing the range of natural frequency and the wave spectrum for the platform in PMA. A fascinating observation emerges as we witness a substantial distance between the range of frequency content and the wave spectrum's dominant frequency. This striking revelation leads to the reassuring conclusion that the platform is assumed to be safe from resonance. The substantial distance between the frequency content range and the dominant frequency suggests that the platform's dynamic response is unlikely to align with the wave excitation, minimizing the risk of resonance.

Moving onward, Figure 3 unveils the frequency band for the platform in SKO, presenting a different narrative. Here, the wave spectrum's dominant frequency falls within the natural frequency range. The situation indicates a higher probability of resonance occurrence. Conducting complete structural vibration testing to assess the structural condition is crucial. Advanced numerical modelling techniques, such as computational fluid dynamics (CFD) and finite element analysis (FEA), can be employed to simulate wave-platform interactions accurately. These advanced modelling methods facilitate the assessment of the dynamic response of offshore structures, aiding in the analysis of resonance phenomena. The information from the assessment can help determine the improvement to be done to the platform. Maintenance considerations become essential to ensure the continued safe operation of the platform in SKO.

Figure 4 illustrates the frequency band of the natural frequency range and the wave spectrum for the platform in SBA. The natural frequency range closely aligns with the dominant frequency of the wave spectrum. Further analysis is required to determine whether maintenance measures are necessary for the platform in SBA. Detailed investigations can include structural integrity assessments, inspection of key components, and monitoring systems to ensure the platform's long-term stability and functionality.

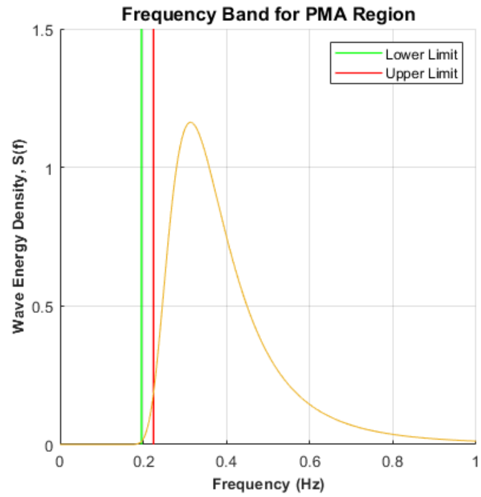

Figure 2 Frequency Band of the Natural Frequency Range and the Wave Spectrum for PMA Region

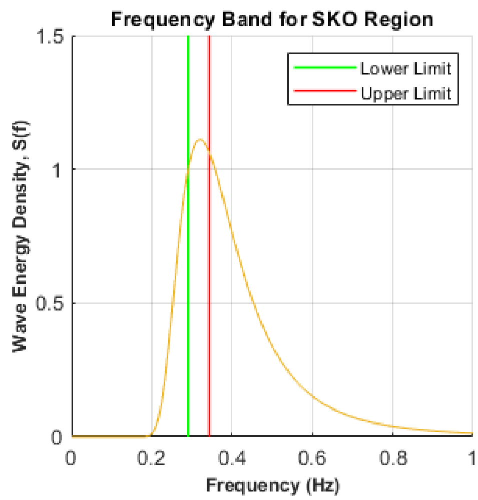

Figure 3 Frequency Band of the Natural Frequency Range and the Wave Spectrum for SKO Region

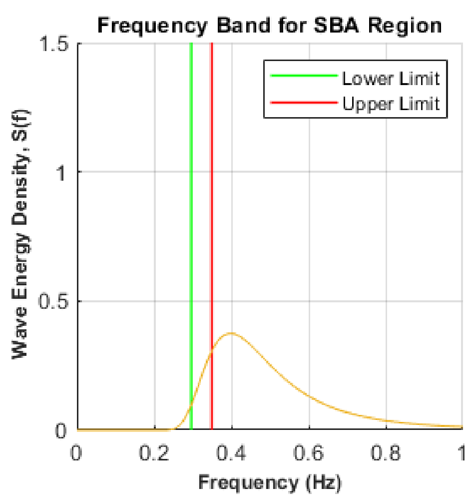

Figure 4 Frequency Band of the Natural Frequency Range and the Wave Spectrum for SBA Region

Examining these revealing graphs reveals the intricate dynamics that drive the conditions observed within each region. The observed differences in the graphs of natural frequency range and wave spectrum among the regions can be attributed to variations in wave characteristics, geographical factors, and platform-specific attributes. These variations influence the interaction between waves and platforms, leading to different resonance potentials and maintenance requirements.

These captivating findings highlight the importance of evaluating the interplay between wave spectral density and natural frequency when assessing offshore platforms' safety and resonance potential. Thus, engineers and decision-makers can make informed choices, implementing appropriate measures to safeguard these vital structures. The significant distance between the natural frequency and the dominant frequency in PMA suggests a lower risk of resonance. In contrast, the alignment of natural frequency and dominant frequency in SKO highlights the need for structural analysis and maintenance. Further analysis is warranted to determine the maintenance requirements for that platform.

4.0 CONCLUSION

This study concludes that understanding wave characteristics and their implications for offshore platforms in Malaysian waters, emphasizing the importance of considering regional variations and conducting thorough evaluations based on wave spectra and natural frequency are practical to verify the stability and safety of offshore platforms. Findings that answered the study's objectives can be summarized as follows. The analysis of the wave characteristics of PMA, SKO, and SBA regions reveals variations in wave heights attributed to geographical location, local weather patterns, and seafloor topography. These differences influence the wave spectrum, with higher wave heights resulting in a more energetic spectrum and broader frequency distribution. The developed energy spectral density shows the wave spectra with different energy distributions and dominant frequencies for each region. PMA's spectrum exhibited a dominant frequency at 0.3125Hz, SKO at 0.3190Hz, and SBA at 0.3971Hz. Comparing the wave spectral density with the natural frequency of the structure, PMA showed a lower resonance risk. Meanwhile, SKO and SBA require further analysis and maintenance considerations to ensure platform safety.

Acknowledgements

The authors acknowledge the research is a contribution from a research member of the Reliability Engineering and Safety Assessment research group of the Faculty of Civil Engineering, UTM, and not funded by any internal or external grant.

References

[1] Mohamad, M., and Daud, S.S.M. 2018. Decommissioning Project in Malaysia: How It Became Valuable and Successful. *Offshore Technology Conference Asia*

[2] Zhang, W., Zhu, J., and Gao, T. 2016. Dynamic Problem, in *Topology Optimization in Engineering Structure Design,* 61-105.

[3] Chopra, A.K. 2007. Dynamics of Structures. *Pearson Education India*.

[4] Ma, G., Zhong, L., Zhang, X., Ma, Q. and Kang H.S. 2020. Mechanism of Mooring Line Breakage of Floating Offshore Wind Turbine under Extreme Coherent Gust with Direction change Conditions. *Journal of Marine Science and Technology,* 25: 1283-1295.

[5] Han, X., Qiao, W. and Zhou, B. 2019. Frequency Domain Response of Jacket Platforms under Random Wave Loads. *Journal of Marine Science and Engineering.* 7(10): 328.

[6] Ishida, H., & Komura, T. (1994, April). Suppression of resonance of offshore platform in irregular waves. In *The Fourth International Offshore and Polar Engineering Conference*. OnePetro.

[7] Barthorpe, R.J. 2011. On Model and Data Based Approaches to Structural Health Monitoring. PhD thesis, University of Sheffield.

[8] Worden, K., Cross, E.J., Dervilis, N., Papatheou, E. and Antoniadou, I. 2015. Structural Health Monitoring: From Structures to System of Systems. *In IFAC Papers Online,* 1-7 Elsevier Ltd.

[9] Gharehbaghi, V.R., Noroonzinejad Farsangi, E., Noori, M., Yang, T.Y., Li, S., Nguyen, A. Malaga-Chuquitaype, C., Gardoni, P. and Mirjalili, S. 2022. A Critical Review on Structural Health Monitoring: Definitions, Methods and Perspectives. *Archives of Computational Methods in Engineering. Springer Netherland,* 29(44): 2209-2235.

[10] Guemes, A. Fernandez Lopez, A. Pozo, A.R. and Sierra Perez, J. 2020. Structural Health Monitoring for Advanced Composite Structures: A Review. *Journnal of Composite Science,* 4(1): 13.

[11] Asiri, S.A. and Al-Zahrani, Y.Z. 2014. Theoretical Analysis of Mechanical Vibration for Offshore Platform Structures. *World Journal of Mechanics.* 04(01): 1-11.

[12] Havigh, S.N. and Askar, M.B. 2017. The Process of Fatigue Analysis on Fixed Metal Offshore Platforms, *Marine Sciences,* 7(1): 10-16.

[13] Gordon, M., Sabbagh Yazdi, S.R., Ismail, Z., Ghaedi, K., Carroll, P., McCrum, D. and Samali, B. 2022. State of the art Review on Advancements of Data Mining in Structural Health Monitoring, *Measurement: Journal of the International Measurement Confederation*, 193 (October): *1-23.*

[14] Chandrasekaran S., Chithambaram, T., and Kader, S.A> 2016. Structural Health Monitoring of Offshore Structures using Wireless Sensor Networking under Operational and Environmental Variability, *International Journal of Environmental and Ecological Engineering,* 10(1): 33-39.

[15] Chandrasekaran, S. and Chithambaram, T. 2018. Structural Health Monitoring of Offshore Buoyant Leg Storage and Regasification Platform: Experimental Investigations, *Journal of Marine Science and Application* 17(1): 87-100.

[16] Saidin, S.S.., Jamadin, A., Abdul Kudus, S., Mohd Amin, N. and Anuar, M.A. 2022. AN Overview: The Application of Vibration-based Techniques in Bridge Structural Health Monitoring. *International Journal of Concrete Structures and Materials.* 16(1): 1-17*.* Springer Nature Singapore,

[17] Liew, M., Lim, E., Shahdan, T.T. and PETRONAS, 2015. *Spectral Analyses of Sea-state Wave Data for the Development of Offshore Metocean Applications: A Malysia Case Study.* Universiti Teknologi Petronas, Malaysia.

[18] Chiang, E., Zainal, Z., Narayana, A. and Seetharamu, K. 2003. Potential. In: Marine Technology Seminar, 1-7.

[19] Vannak, D., Liew, M.S., and Yew, G.z. 2013. Time Domain and Frequency Domain Analyses of Measured Metocean Data for Malaysian Waters. *International Journal of Geological and Environmental Engineering*, 7(8): 549-554.