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Research paper

Efficient Algorithm for Ocean Wave Profile Simulation in Malaysian Waters

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Abstract

This study presents an approach for ocean wave simulation in Malaysian waters by using the eigenfunctions of Prolate Spheroidal Wave Functions in which fewer number of independent random variables are used. It is an efficient approach that can allow the use of state of the art stochastic methods in the analysis and design of offshore structures. An algorithm was also developed for the simulation of the wave in a computer program in which sub-routines were provided to solve the equations and matrices involved. The wave profile for the environmental parameters of the Malaysian offshore locations was simulated and the results presented.

Keywords: Wave Profile; Ocean waves; Malaysian waters

1. Introduction

Currently, there are about 300 offshore platforms operating in various locations in Malaysian waters. More platforms are also in different stages of construction and will eventually be deployed for operations. Several of these platforms are also nearing the end of their design lives and will soon be de-commissioned and possibly replaced [1]. In addition, there is also an increased demand for oil exploration in offshore fields which resulted in the increased demand for deploying such platforms in deeper and harsher waters and to operate for even an extended period of time. Consequently, there is an ever increasing need for a more thorough analysis and more precise design of these platforms in order to ensure that during their operational lives, they can withstand the most severe environmental condition in their location of use [2,4].

Dominant among the load experienced by offshore platforms is the loading due to ocean waves. Analysis and estimation of this load involves the modelling of the ocean wave surface elevation. This refers to the mathematical representation of the ocean surface profile which is used to develop the wave kinematics and hence, the wave load acting on the platforms [5,6].

One of the most powerful tools in the analysis and design of dynamically responding structures subjected to stochastic loading such as offshore platforms which are subjected to waves or wind loading is the Stochastic Finite Element (SFEM) framework. In recent past, stochastic approach in the simulation of real life problems has become more attractive due to the rapid advancement in computational techniques which enables solution of large dimension and complex integrals that are involved [7].

Current methods in temporal and spatial representation of ocean waves for offshore structural analysis and design is by superposition of large number of individual wavelets travelling with different speeds and directions. This is achieved by using trigonometric functions and random phase angles whereby a spectral energy density curve is discretised in to N smaller frequency intervals to obtain wave height- Period pairs for each wavelet. This approach only represents a Gaussian sea when $N \to \infty$. However, this method does not allow efficient structural analysis in the SFEM framework due to the large number of random variables involved in the representation and the size of offshore structures to be analysed [8].

This study therefore aims to present a simplified algorithm for the simulation of ocean waves in Malaysian waters in which only a few number of independent random variables are involved. The method uses Karhunen Loeve Expansion (KLE) [9] with autocorrelation of the sea state as the kernel of the Fredholm integral equation. Sea state representing wave return periods and described by significant wave height and wave period as used for Malaysian offshore environment is selected and used. Eigenfunctions of Prolate Spheroidal Wave Functions (PSWF) are generated and used to cast the matrix eigenvalue problem. A computer algorithm was developed and used to simulate the ocean surface profile.

2. Methodology

2.1 Wave Environment

Offshore structures are designed by selecting an extreme wave event that have highest probability of occurring in a minimum of 50year period. This wave is usually described by Significant wave height H_s and peak period T_p. In this study, three offshore locations in Malaysian waters namely the Peninsular Malaysia Operations, (PMO), Sarawak Operations (SKO) and Sabah Operations (SBO) [10] were selected and the design wave parameters for each of the locations is given in Table 2.1.

Table 2.1: Wave parameters for study locations

LOCATION	H_S (M)	T_P (S)
PMO	10.9	9.5
SKO	11.7	10.9
SBO	7.7	9.6

A JONSWAP spectral energy density model, which is the model used in Malaysian waters was selected and used in the wave representation. The mathematical JONSWAP model is given in Equation 2.1

$$S_{\eta\eta}(\omega) = \frac{1}{2\pi}\frac{H_s^2 k_b^4 k_\gamma}{4\pi T_p^4}\left[\frac{2\pi}{\omega}\right]^5 e^{-\left[\frac{2\pi k_b}{\omega T_p}\right]^4}\gamma^a \qquad 2.1$$

Where; $a = e^{\frac{(\omega-\omega_p)^2}{2\sigma^2\omega_p^2}}$

Parameters used in the JONSWAP spectrum are either measured or predicted as given by many authors. Table 2.2 gives approximate values of the parameters as reported in the literature.

Table Error! No text of specified style in document.**.2:** Parameters of JONSWAP spectrum

Parameter	k_b	k_p	γ	k_γ	σ	T_p
value	1.41	1.29	3.3	0.66	0.07-0.09	k_p*T_z

2.2 Wave Surface Elevation

Karhunen-Loeve Expansion (KLE) is a unified procedure in simulating Gaussian and non-Gaussian process that allows the characterisation of the random process' second moment using un correlated random variables and deterministic orthogonal functions [11].

The general expression of a stochastic field $u(x,t)$ using KLE is given as;

$$u(x) = \bar{u}(x) + \sum_{n=1}^{N}\sqrt{\lambda_n}\xi_n\phi_n(x) \qquad 2.2$$

The function $\bar{u}(x,t)$ is the mean value of the field and for a Gaussian process, it is assumed to be equals to zero. The eigenvalues λ_n and the eigenfunctions ϕ_n are obtained from the solution of the integral equation cast with the auto correlation function $R(t-\tau)$ of the field as the kernel as;

$$\int_D R(t-\tau)\phi_n(\tau)dt_1 = \chi_n\phi_n(t) \qquad 2.3$$

A scheme by [12] in which a sea state can be represented based on the KLE decomposition of the wave signal introduced a method that uses the eigenfunctions of PSWFs with tuneable band width parameter. The surface elevation is then given as;

$$\eta(x,t) = \sum_{n=1}^{N}\sqrt{\lambda_n}\xi_n\phi_n(x) \qquad 2.4$$

The eigenfunctions $\phi_n(t)$ share similar properties with the PSWF [13,14]. They are obtained from the solution of the integral equation given below;

$$P_{i,j} = \frac{1}{2\pi}\int_{-\infty}^{\infty}\psi_i^{c,\omega}\psi_j^{c,\omega}S(\omega)d\omega \qquad (2.5)$$

Here, ψ_n are the eigenfunctions of the PSWFs which are controlled by the band width parameter C. $S(\omega)$ is the one-sided spectral energy density here chosen as the JONSWAP model. The corresponding eigenvalues of the PSWF χ decays rapidly and are cast together with the band width parameter in the formulation of the symmetric matrix Q of form;

$$Q_{i,j} = Q_{j,i} = \chi_i\chi_j CP_{i,j} \qquad (2.6)$$

By solving the above matrix Eigen value problem, the Eigen values and the Eigen vectors provide the means for the solution of K-L integral equation. The Eigen values λ_j and the Eigen vectors β_j^n are used to calculate the eigenfunctions as [12];

$$f_n(t) = \sum_{j=0}^{\infty}\beta_j^n\psi_j^{t,c} \qquad (2.7)$$

Detailed procedure for the KLE representation of a sea state in which the PSWF are used can be found in [12]. The properties of the PSWFs are discussed in [14], their application in signal processing are discussed in [13] while detailed procedure for their evaluation is outlined in [15].

2.3 Computer Algorithm

A computer framework was developed by writing codes in a commercial software to perform the simulation. This includes subroutines for the generation of the PSWF from Legendre polynomials, solution of the tridiagonal matrix eigenvalue problems and the simulation of the wave surface elevation. This procedure is described in a flow chart shown in Figure 2.1

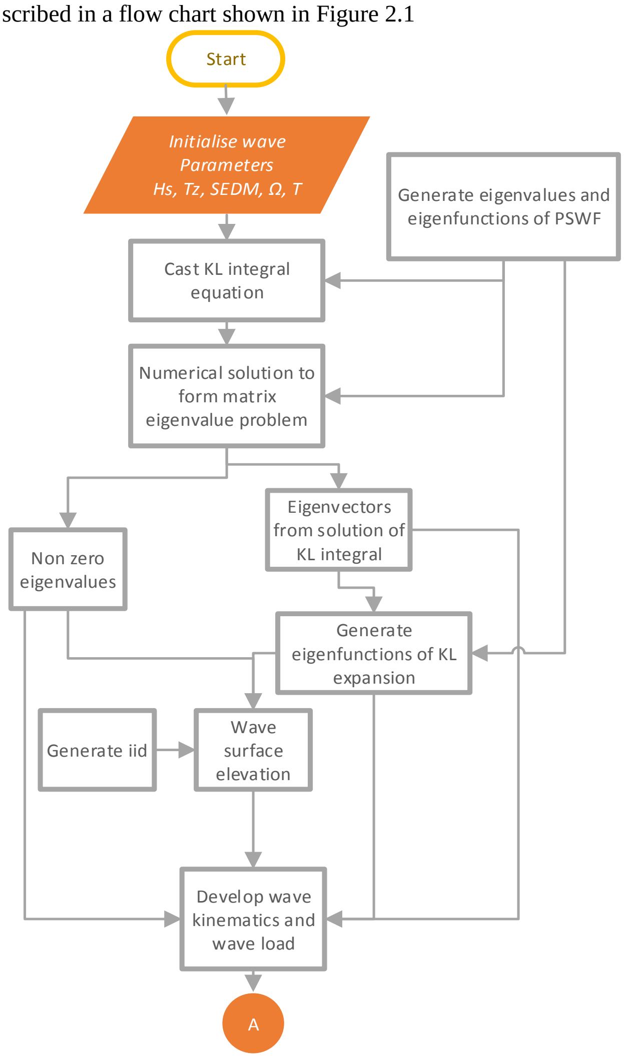

Figure 2.1: Flowchart of the algorithm for simulating wave profile

The algorithm therefore is a computer program for solving the large dimension matrices using Gaussian elimination methods and complicated integrals using numerical quadrature schemes. By following the flowchart in figure 2.1, the software receives input in terms of Spectral density model and environmental wave parameters. It the simulate the wave by using Karhunen-Loeve expansion and eigenfunctions of PSWF. The output given is the mathematical description of the wave with fewer number of independent sources of uncertainties. The results are also visualised by plotting the wave profile.

3. Results and Discussion

Based on the procedure outlined in the previous section, ocean wave profile was simulated using the eigenfunction approach in which fewer number of random variables were involved. Figures 3.1 to 3.3 show the eigenvalues and the corresponding eigenfunctions for the wave parameters in the three offshore locations in Malaysian waters as discussed. The rate of decay of the eigenvalues have shown that as few as five terms can be maintained in the expansion to simulate the wave. This can also be seen in the eigenfunctions as the oscillations of the functions decay rapidly as the number increases. The magnitude of the eigenvalues from the 5th eigenvalue is almost zero, which means that its corresponding eigenfunction does not contribute in the model. In addition, from the 5th eigenfunction, it can be seen that the curves become flatter, also indicating little or no contribution to the expansion.

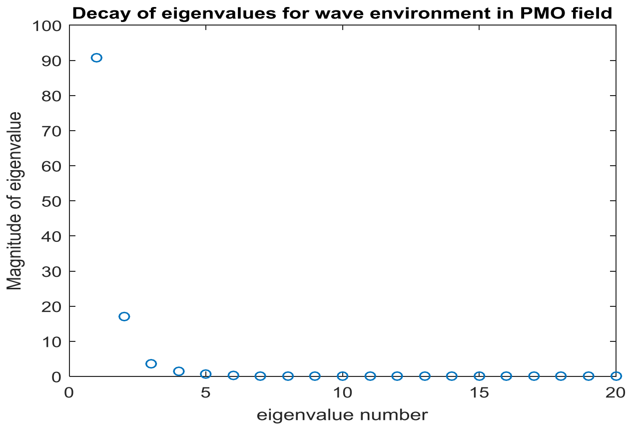

Figure 3.1a Eigenvalues from the solution using parameters of PMO field

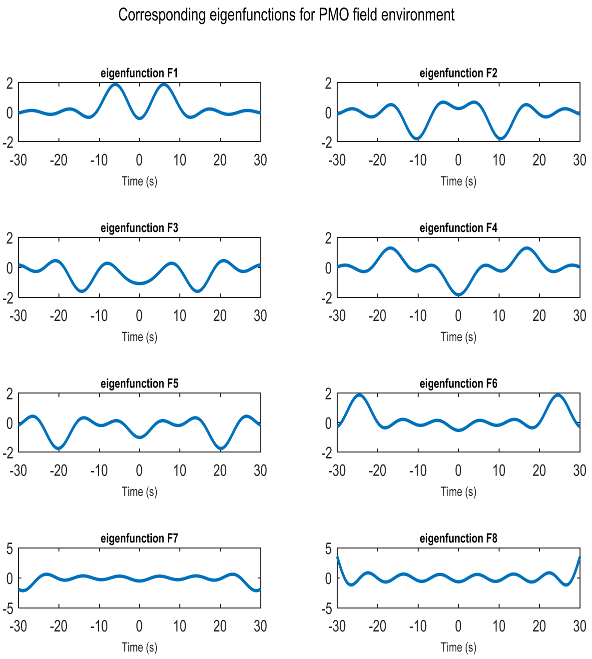

Figure 3.1b: Corresponding eigenfunctions for the eigenvalues in Figure 3.1a

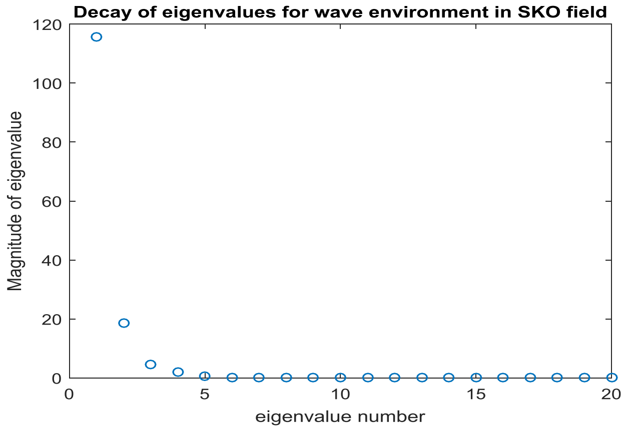

Figure 3.2a Eigenvalues from the solution using parameters of SKO field

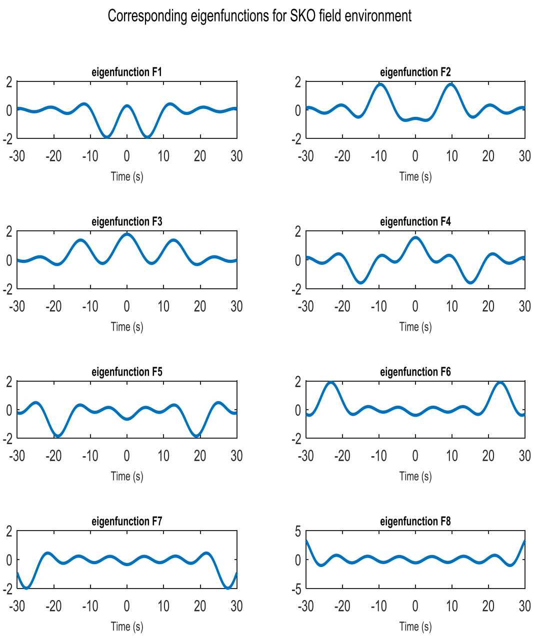

Figure 3.2b: Corresponding eigenfunctions for the eigenvalues in Figure 3.2a

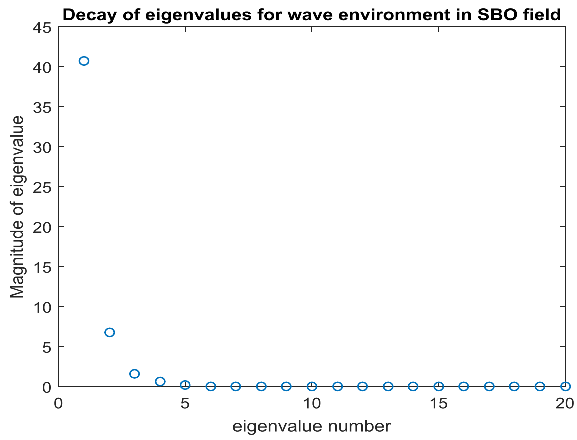

Figure 3.3a Eigenvalues from the solution using parameters of SBO field

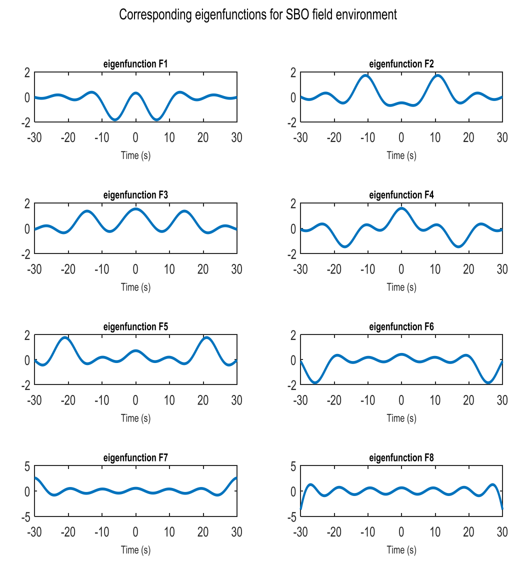

Figure 3.3b: Corresponding eigenfunctions for the eigenvalues in Figure 3.3a

In Figure 3.4, the surface elevation of a wave from the parameters of the three locations simulated with KLE expansion using PSWF by superposition of eight terms as given in Equation 2.4 is shown. This is achieved by selecting the Slepian frequency C of 19.0, 20.0 and 18.0Hz for PMO, SKO and SBO wave simulation and using the eigenvalues and eigenfunctions of the PSWF in the expansion as discussed in previous sections.

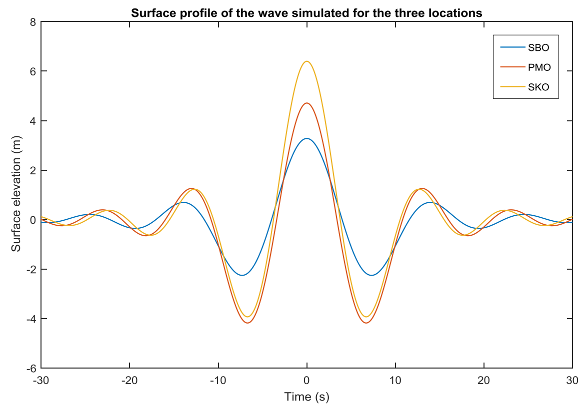

Figure 3.4: Surface profile of the wave simulated for the different locations

In this study, a computer algorithm was developed to simulate the wave using the approach presented. The tridiagonal matrix eigenvalue problem was solved by Gaussian elimination. All the integrations were performed by constructing Gaussian quadrature with weights. The input to the algorithm are the wave significant height and wave period. A subroutine was constructed to read these parameters and compute the Slepian frequency by iterative procedure until convergence. The eigenvalues and eigenfunctions of the PSWF are first developed using another subroutine by using Legendre polynomials. The output after all the computations are displayed by plotting the eigenvalues and eigenfunctions and then the wave profile.

4. Conclusion

This study presented an approach for simulation of ocean wave in Malaysian offshore fields in which fewer number of independent random variables are required. Ocean wave parameters that are used in the design and analysis of offshore structures in Malaysian waters were selected and used to simulate the wave profile. The results of the simulation show that based on the environmental parameters used for each of the locations, the wave in SKO have the highest peak of nearly 7m which is more than twice the peak at SBO of 3.2m and also higher than PMO with 4.5m. This indicates harsher operational environment at SKO than both PMO and SBO. The SBO operational environment have a relatively lower condition in the Malaysian offshore oil and gas exploration environments. The Computer algorithm was developed and used to perform the simulation in a simplified way by solving difficult mathematical integrals and large dimension matrices. The software is made simple and very easy to use by reducing the input requirements to operational environment described by the wave parameters. The software can then use appropriate parameters and mathematical models to simulate the wave and give results including results visualisations.

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