A NOVEL APPROACH FOR PERFORMANCE ANALYSIS OF FLOATING STRUCTURE ENCOUNTERING STORM CONDITIONS

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Abstract – *A marine floating structure may experience a wide range of harsh environmental conditions during its operational lifetime. It is necessary to evaluate the performance of the structure in extreme conditions such as storm to maintain a desirable level of safety. Various approaches are available to analyse the response of an offshore structure in different sea states. However, many of them are computationally time consuming and require a large number of simulations. Moreover, it is not the most realistic approach to analyse the dynamic behaviour of a structure by separately replicating each level of a storm. In this study, a novel numerical model is developed for modelling a storm based on Endurance Wave Analysis (EWA) method. The developed model reduces the computational cost of simulations and takes into account the random nature of the sea environment. This will be beneficial for future risk and reliability analysis that require a great deal of data analysis. The application of the developed method is demonstrated through an analysis of a Floating Storage Unit (FSU) encountering storm conditions with varying sea states in the North Sea.*

Keywords: Hydrodynamic, Storm, Endurance Wave Analysis, Floating Structure

1. INTRODUCTION

One of the prerequisites for improving the safety and reliability of offshore structures is to evaluate dynamic behavior of the structure under severe environmental loads such as storm condition (Zeinoddini et al. 2012). Sea waves have a random nature which cause non-linear forces on the floating structures. Therefore, a time-history analysis has became necessary to obtain more accurate results for the structural response during extreme loading conditions such as catastrophic hurricanes, Ivan, Katrina and Rita in the Gulf of Mexico (Kim and Zhang 2009). Conventional dynamic analysis of marine structures is a time consuming approach as it needs a longer simulation time to generate data for conducting statistical analysis. Recently, Endurance Time Analysis (ETA) method has been developed by Riahi et al. (2009) and later improved by Riahi and Estekanchi (2010) to reduce the computatioanl cost. Results of the studies carried out by Estekanchi et al. (2004); Riahi and Estekanchi (2010) indicate the efficiency and accuracy of this method in the dynamic evaluation of structures subjected to natural disasters such as earthquakes.

This paper aims to develop a novel approach for modeling storm conditions to evaluate performance of marine floating structures. Dynamic behaviour analysis of the structure is the main key point for examining the performance of the vessel in harsh environment. This will examine when the structure is subjected to a storm, whether the behaviour of the vessel will be in a safe condition or whether it will exceed its survival limit conditions. For this purpose, intensifying dynamic modelling of the structure based on EWA is considered for performance analysis of the structure, which develops an extensive range of storm conditions considering the optimum simulation time. In order to illustrate the advantages of the developed methodology, a Floating Storage Unit (FSU) is considered as a real case study. The approach has the capability to be applied for critical analysis of any type of marine structure subjected to a storm. Also, it is helpful for future risk and reliability analysis of these structure for improving the safety of the marine structure in a harsh environment.

2. ENDURANCE WAVE ANALYSIS

The EWA is a simulation-based approach used to evaluate the hydrodynamic performance of offshore structures encountering a wave profile with stepwise increase of the wave height. This method simulates storm conditions based on the concept adopted from ETA in seismic engineering assisting in reduction of the time required for analysis of marine structures in multiple sea states. In EWA method, different sea states are provided in a single time domain by representing wave spectrum into Intensifying Wave Train Function (IWTF). This function is a relatively short duration time series of the irregular water surface elevation. Zeinoddini et al. (2012) tried to put forward short duration irregular wave time histories, such as Constrained New Wave (CNW) which had no fixed frequency but were delivering a desirable maximum crest height . The final wave train function then is defined as Intensifying CNW (ICNW). Accordingly, this approach can be adopted for simulating the increasing trend of storms levels over time, which goes well beyond the design sea state accounting for the random nature of sea waves.

The ICNW wave function is then introduced as a single input of the external excitations for a long-term evaluation of non-linear dynamic analysis. The performance of the structures and the limit states of failures can be investigated based on the EWA results. The capability of considering wave spectrum of different sea state, significant wave heights, irregularity and randomness of the sea waves and requiring relatively short simulation time, are among the advantages offered by EWA (Zeinoddini et al. 2012). More details on the description of this concept can be found in (Diznab et al. 2014; Zeinoddini et al. 2012).

Figure 1 illustrates three different levels of ICNW profile with different sea states adopted for the hydrodynamic simulations of the floating structure. At the beginning, the structure is subjected to a time history wave loading corresponding to a certain significant wave height (Hs) and peak spectral period (Tp) derived from first sea state spectrum ($S_1(w)$). Since the amplitude of the excitation is quite low, the structure remains stable while experiencing this loading (**Case 1**). In the second stage, the significant wave height increases linearly for a same time duration as Case 1. At some point during this stage of a storm the structure will exceed its survival limit causing an intolerable situation for the crew on- board (**Case 2**). In the last stage, the excitation becomes severe such that the floating structure is anticipated to capsize leaving no choice for humans other than evacuating the structure urgently (**Case 3**). EWA will help to evaluate the performance of the structure for any desired level of storm conditions and any reasonable EDPs for future risk assessment and decision making processes.

2.1. Intensifying Constrained New Wave Model (ICNWM)

ICNW is a type of Gaussian process used to model random wave elevations constrained to the most probable new-wave crest at a specific time by considering sea spectrum. In addition to its shorter time analysis, CNW has a capability to model the random nature of the sea waves. The application of this method in determining the extreme response of the structures under wave loadings is proved by previous research (Diznab et al. 2014; Zeinoddini et al. 2012). For this purpose, using the sea spectrum, m separate time series of intensifying CNWs each with a specific sea state and constant duration time (t_d) are joined together to form a standalone time history of the random sea elevation. The k^{th} CNW profile, $\eta_{R_k}(t)$, represents the sea state k ($1 \le k \le m$) which itself is constructed based on the wave energy density spectrum $S_k(\omega)$ at a specific site. The k^{th} CNW covers a time period of $(k-1)\times t_d < t < k\times t_d$. By increasing stepwise the level of wave spectrum $S_k(\omega)$ with a linear trend, as k increases from 1 to k, the intensifying storm profile will be generated. The target operational and survival significant wave height, H_S, and its corresponding energy density spectrum $S(\omega)$ should be placed somewhere halfway and(this next bit seems to be out of place?) last stepwise profile through the sea states 1 to m. The first generation of ICNW in which the growth function is linear, can be expressed as follows (Diznab et al. 2014; Zeinoddini et al. 2012):

$$\eta_{ICNW}(t) = \tag{1}$$

$$\begin{cases} \eta_{R_1}(t) + \rho_1(t)[\alpha_1 - \eta_{R_1}(t_c)] + \frac{\dot{\rho}_1(t)}{\lambda_1^2}\dot{\eta}_{R_1}(t_c), \; 0 < t < t_d, \; S_1(\omega) \\ \eta_{R_2}(t) + \rho_2(t)[\alpha_2 - \eta_{R_2}(t_c)] + \frac{\dot{\rho}_2(t)}{\lambda_2^2}\dot{\eta}_{R_2}(t_c), \; t_d < t < 2\times t_d, \; S_2(\omega) \\ \vdots \\ \eta_{R_k}(t) + \rho_k(t)[\alpha_k - \eta_{R_k}(t_c)] + \frac{\dot{\rho}_k(t)}{\lambda_k^2}\dot{\eta}_{R_1}(t_c), \; (k-1)\times t_d < t < k\times t_d, \; S_k(\omega) \\ \vdots \\ \eta_{R_n}(t) + \rho_n(t)[\alpha_n - \eta_{R_n}(t_c)] + \frac{\dot{\rho}_n(t)}{\lambda_n^2}\dot{\eta}_{R}(t_c), \; (n-1)\times t_d < t < n\times t_d, \; S_n(\omega) \end{cases}$$

where η_{ICNW} is the surface elevation of ICNW, k represents the k^{th} wave profile, α_k is the crest elevation defined as $\alpha_k = \beta H_{\max_k}$. H_{Max} which is the most probable maximum wave height in the sea state k, can be expressed by $H_{\max_k} = 0.707 H_{S_k}\sqrt{\ln N_w}$ (Sorensen 2006).

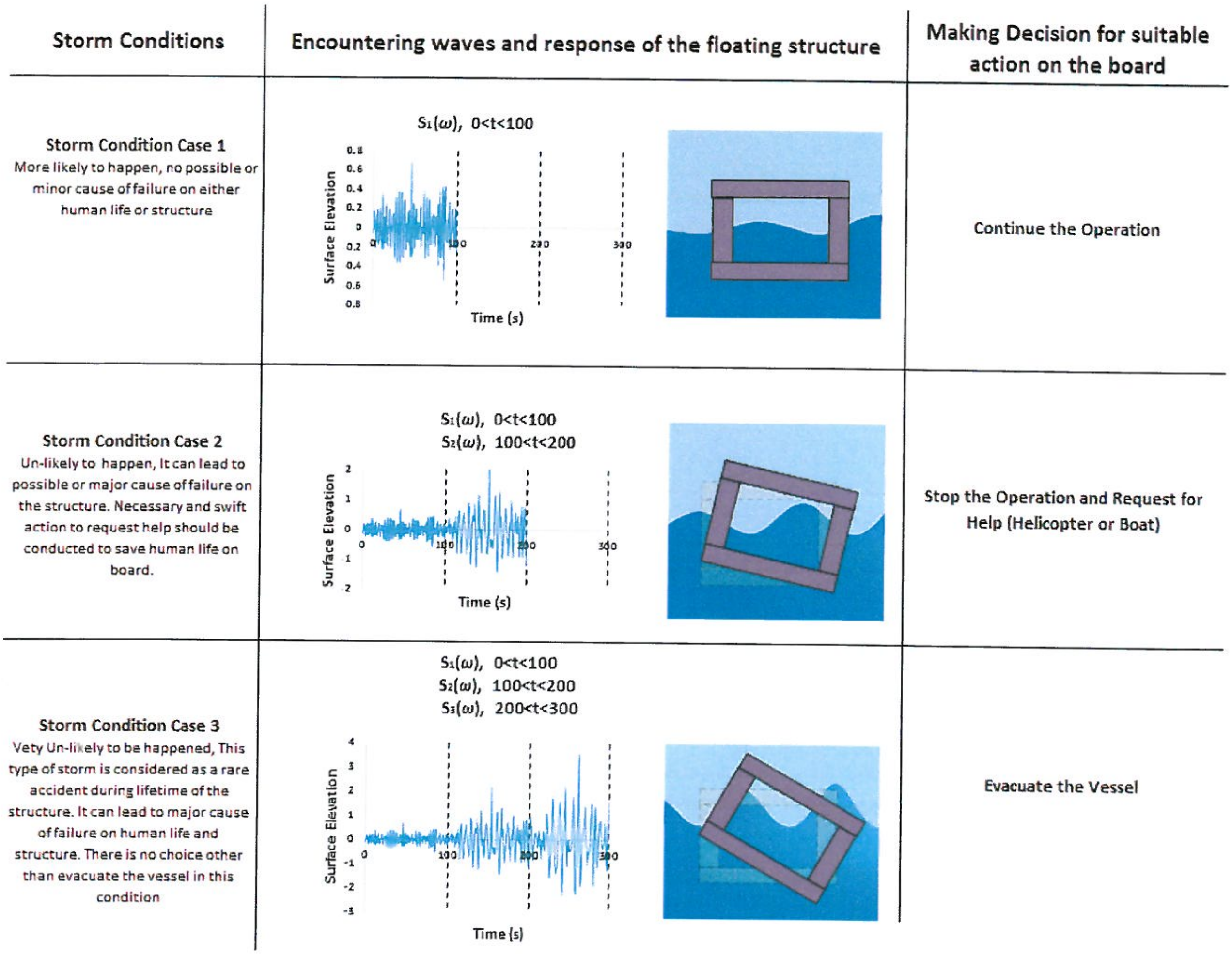

Figure 1 Storm conditions based on the concept of EWA method

Where, N_W is the number of wave cycles during the storm period (t_d). The value of β, coefficient that refer to maximum wave height in each sea spectrum, when using JONSWAP spectrum, has been considered as β=0.58 (Zeinoddini et al. 2012). Time dependent parameters $\rho_k(t)$ and $\dot{\rho}_k(t)$ are the unit of the new wave and its slope autocorrelation function, respectively. λ_k^2 is obtained from the second spectral moment and variance of the wave energy spectrum ($\lambda_k^2 = \frac{m_{2k}}{\sigma_k^2}$). $\eta_{R_k}(t)$ is a random process that can be written as:

$$\eta_{R_k}(t) = \sum_{n=1}^{N} c_{kn} \mathrm{Cos}(\omega_n t + \varepsilon_{kn}) \;, \quad c_{kn} = \sqrt{2S_k(\omega_n)\Delta\omega} \tag{2}$$

By considering the characteristics of the sea waves on a specific site, the minimum required duration time, t_d, should be defined to develop the storm profile. In this study a duration of 100 second is adopted to ensure that a wave profile with all possible wave heights is developed during the storm.

3. DEVELOPED METHODOLOGY

The novel methodology developed in this study will contribute as a powerful tool for hydrodynamic analysis of marine structures during storm conditions to evaluate their critical performance. The outcome of the proposed methodology will assist designer and vessel operators during harsh conditions to have a better view of the structural behavior which is encountering the storm. This methodology in general is illustrated in **Figure 2.** To evaluate the performance of marine floating structures in severe environmental conditions, it is necessary to analyse the stochastic dynamic behavior of the structure in various sea states. However, an extensive number of time-domain simulations are essential to evaluate extreme loads affecting the system.

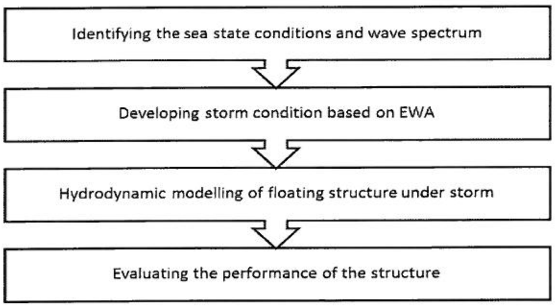

Figure 2 Sequence of the developed methodology

This study is devoted to developing a novel methodology for hydrodynamic analysis of the floating structure under storm conditions. The approach is capable of generating the essential data for investigating the behavior of structure stochastically and it can be used as the basis for future statistical analysis efficiently. For this purpose, EWA method is considered to develop ICNW function for two different reasons: (1) to minimize the duration of the hydrodynamic time-domain simulation by representing a unique wave train function, (2) to reduce the extent of EDP data necessary for performance analysis of the structure. Therefore, the dynamic behavior of the system can be evaluated stochastically with only one simulation time which is more efficient computationally. In order to develop a storm profile, firstly a number of different sea states should be defined according to their sea spectrum. EWA approach will then apply to design intensifying wave train for harsh environment that represents storm situation. To clarify all relevant hydrodynamic theories applied in this study the fundamentals of EWA method is discussed in **section 2. Figure 1** presents an overview of the hydrodynamic analysis for generating ICNW function based on EWA. In the next stage, the effect of storm-based loads on the structures will be assessed. The final response results are then adopted for estimating the EDP for each storm condition to evaluate performance of the structure. The results show the possible situation that the structure can exceed survival conditions during storm.

4. APPLICATION OF THE DEVELOPED METHODOLOGY: A CASE STUDY

4.1 Scenario Development

To demonstrate the application of the developed methodology, a case study is adopted for performance analysis of a Sevan 1000 Floating Storage Unit (FSU) encountering storm. This unit was intended to operate on the Mariner field in the United Kingdom sector of the North Sea (Hanssen 2013). Previously, a number of conventional studies were carried out to investigate the hydrodynamic characteristics of this unit focusing on its performance (Anundsen 2008; Hanssen 2013), however they did not consider the harsh environmental and storm conditions. In this study, Sevan Hull encounters a pre-defined storm profile related to extreme environmental loads to evaluate the dynamic behavior of the structure. According to Brindley and Comley (2014), a number of catastrophic failures have occurred to these structures operating in the North Sea, due to the harsh environmental conditions. This highlights the need for developing a robust methodology that evaluates the performance of the structure more realistically in storm conditions.

4.1. Developing ICNW Storm Profile

In order to develop the ICNW storm wave profile, eleven sea state thresholds are considered. The sea states required to develop the ICNW profile are adopted from the available data received from the North Sea. To model the random and irregular nature of sea wave elevations, JONSWAP spectrum is used for different sea states. Each sea state represents a spectrum for different levels of storm. The survival limits considered in this study for FSU operation are based on the suggestions by Anundsen (2008). Using the ICNW profile and considering these operational safety limits, hydrodynamic analysis of the FSU is conducted to evaluate the performance of the structure under different levels of storm condition. Moreover, to show the advantage of this method in reducing the simulation time, the superimposed conventional Random Sea Elevation (RSE) is compared with ICNW, as presented in Figure 3. As illustrated in the figure, the RSE profile requires more simulation time to observe extreme wave heights. It is usual to run numerical simulation of hydrodynamic analysis for 3-hours for each sea state to observe desired

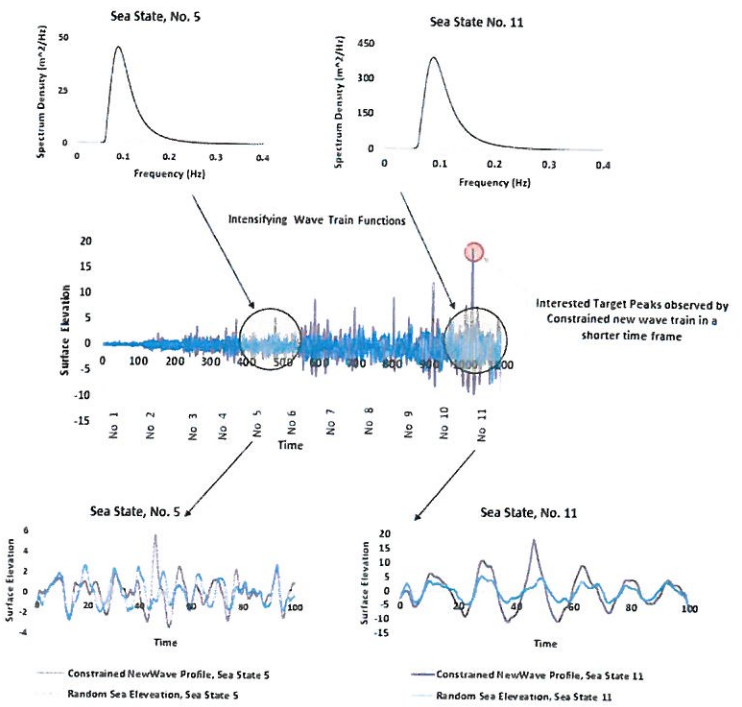

Figure 3. Developed ICNW storm profile based on eleven different sea state for the North Sea site

extreme wave heights as recommended by (Chen and Moan 2004; Ren et al. 2015; Veritas 2007). For each sea state, 11 different 3-hours simulations are needed to be carried out in order to obtain a realistic representation of a storm. However, to generate ICNW profile for this site, only 1100 seconds of simulation time is required to observe different levels of extreme storm conditions in one individual simulation for hydrodynamic analysis. As an example, sea states five and eleven are illustrated individually in Figure 3 to emphasize differences between these two approaches and how the time domain in ICNW reaches its highest level in a much shorter time. In the figure, the wave spectrum for these sea states is shown above the surface elevation profile providing a qualitative representation of Eq. 1 and Eq. 2.

4.2. Hydrodynamic Analysis

In this study, *OrcaFlex* software is used to conduct the hydrodynamic analysis. ICNW wave profile is entered manually in the software to conduct the simulation process and time-domain analysis. The simulations are then carried out to investigate performance of the FSU. To explore the dynamic behaviour of the FSU in detail, the most critical angle of attack is considered for the performance analysis. From the conducted simulations, it is found that 45 degree has the most extreme response which adopted for the performance analysis. To evalaute the dynamic behaviour of FSU in extreme condition, the time history of Heave angle extracted from the results is represented in **Figure 4.** Also, the relevant survival limit states is illustrated in the plot, to show the effect of intensifying level of storm in each sea state. When the storm reaches the significant wave height of 12.56 meters, which is the 9th level in the designed wave profile, the heave motion exceeds the limit of survival condition. In general the vessel can survive a wide range of incident waves below the 9th level, being in a safe zone.

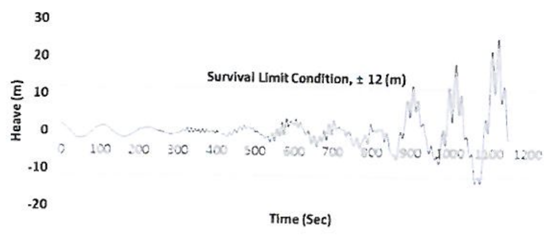

Figure 4 Time history of Heave angle under storm condition.

A new approach for hydrodynamic analysis of marine floating structure has been developed in this paper with the aim of elaborating performance of the object during a storm. The methodology starts with the design of a user-defined storm profile by superimposing different sea states through intensifying wave train function in. This approach has the advantage of evaluating the hydrodynamic response of the structure encountering a storm in a single time frame. The advantages of the proposed framework were demonstrated through simulating an FSU in storm conditions. The results of the analysis indicate that the structure will exceed the survival condition if the storm passes the significant wave height level of 12.65 meter. In addition, the global trajectory of the vessel for transition and rotational response demonstrates the effect of storm on the performance of the structure. The results of this study highlight that the proposed methodology can be used as a useful framework for future risk and reliability analysis considering the dynamic behavior of a floating structure to minimize possible failures such as capsizing. This analysis enables designers and operators to more efficiently assess the reliability of the structures encountering extreme sea state conditions, in a shorter duration of time.

Acknowledgments

The Authors acknowledge the support of the ARC Research Training Centre for Naval Design and Manufacturing (RTCNDM) in this investigation. The RTCNDM is a University-Industry partnership established under the Australian Research Council Industry Transformation grant scheme (ARC IC140100003).

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