ARTICLE IN PRESS

Ocean Engineering xxx (2017) 1–7

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

A novel approach to safety analysis of floating structures experiencing storm

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A R T I C L E I N F O

Keywords:
Harsh environment
Floating structures
Reliability
Wave analysis

A B S T R A C T

Marine floating structures may experience harsh environmental conditions during their operational life span. In order to maintain a safe operation, it is necessary to evaluate the performance of the structure in extreme conditions such as storm. Previously, various approaches were introduced to analyse the response of an offshore structure in different sea states. However, the proposed methods are computationally time consuming requiring a large number of simulations and it is not the most realistic approach to analyse the dynamic behavior of a structure by separately replicating each level of storm. In this study, a novel numerical model of storm is developed based on Endurance Wave Analysis (EWA) concept. The developed model will reduce the computational cost to only one storm record of 1100 s taking into account the randomness of sea environment. The application of this method is demonstrated by assessing a Floating Storage Unit (FSU) responses encountering a storm in the North Sea. The results show that the response of structure is likely to exceed the survival condition while encountering storm level 10 corresponding to a wave height of 12.56 m. The proposed method is beneficial for future risk and reliability analyses that require a great deal of data.

1. Introduction

One of the prerequisites for improving the safety and reliability of offshore structure is to evaluate dynamic behavior of a structure in severe environmental loads such as storm condition, which the structure might become exposed during its lifetime (Arzaghi et al., 2017; Abaei et al., 2017; Bhandari et al. 2015, 2016; Diznab et al., 2014; Zeinoddini et al., 2012). Environmental loads, including waves loading, play a dominant role in the design of offshore structures in various stages of construction, transportation, installation and operation (Zeinoddini et al., 2012). Sea waves has a random nature which cause non-linear forces on the floating structures. Therefore, time-history analysis will become necessary to obtain more accurate results for the structural response during extreme loading conditions. Catastrophic hurricanes such as Ivan, Katrina and Rita in the Gulf of Mexico highlighted the importance of considering the impact of extreme environmental loads on all types of offshore structures. Consequently, there has been an increasing focus on the analysis of extreme waves in the past few years (Cox et al., 2005; Hennig, 2005; Kim and Zhang 2009 Wang et al., 2011). Conventional dynamic analysis of marine structure is a time consuming approach as it needs a longer simulation time to generate data for conducting statistical analysis (Agarwal and Manuel, 2009). For instance, Chen and Moan (2004) carried out a study with twenty different 3-h simulations to generate time-domain responses. Later, Ren et al. (2015) implemented 84,480 times of 1-h short numerical simulations for investigating the performance of a Spar–Torus-Combination (STC) system. It is therefore necessary to rely on more optimum solutions for dynamic analysis of structure to reduce the large time of simulations. Recently, Endurance Time Analysis (ETA) method is developed by Riahi and Estekanchi (2010) and later improved by Riahi and Estekanchi (2010) to reduce the computatioanl cost. The basic concept of this method was first introduced by Estekanchi et al. (2004) in which the structure is exposed to an artificial intensifying acceleration time history. Results of the studies carried out by Estekanchi et al. (2007, 2011); 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. It should be noted that the principles of structural performance under seismic loads and sea wave excitaions are so-called similar to each other, regardless of the fact that the time duration of storm loads is about several hours compared to seismic loads that take place in a short time (5–10 s) (Zeinoddini et al., 2012). According to these differences, Endurance Wave Analysis (EWA) method has beed introduced by Diznab et al., (2014); Jahanmard et al. (2015); Zeinoddini et al. (2012) in order to evaluate non-linear dynamic analysis of marine floating structures subjected to irregular wave forces.

This paper aims at developing a novel approach for developing storm

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https://doi.org/10.1016/j.oceaneng.2017.12.011
Received 18 September 2017; Received in revised form 9 November 2017; Accepted 6 December 2017
Available online xxxx

Please cite this article in press as: Abaei, M.M., et al., A novel approach to safety analysis of floating structures experiencing storm, Ocean Engineering (2017), https://doi.org/10.1016/j.oceaneng.2017.12.011

condition to evaluate performance of marine floating structures. Analysing dynamic behavior of the structure is the main key point for examining the performance of the vessel in harsh environment. This will clarify that as the structure subjected to the storm, when the behavior of the vessel will be in safe condition or when it will exceed its survival limit conditions. For this purpose, intensifying dynamic modelling of the structure based on EWA 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 types of marine structure such as commercial displacement vessels, mooring structures, and marine renewable devices, which is subjected to storm. Also, it is helpful for future risk and reliability analysis of these structure for improving safety of the marine structure in harsh environment.

The remainder of this paper is divided into the following sections; Section 2 explains the concept of EVA for developing different level of storm condition considering only one simulation time. Section 3 discusses the developed methodology and its elements. Section 4 presents the application of the methodology in a real case study and Section 5 highlights the main findings of the present work providing few recommendations for possible future studies.

2. Endurance Wave Analysis

The EWA is a simulation-based approach to evaluating the hydrodynamic performance of offshore structures when encountering a wave profile with stepwise increases of wave height. This method that simulates storm conditions is 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 will then be defined as Intensifying CNW (ICNW). Accordingly, this approach can be adopted for simulating the increasing trend of storms levels over time, which even 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 ability of considering spectral features of the sea state and different significant wave heights and frequencies in a single dynamic analysis, taking into account the 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 the basics of this concept and progressive analysis methodology for assessment of marine structures under extreme waves can be found in (Diznab et al., 2014; Jahanmard et al., 2015; Zeinoddini et al., 2012).

Fig. 1 illustrates the three different levels of ICNW profile with different sea states that are 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 storm the sturcture will exceed its survival limit causing 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 and there will be no choice for the crew rather 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)

CNW 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 analysis time, CNW has the 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 researches (Diznab et al., 2014; Jahanmard et al., 2015; Zeinoddini et al., 2012). Further details about CNW and its application is provided by Taylor et al. (1997).

To model of the storm condition, CNW is used for generating the Intensifying Wave Train Functions (IWTFs). 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 kth CNW profile$\eta_{R_k}(t)$, represents the sea state k ($1 \le k \le m$) which is itself constructed based on the wave energy density spectrum $S_k(\omega)$ at a specific site. The kth CNW covers a time period of $(k-1)\times t_d < t < k \times t_d$. $S_k(\omega)$ By stepwisely increasing the level of wave spectrum 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 last stepwise profile through the sea states 1 to m. This assists in conducting risk escalation assessment since the performance of the structure can be evaluated when the storm condition exceeds the operational and survival limits of a marine floating structure. 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):

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