Ocean Engineering 156 (2018) 167–178

Contents lists available at ScienceDirect

Ocean Engineering

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

A robust risk assessment methodology for safety analysis of marine structures under storm conditions

Mohammad Mahdi Abaei [a], Ehsan Arzaghi [a], Rouzbeh Abbassi [a,*], Vikram Garaniya [a], Shuhong Chai [a], Faisal Khan [a,b]

[a] National Centre for Maritime Engineering and Hydrodynamics, Australian Maritime College, University of Tasmania, Launceston, Tasmania, Australia
[b] Centre for Risk, Integrity and Safety Engineering (C-RISE), Process Engineering Department, Memorial University of Newfoundland, St. John's, NL A1B3X5, Canada

ARTICLE INFO

Keywords:
Risk assessment
Safety analysis
Marine structures
Harsh conditions

ABSTRACT

Accidents involving vessels and/or offshore structures (henceforth referred to as marine structures) may pose high financial, environmental and fatality risk. To effectively manage these risks a methodical approach is required to model accident load and the stochastic behaviour of the marine structure that are arising from storm effects. This paper introduces a proactive framework that identifies and considers all the initial relevant risks. Compared to the conventional approaches that rely on precursor data for accident modelling, the developed methodology utilizes the critical stochastic variables directly from the hydrodynamic analysis of the floating structure. For this purpose, a novel numerical model is proposed to replicate a storm based on Endurance Wave Analysis (EWA) method. This approach reduces the computational cost (time and load) of the simulations. The critical stochastic variables are subsequently used in Bayesian Network (BN) to develop the risk model. The EWA and BN based integrated methodology assists in better understanding of accident causation and associated risk in changing operational conditions. The application of the methodology is demonstrated through a Floating Storage Unit (FSU) experiencing capsizing scenario.

1. Introduction

Failure in operations conducted in the marine environment may pose various major risks in terms of environmental pollution and loss of assets for companies. In the majority of cases, such as exploration of oil and gas reserves and marine transportation, this industry also engages with human life, where accidents may cause human casualties. Therefore, a great deal of research on the improvement of marine safety is carried out to mitigate the associated risks. It is also necessary to take into account the process of risk escalation in a more realistic way rather than relying only on either precursor data or expert judgments. This requires a comprehensive approach when it comes to accident modelling and risk analysis of marine floating systems. However, due to irregularities in the sea environment, the nonlinear dynamics of floating system should be taken into consideration when developing a reliable measure of safety. Catastrophic hurricanes such as Ivan, Katrina and Rita in the Gulf of Mexico highlighted the importance of considering the impact from extreme environmental loads on all types of offshore structures. A large number of marine accidents, such as extreme responses of vessels encountering rough sea waves, have occurred due to harsh environment. For instance, the Mediterranean Sea migrant shipwreck and the Demas Victory a Dubai-based supply ship that sank off the coast in rough seas (Townsend, 2015). These accidents resulted in at least 150 casualities reflecting the detrimental consequences of such disasters on human life. Review of recent maritime disasters confirms that there is a lack of a framework that enables making the optimum decision in case floating structures are about to capsize (Montewka et al., 2014). The critical question is how the safety of the crew on-board can be improved during a marine accident, and how they should manage the situation to survive. That is, if the operating crew were to be supported with a risk-assessment tool that uses the responses of the vessel in different conditions for predicting survivability, they would be able to decide whether to ask for rescue or immediately evacuate the vessel before the accident occurs.

Most of the existing risk assessment models are based on historical data obtained from previous marine accidents, and thus they can be considered reactive instead of proactive (Montewka et al., 2014). For example, Papanikolaou and Eliopoulou (2008) and Konovessis and Vassalos (2008) conducted a risk evaluation study based on regulations and

* Corresponding author.
E-mail address: Rouzbeh.Abbassi@utas.edu.au (R. Abbassi).

https://doi.org/10.1016/j.oceaneng.2018.02.016
Received 11 May 2017; Received in revised form 10 December 2017; Accepted 4 February 2018

Nomenclature

Subscripts

ICNW	intensifying constrained new wave model
EWA	endurance wave analysis
H_s	significant wave height
T_p	peak spectral period
$S(\omega)$	sea spectrum
$\eta_{R_k}(t)$	k^{th} step sea wave profile
t_d	constant storm period time
η_{ICNW}	surface elevation of ICNW
α_k	crest elevation
H_{Max_k}	most probable maximum wave height in the sea state k
N_W	number of wave cycles during the storm period (t_d)
β	coefficient that refers to maximum wave height in each sea spectrum
$\rho_k(t)$	unit new wave autocorrelation function
$\dot{\rho}_k(t)$	slope new wave autocorrelation function
θ_m	maximum angle of positive stability
θ_s	static angle of inclination after damage
m_{2k}	second spectral moment
σ_k	variance of the wave energy spectrum
$Pa(X_i)$	the parent set of variable X_i
$EU(d_i)$	expected utility
d_i	decision alternative
$P(H_s)$	Long-term probability distribution of significant wave height
$P(H_{storm})$	Probability of different level of storm condition encountered by ICNW profile
$P(FR(\theta_n))$	Flooded Response in nth degree
$P(FR(\theta_n))$	Intact Response in nth Degree
$FU(\theta_n)$	Flooded Utility in nth Degree
$IU(\theta_n)$	Intact Utility in nth Degree
$FD(\theta_n)$	Flooded Decision in nth Degree
$ID(\theta_n)$	Intact Decision in nth Degree
FSU	floating storage unit
CPT	conditional probability table
PDF	probability density function
GEV	generalized extreme value
MLE	maximum likelihood estimation
θ	roll angle

worldwide accident experiences, from 1994 to 2004, respectively, to maximize marine transportation safety. With the similar objective, a number of studies have been conducted by previous researchers for improving the level of safety in floating structures (Guarin et al., 2009; Mermiris et al., 2008; Papanikolaou et al., 2010, 2012; Trucco et al., 2008). Recently, Montewka et al. (2014) introduced a systematic framework to estimate the risk for maritime transportation systems with regard to risk escalation based on proactive approaches. However, their method did not consider the associated risks that arose due to harsh environment such as extreme wave loads. There is also no robust tool available to investigate the effect of floating systems responses on human actions on-boards during storm conditions. This motivation will then be reason to investigate the causality of possible accident scenarios in marine harsh environment by the means of advanced probabilistic model. For this purpose, it is essential to integrate the recent approaches of non-linear dynamic analysis of floating structures with advanced probabilistic models to develop a strong risk assessment tool for improving the safety of marine operations in a harsh environment.

For the sake of risk aseessment and decision making, application of several methods were found in the literature among which Maximum Likelihood Estimation (MLE) and Bayesian statistics are recommended for reliability analysis (Sørensen, 2004). To perform a risk-based decision making, Bayesian Network (BN) are increasingly used due to their advantages over other methods such as Fault Tree Analysis (FTA) as discussed by Khakzad et al. (2011), Friis-Hansen (2000), Straub (2004), Tavner et al. (2007). There are three main reasons that Bayesian approaches have been adopted by previous researches. Firstly, this probabilistic model is a promising tool in risk and reliability engineering that allows the comprehensive reflection of available knowledge about the process (Arzaghi et al., 2017; Abaei et al., 2017; Groth et al., 2010; Khakzad et al., 2011; Montewka et al., 2014; Musharraf et al., 2014; Trucco et al., 2008). Secondly, in comparison to other tools such as Analytic Hierarchy Process (AHP), BN performs better in solving decision-making problems when extended to an Influence Diagram (Daniel, 2009; Friis-Hansen, 2000). Thirdly, in a Bayesian approach, it is also possible to convert continuous random variables into a discrete space, enabling the inference of more complicated stochastic relationships amongst many parameters (Friis-Hansen, 2000). That is, each variable involved in the problem can be analyzed explicitly rather than in a binary space (true or false).

To develop a risk assessment and decision-making framework, an optimum method is required for generating the data that represents the stochastic behaviour of the structure in storm condition. 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). As an example, Chen and Moan (2004) carried out a study with twenty different 3-h time-domain simulations to extract the time series of the structure responses. It is therefore necessary to rely on a method that reduces the simulation time for more efficent analysis. Recently, Endurance Time Analysis (ETA) method was developed by Riahi et al. (2009) and later improved by Riahi and Estekanchi (2010) to reduce the computational cost of simulation times. Engineering Demand Parameters (EDPs) such as stress in structural members were investigated through the time-domain records (Zeinoddini et al., 2012). Results of the studies carried out by Estekanchi et al. (2007, 2011) and Riahi and Estekanchi (2010) demonstrate the efficiency and accuracy of this method over conventional methods in the dynamic evaluation of structures during natural disasters such as earthquakes.

Therefore, considering BN as a probabilistic model and ETA as an efficient tool for dynamic analysis of the structure, an integration of theses method should be provided for effective risk assessment. Based on this, this paper aims at developing a robust methodology to improve safety during marine operations. The study will focus on developing a hydrodynamic model to simulate a real condition of the vessel while encountering a storm. Therefore, other events such as loss of communication or loss of engine are not considered in the proposed framework.

Since the dynamic behaviour of the structure is the key point of a marine accident, this methodology utilizes the stochastic nature of the critical response variables of a floating unit. The critical response variables are integrated in the BN to model the structure's failure. The developed BN is then extended to an Influence Diagram (ID) for risk assessment purposes. To illustrate the effectiveness of the methodology, a Floating Storage Unit (FSU) is considered.

The remainder of this paper is divided into the following sections; Section 2 explains the concept of critical response variables in evolving operational conditions. Section 3 an introduction to BN and ID is presented. Section 4 discusses the developed methodology and its elements. Section 5 demonstrates the application of the methodology in a real case study and Section 6 concludes the paper providing the main findings and recommendations for possible future studies.