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Condition monitoring of subsea pipelines considering stress observation and structural deterioration

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ABSTRACT

The increasing demand by the world for energy has prompted the development of offshore oil and gas pipelines as the mode of transportation for hydrocarbons. The maintenance of these structures has also gained much attention for research and development with novel methodologies that can increase the efficiency of integrity management. This paper presents a probabilistic methodology for monitoring the condition of offshore pipelines and predicting the reliability when consideration is given to structure deterioration. Hydrodynamic simulations are carried out for an offshore pipeline to obtain the time history data from which the stress ranges are computed using a rainflow counting algorithm. To model the fatigue damage growth, a Bayesian Network (BN) is established based on a probabilistic solution of Paris' law. Corrosion effects are also incorporated into the network providing a more realistic prediction of the degradation process. To demonstrate the application of the proposed methodology, a case study of a Steel Catenary Riser (SCR) subjected to fatigue cracks and corrosion degradation is studied. This method provided the growth rate of a crack during its lifetime during which the safety of operation can be assessed and efficient maintenance plans can be scheduled by the asset managers. The proposed method can also be applied by the designer to optimize the design of pipelines for specific environments.

1. Introduction

Subsea pipelines are mainly used in the oil and gas industry to transport hydrocarbons from production wells to onshore locations or offshore facilities. These structures are generally safe and reliable due to being designed to withstand severe loading conditions of the environment as well as the internal impacts from the transported medium. Failure rate of subsea pipelines is reported to be relatively lower than for other pipeline systems (Davis and Brockhurst, 2015). However, certain unavoidable factors can cause reduction in the capacity of the structure, resulting in earlier failure (Breton et al., 2010). Degradation process of the structural components such as fatigue damage and external corrosion caused by built up stress, due to cyclic load generated by ocean waves and current flow, are among the factors leading to pipeline failure. The failure of subsea pipeline may generate destructive and catastrophic consequences with economic losses, environmental pollution as well as threats to human life. An example of pipeline failure is the Deepwater Horizon accident in 2010 in the Gulf of Mexico which resulted in a direct economic loss of over 1 billion USD and extensively harmed many marine species in the area (Lin et al., 2014).

Prevention and mitigation measures should be considered to reduce the likelihood of pipeline failures and its overall risk. Frequent maintenance can ensure a reliable operation, however, the high costs associated with the inspection and maintenance of pipelines located further and deeper from shore has led asset owners to seek optimal monitoring plans and maintenance scheduling methods. Condition monitoring and risk-based maintenance planning methods have been utilized in the oil and gas and processing industry to generate cost-effective strategies for minimizing the probability of pipeline failure and mitigating the associated risk (Aljaroudi et al., 2016; Arzaghi et al., 2017; Breton et al., 2010; Li et al., 2016). The developed methods enable consideration of uncertainty of the influencing parameters and system failure. Important infrastructure quantities such as the stress experienced by critical structural members should be monitored to reduce the uncertainties associated with maintenance strategies (Friis-Hansen, 2000). A condition monitoring system integrated with a pipeline leak detection system (LDS) is developed by Aljaroudi et al. (2016) by using the limit state function to monitor time-dependent failure due to corrosion. The associated risk of failure and expected financial cost are then estimated so that asset managers can allocate resources necessary for maintenance. Monitoring the condition of the pipeline can also be conducted with the assistance of a numerical software OrcaFlex which is a known tool in dynamic motion analysis (Orcina, 2014). Research on the dynamic behaviour of offshore pipeline

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conducted by Chibueze et al. (2016) investigated the fatigue on a SCR using OrcaFlex simulation.

Analytic Hierarchy Process (AHP) was used by Dey and Gupta (2001) to identify the factors influencing failures of a pipeline followed by an analysis of the effects of the probability of risk factors on the pipelines. This technique reduces the subjectivity of the decision making process for selecting inspection methods. Kumar and Maiti (2012) highlighted the limitation of AHP, being unable to take into consideration certain interdependencies between risk contribution factors and maintenance policies and feedbacks. They introduced a method that combines fuzzy intervals and Analytic Network Process (ANP) for conducting risk-based maintenance. An improved methodology was proposed by Lin et al. (2014) based on the traditional Fault Tree Analysis (FTA) for a reliability assessment during the design of subsea pipelines. This method, termed as Failure Expansion Tree (FET), aims at including exclusive failure events to uncover potential rare events eliminating subjective risk factors. Although FET increases the accuracy of risk analysis, it does not include the dynamic factors such as time dependent elements into the model due to its static nature (Khakzad et al., 2013). A study by Li et al. (2016) investigated risk associated with leakage failure of submarine oil and gas pipelines where traditional method such as Bowtie was mapped into BN to reduce its limitation. It is proved that BN is an effective probabilistic model for the analysis of problems where dynamic parameters are important.

BNs consist of a group of probabilistic models representing the causal relationships and conditional dependencies between the variables in the model. They have been widely used by researchers for probabilistic risk assessment (PRA) (Bhandari et al., 2015, 2017; Yeo et al., 2016; Weber et al., 2012) and risk-based maintenance planning of offshore and petroleum systems (Abbassi et al., 2016; Pui et al., 2017). Li et al. (2016) carried out a quantitative risk analysis using BN on leakage failure of submarine pipelines by mapping bowtie models into BN using evidence from observations and previous accident data for updating the failure probabilities. Arzaghi et al. (2017) and Friis-Hansen (2000) investigated Reliability Based Maintenance (RBM) methods associated with fatigue crack growth on subsea pipelines and offshore jacket structures respectively using BN. An optimal maintenance plan was generated by constructing a probabilistic deterioration model and extending it to an influence diagram for selecting the optimal maintenance plan. The model developed by Friis-Hansen (2000) was improved by Arzaghi et al. (2017) with the addition of multiple repair alternatives based on the damage growth model.

This study presents a novel methodology for predicting the health condition of subsea pipelines deteriorating due to corrosion effects and fatigue damage. The stress profile of the structure is assessed through hydrodynamic analysis for a wide range of sea states to replicate the operational conditions. Probability density functions of stress range are developed using maximum likelihood estimation and a probabilistic solution of the Paris' Law is adopted to establish a BN model for predicting the fatigue crack growth of the structure. The developed BN integrates the effect of corrosion into the fatigue growth model to represent the degradation process comprehensively. To demonstrate the application of the method, the failure probability of a corroded SCR is estimated in a case study.

1.1. Bayesian Networks

Bayesian Networks (BNs) are probabilistic models presented by directed acyclic graphs (DAGs) consisting of a set of nodes representing random variables, a set of arcs representing the causal relationships between the variables and conditional probability tables (CPTs) (Barber, 2012; Zhi et al., 2016). Unlike the traditional bow-tie method which models the relationship of each random variable in a chronological sequence, BN models the correlation within a set of variables which could be continuous or discrete in time (Neapolitan, 2003). The joint probability distribution of all random variables in a BN is estimated using the chain rule in Eq. (1) which expands the joint distribution into the product of conditional probabilities.

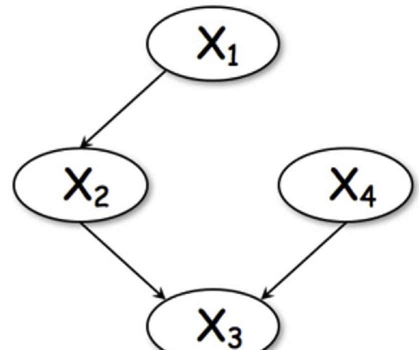

Fig. 1. Schematic of a Bayesian Network.

$$P(U) = \prod_{i=1}^{n-1} \boldsymbol{P}\left(\boldsymbol{X_i}|\boldsymbol{X}_{i+1}, \ldots, \boldsymbol{X_n}\right) = \prod_i P\left(\left(\boldsymbol{X_i}|pa(\boldsymbol{X_i})\right)\right) \tag{1}$$

where $U = (X_1, X_2, ..., X_n)$ is a set of random variables and $pa(\boldsymbol{X_i})$ indicates the set of parent variables of $\boldsymbol{X_i}$. When new information or evidence such as $e = (e_1, e_2, ..., e_m)$ is available for any node, the joint probability distribution in the BN can be updated using the Bayes' theorem, stated in Eq. (2) through which the posterior distribution can be determined.

$$P(U|e) = \frac{P(U, e)}{P(e)}. \tag{2}$$

where $P(U|e)$ is the posterior distribution indicating the probability of U given new information e. Evidence can be termed as 'hard evidence' if exact information is given for the variable, or it could be 'soft evidence' if expressed in a likelihood form in terms of the state of the variables (Trucco et al., 2008). Fig. 1 shows a BN in which node X_2 is referred as the child node of X_1. Both X_1 and X_4 have no parent node therefore being called root nodes and those without any children are named leaf nodes. provides A more detailed explanation of BN concepts and its inference algorithms is provided by Friis-Hansen (2000).

2. Degradation modelling methodology

The developed methodology in this study aims at predicting the probability of failure for subsea pipelines under the simultaneous influence of cyclic loads and corrosion. The developed model provides a tool for asset managers and operators to accurately predict the reliability of the structure enabling them to determine whether maintenance is required. In addition, it will allow the designer to analyse the safety of the pipeline operation based on the sea state of the site of interest and optimize the design, if necessary. Fig. 2 illustrates different steps of the developed methodology with the important procedures of each step.

2.1. Hydrodynamic analysis

To estimate the reliability of the subsea pipeline in an offshore location, the responses of the structure which reflect the extent of experienced stress should be analysed. A typical SCR is modelled as the operating structure which is subjected to fatigue damage. The model illustrated in Fig. 3 consists of four sections which are a flex joint, a stake, a riser pipe and a flow pipe. The critical parts of the structure, which are those most prone to fatigue damage, should be assessed with regards to experienced stress.

Numerical simulation is important for providing more realistic data in predicting structure reliability. Therefore hydrodynamic analysis for the model was carried out in *OrcaFlex* software (Orcina, 2014) with