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Integrated ARMA model method for damage detection of subsea pipeline system

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ABSTRACT

An integrated ARMA model algorithm is developed in this study for the structural health monitoring (SHM) of subsea pipeline system. In which, the partition and normalization procedure is firstly employed in signal pre-processing to remove the influence of various loading conditions, the auto-correlation function of the normalized signal is utilized as a substitute of analysis input to overcome noise effect and avoid the bias in Autoregressive Moving Average (ARMA) model fitting caused by noise disturbance as well. Then, Partial Auto-correlation Function (PAF) method is employed in building optimal ARMA model. With which Autoregressive (AR) parameters serving as damage feature vector, a damage indicator (DI) based on the Mahalanobis distance between ARMA models is defined for damage detection and localization. Dynamic vibration of subsea pipeline system under ambient excitations is numerically simulated in ANSYS software and the acceleration responses of pipeline in various damage cases are analyzed utilizing the proposed integrated method. In numerical study, the finite element (FE) model of a subsea soil-pipeline-fluid system is developed and the undersea hydrodynamic force acting on the pipeline is derived based on Spectral Analysis Method. Finally, the proposed method is proved to be robust and very sensitive to damage. It provides accurate identification of damage existence and damage locations with high time efficiency. Therefore, it can be used for the online SHM of subsea pipeline structures and other civil structures.

1. Introduction

It has been commonly acknowledged that pipelines are the most efficient way of transporting oil and gas products. With the booming offshore oil and gas industry, thousands of kilometres of pipelines have been installed at various water depths and on all sorts of soil conditions. The economy of the whole world is heavily dependent upon an extensive network of pipelines to transmit the energy sources. Pipelines are susceptible to a wide variety of damage and aging defects. Some of the most common causes of failure in pipelines are corrosion, stress cracks, seam weld cracks, material flaws, and externally induced damage by excavation equipment, etc. Thousands of accidents have evidenced the consequence of pipeline failure is disastrous both economically and environmentally. Therefore, maintaining its structural integrity and reliability is essential to the world's energy requirements [1].

Currently, in the pipeline industry, a single method for detecting or monitoring damage in a pipeline does not really exist. Instead, a combination of several different techniques is usually implemented in industries. For the oil and natural gas pipeline industry, destructive and non-destructive inspection techniques are commonly used together to ensure the integrity of transmission lines. When the geometry of the pipeline permits, non-destructive techniques, such as magnetic flux method and ultrasound wave method, are primarily used to ensure the structure's integrity. However, such methods are limited by the size of the device available. One possible solution to these limitations is a more reliable and more economical monitoring system that involves a damage detection process known as structural health monitoring (SHM). The process of SHM involves the use of an array of sensors installed over a structure to perform periodic or online observations of the system's dynamic response. The observations are then analyzed to determine if damage exists in the system and the current status of the system's health. After an extreme event, such as a pipeline experiencing a severe earthquake, a SHM system can be implemented "for rapid condition screening and to provide, in near real time, reliable information regarding the integrity of the structure" [2]. Ultimately, the output from a SHM system allows engineers to perform a quantitative evaluation of the structural conditions and assess its ability to safely and reliably perform its designed function. The SHM technology is increasingly being

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realized by the pipeline industry as a possible method to improve the safety and reliability of pipeline structures and thereby minimize the failure occurrence possibility and operation cost.

The damage detection plays the most pivotal role in the SHM process. In recent years, the vibration based damage detection technique has been recognized and intensively studied as a promising tool for monitoring structural conditions and detecting structural damages. The technique is undergoing continuous improvement in analysis and instrumentation. The basic concept behind it is that modal parameters (notably frequencies, mode shapes, and modal damping) are functions of the physical properties of the structure (mass, damping and stiffness). Therefore, changes in the physical properties, such as reduction in stiffness resulting from the onset of cracks or loosening of connection, will cause detectable changes in these modal properties [3]. The vibration-based damage identification methods can be classified into two categories, namely, the modal-based damage detection techniques [4,5] and the time-series based techniques.

In practice, it is hardly possible to artificially excite the pipelines in deep water to measure the input or the output signals, which results in the accurate identification of the offshore pipeline system modal parameter more difficult. Therefore, a practical vibration-based damage detection technique should be applicable to the ambient vibration of pipelines under marine environment. The time-series based damage detection techniques are capable of achieving the first two steps of damage detection, namely, detecting the damage existence and damage location. This type of methods accomplish structural damage detection through the direct analysis of the online measured response signal involving no modal parameter identification, which makes the realization of this type of methods simpler and faster. Therefore, it is feasible to apply such methods to the continuous monitoring of in-service structures. Research on this area has become very hot during the last decade, with many new methods welled up. Among the time-series related methods for structural damage detection, the representative ones include Wavelet analysis method and Autoregressive Moving Average (ARMA) model method. Kim and Melhem [6] classified the wavelet-based damage detection methods into three categories: (1) variation of wavelet coefficients; (2) local perturbation of wavelet coefficients in a space domain; and (3) reflected wave caused by local damage, and provided an extensive review of the research on each aspect, respectively. Then, more specific applications, namely, crack detection of a beam and mechanical gear and roller damage were presented. Reda Taha and Lucero [7] proposed integrating wavelet multi-resolution analysis (WMRA) and artificial neural networks (ANNs) for intelligent structural health monitoring (ISHM), and demonstrate this method to quantify evidence of damage levels in structures by means of the computations of fuzzy set theory. Sun and Chang [8] developed a statistical pattern classification method based on Wavelet packet transform (WPT) for structural health monitoring. In which, a novel condition index, the wavelet packet signature (WPS) and its thresholds for damage alarming was established using the statistical properties of the signal from successive measurements. Han et al. [9] proposed a damage detection index called wavelet packet energy rate index (WPERI), based on the WPT components of the structural vibration data, for damage detection of beam structures. Ren and Sun [10] defined wavelet entropy, relative wavelet entropy and wavelet-time entropy as damage feature to detect damage occurrence and damage location with a reference signal simultaneously measured from any undamaged location of the structure. Yun et al. [11] proposed a decentralized damage identification method using wavelet signal analysis tools embedded on wireless smart sensors, in which the wavelet entropy indices calculated based on discrete wavelet coefficients of acceleration signal in sensors were used for damage identification. The proposed index was experimentally validated as a damage-sensitive signature that can be obtained both at different spatial locations and time stations to indicate existence of damage. Carden and Brownjohn [12] proposed a statistical classification algorithm based on analysis of a structure's response. The time-series responses were fitted with Autoregressive Moving Average (ARMA) models and the ARMA coefficients were fed to the classifier which was capable of learning in an unsupervised manner and forming new classes when the structural response exhibits change. Accordingly, different structural damage states were identified. Gul and Catbas [13] utilized the time series modelling methods, i.e., ARMA model method, in conjunction with Mahalanobis distance-based outlier detection algorithms to identify different types of structural changes on different structures through the analysis of ambient vibration data. Wang and Ong [14] developed a damage detection scheme using autoregressive-model-incorporating multivariate exponentially weighted moving average (MEWMA) control. In which, special procedures to allow for the uncertainty involved in process parameter estimation as well as those for control limit determination were proposed for structural damage detection application. Despite of rapid development of the time-series based methods, there are several problems need to be investigated and solved, such as: (1) the time-series based methods are sensitive to environmental and operational variations, such as varying temperature, moisture, and loading conditions affecting the dynamic response of the structures; (2) the accuracy of these methods is largely influenced by the noise contamination level; and (3) the selection and construction of the feature index of structural damage are very flexible and have a lot of variations. It should be noted that none of these methods have been applied to detecting subsea pipeline conditions. As discussed above, reliable vibration measurement of subsea pipelines are more difficult owing to harsh environment, complex wave-pipeline-soil interaction and high damping from supporting soil and surrounding water. The measured vibrations are more susceptible to noises. Change in vibration responses may be governed by other parameters such as changing wave conditions instead of damage. Therefore, these make detection of the subsea pipeline conditions based on measured vibrations more challenging than detecting an onshore structure conditions.

In the present study, an integrated method based on ARMA algorithm is developed to perform online structural health monitoring of the subsea pipeline systems. In this method, the acceleration response of the pipeline is collected for analysis. In which, a partition and normalization procedure is firstly introduced in signal pre-processing to reduce the effect of environmental and operational condition variations, such as varying temperature, moisture, and loading conditions on structural response. Then, the auto-correlation function of the preprocessed acceleration signal is utilized as a substitute of the analyzing input to eliminate the influence of noise contamination and avoid bias in fitting ARMA model. Before building up ARMA model, Partial Auto-correlation Function (PAF) [15] method is employed for estimating an optimal AR model order. Then, an economical ARMA model is fitted and the corresponding AR parameters are obtained. With the AR parameters serving as the damage feature vector, a Mahalanobis distance model is established for each analysis input. By analyzing the data from the undamaged state, the baseline model of the intact state can be determined. Finally, a damage indicator (*DI*) is defined by scoring the Mahalanobis distance between the baseline ARMA model and the ARMA model of live testing data, based on which, the detection and location of the damage can be realized. The theoretical background of the proposed integrated ARMA model method is presented in Part 2.

In the present study, the efficacy and applicability of the proposed integrated ARMA model method to the SHM of subsea pipelines is tested and verified through numerical simulations.