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ScienceDirect

Procedia Engineering 188 (2017) 148 – 155

Procedia Engineering

www.elsevier.com/locate/procedia

6th Asia Pacific Workshop on Structural Health Monitoring, 6th APWSHM

Guided wave propagation and damage detection in composite pipes using piezoelectric sensors

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Abstract

Composite materials have many attractive properties, e.g. light-weight combined with high mechanical strength, and are recognized as an enabling technology for deep-water high pressure high temperature (HPHT) and corrosive environment applications. However, composite still has a barrier to entry in relation to steel due to limited field experience and lack of systematic failure prediction and assurance of in-service performance. Advances in such areas would enable the use of composites in a wider range of applications. Evaluation of in-service prototypes offers a partial solution but is costly. Thus a method that allows constant health monitoring of the composite in real-time and in-situ would be extremely useful. Ultrasonic guided wave-based structural health monitoring (SHM) technology is one of the most prominent options in non-destructive evaluation and testing (NDE/NDT) techniques. To investigate the feasibility of guided wave-based SHM for composite pipes, propagation characteristics of guided waves in an epoxy hybrid carbon/glass fibres pipe are systematically studied using finite element (FE) simulation and experiments. Both axisymmetric modes of propagation, the longitudinal L(0,n) and torsional T(0,n) modes are considered in the simulation process, however only the longitudinal modes can be captured by the piezoelectric sensors. Additionally, the tuning curves experimentally plotted are used to obtain the frequency with the maximum amplitude of each guided mode. Finally, guided waves in the composite pipe are tested with artificial defects (gel coupled coins) to understand the behaviour of guided waves after interaction with the defects. The different condition of artificial defects, e.g., the defect size and defect location are studied to find out the proper condition and limitation of using guided waves to monitor and inspect composite pipes.

Peer-review under responsibility of the organizing committee of the 6th APWSHM

Keywords: Lamb waves; composite pipes; finite element method; piezoelectric sensors; dispersion curves; damage deection

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Peer-review under responsibility of the organizing committee of the 6th APWSHM
doi:10.1016/j.proeng.2017.04.468

1. Introduction

Many variants of high performance steels have the high strength, stiffness and good performance at high temperatures required for subsea oil and gas pipes. However, corrosion is the significant drawback in the use of steel pipe for offshore deployment, estimated to cost the offshore oil and gas industry more than $1.3 billion every year. Steel corrosion poses a threat which often seriously undermines the structural integrity of oil and gas pipes. Corrosion of steel can be dealt with by a range of techniques such as coating, painting, sacrificial anodes and chemical inhibitors. However, none of these methods is 100% successful, most are expensive and, in the case of inhibitors, they can represent a seriously detrimental environmental threat.

Although carbon steel and copper nickel alloy pipe had traditionally been used on offshore platforms, advanced composites were known to be stronger, more resistant to corrosion, and lighter than steel. For example, composite pipe with a 6-inch diameter weighs 4 lb/ft, whereas copper nickel pipe with the same diameter weighs 24 lb/ft. There is, however, obstacles to using composite piping that were related primarily to the lack of test data to support the materials' long-term durability.

Advances in such areas would enable the use of composites in a wider range of applications. Evaluation of in-service prototypes offers a partial solution but is costly. Thus a method that allows constant health monitoring of the composite in real-time and in-situ would be extremely useful. Ultrasonic guided wave-based structural health monitoring (SHM) technology is one of the most prominent options in non-destructive evaluation and testing (NDE/NDT) techniques. For the purpose of composite pipe inspection, simulation analysis and experiments of ultrasonic guided waves are required to understand the characteristics of wave propagation along the pipe waveguide and the interaction of the guided wave with the defects in the composite pipes.

In solid hollow cylinders, three modes of wave can propagate: (i) longitudinal modes which propagate along the axial direction by a compressional motion, L(0,n); (ii) torsional modes which propagate along the axial direction by shear motion parallel to the circumferential direction, T(0,n); and (iii) flexural modes which propagate along the axis by a flexural motion in a radial direction, F(m,n). The modes of longitudinal and torsional waves in cylindrical structures are equivalent to Lamb wave and SH wave modes in plates, respectively. On the other hand, the flexural mode is the specific mode for a cylindrical structure [1]. The equivalences between guided wave modes in hollow cylinders and Lamb wave modes in plates are described in references [2-4]. The longitudinal and torsional modes are axisymmetric while the flexural mode is non-axisymmetric. The notation for each mode is (m,n) where 'm' is a circumferential order (the number of wavelengths around the circumference; m=0 is axisymmetric mode) and 'n' is the number of mode shapes.

A rapid screening technique for corrosion detection has been studied using ultrasonic guided waves [5]. Moreover, the improvement of the sensitivity and reliability of the guided wave inspection is necessary. Rose et al. [6] showed that several possible defects can be detected correctly due to the sensitivity of different frequencies and modes of guided waves. For multi-layered pipes, most literature was focused on metallic pipes with coating, painting or other layers of material. Ultrasonic guided waves were used to detect the delamination of coating and flaws of coated pipes [7].

Guided waves open the way for SHM on long distance to develop self-sending structures of large dimensions without necessarily increasing the number of sensors and thus without increasing the complexity of the monitoring system. However, guided wave or Lamb wave signals are difficult to characterise due to the multimodal character of the waves. Numerical analysis is used to obtain wave numbers, dispersion curves, etc. Well-known computational approaches were developed to obtain the dispersion curves for multi-layered and axisymmetric structures, namely the transfer matrix method [8] and the global matrix method [9]. Commercial software such as "Disperse" [10] and "Matlab code PCDisp" [11] have been developed to calculate the dispersion curves for plates and cylindrical structures from these matrix methods. However, complex structure (multi-layered, anisotropic) is still a limit for these analyses. This leads to simulation and visualisation using finite element method (FEM) to model numerically the waveguides and wave propagation. FEM is the most common method for analysis wave propagation in the structures due to its simplicity and flexibility for arbitrary geometries and materials with various boundary conditions [12-15].

FE analysis of isotropic hollow cylinders for axisymmetric vibration in comparison with experimental results showed excellent agreement [16]. The dispersion properties of guided wave propagation in isotropic and multi-layered hollow cylindrical waveguides were developed [17, 18]. However, based on the author's knowledge, most of the literature on guided wave behaviour in non-isotropic hollow cylinders focuses on metallic pipes with coating, painting or other substance layers. There is a lack of studies involving 3D FE simulation of guided wave propagation behaviour