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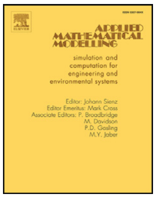

Identification of wall-thinning and cracks in pipes utilizing vibration modes and wavelets

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ABSTRACT

Internal surface damage such as wall-thinning and cracks in piping systems are mainly caused by chemical reactions, heat, erosion, solid carrying fluids or a combination of such influences. Early detection of such surface damage is crucial in order to avoid sudden failure and the subsequent downtime losses and safety hazards. In this paper we develop methods for inner damage identification in pipes utilizing the vibration mode shapes. Wall-thinning and cracks are modeled by smooth gradual change and abrupt change in the internal surface of the pipe, respectively. Since wavelets are very efficient in detecting fast changes in signals and their derivatives, they are primarily used to detect crack development. While wavelets cannot be used to detect smooth wall-thinning changes, they can, nevertheless, be used to detect the beginning and end of such damage. We develop a new method for identifying the profile of the inner surface of the pipe, once the wavelet transform indicates that damage is taking place. The identification process requires the shape of one vibration mode of the pipe and does not require the elaborate monitoring and tracking of changes in the modal characteristics. No baseline data are needed aside from the nominal values of the pipe parameters. In addition to damage localization, the developed identification method is capable of quantizing damage severity from the identification of a more accurate profile of the inner surface of the pipe. The motivation and methods used in this work are introduced first in a general setting and then demonstrated by several pipe examples. The numerical simulations carried out here indicate the effectiveness of the developed approach.

1. Introduction

Internal surface damage such as wall-thinning and cracks in piping systems are mainly caused by chemical reactions, heat, erosion, solid carrying fluids or a combination of such influences. In addition to cracks, the problem of internal surface damage is common to both steel and composite material pipes. For instance, flow Accelerated Corrosion (FAC), also known as Erosion-Corrosion (EC), is a serious safety and reliability problem facing carbon–steel pipes exposed to flowing water or steam in power generation plants. This phenomenon results in wear and thinning of large areas of pipes and fittings, which could compromise their structural integrity and thereby lead to sudden failures, [1].

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The problem also exists in nonmetallic pipes. Fiberglass-Reinforced Plastic (FRP) pipes have become a viable alternative to protected steel, stainless steel and other metallic pipes in several applications related to power generation. Surface attack is the most obvious type of aging damage in FRP piping. Accordingly, wall-thinning is a serious safety and reliability problem facing FRP piping in water systems and power generation plants, [2]. The problem is equally crucial to the oil and gas industry when oil, gas and solids flow together through piping systems.

Early detection of internal wall-thinning and cracks in pipes is an essential part of preventive strategies that aim to eliminate or at least reduce the risk of operation interruption as well as safety hazards in the field. If left unmonitored, internal surface damage may result in sudden failures that present potential threats to human safety and environment, in addition to shutdowns and production losses.

Various non-destructive evaluation (NDE) techniques have been developed to detect damage and cracks in piping systems. These techniques include Radiography [3, 4], Acoustic techniques such as ultrasonic probes, laser ultrasound [5, 6], low power impulse radar, acoustic emission, elastic wave emitter-detector pairs, thermography [7] and Microwave electromagnetic imaging [8].

However, NDT methods are difficult to apply in the field and are limited in terms of the area and thickness of coverage as well as the interpretation of the measurements. They are not well-adapted to continuous online monitoring. Radiography-based techniques cannot detect air filled defects such as cracks; images need to have a dimension parallel to the radial direction of the beam, [3, 4]. Therefore using conventional radiography will not allow for detecting thickness variations. Ultrasonic tomography was reported to depend on the size and shape of the aggregates [5]. Longitudinal ultrasonic wave scanning techniques [9] could not penetrate deeply inside highly attentive materials such as composites. Infrared thermography [7] is not accurate because we can only measure the amplitude of the heat signal and not its continuous distribution. Also, it is difficult to use this technology for deep detection especially for thick composite layers. In addition, the heat applied to the measurement location for building the thermography profile may change the properties of the FRP materials. The difficulties of using the infrared techniques are summarized by Udaya et al. [10].

The idea of using the induced change in the vibrational modal characteristics has been employed in characterizing defects in some structural and mechanical systems. The analysis and numerical modeling of natural frequency shifts due to the presence of an open crack has been addressed in an Euler–Bernoulli beam [11, 12]. Khulief and Mohiuddin [13] developed a finite element formulation and simulated the effect on the modal characteristics of a rotating shaft due to a crack. Xiang et al. [14] and Dong et al. [15] used wavelet-based finite elements to identify cracked rotors in terms of modal parameters. In their approaches, the crack was modeled by a weightless rotational spring. The crack location and size were identified from three contours corresponding to the first three natural frequencies. A database was constructed for these natural frequencies under various values of location and size of the crack. Special treatment was needed to handle the possible symmetries of the problem.

In the aforementioned studies, the emphasis was on crack identification in steel beams with solid rectangular or circular cross-sections. In a review of the reported methods for damage detection in bridges, Cruz and Salgado [16] compared the three main vibration-based detection techniques. The first and simplest is the Coordinate Modal Assurance Criterion (COMAC), which relies on the correlation between the nodal displacements associated with a set of mode shapes. The COMAC method may only produce reliable results when a severe damage is present, in addition to its susceptibility to signaling false alarms. The second method adopts the mode shape curvature as a means of damage identification. This method was found to produce acceptable results only in the case of severe damage and smooth modal shapes. The reason for these limitations is that the method relies on comparing the mode shape curvatures of the intact and damaged structure, which would be detectable in case of severe damage. Abrupt changes such as cracks may not produce smooth mode shapes. The third vibration-based method depends on calculating the Damage Index (DI), which represents the strain energy stored in a certain modal deformation of the structure. However, the performance of the DI method was found to be dependent on the accuracy of the mode shape curvature; thus suffering from the same problems of the curvature methods. In addition, the wavelet-based methods were also addressed. Zhong and Oyadiji [17] presented an approach, based on the difference of the continuous wavelet transforms (CWTs) of two sets of modal shape data, for damage detection in beam-like structures with cracks. Their approach appears to require a rather big number of sampling points. Furthermore, it depends on the symmetry properties of the mode shape being measured. False cracks may be signaled if mode shapes become nonsymmetrical. Xu et al. [18] explored the potential of utilizing of operational deflection shapes as a viable alternative for the mode shapes in detection of damages in plates. In a recent review, Fan and Qiao [19] assessed the potential of signal processing and optimization techniques in enhancing the vibration-based damage detection in beam-like and plate structures. However, they concluded by recognizing the need for further research to develop techniques that are capable of damage quantification and robustness in detecting multiple damages.

Very few studies, which considered annular cross-sections such as pipe structures, have been reported. The effect of a crack on the local flexibility of steel pipes conveying fluid was addressed [20–22]. Simola et al. [23] presented a comparison of two statistical methods to estimate rupture frequencies in pipes. The first is based on a probabilistic fracture mechanics model while the second is based on statistical estimation of rupture frequencies from a large database. Crack identification in steel pipes filled with fluid and the possibility of detecting localized damages from frequency measurements was only investigated recently by Dilena et al. [24]. However, the theoretical analysis presented in [24], was concluded by suggesting the need for further investigations.