International Journal of Solids and Structures 51 (2014) 2729–2743

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

Detecting and describing a notch in a pipe using singularities

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ARTICLE INFO

Article history:
Received 3 January 2013
Received in revised form 18 December 2013
Available online 18 February 2014

Keywords:
Pipe
Notch
Singularity
Cutoff frequency
Guided waves

ABSTRACT

A hybrid Semi-Analytical Finite Element (SAFE) and standard finite element procedure is adopted to simulate ultrasonically generated waves traveling in an infinitely long steel pipe having an open, rectangular notch. Numerical illustrations indicate that dispersive guided waves can be used to locally detect and characterize such a notch. A frequency oriented approach is preferred because a problematic separation in time is circumvented when incident waves overlap their reflections from the nearby notch. The notch is discerned straightforwardly because distinctive singularities are introduced that differ from those observed at the modal cutoff frequencies in a Frequency Response Function (FRF) of a comparable but undamaged pipe. Its characterization is (suggested) demonstrated for a (non)axisymmetric notch by using several of the smallest differences in the frequencies at which the two set of singularities occur. Consequently an external stimulus that simultaneously excites more than one mode is beneficial.

1. Introduction

Pipelines are used extensively to transport fluids. For example, the Alberta Energy and Utilities Board (EUB) reports (Alberta Energy and Utilities Board, 2007) that a total of 377 248 km of energy related pipeline was under its jurisdiction at the end of 2005. The same source also indicates there were a total of 12 848 pipeline "incidents"[1] between 1990 and 2005. About 95% of the reported incidents led to a pipeline leak or rupture. Moreover, corrosion was cited as the primary form of failure, representing approximately 70% of pipeline failures. Hidden, internal corrosion was responsible for around five times more failures than external corrosion. Although these statistics are the most currently available, they apply only to Alberta, Canada. Notwithstanding, it is clear that extensive networks of pipelines are in widespread use and they are prone to occasional failure. Given that the monetary and, less often, human costs of a pipeline failure can be extraordinarily high (Andersen and Misund, 1983), a method of inspecting pipelines is required to detect and size defects. Furthermore, the method should be nondestructive and ideally non-invasive because the infrastructure is already in service.

Ultrasonic Inspection (UI) is one of the most attractive choices for pipeline inspection. Body waves have been used for many years in a variety of UI applications, such as pulse-echo, through-transmission, resonance, etc., to perform tasks like flaw detection, thickness measurement, and characterization of a material's properties (Krautkrämer and Krautkrämer, 1977). Guided waves, on the other hand, are appealing because they can propagate over long distances, say tens of meters (Alleyne and Cawley, 1996; Rose and Quarry, 1999), and they are capable of rapidly interrogating entire structures, including otherwise inaccessible regions (Rose and Quarry, 1999). Early attempts by Mohr and Hoeller (1976) as well as Silk and Bainton (1979), for instance, of using guided waves for pipe inspection focussed on the torsional and longitudinal wave modes and considered spurious reflections as an indication of damage. More recent work as illustrated in, for example, Alleyne and Cawley (1996), the seminal work by Alleyne et al. (1998), Rose and Quarry (1999), Hay and Rose (2002), Cawley et al. (2002), Demma et al. (2004) and Ma et al. (2006) has focussed also on reflections of axisymmetric pipe modes from defects. In order to excite only these modes, or "focus" them at a desired location, special ring or "comb" transducers as well as equipment like angle beams, wedges, or time-delay, periodic linear arrays/phased arrays were employed as exemplified in Mohr and Hoeller (1976), Silk and Bainton (1979), Alleyne and Cawley (1996), Rose et al. (1996), Rose and Quarry (1999) and Mu et al. (2007). However,

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[1] Note that incidents occurring within facilities such as satellites, batteries, or plants *are not* considered part of the pipeline system and, therefore, are not included.

http://dx.doi.org/10.1016/j.ijsolstr.2014.02.002
0020-7683/

the use of flexural waves (Shin and Rose, 1998, 1999; Li and Rose, 2001; Rose et al., 2003) has been infrequent because "the acoustic field is much more complicated than the case of axisymmetric modes" (Shin and Rose, 1998).

Although noticeably more effort has been expended in detecting damage in pipes (and plates) by using reflections, changes in wave speeds and dispersion curves of guided waves, cutoff frequencies have been used merely to detect thinning in plates, as in Rose and Barshinger (1998), Zhu et al. (1998) and Silva et al. (2003). Thinning was examined by exciting a guided wave mode near its cutoff frequency and monitoring the disappearance of the modal response when part of the plate's thickness was below the critical value for the mode to propagate. However, the seemingly straightforward extension to pipes does not seem to have been given. Moreover, there appears to be only one reference, Stoyko et al. (2010), employing guided wave cutoff frequencies of an undamaged pipe to *simultaneously* find its wall thickness and material properties. On the other hand, the identification of spatially decaying modes, which are introduced in a pipe by a notch and are analogous to end modes (Oliver, 1957), has not been reported.

The first objective of this paper is to demonstrate that singularities[2] distinct from an undamaged pipe's cutoff frequencies are present when a notch is introduced. These singularities are analogous, in some sense, to the end modes reported by Oliver (1957). A second objective is to describe a technique that takes advantage of these singularities to characterize the dimensions of an axisymmetric notch in a pipe. The last objective is to suggest that the extension to nonaxisymmetric and more general notch geometries is straightforward but computationally expensive.

The proposed technique to detect and characterize the dimensions of an axisymmetric notch has a number of advantages. It utilizes the classical and simplest means, i.e., a radial point load acting on the pipe's outer surface, of introducing ultrasonic energy into a pipe to simultaneously excite a number of modes. The notch may be detected by simply examining the spectral density of a measured displacement response to see if it contains the characteristic features described in Section 3.5. As frequency differences are used to infer a notch's dimensions, the need for consistent coupling is reduced somewhat compared to methods that make use of amplitude changes. A single measurement can yield sufficient information to determine an axisymmetric notch's dimensions. This attribute offers an advantage over methods that rely on the excitation of a single mode to determine a reflection coefficient, say, as at least two modes are required to *uniquely* determine even an axisymmetric notch's dimensions (Demma et al., 2004). This advantage becomes more important as the number of dimensions required to characterize a (n idealized) notch increases. Moreover, as the proposed method makes use of measurements relatively close to a notch, where waves incident and scattered by the notch may interact (in the reflected field), only modest lengths of pipe are required. Also there is no need to separate modal contributions on the basis of disparate wave speeds. However, the procedure can be applied only locally to a notch as waves are used whose amplitudes decay exponentially from a notch's boundary. The technique complements, therefore, other methods that can rapidly screen long lengths of pipe (see, for example, Alleyne et al., 1998, 2001; Rose and Quarry, 1999; Cawley et al., 2002; Mu et al., 2007).

The newly discovered singularities are demonstrated to exist first by applying the hybrid Semi-Analytical Finite Element (SAFE) in combination with a standard finite element procedure as in, for example, Rattanawangcharoen et al. (1997), Zhuang et al. (1997), Mahmoud et al. (2004) and Benmeddour et al. (2011) to axisymmetric notches in a (hollow) steel pipe. The pipe is assumed to be homogeneous, linearly elastic, isotropic, and uniformly right circular. A parametric study is undertaken subsequently in which the radial depth and axial extent of outer surface breaking, rectangular axisymmetric notches are varied independently. The results are used to illustrate how the frequency difference between the new singularities and an undamaged pipe's cutoff frequencies can be used to detect a notch and determine its size. Notwithstanding that internal corrosion occurs more often than external corrosion, solely outer surface breaking notches are considered because the simulations presented here can be partially corroborated by existing experimental data (Alleyne et al., 1998). The examples suggest that *almost*[3] any set, which contains a sufficient number of accurate frequency differences, will give the same inverse solution. Note, however, that uniqueness is not proven, it is merely suggested. The modes may be selected generally but usually on the basis of ease of experimental implementation.[4] The extension to nonaxisymmetric notches is suggested by showing that the singularities exist also in the more general three-dimensional case. Then conclusions and closing remarks are made. An appendix which provides comparisons between the predictions that arise from the simulations and other's, independently obtained experimental data (Alleyne et al., 1998) concludes the paper.

2. Hybrid SAFE and standard finite element

2.1. Overview of hybrid wave function-standard finite element approach

A hybrid wave function-standard finite element approach can be used to model wave scattering by a nonhomogeneity in an otherwise continuous waveguide. The methodology employs a conventional finite element description to model the displacement field in a region completely enclosing the nonhomogeneity. On the other hand, the displacement field in the remainder of the waveguide is described in terms of a modal expansion of the wave functions of the undamaged waveguide. An incident wave field is generated outside the conventional finite element region. Waves are scattered by the nonhomogeneity. The scattered wave field is obtained by enforcing continuity (displacements and stresses/nodal forces) between the finite element and wave function expansion regions. In a hybrid SAFE and standard finite element model, the wave functions are obtained by applying the SAFE methodology to the waveguide, rather than using a method that provides "exact" wave functions.

Fig. 1(a) shows standard orthographic views of a pipe having a nonaxisymmetric, outer surface breaking notch. The notch takes the role of the nonhomogeneity when applying the hybrid wave function-standard finite element approach. It can be seen from Fig. 1(a) that the notch may be bounded by the planes $z = 0$ and $z = -2z_{\mathrm{FE}}$, which are used to demarcate the axial extents of the finite element region. The motion in pipe outside the finite element region is described in terms of a wave function expansion of the undamaged pipe's normal modes. An incident wave field is generated by the transient input excitation, shown as a radial point force in the figure, applied in the $z = z_{\mathrm{L}}$ plane. Wave scattering by the notch will give rise to a combined incident and reflected

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[2] The term singularity is used here to indicate a frequency at which a displacement response of a given guided wave mode becomes very large and behaves similarly to a resonant frequency of an undamped single degree of freedom oscillator.

[3] The T(0,1), L(0,1), and F(1,1) modes, for example, are excluded because they always have a zero singularity frequency for a simple homogeneous, isotropic pipe and, hence, they are unsuitable.

[4] The F(3,2) and F(11,2) modes, say, have no radial displacement component at their respective cutoff frequencies. Consequently, neither mode would be detectable at (or near) their cutoff frequencies by a transducer which measures a solely radial displacement.