



Monitoring pipe wall integrity using fiber Bragg grating-based sensing of low-frequency guided ultrasonic waves

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ARTICLE INFO

Keywords:

Fiber Bragg grating
Annular cylinders
Feature-guided waves
Pipe eccentricity
Structural health monitoring

ABSTRACT

Recent literature shows that low-frequency ultrasonic guided waves experience mode confinement and loss of axis-symmetry in pipes with axially uniform features such as eccentricity. Considering extended wall loss as a case of uniform eccentricity, this paper proposes to monitor pipe integrity by measuring changes to the modal structure of low-frequency axisymmetric L(0,2) longitudinal guided waves. Fiber Bragg gratings are shown to be effective in detecting changes to L(0,2) modal characteristics, providing a novel route to health monitoring of pipe assets.

1. Introduction

Transmission pipelines are widely used in oil, petrochemical and power plant industries where efficient structural health monitoring (SHM) techniques ensuring the reliability and early defect detection are essential [1]. Ultrasonic guided waves are attractive for SHM of pipes, due to their ability to propagate over long distances from a single transducer location [2,3], and potential to inspect both internal and surface defects [4].

A common issue in such pipe structures is cross-sectional irregularity such as eccentricity or local wall thinning which can arise either due to manufacturing limitations or due to prolonged usage and hence is an essential parameter to be monitored continuously [5,6]. One example of cross-sectional irregularity due to prolonged usage is flow-accelerated corrosion (FAC), which is a common chemical corrosion process in carbon or low-alloy steels leading to wall-thinning over an extended axial region [7]. Since wall thinning might ultimately lead to wall rupture, it is important to detect such irregularities early in pipes.

Recent research has shown that thinned areas of a pipe annulus can act as features that can confine and guide longitudinal L(0,2) ultrasonic guided wave modes, commonly known as ‘feature-guided waves’ (FGW) [8–10]. Such FGW modes can be potentially exploited for detecting pipe eccentricity. The feature-guiding effect (mode confinement) is strongly dependent on the extent of the eccentricity (wall thinning).

The key to observe FGW arising from pipe wall anomalies, is to detect accurately the amplitudes of a chosen guided-wave mode at various angular positions around the pipe circumference. Typically, laser Doppler vibrometry has been used to detect feature-guided waves

[9,11–15]. Unfortunately, measurement of mode amplitudes at various positions across the circumference of a pipe using LDV or even piezoelectric or Magnetostrictive (MsS) sensors is a challenging task on field.

Using LDVs for such applications is beyond the scope of most site conditions, as they may require custom-created robotized gantries and also full-field access to the pipe circumference. MsS Sensors, as they exist today, cannot provide individual amplitude at specific positions, and only yield a value averaged over all circumferential measurement nodes. On the other hand, with piezoelectric sensors, the major problem in measuring amplitudes accurately, is to ensure uniform contact with the pipe at all monitoring nodes, and this is very difficult to achieve in practice. Mistakes can be made in the prediction, if mode amplitude is not recorded accurately at one of the sensors due to poor contact – and this can be wrongly interpreted as ‘mode focusing’ or FGW in this approach. Moreover, using piezoelectric sensors would require creating customized rings that can hold them in place and special mechanisms or rings of different sizes would be needed to account for various pipe diameters. In the current article, a more practical approach to detect such FGW modes using FBG sensors is presented, and is the key aspect of this work.

Since FBG sensors are pasted directly on and can conform to the pipe surface, no special mechanisms are necessary to deploy them [16,17]. Moreover, for pipe health monitoring, in addition to the ability to perform in harsh environmental conditions, the low-loss property of an optical fiber allows long distance health monitoring from a single end of the fiber [18]. Additionally, FBG sensors have a highly directional response due to their cylindrical geometry with high aspect ratio [19]. This property aids in preferential detection of guided wave modes

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propagating in the structure based on their orientation, which has been demonstrated recently by the authors [20,21].

In this paper, a FBG-based field-deployable technique for monitoring pipe wall loss using changes to modal characteristics of low-frequency guided waves is presented. Our studies focus on the second axisymmetric longitudinal pipe mode, $L(0,2)$. Even though uniform eccentricity which causes wall-thickness loss over an extended axial region arises primarily due to manufacturing errors, this could also approximate those caused due to effects such as FAC. The experimental results based on pipe dimensions that are typically used in process industries confirm that with increase in pipe eccentricity, the $L(0,2)$ mode loses its axisymmetry and gets focused in the thinner region of the pipe cross-section. Moreover, the $L(0,2)$ mode also has a reduction in its velocity. Together, these two measurements provide a novel route to detect pipe wall anomalies such as extended wall loss.

2. Materials and methods

A key challenge in the structural health monitoring of metallic pipes is the excitation of a pure longitudinal wave. The particle motion in an $L(0,2)$ mode is along the cylindrical axis and the strain is uniformly distributed through the pipe wall [9], thereby making it suitable to detect cross-sectional changes in pipes.

Fig. 1 shows the dispersion profile of a concentric seamless mild steel pipe of 60 mm outer diameter (OD) and 50 mm inner diameter (ID) obtained using DISPERSE software package [22]. Such a pipe dimension is chosen for our experiments as they are typically used in process industries.

It can be observed that the $L(0,2)$ mode is relatively non-dispersive around 100 kHz which further makes it attractive for long range inspection. Also, since mode energy attenuation is dependent on excitation frequency, guided wave measurements are typically carried out at lower frequencies. Moreover, practical guided wave non-destructive testing is typically performed at 100 kHz [23,11] to have better sensitivity to defects and hence this frequency has been chosen for our studies. Nevertheless, the velocity dispersion characteristics of the mode depends on the frequency-thickness product of the material.

Experiments were performed using seamless mild steel tubes of 60 mm OD and 50 mm ID, and axially uniform eccentricities (e) of 1.5, 2.5, and 3 mm were introduced in separate samples using the eccentric turning process. The length of the samples used for experiments was ~50 cm, which was decided by the potential for eccentric turning process at the workshop facility of IIT Madras. It is to be noted that the whole length of the pipe is eccentric. A schematic illustrating the pipe

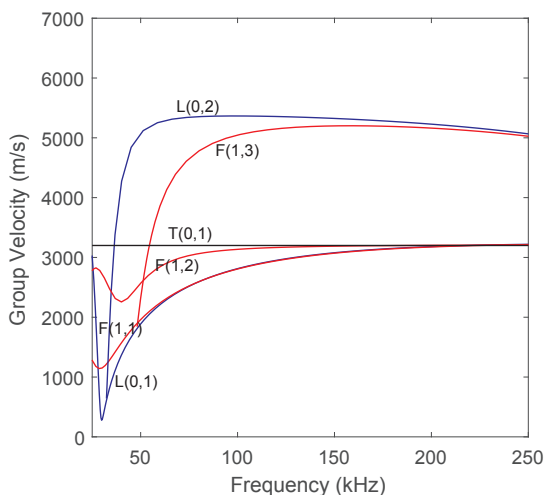


Fig. 1. Dispersion profile of ultrasonic guided modes in a seamless mild steel concentric pipe having OD of 60 mm and ID of 50 mm.

cross-section is shown in Fig. 2(a) and (b).

$L(0,2)$ mode was generated on such mild steel pipes using a novel iron-based magnetostrictive (MsS) transducer developed at the Center for NDE, IIT Madras [3,24]. The transducer was excited in the axial (in-plane) direction through a 5-cycle Hanning windowed tone-burst with a center frequency of 100 kHz generated by a RITEC pulser-receiver (RPR 4000, RITEC Inc., USA). The excitation was given symmetrically using eight MsS strips of 10 cm length bonded symmetrically around the outer annulus circumference. These strips were excited using a transmitter coil connected to the pulser-receiver. As a consequence, owing to the magnetostrictive property of the transducer, the electrical signals are subsequently converted to mechanical displacements in the axial direction thereby generating axisymmetric longitudinal $L(0,2)$ mode. The preferential excitation of $L(0,2)$ is ensured by uniform placement of the axially oriented MsS strips in the azimuthal plane.

For validation purposes, the generated $L(0,2)$ mode was captured at different monitoring points around the cross-section using a Polytec heterodyne (Polytec GmbH, Waldbronn, Germany) laser Doppler vibrometer (LDV), which measures the out-of-plane displacement at a target point. A thin reflective film was attached on the surface to enhance optical backscatter of the probe laser beam. The laser beam is oriented in a direction normal to the end cross-section of the annulus so that we primarily interrogate the axisymmetric longitudinal modes.

Further experiments were conducted using FBG sensors for capturing the $L(0,2)$ modes. Since the generated modes are in the axial in-plane direction, FBG sensors pasted at several locations each separated by 45° on the pipe sample and are oriented along the same direction to preferentially detect these modes [20]. Fig. 2(a) and (b) illustrates the location of monitoring points along the pipe cross section. Investigations were carried out to observe the normalized amplitude distribution of $L(0,2)$ mode along the pipe circumference. In order to achieve consistency and further compare the FBG measurements with LDV measurements, the FBG sensors were also pasted at the pipe end as shown in Fig. 2(c).

A tunable laser source (TLS) based FBG interrogation technique is used as it offers very high sensitivity [25]. Since the TLS wavelength is tuned at the slope of FBG reflection spectrum, the FBG wavelength modulation gets converted to optical intensity variations which is then fed to an avalanche photodiode transimpedance amplifier (APD-TIA-12/2 oemart.com) module through a circulator as shown in Fig. 2(c). A band pass filter of 5 kHz to 1.25 MHz is implemented to eliminate unwanted frequencies. The electrical output from analog circuit is then observed and recorded on DSO, which operates at a sampling rate of 40 MSa/s. To improve the signal to noise ratio of the captured signal, a digital adaptive line enhancement algorithm based on least mean squares (ALE-LMS) is employed [26].

3. Results

Initial experiments were conducted on a seamless mild steel concentric pipe having OD of 60 mm and ID of 50 mm. The FBG sensor is placed 50 cm away from the acoustic source which provides longitudinal excitation at a frequency of 100 kHz. The waveform captured by the FBG sensor is compared with that captured using a Doppler vibrometer to verify that the measurements are equivalent. The time domain response captured using DSO is shown in Fig. 3. From this trace, we observe that the FBG sensor provides data quite similar to that from the Doppler vibrometer and also that it corresponds to a longitudinal mode. However, there is a slight offset in both the time traces. As explained previously, in order to detect in-plane $L(0,2)$ mode, out-of-plane LDV measurements were carried out at the pipe cross-sectional end. However, to detect longitudinal modes with maximum sensitivity the FBG sensors were pasted axially on the pipe wall but also near the cross-sectional end to be in consistency with LDV measurements. This small change in the distance between the FBG and LDV monitoring points resulted in a slight offset in the captured traces.

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