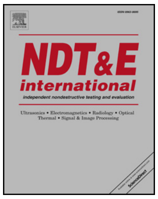
NDT and E International 100 (2018) 55–63

Contents lists available at ScienceDirect

NDT and E International

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



Spectral subtraction and enhancement for torsional waves propagating in coated pipes

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ARTICLE INFO

Keywords:
Guided waves
Denso tape coated pipe
Backward wave cancelling
Spectral subtraction
Spectral enhancement

ABSTRACT

Ultrasonic guided waves are routinely used for inspection of pipelines. The technique is well established for uncoated pipes where attenuation is very low. However, when the pipe is coated, buried or immersed, sound energy will be absorbed by the coating or radiate into the surrounding medium. Attenuation will increase and the scanning distance will be significantly reduced. The noise level can also increase when the condition of the coating material degrades with age and the bonding condition between pipe and coating becomes unevenly distributed. The increase of attenuation ratio and noise level therefore makes the inspection of ultrasonic waves propagating in coated and buried pipelines particularly difficult. It is often desirable to identify small features amongst the noise floor. To improve signal to noise ratio under these conditions, two techniques are proposed for the study of the propagation of torsional waves in Denso Tape coated pipes. A frequency domain, backward wave cancelling algorithm is used to eliminate the reflected waves coming from the backward direction and clean up the signal. On this basis, a spectral subtraction method is used, which requires knowledge of a small section of pipe that includes no real features, so that the signal from this region provides the characteristic noise signature of the pipe itself. The spectrum of the noise signature is calculated and then subtracted from the total signal using a sliding window technique. Furthermore, a signal region, for instance , the reflected signal from a pipe weld or end, is specified. This represents the characteristic of the incident signal and any signal similar in shape will be enhanced using the sliding window technique. These two techniques serve to reduce the noise floor and enhance small signals that may be buried in it. This is important for ultrasonic non-destructive testing applications in coated and buried pipes.

1. Introduction

Ultrasonic guided waves are routinely used for non-destructive inspection of pipelines. This is normally based on a pulse-echo principle, and the technique is highly successful for pipelines that are uncoated and unburied, so that attenuation is low [1–4]. Recently, the technique has been advanced to address problems in more challenging conditions, such as coated and/or buried pipelines. The coating material is normally viscoelastic, and absorbs sound energy while for buried pipelines, sound energy can leak into the surrounding medium. In both cases, attenuation of guided waves is high in the conventional long range ultrasonic testing frequency range from 20 kHz to 100 kHz and the effective scanning distance of guided waves is thus significantly reduced. Furthermore, in addition to the reduction in signal strength, the noise level can also increase, especially for coating materials that have been present for a number of years. In this case, bonding conditions between the coating material and the pipe substrate become uneven due to pressure changes and temperature variations around the pipe, etc., and noise signals are created. It is thus often necessary to identify small signals that may be beneath the noise floor and signal interpretation is very challenging, because of the randomness of the noise signature. This article studies the propagation of torsional waves in a pipe coated with Denso Tape, wrapped evenly onto the pipe by a wrapping machine. The maximum coating length studied here was 5.5 m, and it can already be seen at this length that the reflected signal from a pipe feature (weld) is lower than the amplitude of some noise peaks. A spectral subtraction and enhancement algorithm is proposed to improve signal to noise ratio. A sliding Hanning window is used to remove the noise spectrum and enhance the signal spectrum segment by segment. The signal is then reconstructed through inverse Fourier transformation

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https://doi.org/10.1016/j.ndteint.2018.08.009
Received 9 January 2018; Received in revised form 31 July 2018; Accepted 24 August 2018

and combination of segments.

The attenuation of guided axisymmetric elastic waves in Bitumen coated pipes has been studied by Kirby et al. [5,6] who present a hybrid finite element model to study the scattering of torsional and longitudinal waves from axisymmetric defects in coated pipes. The material properties of Bitumen are extracted by comparing theoretical predictions with experimental measurements for two different incident modes over a large frequency range. Kuo and Suh have proposed an analytical model to study propagation of longitudinal waves in a multi-layer coated pipe [7]. The influence of multi-layer viscoelastic coating materials on wave dispersion and attenuation is investigated. Leinov et al. have studied the attenuation of axisymmetric elastic waves in pipes that are coated and buried [8,9]. They found that low impedance (product of density and the real part of the shear velocity) coating materials could trap sound energy inside the pipe so that little energy leaks into the surrounding medium. Duan et al. presented an efficient one dimensional numerical model to study wave propagation in coated and buried pipes [10]. A new stretching function is proposed to allow the model to converge quickly even with a thin, perfectly matched layer (PML). A similar sound isolation effect could be observed for coating material with impedance larger than that of the surrounding medium. However, this isolation may occur at a higher frequency range. An extensive list of reference papers can be found in the literature which are related to guided wave propagation in coated and/or buried pipes [11–20].

Benmeddour et al. [21] and Duan et al. [22,23] presented a hybrid, finite element model to study wave scattering from a non-axisymmetric defect in a solid cylinder, uncoated pipe and coated pipe, respectively. A small section of the waveguide is meshed which ensured that the model could be executed quickly. The modal amplitude of scattered flexural modes is presented, in addition to the usual axisymmetric modes. Duan et al. [24] further presented a numerical model to study scattering of torsional waves from an axisymmetric defect in a buried pipe. The perfectly matched layer method is used to close the problem both in the central finite element section and in the uniform modal expansion region. Sun et al. [25] studied the mode conversion behaviour of Lamb and shear-horizontal waves in a plate to longitudinal and torsional guided waves in a pipe. EMAT transducers were developed to produce waves in the plate. The plate was then wrapped onto the pipe in two different waves, which facilitated the study of different mode conversion behaviour. A number of other analytical and numerical techniques have been proposed to study wave scattering from discontinuities in waveguides [26–31].

These references investigate the physics of the problem. The length of the coated and/or buried section in the experimental measurements [5,6,8,9] was very small, usually less than 2 m, so that the reflected signal from a defect or pipe end could be identified clearly. In practical non-destructive testing applications on coated pipe, a small section of the coating is removed to allow the ultrasonic transducers to be mounted onto the wall. If the pipe is buried, then excavation work is required to allow access. It is thus desirable to scan the longest possible pipe section in a single pass. In this case, the reflected signal from a pipe feature can be lower than the noise floor, and interpretation of the signal is challenging. To clean up the signal, a common practice is to sum and average the signals received from all the transducers in each ring. This then delivers the axisymmetric modes. However, because of the differences between transducers, coherent noise can appear, in addition to other environmental and electric noise.

Furthermore, the signal can also be reflected several times between different features when interpretation of the signal could be improved by cancelling reflected waves coming from the backward direction. Kemp et al. proposed a time domain algorithm to separate forward and backward acoustic waves using multiple microphones [32]. Two calibration runs were carried out to measure the time domain transfer functions for each pair of microphones. The loudspeaker and calibration tube are also interchanged between these measurements to allow calculation of forward and backward transfer functions. This arrangement is difficult in an industrial context, so that Groves and Lennox proposed a method to simplify the calibration procedure [33]. A source tube run out is used to increase the length of the signal. This allowed forward travelling waves to be windowed out and thus forward intermicrophone transfer functions to be measured. The backward transfer functions are then calculated by reversing the forward travelling waves. Groves and Lennox [33] also tested another wave separation algorithm which significantly simplifies the calibration procedure; however, the result may include/generate more low frequency interference. These algorithms are proposed for acoustic waves propagating in air, and the loudspeaker and microphones are separated using a source tube. For elastic waves, the same transducers used to generate the waves are used to receive them, so that modifications are required and the transfer functions have to be measured in a different way, reported in section 3 of this paper.

The wave separation techniques are only used to separate forward and backward propagating waves. They can reduce the number of pulses and simplify the interpretation of signals, however, they cannot improve signal to noise ratio. When the amplitude of the reflected signal is lower than the noise level, additional signal processing algorithms are required. Currently, there is no well-established method for improving signal to noise ratio for guided waves propagating in coated and/or buried pipes. The major difficulty is that the piezoelectric and coherent noise is coming from differences between transducers or uneven pipe conditions. This type of noise is associated with high order flexural modes which are also dispersive [22,23]. The wave modes of coherent noise are unknown and highly problem dependent, thus making them difficult to remove. In speech analysis, a spectral subtraction algorithm is widely used to reduce acoustically added noise [34–40]. This suppresses stationary noise relative to speech by subtracting the spectral noise bias calculated during non-speech activity. A sliding window is used to remove noise, segment by segment. This algorithm requires the noise spectrum to be estimated accurately. If the noise estimate is not perfect, then remnant noise will appear. The remnant noise is distracting to humans and causes hearing fatigue. A number of variations have been proposed based on this algorithm. Upadhyay and Karmakar presented a comparison and simulation study of different forms of subtraction-type algorithms [40]. The task is to produce more pleasant speech with minimal remnant noise.

In this article, the spectral subtraction algorithm is used to remove noise associated with the torsional wave T(0,1) propagating in coated pipes. This is important for non-destructive inspection of coated pipes when the guided wave signal becomes comparable to the noise because of its high attenuation due to the coating. Denso Tape material is used here, and material properties of the coating have been studied theoretically and experimentally by Duan et al. [41]. The focus is to clean up the signal by removing travelling components of the torsional wave mode reflected from the backward direction and improving signal to noise ratio. The frequency domain wave separation algorithm is used, and the transfer functions between two rings of transducers are calculated by the reflected signals from welds and pipe ends. The spectral subtraction method is used to remove environmental, piezoelectric and coherent noise. The coherent noise could be a mode converted signal from the T(0,1) mode, and is thus related to T(0,1) which means that it is not possible to remove all the coherent noise using the spectral subtraction method. A spectral enhancement technique is proposed in which the windowed signal is enhanced if there is a high similarity between the signal and a T(0,1) mode. The structure of the paper is as follows. The introduction is presented in section 1. The experimental procedure is given in section 2, and the signal processing algorithm is presented in section 3. The results and discussions are presented in section 4. Finally, conclusions are drawn in section 5.