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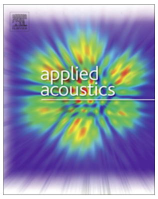

# Dispersion and attenuation by transmission, reflection, and mode conversion in welded pipes

Bouko Vogelaar [a,]*, Michael Golombok [b]

[a] Eindhoven University of Technology, Department of Mechanical Engineering, Groene Loper 15, 5600 MB Eindhoven, The Netherlands
[b] Shell Global Solutions International B.V., Kessler Park 1, 2288 GS Rijswijk, The Netherlands

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ABSTRACT

Torsional wave dispersion and attenuation in an open empty welded pipe are determined from a multi-receiver position reflection experiment. The fundamental torsional wave is dominantly reflected at the free end and the converted non-axisymmetric flexural modes are naturally attenuated. The resulting phase velocity contours are in agreement with theoretical predictions. The transmission losses are quantified and compared to those reflective elements associated with end and weld reflection. At any reflective node, the incident wave is split between back and forward preserved mode scattering ("reflec tion/transmission"), conversion to other modes plus energy lost by absorption. The ratios for each element are quantified.

## 1. Introduction

Permanent guided wave monitoring of extended piping is a promising inspection technique in the petrochemical industry [1,2]. Acoustic waves are excited along the pipeline being tested and the reflected signals are detected by distributed sensors mounted on the outer wall of the pipelines. The pipe acts as a cylindrical waveguide allowing longitudinal, torsional, and flexural wave types [3,4]. Each wave type contains numerous wave modes. These attenuate and propagate at a characteristic speed and damping, dictated by the pipe material, pipe wall thickness and diameter. Wave attenuation and mode conversions occur at axial symmetric impedance transitions, such as welds and pipe ends. Fig. 1 is a simplified representation of an incident wave subject to reflection, transmission, and mode conversion. In addition, attenuation (as leakage) occurs at strong impedance transitions from the pipe wall to the surrounding material, such as external coating or internal fluid.

The minimum sensor density to give full coverage along the pipeline is thus governed by the damping of guided waves. The inspection potential requires knowledge of the level of attenuation in bare, fluid-filled, coated, and buried pipes.

We have previously shown that the torsional wave mode is preferred for this purpose, because it is dispersion free [5]. Torsional waves have pure tangential polarization in the circumferential direction. In contrast to this, flexural waves have a strong radial component to bend the pipe and accordingly a minor tangential and axial component. Longitudinal waves have dominant axial polarization and no tangential component and are not considered in this paper.

The aim of this paper is to assess the individual loss contributions to torsional wave attenuation in a bare empty pipe in air. First, a multi-receiver position data set is acquired and processed to identity the various wave modes. Second, spectral attenuation analysis shows that the dispersive non-axisymmetric wave modes are heavily attenuated. Third, temporal attenuation analysis separates and quantifies the various loss factors in terms of transmission, free end and weld reflection, and mode conversion. By understanding the degree of damping of these individual contributions, one can determine the inspection range of the torsional wave for structural health monitoring under the tested conditions.

## 2. Background

The dispersion and attenuation of acoustic waves along cylindrical structures has been studied extensively, e.g. [6,7]. Analytical and numerical models exist for the exact calculation of dispersion curves of structures with simple cross sectional geometry, such as plates and pipes [8].

Among the different types of modes that propagate along the pipe walls, the torsional mode has advantages of having a high sensitivity to cracks and suffers less attenuation than flexural and longitudinal modes, since it is uncoupled to either internal or external

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* Corresponding author.
*E-mail address:* b.b.s.a.vogelaar@tue.nl (B. Vogelaar).

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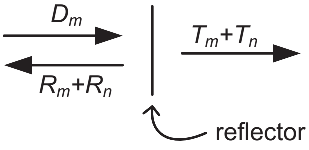

**Fig. 1.** Simplified representation of an incident wave hitting a reflector (such as a weld or pipe end). The direct wave $D_m$ has mode *m*. The reflected waves *R* and transmitted waves *T* have mode *m* and converted mode *n*.

fluids [9]. In the absence of energy leakage into surrounding solids, the damping of the torsional wave modes comes from the viscoelastic properties of the pipe itself and/or scattering by its internal structure.

Numerical models on the propagation of torsional wave modes rarely take this internal damping in the pipe material into account [10]. In addition, appropriate input values in spring-dashpot modeling of attenuating waves in materials are not commonly known or measured [10]. It would be valuable to measure wave attenuation versus frequency of materials with complex values as input for numerical models [11]. Complex values also allow the definition of absorbing behavior of the infinite long modeled structure, while using a relatively small number of mesh elements.

Despite the use of torsional waves for guided wave inspection [9,12–20] wave attenuation is still a decisive issue that affects inspection performance mostly regarding its range and sensitivity [21].

Bilayered pipes with internal or external viscoelastic coating have been measured by Luo and Rose [22]. Ma et al. [23] measured the scattering of the fundamental torsional mode by a local axisymmetric layer coated inside a pipe. Ma et al. [24] extended their study by taking into account more realistic sludge and blockage characteristic, including irregular axial and circumferential profiles of the sludge layer, imperfect bonding state between the sludge and the pipe and the material damping of the sludge. Mu and Rose [25] solved the problem of axisymmetric and flexural wave dispersion and attenuation in free hollow cylinders with viscoelastic coatings by a semi-analytical finite element method. Jia et al. [26] did numerical calculations on guided wave propagation in single and double layer hollow cylinders embedded in infinite media.

The extensive experimental study of Cobb et al. [27] shows that for an uncoated steel pipe at room temperature the measured attenuation values are <0.05 dB/m at 10 kHz, <0.16 dB/m at 30 kHz, and <0.25 dB/m at 50 kHz (these are the values for the coal tar epoxy (CTE) coated pipe with a coating type similar to bare or painted pipe). Typical attenuation coefficients of −0.05 dB/m of 30 kHz torsional waves in empty bare steel pipes are reported by Kwun et al. [28]. Leinov et al. [29] also reported attenuation values of less than −0.1 dB/m around 20 kHz in bare steel pipe in air.

Cobb et al. [27] measured a torsional wave attenuation of 0.24 dB/m at 40 kHz on a CTE coated pipe from the exponentially decaying amplitude envelope of multiple end reflections. Attenuation values calculated in this manner, however, discount the losses from boundary reflections, which Cobb et al. [27] assumed being negligible given the acoustic impedance difference between steel and air. Yibo et al. [30] reported that girth welds consistently reflect 20% of the incident torsional wave energy at 28 kHz. They reported that the signal of the torsional wave echos reached the noise level after propagating 20 m in a painted mild steel pipe with several girth welds and an elbow. Nevertheless, the torsional guided wave successfully detected two artificial defects at 12 and 13 m from the source location. Yibo et al. [30] concluded that the torsional wave is more sensitive to axial defects than the longitudinal wave.

## 3. Experiment

### 3.1. Pipe

The tested pipe has an outer diameter of 80 mm and wall thickness of 2.0 mm. The pipe is straight with open axisymmetric ends at 0 m and 12.6 m and has an axisymmetric tungsten inert gas weld at 6.3 m, see Fig. 2. The wall is composed of carbon steel, having a shear wave velocity of 3.2 km/s. The pipe is supported by three trestles causing negligible acoustic loss. The pipe is assumed to uniformly attenuate the torsional wave during transmission.

### 3.2. Acoustic equipment

The acoustic set-up uses two piezoelectric shear wave transducers mounted on the pipe wall. The emitting and receiving transducers contain a piezoelectric shear element, sensitive to transverse displacement. The transducer element size is 1 in. diameter; its flat face is mounted on the curved pipe wall without wedges or shoes. Attenuation by the transducers being attached to the pipe is ignored.

An arbitrary wave form generator feeds an amplifier with a single sine pulse of 15 kHz. The amplified signal is fed into the emitting shear transducer. This frequency is found to yield a strong signal. The associated torsional wavelength is near the pipe nominal circumference (0.2 m) and resonance like performance at the torsional ring frequency occurs [5].

The detected signal is recorded over 10 ms by a digital oscilloscope with a sampling interval of 1 µs, thus containing $10^4$ data points per recording. Typically 64 successive recordings with a burst period of 500 ms are captured and transferred to a computer for offline signal processing.

### 3.3. Acquisition procedure

The calculation of intrinsic attenuation (see below), necessitates the signal recording at different spatial positions along the pipe, so the receiver is subsequently moved lengthwise along the pipe. The emitter is left in place at pipe end *A*, see Fig. 2. The first receiver position is at 0.1 m from pipe end *A*. The next series is captured after moving the receiver over 0.1 m and repeated alike to collect measurements at 125 axial positions. Equidistant steps of 0.1 m are about half the torsional wavelength, so spatial aliasing is expected.

## 4. Data analysis

### 4.1. Dispersion analysis

We use the so-called delay-and-sum method to identify the various wave modes propagating in a pipe. This method was described

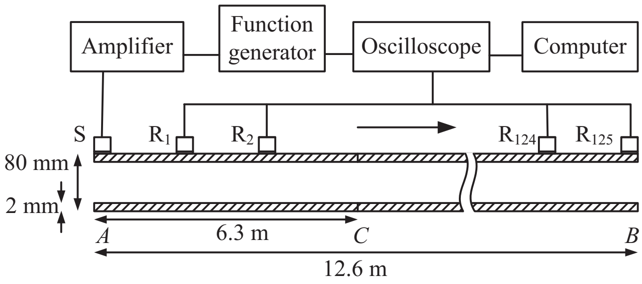

**Fig. 2.** Multi-receiver position set-up for attenuation measurements in a pipe. Source *S* is fixed at pipe end *A*. Receiver *R* is progressively moved toward pipe end *B*. The weld is halfway the pipe at point *C*.