Tunnelling and Underground Space Technology 83 (2019) 18–26

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

An electromagnetic sensor to locate service laterals during the trenchless lateral reinstatement

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ARTICLE INFO

Keywords:
Laterals
CIPP
Sensor
Waveguide

ABSTRACT

Lateral reinstatement is the last step in the rehabilitation of buried pipes using cured-in-place pipe (CIPP) liners, where the service laterals sealed by the freshly installed liner are cut open. In this paper, a low cost sensor based on the open-ended rectangular waveguide based non-destructive testing (NDT) technique that was developed in the past is extended for lateral detection. Its performance is tested inside metallic and non-metallic host pipes. Numerical modeling of the sensor and experimental validations are carried out. A dedicated electronic circuit and a servo controlled scanning mechanism are developed so that the sensor can be retrofitted on the robotic cutters used for lateral restoration in the trenchless industry.

1. Introduction

Rehabilitation of deteriorated waste and potable water pipes using cured-in-place pipe liners (CIPP) is a popular trenchless method used to extend the service life of utilities (Najafi, 2010; Allouche et al., 2005; Allouche et al., 2014). After a host pipe is lined, the service laterals (side-connections) connected to it are sealed by the freshly installed liner, and they have to be reinstated (cut open) to complete the rehabilitation process (Sterling et al., 2012). Lateral restoration is a critical step and it must be completed without damaging the liner. Typically, remote controlled vehicles fitted with cutting tools are sent through host pipes to reopen the blocked connections. In certain cases, it is difficult to precisely locate these hidden laterals. Current practices to locate them include pre-installation surveys to record coordinates of these laterals prior to lining. However, these estimates are often inadequate to engage the cutting tool precisely. When a thin non-reinforced CIPP is used (e.g. in gravity sewers) the internal pressure applied during installation creates visible depressions (dimples) on the liner adjacent to the side-connections and these dimples are later identified with a CCTV camera. On the other-hand, CIPP used in pressure pipes (potable water and sewer force mains) are often reinforced with glass, carbon or Kevlar fibers to provide extra stiffness. Dimples do not form here easily because the pressure applied during CIPP inversion and curing is insufficient (Bradley, 2009). It is also harder to see tiny depressions inside small diameter pipes. A typical reinstatement operation usually takes about 20 min or less per lateral, provided its location is known accurately. If not, it becomes a time consuming process. Accidental damage to the liner (e.g. cutting it at an inappropriate site) often requires extensive repairs using ‘dig-and-replace’ methods which cause traffic disruptions and significant economic losses (as much as USD 10 k per lateral) (Bradley, 2009). Thus, accurate detection of these hidden laterals is important.

In this article, an electromagnetic sensor to detect hidden laterals is presented. The liner is irradiated by electromagnetic waves emitted by an open-ended rectangular waveguide that is placed adjacent to its surface. The local anomalies behind the liner in terms of the dielectric and geometrical properties are quantified by measuring the reflection coefficient of the waveguide. This NDT technique was originally proposed by Yeh and Zoughi (1994) for the detection of fatigue cracks on metallic surfaces operating at 24 GHz. Here it is adopted at a different frequency for lateral restoration. This sensor can be integrated with the robotic cutters used for lateral restoration. It is also applicable for a variety of metallic and non-metallic pipes used in buried infrastructure. In this paper, the following aspects of this sensor are discussed: (a) feasibility study conducted using numerical modeling, (b) experimental validation of this model carried out using a Vector Network Analyzer (VNA) as the primary instrumentation, (c) implementation of dedicated radio-frequency (RF) electronics to replace the VNA, (d) experimentation conducted inside CIPP lined PVC, steel and cast-iron pipe samples, and (e) automatic CIPP surface scanner using a robotic arm retrofitted with the sensor are discussed.

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[1] Portions of this research was conducted when the author was a graduate student at Louisiana Tech.

https://doi.org/10.1016/j.tust.2018.09.006
Received 23 October 2017; Received in revised form 11 July 2018; Accepted 12 September 2018

2. Current practices

At present, the visual identification of CIPP dimples is a common method employed to find hidden laterals. These side-connections are essentially discontinuities (or gaps) in the host pipe and several non-destructive testing (NDT) methods can be potentially applied to identify these gaps. McGrew and Rinehart (2006) disclosed an infrared thermal imaging system for this purpose. In an electrically conductive host pipe, magnetic eddy current sensors (He et al., 2010) can be used or even a simple permanent magnet can locate these gaps in ferrous alloy pipes that attract the magnet. However, a significant portion of the buried infrastructure consists of electrically non-conductive and non-magnetic pipes including asbestos cement, polyvinyl chloride (PVC), high density polyethylene (HDPE), reinforced concrete (RCP) and vitrified clay pipes (VCP). In some of these cases, active or passive markers are inserted into the lateral before lining and these markers are later picked up. For example, a sonde or a plug capable of emitting radio frequencies can be inserted into a lateral and in-pipe receivers can be used to track these hidden markers. Laterals can also be restored by entering into it from the house side (Oy, 2013). However, accessing all of them can be a time consuming process. Other sophisticated sensors like in-pipe Ground Penetrating Radars (GPR) (Jaganathan et al., 2010) and ultrasonic transducers (UT) which are used to measure the CIPP thickness (Allouche et al., 2014) are also applicable here. But they are tedious to deploy inside small pipes from remote controlled robots. UT requires a smooth contact surface to couple the ultrasonic vibration, and the relatively uneven surface of CIPP creates complications. Similarly, operating a conventional air-coupled radar inside a small pipe is also problematic due to several reasons including signal clutter and bulky electronics. Alternatively, the sensor proposed here offers several advantages including compactness, high resolution, ease of operation and interpretation of the output data. Its low cost hardware can be customized for small diameter pipes. It is also applicable inside a wide variety of metallic and non-metallic pipes.

3. Operating principle

An open-ended rectangular waveguide excited with the dominant mode is used as the primary sensing probe. A typical rectangular waveguide is a hollow metallic tube used to transmit electromagnetic waves. A short length of this waveguide is used as a probe, which is essentially an antenna that radiates electromagnetic waves. It has a rectangular aperture at the front end and the other end is closed. The larger size of the rectangle is indicated by a and the smaller length by b. The internal depth of the cavity is d. A coaxial feed is provided near the closed end for excitation. The aperture is placed adjacent to the CIPP liner and irradiated with microwaves. The waves emitted enter into the open space and couple with the liner. Depending upon the local dielectric and geometrical properties encountered, a portion of the wave will be reflected back into the waveguide causing a shift in the standing wave pattern, which is quantified by measuring the reflection co-efficient specified by the S-parameter (S_{11}) at the feed point. S_{11} is a complex quantity represented by magnitude and phase. As the liner is scanned by this probe, variations in S_{11} that occur are indicative of the local anomalies in the composite liner-pipe-soil structure. The probe is slowly revolved inside the pipe and S_{11} is recorded as a function of cylindrical coordinates - angle θ and distance z. Fig. 1 shows a schematic of this setup. The waveguide aperture is either in contact with the liner or a few millimeters away. The larger side a is aligned either along or perpendicular to the host pipe axis. A constant standoff distance between the probe and liner is maintained. The data from the section with intact pipe wall backed by soil is seen as the reference signal (background) which will remain steady and deviations from this baseline indicates the hidden anomalies. The signal obtained as the probe traverses a lateral will have a specific signature which is used to differentiate it from the background. In this paper, we primarily rely upon the magnitude of S_{11} without considering its phase. This simplifies the electronics required to operate the sensor. However, previously both magnitude and phase have been shown to be sensitive for detecting surface cracks and other defects (Yeh and Zoughi, 1994). Next the background information about rectangular waveguides are given.

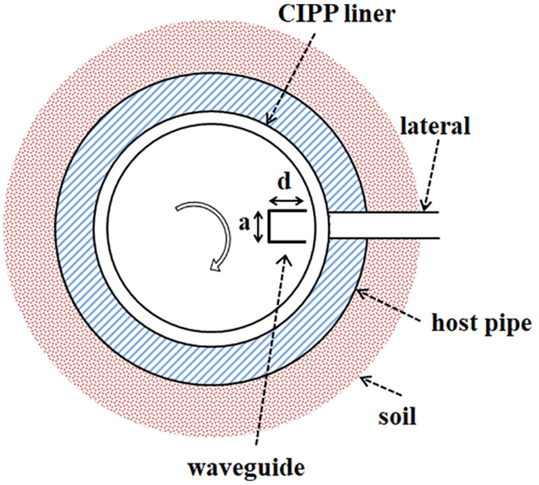

Fig. 1. Schematic of the proposed sensor inside a section of lined pipe.

A rectangular waveguide can support transverse electric (TE) and transverse magnetic (TM) modes. These modes have cutoff frequencies below which propagation is not possible (Pozar, 2009). A guide filled with a material of permeability μ and permittivity ϵ have cutoff frequencies given by Balanis (1999)

$$(f_c)_{mn} = \frac{1}{2\pi\sqrt{\mu\epsilon}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}\left.\begin{matrix} m & = 0,\,1,\,2\ldots \\ n & = 0,\,1,\,2\ldots \end{matrix}\right\} m = n \neq 0 \tag{1}$$

where f_c represents the cutoff frequency of a given mode mn, a is the width and b is the height of its rectangular cross-section. The mode with lowest cutoff (called as the dominant mode) is the TE_{10} mode ($m = n = 0$). In this NDT technique, the waveguide is excited by this dominant mode. For this application, a hollow guide (WR-137) with a rectangular cross-section of $a = 34.8$ mm and $b = 15.8$ mm is chosen as the probe. It has $f_c = 4.30$ GHz for the TE_{10} mode. The next higher order TE_{20} mode has $f_c = 8.60$ GHz. Ideally, we can operate the sensor between these two cutoff frequencies. However, the recommended range for this guide is between 5.85 GHz and 8.20 GHz (Pozar, 2009). This waveguide is chosen for its compact dimensions which are comparable to the size of laterals to be detected and its frequency range can also provide adequate resolution and depth of penetration required to see through the commonly used CIPP liners.

This NDT technique was originally proposed by Yeh and Zoughi (1994) for locating sub-millimeter wide surface cracks on metallic surfaces. Yeh and Zoughi (1994) used a much smaller waveguide operating at 24 GHz. Since then, this technique has been adopted for other purposes including the inspection of dielectric coated metallic surfaces (at 24 GHz) (Huber et al., 1997), non-contact disbond and delamination detection in planar stratified dielectric media (Bakhtiari et al., 1994) and surface crack detection in cementitious materials (at 10 GHz) (Nadakuduti et al., 2006). Theoretical analyses of this technique for various applications are available in the literature. For example, an analytical solution to predict the response of a crack on metallic surfaces (referred as the *crack characteristic signal*) irradiated by rectangular waveguide is given in Yeh and Zoughi (1994). Moments method (MM) based analysis of crack detection on dielectric coated metallic surfaces is given in Huber et al. (1997). Electromagnetic properties of a rectangular waveguide radiating into N-layered planar dielectric media is calculated analytically in Bakhtiari et al. (1994). Compared to these cases the geometry involved here is more complicated. Next the