NDT&E International 85 (2017) 20–26

Contents lists available at ScienceDirect

NDT&E International

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

# Visualization of metal tube damage using double helical microstrip lines and self-sensing time-domain reflectometry method

Ryosuke Matsuzaki[a,*], Masahiro Kawasaki[a], Akira Todoroki[b]

[a] Department of Mechanical Engineering, Tokyo University of Science, 2641 Yamazaki, Noda, Chiba 278-8510, Japan

[b] Department of Mechanical Sciences and Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo 152-8552, Japan

ARTICLE INFO

*Keywords:*
Time-domain reflectometry
Self-sensing
Finite-difference time-domain method
Crack
Visualization

ABSTRACT

The present study investigates crack visualization in a metal tube using self-sensing time-domain reflectometry with double helical microstrip lines (MSLs). The double helical MSL functions as a long-range sensing line without bend sections. It uses a differential circuit to reduce cross-talk noise. The electromagnetic field simulation results clarified that cross-talk noise is decreased when using the differential circuit. The experimental results confirmed a sudden change in the amplitude at the crack location and demonstrated that the crack was detectable. The crack existence probability obtained using the estimated value and estimation error variance from the Kriging approximation indicates a very high probability at the crack location.

## 1. Introduction

Knowledge regarding the integrity of tubes is critical in industry, as they are used structurally and as piping for water, gas, and oil lines. Currently, ultrasonic testing methods [1,2], electromagnetic testing methods such as the eddy current testing method [3,4] and the magnetic flux leakage test method [5,6], visual inspection using a camera [7,8], and thermographic flaw detection [9] are available to detect damage in tubes. Inspecting all piping is a time consuming task as the length of piping is extensive and these methods can inspect only a small area at a time. Visual inspection using a camera and thermographic methods are also limited, as the former cannot be used while the tube is in use, and the latter cannot remotely inspect tubes that are covered with materials such as insulation.

To accurately detect damage in a wide area, flaw detection methods using a guided wave, which is a type of ultrasonic wave, are being studied [10,11]. However, the soil around underground piping [12] and the curvature of the pipe [13] change and dampen the wave, reducing the accuracy of detection. A method using a fiber Bragg grating has also been proposed for detecting flaws in a wide area [14,15]. Unfortunately, the use of this method is also limited, because optical fiber systems are expensive. Although non-destructive testing using a wireless system is feasible to apply to a large structure [16–18], numerous sensors are required to inspect the entire structure, making it unsuitable for inspections over a long period. Therefore, a technique capable of detecting flaws over a wide area at one time using low-cost equipment is sought.

An inspection method that applies the time-domain reflectometry (TDR) method [19] has been proposed as a solution. The TDR method inputs a steeply rising electrical signal waveform, such as pulsed or stepped waves, into a transmission line to observe the reflected wave generated by a change in characteristic impedance caused by damage or distortions. Chen et al. used the TDR method as a damage detection technique and embedded multiple sensors in reinforced concrete specimens; they demonstrated that the shape of a crack can be detected from the sensor deformation due to damage to the specimen [20]. Cataldo et al. detected damage in a water pipe by arranging metal wire(s) over an underground water pipe and using the change in soil permittivity caused by water leakage [21]. Todoroki et al. and Pandey et al. applied the TDR method to damage detection in carbon fiber reinforced plastics (CFRPs) by attaching conductive plates to its surface; they demonstrated its ability to detect cracks in a short period of time [19,22] and its validity through further analysis [23]. This technique was more reliable than embedding sensors for detecting damage because it used CFRP, the object of inspection, as the transmission line. However, the technique could not generate sufficient information in the transverse direction of the sensor.

To solve this issue, Todoroki et al. arranged a microstrip line (MSL) as the sensor and proposed a self-sensing TDR method using the conductivity of carbon fibers as a damage detection technique [24]. They positioned the MSL two-dimensionally to cover a wide area during one inspection to detect the fiber break damage of a through crack [25], and demonstrated the capability of detecting fiber breakage caused by impact [26]. However, these TDR measurement results are

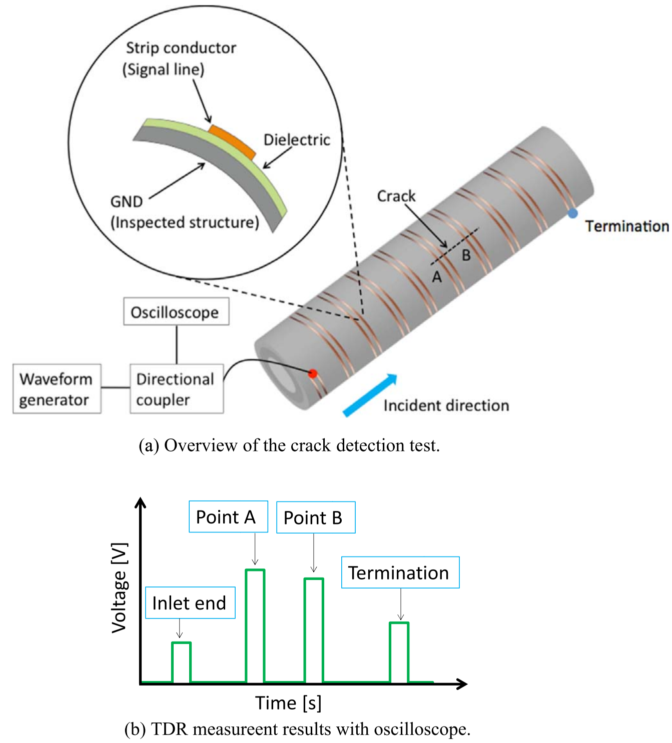
* Corresponding author.
*E-mail address:* rmatsuza@rs.tus.ac.jp (R. Matsuzaki).

http://dx.doi.org/10.1016/j.ndteint.2016.10.002
Received 17 December 2015; Received in revised form 7 September 2016; Accepted 14 October 2016
Available online 15 October 2016
0963-8695/ 

expressed as a voltage on the vertical axis with time on the horizontal axis; therefore, it is difficult to intuitively determine the location of the damage. Many studies have been conducted to visualize the results of non-destructive tests to facilitate the identification of damaged areas [27–29]. However, because of the numerous sensors used for visualization, numerous outputs are also obtained. Matsuzaki et al. arranged the MSL in two dimensions and demonstrated that the location of a crack can be visualized with fewer outputs by taking advantage of the increased information in the orthogonal direction of the sensors [30]. When an MSL is arranged in this formation, cross-talk noise must be considered. Because crosstalk noise makes the identification of crack location from the visualization difficult, Matsuzaki et al. changed the wiring method to a differential circuit to reduce cross-talk noise [31].

In thin tubes, such as those found in a pressure vessel, the stress in the circumferential direction is twice that in the axial direction; thus, the crack extends in the axial direction. As damage detection using the TDR method with the MSL detects cracks transversing the MSL, many turns will be required to apply this method to a long tube. The bends in the MSL, however, will cause undesirable reflected waves [32]. For this reason, it is difficult to inspect a wide area of the tube by arranging the MSL two-dimensionally, as was used for the flat plate.

To solve these issues, the MSL is arranged helically around the tube, and is further doubled so as to reduce the effect of the noise. This configuration reduces the reflected wave caused by the turns and cross-talk noise and makes inspection of a wider area possible. This study analyzes the differential circuit model using the finite-difference time-domain (FDTD) method and investigates its validity using the electric field distribution, which cannot be observed in an experiment. We also examine whether the damage can be accurately detected using a self-sensing TDR method with two MSLs arranged in a double helix around an aluminum tube.



(a) Overview of the crack detection test.

(b) TDR measureent results with oscilloscope.

**Fig. 1.** Schematic of self-sensing TDR with double helical MSL self-sensing time-domain reflectometry method for crack detection test. (a) Overview of the crack detection test. (b) TDR measurement results with oscilloscope.

## 2. Concept

### 2.1. Self-sensing TDR method with double helical MSLs

An MSL, a type of transmission line, is used as the object of the TDR method. The MSL consists of a conductor (GND), a strip conductor, and a dielectric; the strip conductor is arranged in parallel with the GND, between which the dielectric is placed. This structure allows transmission of high-frequency electromagnetic waves. Because the specimen is used as a GND and acts as self-sensing TDR in this study, it must be made of electrically conductive materials such as metal. The mechanical strength will not be reduced because the embedded sensors, i.e., the dielectric and strip conductors, are attached to the specimen. An MSL was adopted in this study because it consists of two layers of conductive material and is easy to manufacture. In contrast, conventional striplines are more difficult to manufacture because they require upper, middle, and lower layers of conductor patterns in order to assemble the transmission line before the dielectric material can be inserted. Although the presence of an overlay on the MSL will prevent false positives caused by the surrounding environment, we omitted the overlay in order to simplify the manufacturing of the sensor and eliminate the possibility of an impedance change caused by damage to the overlay. Moreover, the existence of an overlay may cause additional loss in the wave transmission, which is undesirable when long distance detection is required.

Fig. 1 shows a schematic diagram of the test using the self-sensing TDR method with double helical MSLs. A waveform generator, an oscilloscope, and the cable from the specimen are connected as shown in Fig. 1(a). The electrical signals are used as input to the specimen, and the reflected waves are observed. The characteristic impedance changes, thereby causing the creation of the reflected wave and transmitted waves at the contact terminal where different transmission lines meet, at the end terminal and damage location. The magnitude and polarity of the ratio between the reflected voltage $V_r$ and the incident voltage $V_i$ are determined by the mismatch of the characteristic impedances at the discontinuity, as in [33]:

$$\frac{V_r}{V_i} = \frac{Z_b - Z_a}{Z_b + Z_a} \tag{1}$$

where $Z_a$ and $Z_b$ are the characteristic impedances of the sensors at the locations just after and just before the discontinuity, respectively. When the MSL is damaged, the absence of a GND at the location increases the characteristic impedance, thus generating a reflected wave that is positive in phase. This allows estimation of the damage location using the time difference of the reflected waves from the input terminal and the damage location. The arrival time of the oscilloscope also differs because the propagation distance varies based on the location of the generated reflected wave. Therefore, when a crack develops in multiple MSL lines, as shown in Fig. 1(a), the oscilloscope indicates a reflected waves corresponding to the respective crack based on the corresponding time, as shown in Fig. 1(b). Because the crack is an open defect in a metal tube, it may act like a quarter-wave transformer when the necessary conditions, such as impedance and frequency, are satisfied, which may reduce the magnitude of the reflection. However, it is rare that the conditions are satisfied without conscious design. Thus, this may not be problematic. It should be noted that a loss of transmission power can be caused by low conductance and surface roughness of the conductor [34]. Therefore, by measuring the amplitude of the background voltage over a long period of time, the proposed MSL may be applied to the detection of corrosion or pipe wall thinning.

### 2.2. Cross-talk reduction using a differential circuit

Inverse-phase waveforms with equal absolute values of voltage will be set as an input to each of the two balanced strip conductors of the differential circuit. Therefore, the differential circuit is affected less by the external noise and is capable of suppressing emission of noise to