NDT&E International 66 (2014) 34–42

Contents lists available at ScienceDirect

NDT&E International

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

Crack visualization of metallic structures using time-domain reflectometry with two-dimensional microstrip lines

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ARTICLE INFO

Article history:
Received 18 November 2013
Received in revised form
6 April 2014
Accepted 18 April 2014
Available online 2 May 2014

Keywords:
Time-domain reflectometry
Nondestructive testing
Microstrip line
Crack
Visualization

ABSTRACT

The present study investigated crack visualization in metallic structures using time-domain reflectometry with a two-dimensional microstrip line. 2D inspection was enabled by covering the inspected structure surface with the microstrip conductor to compensate for the lack of information in the transverse direction. The experimental results demonstrated that crack propagation could be clearly visualized. However, false cracks appeared at the same position regardless of the crack position. The electromagnetic field simulation results clarified that the false cracks observed in the experiments were caused by cross talk. The problem can be eliminated by arranging the microstrip conductor appropriately.

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1. Introduction

Accidents due to aging of large-scale structures such as railroads, bridges, and tunnels have posed a problem in recent years. To prevent accidents, damage must be detected and repaired in advance. Therefore, conducting periodic inspections of structures is very important [1,2]. Damage to these large-scale structures is inspected by nondestructive techniques such as X-rays [3,4], ultrasonic tests [5], hammering, visual observation, and sometimes wireless inspection [6–8]. Although X-rays and ultrasound allow information on invisible embedded damage to the structures to be acquired, these methods are usually scanning types; thus, inspection of an entire large-scale structure requires a very long time. In addition, this inspection also causes problems because operations of the structures have to be stopped. Techniques that can inspect damage to large-scale structures in a short time even during operation are in high demand.

Time-domain reflectometry (TDR) has been proposed as an inspection method that fulfills the above conditions [9]. TDR is a technique that propagates a sharply rising electrical signal such as a pulse wave or step wave to a transmission line and measures the reflected wave to determine characteristics of the impedance variation caused by damage or strain [10,11]. Because TDR can be done by setting a single measurement point at the end of the microstrip conductor and continuously inspects a fairly long range with less attenuation than ultrasonic inspection using guided waves, the method has the potential to inspect entire large-scale structures in a short time while they are in service.

Several studies have developed damage detection techniques using TDR. Chen et al. [12] embedded transmission lines into reinforced concrete. They utilized the deformation of the transmission line due to damage of the inspected structures and demonstrated that the configuration of a crack can be detected. Obaid et al. [13] also embedded an electrode in carbon fiber reinforced plastics (CFRPs) to detect cracks using the TDR method. However, their method requires embedding the electrode at the time of construction of the structure. To solve the installation problem, Todoroki et al. [14,15] proposed self-sensing TDR for CFRPs, in which the carbon fibers are adopted as a microstrip line of TDR for damage monitoring, and showed that the position and size of a crack can be measured in a short time.

Although the crack position can be detected along the microstrip conductor by conventional TDR techniques, information on damage in the transverse direction of the microstrip conductor is quite lacking. Therefore, multiple sensors need to be used to compensate for the lack of information. Another problem with conventional TDR is that the crack data are represented in terms of time-voltage, and the crack position is difficult for general TDR users to intuitively understand.

The present study involved investigation of a new method for crack visualization in metallic structures. The proposed method uses TDR with a two-dimensional (2D) microstrip line (MSL)

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http://dx.doi.org/10.1016/j.ndteint.2014.04.007
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arranged in two dimensions to compensate for the lack of information in the transverse direction. A problem with 2D MSL is that the incident signal wave may leak to the adjacent microstrip conductor and reflect at the microstrip conductor terminal and curved parts, which degrades the signal-to-noise ratio. Therefore, the present study also clarified these effects attributed to the application of TDR with 2D MSL through experiments and numerical unsteady electromagnetic simulations.

2. Crack visualization using TDR with 2D MSL

2.1. TDR with 2D MSL

An MSL is an electrical transmission line with a three-layer structure comprising a microstrip conductor (signal line), dielectric materials, and electric conductive ground (GND) from top to bottom, as shown in Fig. 1. In the present study, the inspected structures were used as the ground layer of the MSL. Thus, the film sensor comprising dielectrics and a microstrip conductor was stuck on the surface of the inspected structures. Note that the inspected structures must be made of an electrically conductive material such as steel. Because embedding a sensor inside the structure is not necessary, sensor installation does not reduce the strength, and the method can be widely applied to existing

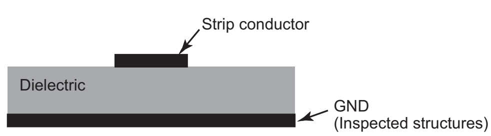

Fig. 1. Schematic of cross section of microstrip line.

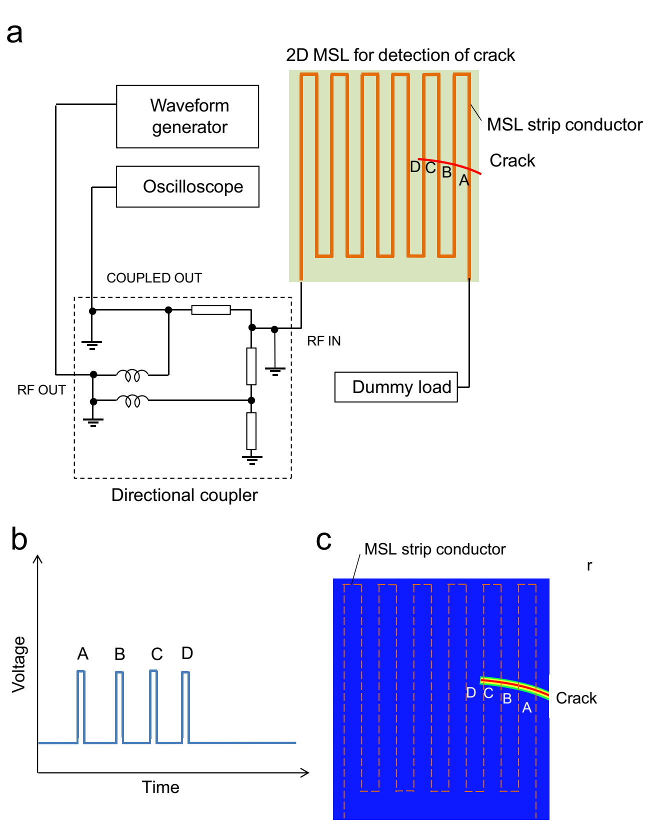

Fig. 2. Schematic of TDR with 2D MSL for crack visualization: (a) overview of inspection equipment; (b) TDR measurement results with oscilloscope; (c) crack visualization.

structures. Because the structures act as the transmission line, the damaged state directly affects the measured TDR data; thus, high sensitivity and reliability are also expected compared with indirect TDR that attaches all three layers of the MSL to the structure.

The schematic of the proposed inspection and visualization is shown in Fig. 2(a)–(c): inspection equipment, typical measurement results with an oscilloscope, and crack visualization, respectively. 2D inspection of the flat surface is realized by covering the inspected structure's surface with the microstrip conductor turned multiple times back and forth. Thus, the entire in-plane area can be inspected by setting a single measuring point at the end of the microstrip conductor.

In TDR, the incident wave is transmitted and reflected where the characteristic impedance varies. When the characteristic impedance changes from Z_a to Z_b due to the presence of a crack, the reflected wave V_r is [10]

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

where V_i is the voltage of the incident wave. When there is a crack in the metallic structure, part of the GND is disconnected, and the characteristic impedance changes; a reflected wave from the crack is then observed. The crack configuration can be determined from the measured reflection waves. For example, if the crack grows and straddles multiple microstrip conductors at points A–D, as shown in Fig. 2(a), multiple peaks corresponding to points A–D are detected on the measured waveform, as shown in Fig. 2(b). The time-domain data are used to transform the peak positions into geometric positions on the MSL. Consequently, crack configurations can be visualized as a contour figure, as shown in Fig. 2(c).

However, when a microstrip conductor is arranged in two dimensions, crosstalk between microstrip conductors and reflection at the corner of the microstrip conductor may occur. Crosstalk is a phenomenon when two or more transmission lines are arranged in parallel: the signal waveform transmitted along one transmission line leaks to the adjacent transmission line. Crosstalk has a strong influence when the gap between transmission lines is narrow or the parallel section is long [16,17]. With the TDR method, a reflected wave may occur at three possible points: between wave generator and oscilloscope, at the connection between microstrip conductor and coaxial cable used to connect the apparatus, and the end of the microstrip conductor. Reflected waves at these locations may decrease the signal-to-noise ratio or even produce misleading data by appearing as false cracks in crack visualization. To suppress these influences, the following measures were taken:

(i) The wiring interval is four times or more the width of the microstrip conductor to counteract crosstalk.

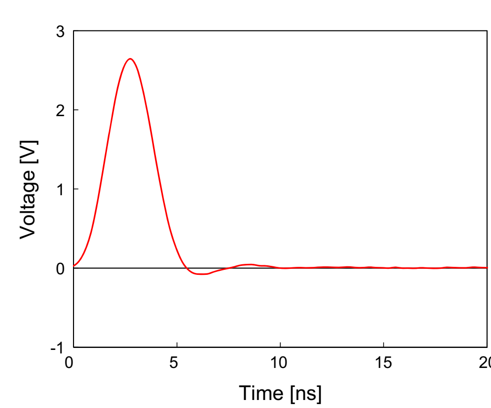

Fig. 3. Incident waveform used in experiments of TDR with 2D MSL.

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