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Optimizing the frequency range of microwaves for high-resolution evaluation of wall thinning locations in a long-distance metal pipe

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ABSTRACT

A vector network analyzer (VNA) and a self-designed coaxial-line sensor are utilized in this study to generate the time domain response of microwave signals. The frequency range of the signals is optimized by analyzing the time domain response. Thereafter, the pipe wall thinning (PWT) location is quantitatively evaluated by measuring signals at the optimum frequency range and extracting the time of flight (TOF) information corresponding to the PWT location. To approach a pipe with different PWT degrees and lengths, two brass pipes with inner diameters of 17.0 mm and lengths of 453 mm and 455 mm, and six brass joints having different inner diameters and lengths were used between the two pipes in turn to construct the combined pipes that were used in the experiment. By using the frequency range of 22.0–35.0 GHz, the maximum errors of evaluations are less than 0.38% and 1.04% of the full lengths of the pipes under test for the start and end points of the PWT sections, respectively. When the length of the PWT section increases, the evaluation precision also increases. This result indicates that a quantitative method for evaluating the PWT locations in the pipe under test with relatively high resolution and precision is established.

1. Introduction

Metal pipes have been widely used in many industries since the 1960s. During the service of the pipes, wall thinning is one of the most typical defects and is an especially important symptom of future failure in pressure vessels [1–3]. Pipe wall thinning (PWT) is a serious defect that can cause the normal pressure of the pipe wall to reach overload levels because of the reduced wall thickness, and the overloading pressure of the pipe wall can lead to pipe bursting. In the past 20 years, PWT has become a serious problem for many pipelines whose service time exceeding tens of years. Accidents caused by PWT have occurred frequently around the world and caused severe economic losses and social damages. Therefore, the development of efficient and nondestructive methods for detecting PWT defects, as well as their quantitative evaluation, especially for long-distance pipes, is mandatory for the effective maintenance and lifetime prediction of pipelines.

The PWT problem is twofold. One is the PWT degree, which means the depth and length of PWT. It contains important information concerning the safety and lifetime of pipes. The other is the PWT location, which is important for the detection and maintenance of in-service pipes, especially long-distance pipes. Recently, many researchers have focused on developing nondestructive testing (NDT) techniques for detecting PWT defects [3–11]. However, most of these methods can only inspect a pipe locally, and all of them are difficult to use to measure long-distance pipes buried underground, placed in the walls of some concrete buildings, or under other similar conditions. In reality, all those methods generally require lots of time and labor to inspect a long-distance pipe, and they can only solve part of the first aspect of the PWT problem.

Microwave NDT has been used to overcome the shortcomings of the aforementioned methods because microwaves can propagate long distances with quite little attenuation in a low-loss dielectric medium [12]. In microwave NDT, a metal pipe under test (PUT) can be promisingly taken as a circular waveguide [12–15], and all of the energy of the microwave signals is confined inside the pipe. Moreover, the propagation and attenuation of microwaves in the pipe are independent of the surrounding conditions of the pipe.

In Ref. [12], the PWT degrees of a 2 m long pipe were remotely examined and quantitatively evaluated with high precision in the frequency domain. On the other hand, the time domain response (TDR) of microwave signals, which is derived from inverse fast Fourier Transform (IFFT) of the frequency domain signals, has been used as an effective tool for detecting fault locations in a metal pipe [13]. However, in Ref. [13], the frequency range (13.0–21.0 GHz) including only the pure fundamental mode TM_{01} signal

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was utilized in order to realize single mode measurement. It is found that the response resolution of the time of flight (TOF) in this frequency range is not high enough, and the reflected signals from the start and end points of the PWT section overlapped and were difficult to separate when the length of PWT was short. In this paper, a method with higher response resolution, which has the ability to resolve two closely spaced responses in the time domain, was demonstrated. By optimizing the sweeping frequency, a method using the frequency range of 22.0–35.0 GHz, including both the fundamental and the first-high-order mode signals to detect the PWT locations, was built that can successfully evaluate the start and end points of a PWT defect with a length no less than the inner diameter of the pipe. Here, a reference pipe under the open condition was utilized to calibrate the group velocity and to confirm that there was no overlap between the reflections of the fundamental and high-order mode signals.

2. Experimental approach

The experimental instrument is composed of a vector network analyzer (VNA), a self-designed coaxial-line sensor, and a PUT, as shown in Fig. 1. The sensor is made from a standard coaxial-line cable and connector [13], and it serves as both the transmitting and receiving ports for the microwave signals.

The pipe specimens tested in this paper are composed of two pipes with inner diameters of $d_1=17.0$ mm, six joints, and a connector used to connect each joint between the two pipes. All of them are made of brass. The lengths of the two pipes, labeled P1 and P2 in this paper, are $l_{11}=453$ mm and $l_{12}=455$ mm, respectively, and the wall thickness of both pipes is $t=1.0$ mm. The six joints, which are used to introduce PWT sections with different PWT degrees and lengths in the combined pipe, are separated into two groups, A and B, by their different lengths of $l_2=17.0$ and 51.0 mm. In each group, there are three joints with different inner diameters, d_2, as specified in Table 1. These joints are used in turn to construct different PWT sections in the combined pipe. During the experiment, six combined pipes with PWT defects of different degrees and lengths were constructed, as shown in Fig. 2, using P1, P2, and the connector and joints mentioned above. In this figure, l_0 denotes the total length of the PUT, and d_1 is the inner diameter of the section free from PWT, while t is the wall thickness of the pipe. The symbols t_1 and l_2 represent the PWT depth and length of the PWT sections, respectively, and d_0 denotes the inner cable of the sensor and has a value of $d_0=6.5$ mm.

Before measuring the pipe, electrical calibration (E-cal) of one flexible cable of the VNA was carried out to set the zero time reference plane at the end of the flexible cable. During the experiment, microwave signals were generated by the VNA and coupled into the pipe through the coaxial-line sensor. The VNA was set to work at the S_{11} mode so that the same port of the sensor detected the microwave signals reflected from both the PWT sections and the terminal of the PUT. While sweeping the frequency within the proper range, the corresponding amplitudes of response signals containing PWT information were measured. The frequency domain signals were obtained directly, from which the time domain results were calculated through IFFT. TOF, which is defined in this paper as the arrival time of any reflection peak of the microwave signals leaving and returning to the reference zero time interface, can then be extracted from the time domain analysis of the signals.

To obtain high precision in the time domain, measurements of 1601 sweeping points were adopted in the experiment. The time domain measurements are designed to be carried out in two steps. The first step is to measure the pipe in the time domain range that is wide enough to contain all of the time domain responses, i.e., responses according to all of the discontinuous points from the calibrated zero time interface to the terminal of the PUT. After collection of general information on the PWT location in the pipe, the second step is to measure the pipe in a more focused (much narrower range) time domain range where large reflections occur corresponding to the PWT location. As a result, more detailed information of the PWT can be extracted from the reflection peaks expanded on the time axis. The two steps are carried out with the same number of sweeping points. Thus, the time precision of the second step is much higher, under which the smaller time range is measured.

Table 1
Detailed geometric parameters of the joints.

Joint number	A1	A2	A3	B1	B2	B3
Length, l_2 (mm)	17.0			51.0		
Inner diameter, d_2 (mm)	17.10	17.20	17.40	17.20	17.40	17.80
PWT degree, % t	5	10	20	10	20	40

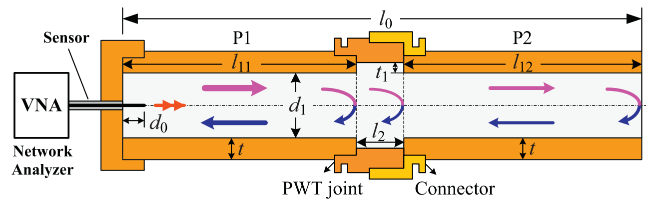

Fig. 2. Schematic diagram of the experimental setup and the signal propagation and reflection within the combined pipe.

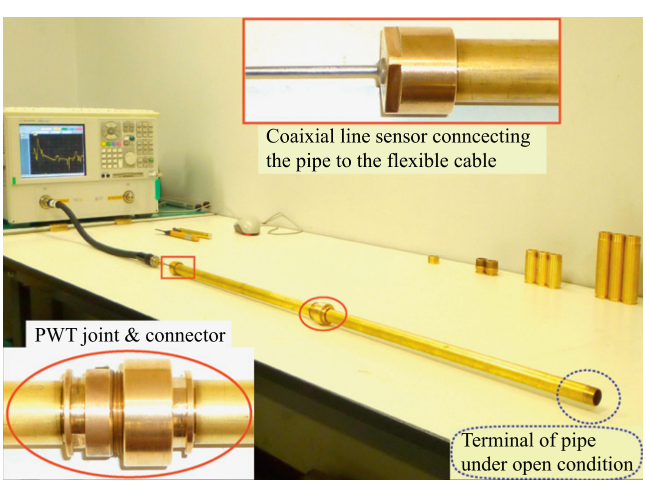

Fig. 1. Overall photograph of the experimental instrument.

3. Theoretical analysis

As mentioned above, the frequency domain response (FDR) of the microwave signals is obtained directly when sweeping the frequency at a fixed range, and the TDR is calculated through IFFT of the FDR. By calibrating the group velocity in the pipe and analyzing the TOF corresponding to the PWT location at the time domain, the PWT locations can be quantitatively evaluated. The resolution of the evaluated locations is determined by the response resolution of the reflected signals in the time domain. In this section, we focus on the theoretical analysis of the relationship between the frequency range selection and the time domain response, especially the response resolution of the signals. In addition, the analyses of the TOF data and the calibration of the