Remote Detection and High Precision Evaluation of Wall Thinning Volume in a Metal Pipe

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Abstract

We report a nondestructive method to measure the pipe wall-thinning (PWT) remotely using microwaves. A microwave vector network analyzer (VNA) and a self-designed transmitting and receiving (T&R) coaxial-line sensor are employed in the experiment to generate microwave signals propagating in the metal pipe where the frequency was swept from 14.08 to 14.12 GHz. A brass pipe with inner diameter of 17.03 mm, 1.0 mm wall thickness, 2.0 m length, and connected respectively with 9 joints having the lengths of 17.0 mm and PWT volumes from 0 to 550 mm^3 were measured. By taking the pipe as a circular waveguide of microwave, after building up a resonance condition and then solving the resonance equations, the remote detection method is achieved. By comparing the experimental results with the evaluated ones using our method, it is found that the evaluated results agree well with the experimental ones, it indicates that a high precision evaluation method is established.

Keywords: Remote detection, Wall thinning, Microwave, Nondestructive measurement, Metal pipe

1. Introduction

Metal pipes are used widely in industry. From 20 years ago, accidents due to pipe wall thinning were reported frequently all over the world. PWT is one of the most serious defects in pipes used in industry [1,2]. Efficient detection and quantitative evaluation of wall thinning in pipes are very important issues for prediction of lifetime of the pipes in order to avoid severe accidents.

Recently, many nondestructive testing techniques, such as x-ray [3], electrical potential drop [4], ultrasonic [5,6], magnetic flux leakage [7], eddy current testing [8] and so on, have been used for the measurement of PWT. However, all of them can only inspect a pipe locally, and are difficult to measure pipes buried under ground, in walls of some structures, or other buried conditions. Because a metal pipe can be taken as a circular waveguide of microwave, and based on the fact that microwave can propagate to a very long distance with quite little attenuation in media as air, petroleum, gasoline, or any other low-loss dielectric materials, and what is more, because all the energies are confined inside the metal pipe and the propagation and attenuation of microwaves in the pipe are independent of the pipe's surrounding conditions, microwaves are adopted here.

The time of flight of microwave has been used to detect the locations of cracks in the pipe [9,10], but because the degree of PWT is generally more important than its location for predicting the life time of the pipe. In this research, we focus on the quantitative measurement of the PWT volume using microwaves. After confirming the working mode of microwave for certain frequencies, the wavelength of microwave in the pipe is a function of the frequency and the inner diameter of the pipe [11], so after tracing the route of microwaves propagating in the pipe and building up the resonance condition of microwaves propagating in the pipe, and then by solving the resonance equations, the PWT volumes are evaluated.

2. Experimental approach

The experimental instrument is composed of a set of pipe specimens, a microwave network analyzer, and a T&R coaxial-line sensor. The photograph of the instrument is shown in Fig.1, and the schematic diagram of the inspected pipe is shown in Fig.2.

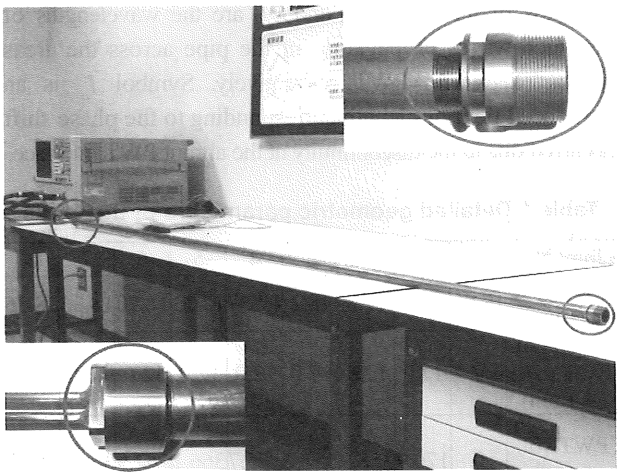

Fig.1 Overall photograph of the microwave network analyzer, pipe, sensor, and joints

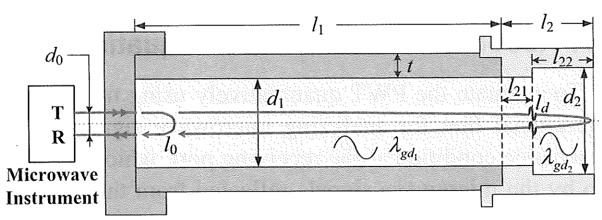

Fig.2 Schematic diagram of resonance structure in the pipe connected with PWT joint

The pipe specimens are composed of a brass pipe with inner diameter of $d_1 = 17.03$ mm, wall thickness of t = 1.0 mm and length of $l_1 = 2.0$ m, and three groups of PWT joints with a length $l_2 = 17.0$ mm and different PWT volumes. The first group of joints are composed of three joints, which have the character that each of them has a homogeneous 17.0 mm long PWT part. The second group of joints are also composed of three joints and their PWT part having a length of 12.0 mm. The third group are composed of two joints and their PWT part having length of 9.842 and 14.932 mm, respectively. The three groups of joints are numbered as No. 1 to No. 8 successively, and whose detailed geometric parameters are shown in Table 1. Also, to form the same total length, another joint with the same length of $l_2 = 17.0$ mm but without PWT (i.e., the inner diameter is the same as that of the pipe) is used in the experiment and numbered as No. 0, its geometric parameter is also shown in Table 1. The schematic graph of the joint connecting with the pipe is shown in Fig.2.

In Fig.2, the "Microwave Instrument" refers to the network analyzer, the T and R represent transmitting and receiving port of the sensor, respectively. Symbol d_0 is the distance between the two ports; l_0 is the path along which microwaves propagate directly to the receiving port; d_1 is the inner diameter of pipe without PWT and having the length l_1; l_2 is the total length of the joint; l_{21} is length at the part in the joint without PWT; d_2 is the inner diameter of the PWT part with a constant PWT value and having the length $l_{22} = l_2 - l_{21}$, and t is the wall thickness of the pipe. λ_{gd_1} and λ_{gd_2} are the wavelengths of the microwaves propagating in the pipe across the areas without and with PWT respectively. Symbol l_d is an introduced fictitious length corresponding to the phase shift occurred due to the discontinuity at the abrupt PWT interface.

Table 1 Detailed geometric parameters of the joints

Joint No.	0	1	2	3	4	5	6	7	8
Diameter, d_2 (mm)	17.03	17.4	17.8	18.2	17.57	18.13	18.70	18.36	18.36
Length of PWT part, l_{22} (mm)	0	17.0	17.0	17.0	12.0	12.0	12.0	9.842	14.93
PWT vol. (mm^3)	0	170.9	358.9	551.2	175.7	366.1	562.9	364.3	552.7

3. Theoretical analysis

3.1 Resonance condition and equations

To evaluate the PWT quantitatively using microwave, the crucial hint for analyzing microwave signals is the resonance condition at the receiving port, which are built up by the microwave signals reflected from the terminal of the pipe (after propagating along the pipe and reflected from the terminal) and that going directly to the receiving port along a route having length larger than d_0, the direct distance of the two ports, with length l_0, without propagating in the pipe. Here, $l_0 = F(\lambda_{gd_1})d_0$. $F(\lambda_{gd_1})$ is a function of the wavelength in the pipe at the part without PWT, and the proportional expression of l_0 is based on the fact that the larger d_0 will have the larger l_0 and $d_0 \to 0$ corresponds to the $l_0 \to 0$. The schematic diagram of resonance structure in the pipe has been shown in Fig.2.

When taking $l_{Total} = l_1 + l_2$ and expressing the propagation route in wavelengths of microwave, the equation for the difference of distance that microwaves propagate along the two routes can be written as follows [11],

$$2l_{Total} - l_0(f_q) + 2l_d(f_q) = (m+x)\lambda_{gd_1} + (n+y)\lambda_{gd_2} \quad (1)$$

with

$$m, n \in N \text{ and } 0 \le x, y < 1 \quad (2)$$

N is the set of natural number. f_q is the qth resonance frequency of the pipe connected with a PWT joint. The integral number m means the times of full wavelength in the pipe at the part without PWT, the $0 \le x < 1$ means the time of wavelength less than a full one, and the $(m+x)$ is the total times of wavelengths. Similarly, the integer n means the times of full wavelength in the round trip along which the microwave propagating in the joint at the part with PWT, the $0 \le y < 1$ and $(n+y)$ have the similar meanings as $0 \le x < 1$ and $(m+x)$. Therefore, $(m+x)\lambda_{gd_1}$ corresponds to the difference of distance for the two different route along which microwave propagates in the pipe at the part without PWT, and the $(n+y)\lambda_{gd_2}$ the length of round trip along which microwave propagates in the pipe at the part having PWT.

Eq. (1) can be written in the separated form as

$$\begin{cases} 2(l_1 + l_{21}) - l_0(f_q) = (m+x)\lambda_{gd_1}(f_q) \\ 2l_{22} + 2l_d(f_q) = (n+y)\lambda_{gd_2}(f_q) \end{cases} \quad (3)$$

It is known that when the microwave propagates a full wavelength, its phase will change 2π. The phase change in Eq. (3) can be expressed as

$$\begin{cases} (m+x)\lambda_{gd_1}/\theta_1 = \lambda_{gd_1}/(2\pi) \\ (n+y)\lambda_{gd_2}/\theta_2 = \lambda_{gd_2}/(2\pi) \end{cases} \quad (4)$$

therefore,

$$\begin{cases} \theta_1 = 2\pi(m+x) \\ \theta_2 = 2\pi(n+y) \end{cases} \quad (5)$$

θ_1 and θ_2 mean the phase changes in the round trip along the pipe at the parts without and with PWT, respectively.

Therefore, the whole difference of phase change for microwave propagating along the two routes expressed in Eq. (1) can be expressed as

$$\theta = \theta_1 + \theta_2 = 2\pi(m + x + n + y) \tag{6}$$

The resonance is under condition that the difference of phase change is integral times of 2π, so the resonance condition of Eq. (1) or (3) can be expressed as

$$q = (m + n + x + y) \in N \tag{7}$$

From Eqs. (7) and (2), the resonance condition can also be written in a simpler form as

$$x + y = 1 \tag{8}$$

Eqs. (7) and (8) mean that the resonance condition is formed only when the difference of the distance that microwave propagates along the two routes in the pipe is natural times (q times) of wavelength, i.e., the two routes of microwave signals can form the resonance only when they having the phase difference of $2\pi q$. This is the detailed physical meaning of symbol q.

Eq. (1) can be written in function of PWT volume as

$$2l_{Total} - l_0(f_q) + 2l_d(f_q) = q \cdot \lambda_{gd_1} - p(f_q) \cdot V \tag{9}$$

with

$$p(f_q) \cdot V = (n + y)(\lambda_{gd_1} - \lambda_{gd_2}) \tag{10}$$

Symbol V expresses the PWT volume, and $p(f_q)$ is an undetermined parameter. When the wall thinning thickness is expressed as $s = (d_2 - d_1)/2$, then we have

$$V = \pi[(s + d_1/2)^2 - (d_1/2)^2]l_{22} = \pi(d_1 s + s^2)l_{22} \tag{11}$$

When $s/d_1 \leq 1/10$, which is the general condition of the usual PWT, the PWT volume can be written in brief as

$$V \approx V_{\text{appr}} = \pi d_1 s l_{22} \tag{12}$$

with error of approximation $(V - V_{\text{appr}})/V \leq 9\%$.

When joint No. 0, the joint without PWT, is used, similar as Eq. (1), only omitting the parameter l_d taking account for the fictitious path at the interface of discontinuity, the equation describing the difference of distance that microwave propagates along the two routes in the pipe connected with the joint that without PWT can be written as follows,

$$2l_{Total} - l_0(f'_q) = q \cdot \lambda_{gd_1}(f'_q) \tag{13}$$

where f'_q is the resonance frequency of the pipe connected with the joint without PWT, and q is the same as that of the pipe connected with a PWT joint.

3.2 Solving the resonance equations

Now, there are two groups of resonance equations, one group is Eqs. (9) and (10) for pipe with PWT, the another is Eq. (13) for pipe without PWT, the resonance conditions are both expressed in Eq. (7).

The method to solve the resonance equations and to evaluate the PWT volume can be separated to the following two steps. The first step is using the comparatively simpler Eq. (13) to construct and solve $l_0 = F(\lambda_{gd_1})d_0$ and to solve the q simultaneously, and the second step is to using the l_0 and q to solve Eqs. (9) and (10).

To carry out the mentioned two steps, at first the detailed expression of wavelength should be introduced. In general, the wavelength of a circular waveguide having a relation with the working mode of microwave and being a function of applied frequencies can be expressed as [12]

$$\lambda_g = 1\Big/\sqrt{\mu\varepsilon f^2 - [p_{nm}/(\pi d)]^2} \tag{14}$$

Here, μ and ε are the permeability and the permittivity of the media in the pipe (air is used as the medium here, so that $\mu = \mu_0$ and $\varepsilon = \varepsilon_0$), f is the applied frequency, d is the inner diameter of the pipe, p_{nm} is the mth root of the first kind Bessel function for TM modes [12].

When the microwave signal is introduced directly into the pipe through a coaxial line, the electromagnetic field at the terminal of the coaxial line sensor determines that the working modes exist in the circular waveguide are all TM modes, and among which the dominant mode is TM_{01}-mode. When sweeping frequency is between the cut-off frequency of the dominant mode and that of the first higher order mode, the mode for applied frequencies is the single TM_{01}-mode. In this paper, only the dominant TM_{01}- mode is used, for which we have

$$p_{nm} = p_{01} = 2.4048 \tag{15}$$

Because the inhomogeneity of the inner diameter of the pipe will aggravate the evaluation precision, a useful method to detect the average of the inner diameter of a pipe is derived and its expression is as follows [11],

$$d_E = p_{01}\Big/\left(\pi f_{cTM_{01}}\sqrt{\mu\varepsilon}\right) \tag{16}$$

d_E is the exact average inner diameter of the pipe, and $f_{cTM_{01}}$ is the cutoff frequency of TM_{01}-mode.

The same as shown in Fig.2, in Eqs. (1), (9) and (13), there is a propagation variable l_0 being expressed as $l_0 = F(\lambda_{gd_1})d_0$, $F(\lambda_{gd_1})$ is a function of the wavelength in the pipe at the part without PWT. In our previous research [11], a method to determine l_0 is established and demonstrated in detail.

In Eq. (9), $l_d(f_q)$ is generated by the discontinuity at the PWT interface, i.e., for the pipe without PWT

$l_d(f_q)=0$. So $l_d(f_q)$ should be a function of PWT condition of the pipe and of the applied frequencies. Therefore, l_d can be expressed as $l_d = a_0(f_q)V/2$.

After l_0 and q are determined, for the PWT condition, Eq. (9) becomes

$$2l_{Total} - l_0(f_q) = q\lambda_{gd_1} - p'(f_q)V \tag{17}$$

where $p'(f_q) = p(f_q) + a_0(f_q)$.

Eq. (17) also satisfies the limit condition that when the pipe is without PWT, then $V=0$ and f_q becomes f'_q, and Eq. (17) degenerates to Eq. (13).

For simplification and easy to calibrate, taking

$$p'(f_q) = a_2 f_q \tag{18}$$

when using one joint whose PWT volume is known (i.e., V is known) for calibration, it is easy to solve the a_2 from Eq. (17), and then from Eq. (18), the $p'(f_q)$ can be easily calculated.

In this paper, joint No. 2 (with known PWT volume of 358.9 mm^3, see Table 1) is used for calibration.

Finally, from Eq (17), the PWT volume is evaluated to be as follows,

$$V_{\text{eval}} = [q\lambda_{gd_1} + l_0(f_q) - 2l_{Total}]/p'(f_q) \tag{19}$$

4. Results analysis and conclusion

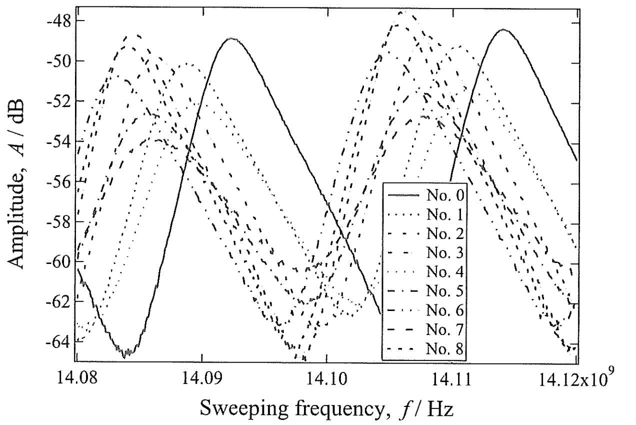

Fig.3 Experimental results of amplitudes versus sweeping frequencies of microwaves when the pipe is connected with different PWT joints

Fig.3 shows the measured amplitudes of microwave signal versus the sweeping frequencies, in the case that the pipe connected with the joints from No. 0 to No. 8. It can be found that the resonance frequencies (peaks of waveforms) are changed due to the wall thinning, with the increase of the PWT volume, the resonance frequencies decrease step by step. It is in accordance with the fact that the wavelength of guiding wave is correlative with the inner diameter of the waveguide.

From the waveforms at frequencies 14.08 ~ 14.10 GHz, it is found that for the PWT joints No. 0 to No. 8, with the increase of 562.9 mm^3 PWT volume, the resonance frequencies decrease from 14.0828 to 14.0923 GHz, i.e., 9.5 MHz frequency change is found, considering the resolution of the microwave instrument, this method is quite useful for detecting the PWT values.

To determine the high precision inner diameter of the pipe, using the method described in Ref[11], from 4 times of random measurement, the cut-off frequency of TM$_{01}$-mode is found to be between 13.47670 and 13.476775 GHz, and then from Eq. (16), the average inner diameter d_E is calculated to be 17.02823 mm with evaluation error less than ±0.05 μm.

To determine the parameter l_0, ten neighboring resonance frequencies were measured in the experiment by sweeping frequency at 14.00 ~ 14.21 GHz, and from Eqs. (14) and (15), ten corresponding wavelengths are calculated. Then using the calibration method described in Ref[11], the q and the ten different l_0 corresponding to the ten wavelengths are solved. It is solved as $q_0 = 51$. Then the ten calculated l_0 and the corresponding wavelengths are shown together in Fig.4 in form of blue triangle markers. In Fig.4, using Least Square method, linear curve-fitting is used, and the linear curve-fitting results matches well with the experimental ones.

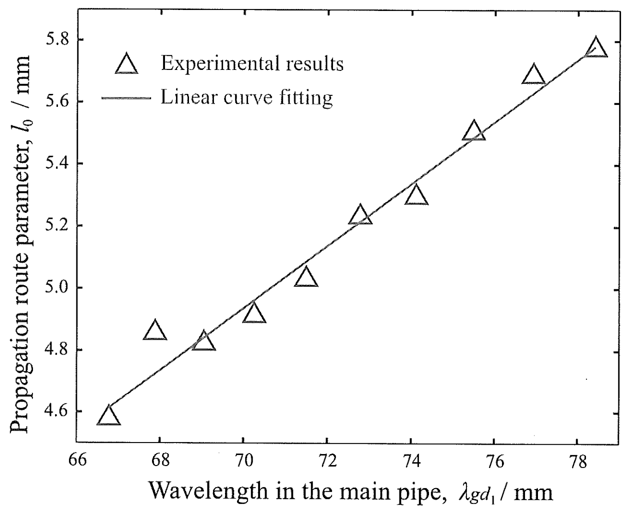

Fig.4 Experimental method to determine the path length l_0 using neighboring resonance frequencies

With two undetermined coefficients, linear expression of l_0 can be written as follows

$$l_0 = F(\lambda_{gd_1})\cdot d_0 = (a_0\lambda_{gd_1} + b_0)d_0 = a_1\lambda_{gd_1} + b_1 \tag{20}$$

By using the linear curve-fitting in Fig.4, the a_1, b_1 are solved to be $a_1 = 0.60203987$ and $b_1 = -0.0125209$, l_0 is achieved.

As described in Section 3.2.3, to solve the a_2 in Eq. (20), joint No. 2 (with known PWT volume of 358.9 mm^3, see Table 1) is used for calibration. It is solved as

$a_2 = 4.0115 \times 10^{-9}$ ($m^{-2} \cdot Hz^{-1}$).

For the two groups of resonance frequencies in Fig.4,

$$\begin{cases} q_1 = q_0 + 4 \\ q_2 = q_0 + 5 \end{cases} \quad (21)$$

For the experimental results shown in Fig.3, using Eqs. (18), (19) and the parameters a_1, b_1, a_2 and the q expressed in Eq. (21), for the comparatively lower frequency results at range 14.08 ~ 14.10 GHz, the evaluated PWT volumes in comparison with the nominal ones are shown together in Fig.5.

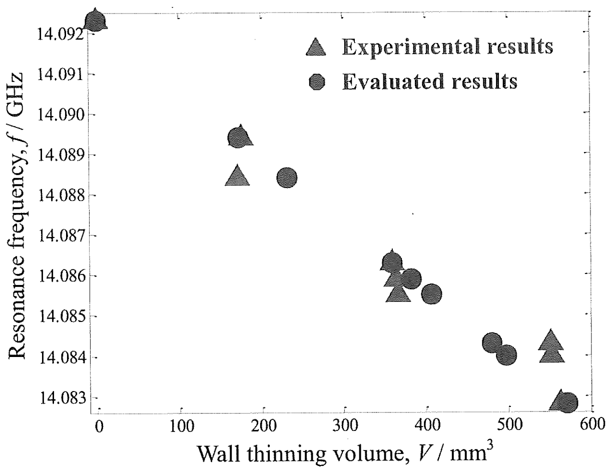

Fig.5 The evaluated results comparing with the experimental ones of the comparatively lower frequency results in Fig.3

The triangle markers in Fig.5 show the relationship of resonance frequencies extracted from Fig.3 and the PWT volumes. It can be found that with the increase of the PWT volume (i.e., with the aggravation of the PWT degree), the resonance frequencies decrease step by step.

The circle markers in Fig.5 show the evaluated results when using the same resonance frequencies as the triangle markers.

By comparing the evaluated results with experimental ones in Fig.5, for pipe having 17.03 mm inner diameter, it is found that the evaluated results agree well with the experimental ones, it indicates that this method can be used for remote detection and quantitative evaluation of PWT volumes.

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