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A high-efficiency nondestructive method for remote detection and quantitative evaluation of pipe wall thinning using microwaves

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ABSTRACT

We report an efficient nondestructive evaluation (NDE) 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 were employed in the experiment to generate microwave signals propagating in the pipe where the frequency was swept from 14.00 to 14.20 GHz. A brass pipe with inner diameter of 17.03 mm, 1.0 mm wall thickness, 2.0 m length, and connected, respectively, with 6 joints having the length of 17.0 mm and PWT from 0% to 60% of wall thickness was measured. By taking the pipe as a circular waveguide of microwave, after building up a resonance condition and then solving the resonance equations, the evaluation of PWT was realized. By comparing the evaluated results obtained using our suggested method with the nominal inner diameters of the joints, the maximum evaluation error is found to be less than 0.05 mm, which is less than 0.294% of the inner diameter of the pipe, which indicates that a high precision evaluation method is established.

1. Introduction

Metal pipes are used widely in industry, such as oil and gas transportation, chemical industry and various kinds of power plants. Since the decade before last, accidents caused by pipe wall thinning have been reported frequently all over the world. Pipe wall thinning (PWT) is one of the most serious defects in pipes used in industry [1,2]. Efficiently detecting and quantitatively evaluating the PWT in these pipes is a very important issue for predicting the lifetime of pipes and avoiding severe accidents economically.

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, except for the hollow cylindrical guided wave (HCGW) of ultrasonic method [6], all of them can only inspect a pipe locally. Even though HCGW can propagate a long distance along an isolated pipe, the ultrasonic energy will attenuate much faster when there are many girth welds on the surface of the pipe [9]. Besides, all of the aforementioned methods are difficult to measure pipes buried under ground, in walls of some structures, or under other buried conditions. This is the main shortage for the HCGW method, because the ultrasonic energy will attenuate much faster in the pipe surrounded by different kinds of media such as earth, concrete, or water [10]. As a result, all the existing methods generally take lots of time and labor to inspect a large scale pipe under many practical conditions.

Microwave can be used to overcome the shortcomings of the mentioned methods above, because it can propagate a very long distance with quite little attenuation in the medium of air, petroleum, gasoline, or any other low-loss dielectric materials. In microwave inspection, a metal pipe under test can be taken as a circular waveguide [11], and all the energy of the propagating microwave is confined inside the pipe so that the propagation and attenuation of microwave in the pipe are independent of the pipe's surrounding conditions. The time of flight (TOF) of microwave has been used to detect the locations of cracks in the pipe [12,13], however, the degree of PWT is generally more important than its location for predicting the lifetime of the pipe. In our previous work [11], the PWT in a metal pipe was firstly detected utilizing the resonance phenomenon of microwave at a short-end condition with high microwave frequencies, and the possibility to quantitatively evaluate the PWT using microwaves was proved by comparing the experimental and theoretical analysis results. In this study, we focus on establishing a systematic nondestructive evaluation method using microwaves to inspect a pipe in a large scale at an open-end condition and to measure the PWT remotely with the dominant mode frequencies. After confirming the working mode of microwave for certain frequencies, the wavelength of microwave in a waveguide is a function of the frequency and the inner diameter of the pipe [14]. As a result, after determining the wavelength of microwave at the PWT part, the inner diameter including the direct information of the PWT degree can be evaluated. By tracing the route of microwave propagating in the

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pipe, the resonance condition of the microwaves propagating in the pipe is established, and then by solving the resonance equations, the PWT degrees are evaluated.

2. Experimental approach

The experimental instrument is composed of a microwave vector network analyzer (VNA) and a self-designed transmitting and receiving (T&R) coaxial-line sensor. The photograph of the instrument is shown in Fig. 1, and the schematic diagram of the measured pipe is shown in Fig. 2. The pipe specimens consist of a brass pipe with inner diameter of $d_1=17.03$ mm, wall thickness of $t=1.0$ mm and length of $l_l=2.0$ m, and six joints with a length of $l_2=17.0$ mm and inner diameters of d_2. These six joints with different inner diameters which are numbered as no. 1–no. 6 successively act as different PWT conditions. The nominal values of the inner diameters of the joints are shown in Table 1. In the case of no. 1 joint, its PWT value is zero, i.e., the inner diameter of which is the same as that of the pipe, $d_2=d_1$. The schematic diagram of the PWT joint connecting with the pipe is shown in Fig. 2.

The "Microwave Instrument" in Fig. 2 refers to the microwave VNA, and 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 the length of path along which microwaves propagate directly to the receiving port; d_1 the inner diameter of pipe without PWT and having the length l_1; d_2 the inner diameter of the PWT joint with a constant PWT value and having the length l_2; t the wall thickness of the pipe. Symbols λ_{gd_1} and λ_{gd_2} are the wavelengths of the microwaves propagating in the pipe at the areas without and with PWT respectively, and l_d is an introduced fictitious length corresponding to the phase shift occurred due to the discontinuity at the abrupt wall thinning interface.

Frequency domain measurement is employed in the proposed method. During the experiment, the microwaves generated by the microwave VNA were coupled into the pipe through the transmitting port of the T&R coaxial-line sensor. The experiments were carried out on the pipe connecting, respectively, with each of the PWT joints shown in Table 1. The interference results of the microwaves reflected from the terminal of the PWT joint (after propagating along the pipe) and those going directly to the receiving port (without propagating along the pipe) were detected by the receiving port of the sensor. When sweeping the frequency within a proper range, the corresponding amplitudes containing information of the resonance frequencies were measured and recorded. The resonance frequencies were used as the input parameters of the theoretical analysis to evaluate the PWT degrees quantitatively.

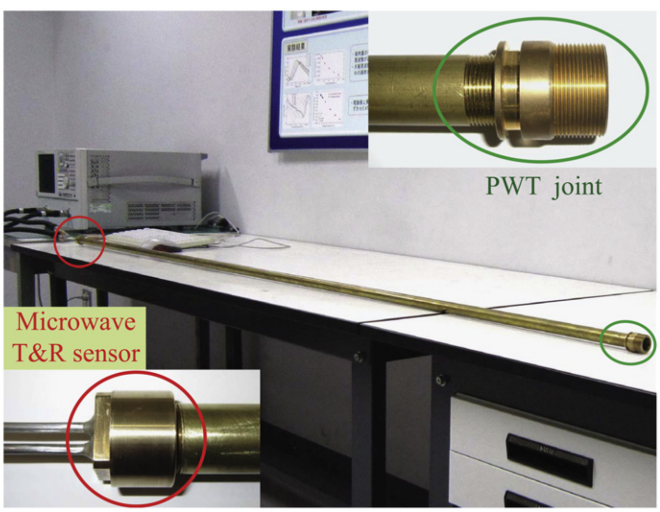

Fig. 1. Overall photograph of the experimental instrument.

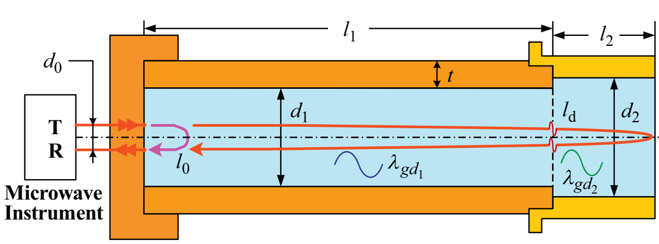

Fig. 2. Schematic diagram of the interference mechanism in the pipe connected with a PWT joint.

Table 1
Detailed geometric parameters of the joints.

Joint's no.	1	2	3	4	5	6
Diameter, d_2 (mm)	17.03	17.10	17.20	17.40	17.80	18.20
PWT degree (%t)	0	3.5	8.5	18.5	38.5	58.5

3. Theoretical analysis

3.1. Resonance condition and resonance equations

To evaluate the PWT quantitatively using microwave, the crucial hint for analysis is the resonance condition at the receiving port. The resonance condition is built up by the microwave signals reflected from the terminal of the pipe and those going directly to the receiving port along a route with length $l_0=F(\lambda_{gd_1})d_0$. $F(\lambda_{gd_1})$ is a dimensionless function of the wavelength in the pipe without PWT with values larger than 1. The expression of l_0 is based on the fact that the larger d_0 corresponds to the larger l_0 while $d_0\to 0$ corresponds to $l_0\to 0$. In addition, the terminal condition in the measurement is not under the ideal open circuit condition which introduces a fictitious length at the end of the pipe. For conciseness, the influence at the terminal is counted in the length l_0 and expresses the combined l_0 approximately as $l_0=G(\lambda_{gd_1})$.

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

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

where m, $n\in N$ and $0\le x$, $y<1$.

N is the set of natural number. f_q the qth resonance frequency of the pipe connected with a PWT joint. The term $(m+x)\lambda_{gd_1}$ refers to the difference of distance between the two different routes in the pipe at the part without PWT, in which the integer m is the number of full wavelength, and the proper fraction x means the fraction of a full wavelength. Similarly, $(n+y)\lambda_{gd_2}$ refers to length of the round-about trip along which microwave propagates in the joint with PWT, in which n and y have the similar meanings as m and x.

Considering the differences of distance that microwaves propagating in the pipe at the parts without and with PWT, respectively, Eq. (1) can be written in the separated form as

$$\begin{cases} 2l_1-l_0(f_q)=(m+x)\lambda_{gd_1}(f_q) \\ 2l_2+2l_d(f_q)=(n+y)\lambda_{gd_2}(f_q) \end{cases} \quad (2)$$

It is known that when the microwave propagates a full wavelength, its phase will change 2π. The phase change in

Eq. (2) can be expressed as

$$\begin{cases} (m+x)\lambda_{gd_1}/\theta_1=\lambda_{gd_1}/(2\pi) \\ (n+y)\lambda_{gd_2}/\theta_2=\lambda_{gd_2}/(2\pi) \end{cases} \tag{3}$$

therefore,

$$\begin{cases} \theta_1=2\pi(m+x) \\ \theta_2=2\pi(n+y) \end{cases} \tag{4}$$

θ_1 and θ_2 refer to the phase changes in the roundabout trips 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

$$\theta=\theta_1+\theta_2=2\pi(m+x+n+y) \tag{5}$$

The resonance happens when the difference of phase change equals to integer times of 2π. Therefore, the resonance condition can be derived

$$q=(m+n+x+y)\in N \tag{6}$$

Taking the integral values of m and n into account, Eq. (6) can be written in a simpler form as

$$x+y=1 \tag{7}$$

Eqs. (6) and (7) show that the resonance condition is formed only when the difference of the distance that microwave propagates along the two routes in the pipe is integer times (q times) of wavelength, i.e., the two routes of microwave signals can form the resonance only when they have the phase difference of $2\pi q$.

For microwaves propagating along the two routes in the pipe connected with the joint without PWT, l_d in Eq. (1) equals to zero. The equation describing the difference of distance can then be written as follows:

$$2l_{Total}-l_0(f'_q)=q\cdot\lambda_{gd_1}(f'_q) \tag{8}$$

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. Solution of the resonance equations

The wavelength in a circular waveguide has a relation with the working mode of microwave at applied frequencies and can be expressed as [14]

$$\lambda_g=1\Big/\sqrt{\mu\varepsilon f^2-[p_{nm}/(\pi d)]^2} \tag{9}$$

where the μ and ε are the permeability and the permittivity of the media in the pipe; f the operating frequency; d the inner diameter of the pipe; p_{nm} the mth root of the first kind Bessel function $J_n(x)$ for TM modes, i.e., $J_n(p_{nm}=0)$ [14]. Air is used as the medium in our experiment, hence $\mu=\mu_0=4\pi\times10^{-7}$ H/m and $\varepsilon=\varepsilon_0=8.854\times10^{-12}$ F/m.

When the microwave signal is introduced directly into the pipe through a coaxial-line sensor, the electromagnetic field at the terminal of the coaxial-line sensor determines that the working modes existing in the circular waveguide are all TM modes, and among which the dominant mode is TM_{01}-mode. When sweeping the frequency between the cut-off frequency of the dominant mode and that of the first higher order TM mode, only the TM_{01}-mode exists. In the experiment, only the frequency ranges of the TM_{01}-mode were used, for which it is $p_{01}=2.4048$.

3.2.1. Determining the propagation variable l_0

As mentioned in Section 3.1, $l_0=G(\lambda_{gd_1})$ is the equivalent propagation route introduced by the distance between the T&R ports of the sensor and the terminal condition, in which $G(\lambda_{gd_1})$ is a function of the wavelength in the pipe without PWT. It should be calibrated before the quantitative evaluation. A method to determine l_0 is established and demonstrated in detail in this section.

To make the total length the same as the pipe connecting, respectively, with different PWT joints so as to make the values of q in Eq. (8) the same as that in Eqs. (1) and (2), the calibration was carried out by connecting the pipe with the joint without PWT (joint no. 1) to determine the l_0 and q in Eq. (8).

In order to increase the calibration precision, the sweeping frequency range containing ten neighboring resonance frequencies (NRFs) was measured in the experiment. For the ten NRFs, q can be expressed as q_0 to q_0+9 in Eq. (8). When the resonance frequencies are extracted from the experimental results, the corresponding wavelengths in the pipe without PWT can be calculated using Eq. (9).

After the ten wavelengths corresponding to the NRFs have been determined, the q_0 and $l_0(f'_{q_0})$ are firstly solved from Eq. (8) simultaneously with considering l_0 to be

$$d_0<l_0<\lambda_{gd_1}(f'_{q_0}) \tag{10}$$

where the wavelength $\lambda_{gd_1}(f'_{q_0})$ is larger than $10d_0$ in the experiment. Thereafter, for the other nine wavelengths with q from q_0+1 to q_0+9, their corresponding $l_0(f'_q)$ can be solved from Eq. (8) one by one.

When plotting the ten $l_0(f'_q)$ versus their corresponding $\lambda_{gd_1}(f'_q)$ in the same figure, the relationship between $l_0(f'_q)$ and $\lambda_{gd_1}(f'_q)$ can be determined by curve-fitting using Least Square method (LSM).

3.2.2. Determining the discontinuity parameter l_d at the PWT interface

For the pipe under PWT conditions, the fictitious length l_d introduced by the discontinuity is calibrated in this section before the quantitative evaluation.

Using the resonance equation Eq. (6), Eq. (2) can be expressed as

$$2l_2+2l_d(f_q)=[q-(m+x)]\lambda_{gd_2}(f_q) \tag{11}$$

where (m+x) can be written as

$$m+x=[2l_1-l_0(f_q)]/\lambda_{gd_1}(f_q) \tag{12}$$

After l_0 and q are determined, $(m+x)$ can be solved from Eq. (12), and then the undetermined parameters in Eq. (11) are $l_d(fq)$ and $\lambda_{gd_2}(f_q)$. Therefore, in order to solve $\lambda_{gd_2}(f_q)$ from Eq. (11), $l_d(f_q)$ should be calibrated. $l_d(fq)$ is generated by the discontinuity at the PWT interface, therefore, it should be a function of the applied frequencies and the two inner diameters of the pipe at both sides of the interface. Since the wavelength is just right the combining function of the frequency and the diameter, l_d can be assumed as a function of the wavelengths

$$l_d=a_2(\lambda_{gd_1}-\lambda_{gd_2})/2 \tag{13}$$

where a_2 is an undetermined constant. Eq. (13) satisfies the limit condition that for the pipe without PWT, i.e., $\lambda_{gd_2}=\lambda_{gd_1}$, l_d equals zero.

Therefore, Eq. (11) can be written as

$$2l_2+a_2(\lambda_{gd_1}-\lambda_{gd_2})=[q-(m+x)]\lambda_{gd_2} \tag{14}$$

In Eq. (14), the unknown parameters are only a_2 and λ_{gd_2}. When using one joint whose PWT value is known (i.e., d_2 is known) for calibration, its corresponding λ_{gd_2} can be calculated from Eq. (9), and then the a_2 can be calibrated from Eq. (14). In this paper, joint no. 6 with PWT value of 0.585 mm is used for calibration.

3.2.3. Equation solving

The final difference of the propagation route in the pipe without PWT has been expressed in Eq. (12) and $(m+x)$ can be solved from this equation. Then from Eq. (14), the wavelength in the wall thinning part of the pipe can be achieved as

$$\lambda_{gd_2} = (2l_2 + a_2\lambda_{gd_1})/[q-(m+x)+a_2] \quad (15)$$

Finally, substituting Eq. (15) into Eq. (9), the diameter of wall thinning part is evaluated to be

$$d_2 = 2.4048\Big/\left[\pi\sqrt{\mu_0\varepsilon_0 f_q^2-(1/\lambda_{gd_2})^2}\right] \quad (16)$$

4. Result analysis and discussion

During the calibration of l_0, the microwave signals at the frequency range from 14.00 to 14.20 GHz, which contains ten NRFs was measured, and all these ten NRFs were used for curve-fitting. In the evaluation of PWT degrees, the same frequency range was measured and analyzed. It is found that for all the resonance frequencies, the proposed method gives almost the same evaluation result. For conciseness, only the experimental results at the frequency range from 14.12 to 14.16 GHz are presented here.

Fig. 3 shows the measured amplitudes of the microwave signal versus the sweeping frequencies, in the case that the pipe is connected with the joints from no. 1 to no. 6. It can be found that the resonance frequencies corresponding to the peaks of waveforms are changed due to the wall thinning. With the increase in the wall thinning degrees, 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 between 14.12–14.14 GHz and 14.14–14.16 GHz shown in Fig. 3, it is found that for the PWT joints no. 1 and no. 2, with the increase in 35 μm wall thinning, the resonance frequencies decrease from 14.1365 to 14.1357 GHz (0.8 MHz frequency change) and from 14.1590 to 14.1585 GHz (0.5 MHz frequency change) are found, respectively. Take advantage of the minimum frequency resolution 1 Hz of the microwave instrument, the proposed method has a quite high resolving power for detecting the PWT values.

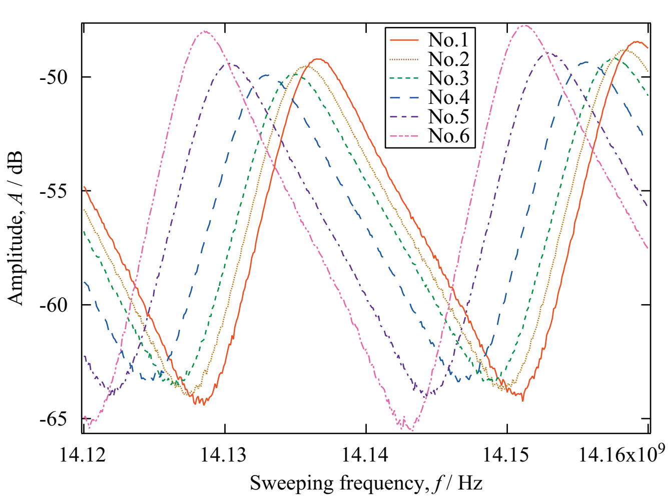

Fig. 3. Experimental results of the amplitudes versus sweeping frequencies of microwaves when the pipe is connected with different PWT joints.

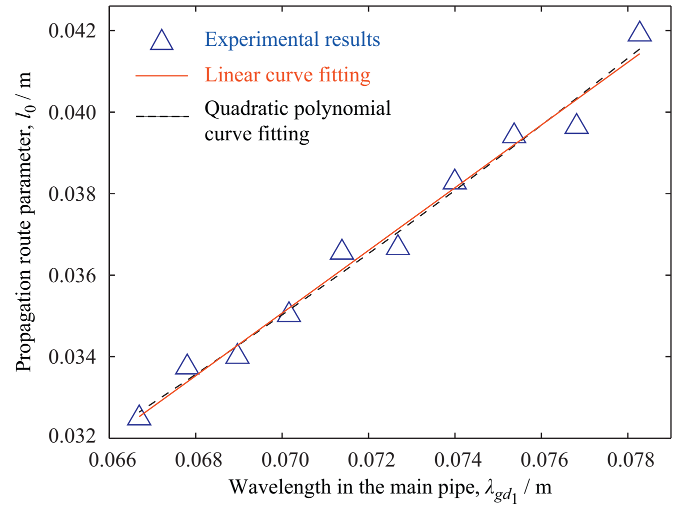

Fig. 4. Determining the path length l_0 using NRFs of experimental results.

Using the method described in Section 3.2.1, $q_0=51$ and the ten different values of l_0 corresponding to the ten NRFs are solved. The ten calculated l_0 versus the corresponding wavelengths are shown together in Fig. 4 in the form of triangle markers. In Fig. 4, using LSM, both the linear and quadratic polynomial curve-fitting results are displayed. It is found that both kinds of curve-fitting methods match the triangle markers well and give almost the same fitting results. For convenience, the linear curve-fitting is adopted and l_0 can be expressed as follows:

$$l_0 = G(\lambda_{gd_1}) = a_1\lambda_{gd_1} + b_1 \quad (17)$$

where a_1, b_1 are solved to be $a_1=0.76867494$ and $b_1=-0.01873670$.

If l_0 in Eq. (8) can be expressed exactly as a linear function of λ_{gd_1} as shown in Eq. (17), three NRFs are enough to solve the three unknown parameters a_1, b_1, and q. However, this linear relationship is rarely satisfied rigorously, mainly because the pipe and joint with an open-end is not exactly under the open circuit condition. Therefore, it is suggested that more than 5 NRFs should be used to improve the calibration precision and the robustness of this method.

As described in Section 3.2.2, to solve the a_2 in Eq. (14), the joint no. 6 (with known PWT value of 0.585 mm) is used for calibration. It is solved that $a_2=0.218$.

For the resonance frequencies extracted from the peaks of the experimental results around higher frequency range14.14–14.16 GHz shown in Fig. 3, q equals q_0+7.

Using Eqs. (12), (15) and (16), for the higher frequency resonance results shown in Fig. 3, the evaluated PWT degrees in comparison with the nominal ones are shown together in Fig. 5.

The triangle markers in Fig. 5 show the relationship of the joints' nominal inner diameters and the resonance frequencies extracted from the higher frequency results shown in Fig. 3. It can be found that with the increase in the inner diameter (i.e., with the aggravation of the PWT degree), the resonance frequencies decrease step by step.

The circle markers in Fig. 5 represent the inner diameters of the joints evaluated from the measured resonance frequencies mentioned above.

By comparing the evaluated results with the nominal ones shown in Fig. 5, it is found that for the pipe having a 17.03 mm inner diameter, the maximum error of evaluated inner diameter is less than 0.294% (i.e., 0.05 mm). Since the dominant mode frequencies were used in the experiment, a high ratio of signal to noise was obtained and, thereby, a high precision measurement was realized.

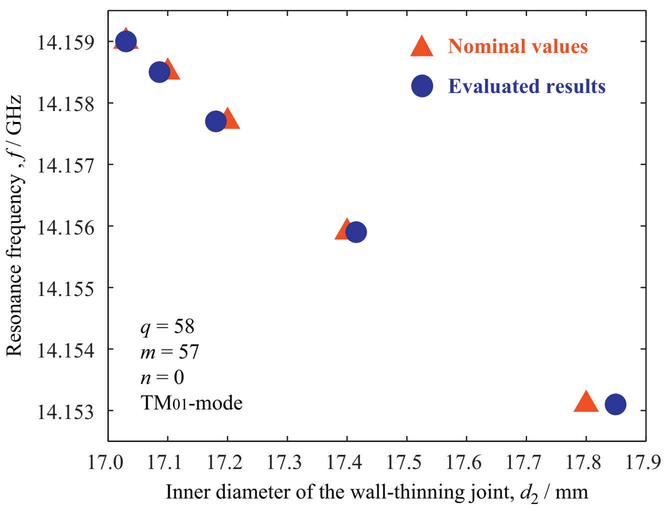

Fig. 5. Comparison of the evaluated inner diameters of the joints and the nominal ones.

It is noted that this paper only deals with an ideal experimental condition with an abrupt and full-circumference diameter change. Since the smallest PWT degree in the paper is as small as 70 μm changing in diameter, it also can be considered as a smooth PWT approximately. Therefore, this method could also be used for the pipe having a smooth PWT interface or having a PWT confined to only a part of the circumference. Because the proposed method is established by analyzing the change of the wavelength of microwave in the pipe, for the two conditions mentioned above, the wall thinning evaluation can be converted into the analysis of the changed wavelength. Thus, if the degree of the wall thinning is large enough, the high precision evaluation can still be realized independent of the shape of wall thinning. In addition, the paper deals with an ideal pipe. If the pipe has welds or fittings changing the inner diameter of the pipe, an additional reflection will occur, which will affect the evaluation result of the proposed method.

5. Conclusions

In this paper, microwaves are creatively adopted to detect and evaluate the PWT degrees remotely and quantitatively with high efficiency.

From the measured amplitudes of the microwave signal versus the sweeping frequencies, it can be found clearly that for the same length pipe with different wall thinning values, the resonance frequencies are different. The relationship is that with the increase in the PWT degrees, 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 circular waveguide.

Then by tracing and reconstructing the propagation route, the equations describing the route of propagation and then the resonance equation are derived.

Finally, by analyzing, decomposing and solving the resonance equations, a group of resonance results of the pipe having a 17.03 mm inner diameter and connected, respectively, with six PWT joints having different PWT degrees is analyzed and whose resonance frequencies are used for evaluating the PWT degrees of these joints. From comparison of the evaluation results of the inner diameters of these joints and the nominal ones, it is found that the maximum evaluation error is less than 0.294%. It hints that a high efficiency nondestructive remote detection method with high evaluation precision has been achieved.

It should be noted that, although the PWT joints having the same length were measured at the terminal of the pipe in this paper, the proposed method is possible to be used independent of the pipe length and, the position and the length of the PWT. In addition, since the measurement was carried out under the open-end condition, the proposed method will have a great potential for the practical applications.

References

[1] Dooley RB, Chexal VK. Flow-accelerated corrosion of pressure vessels in fossil plants. Int J Pressure Vessels Pip 2000;77(2-3):85–90.
[2] Vageswar A, Balasubramaniam K, Krishnamurthy CV, Jayakumar T, Raj B. Periscope infrared thermography for local wall thinning in tubes. NDT & E Int 2009;42(4):275–82.
[3] Kajiwara G. Improvement to X-ray piping diagnostic system through simulation (measuring thickness of piping containing rust). J Test Eval 2005;33(5):295–304.
[4] Shimakawa T, Takahashi H, Doi H, Watashi K, Asada Y. Creep-fatigue crack propagation tests and the development of an analytical evaluation method for surface cracked pipe. Nucl Eng Des 1993;139(3):283–92.
[5] Leonard KR, Hinders MK. Lamb wave tomography of pipe-like structures. Ultrasonics 2005;43(7):574–83.
[6] Nishino H, Takemoto M, Chubachi N. Estimating the diameter thickness of a pipe using the primary wave velocity of a hollow cylindrical guided wave. Appl Phys Lett 2004;85(6):1077–9.
[7] Ding J, Kang Y, Wu X. Tubing thread inspection by magnetic flux leakage. NDT & E Int 2006;39(1):53–6.
[8] Nestleroth JB, Davis RJ. Application of eddy currents induced by permanent magnets for pipeline inspection. NDT & E Int 2007;40(1):77–84.
[9] Li Y, Sun L, Song Z, Zhang Y. Study on energy attenuation of ultrasonic guided waves going through girth welds. Ultrasonics 2006;44(S1):e1111–6.
[10] Aristégui C, Lowe MJS, Cawley P. Guided waves in fluid-filled pipes surrounded by different fluids. Ultrasonics 2001;39(5):367–75.
[11] Ju Y, Liu LS, Ishikawa M. Quantitative evaluation of wall thinning of metal pipes by microwaves. Mater Sci Forum 2009;614:111–6.
[12] Abbasia K, Ito S, Hashizume H. Prove the ability of microwave nondestructive method combined with signal processing to determine the position of a circumferential crack in pipes. Int J Appl Electromagn Mech 2008;28(4):429–39.
[13] Abbasia K, Motlaghb NH, Neamatollahia MR, Hashizume H. Detection of axial crack in the bend region of a pipe by high frequency electromagnetic waves. Int J Pressure Vessels Pip 2009;86(11):764–8.
[14] Pozar DM. Microwave engineering. Second Edition. N.Y: John Wiley & Sons; 1998.