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Remote Detection and Quantitative Evaluation of Wall Thinning Volumes in a Metal Pipe

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ABSTRACT

We report a nondestructive method to measure the pipe wall-thinning (PWT) volumes 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 14.00 to 14.21 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

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1. Introduction

Metal pipes are used widely in industry. From 20 years ago, accidents due to pipe wall thinning (PWT) 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 [9], 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.

PWT problem generally has two aspects as the PWT locations and degrees. The time of flight of microwave has been used to detect the locations of cracks in the pipe [10,11], however, the PWT degree is generally more important than the location for predicting the life time of the pipe. In our previous work two years ago [9], the PWT in a metal pipe was firstly detected using the resonance phenomenon of microwave at a short-end condition with microwave frequencies higher than 47 GHz, and the possibility to quantitatively evaluate the PWT degrees using microwaves was firstly proved by comparing the experimental and theoretical results. Recently, we made some progress and established 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 degrees remotely with the dominant mode frequencies [12]. However, both of our previous studies [9,12] deal with PWT degrees under the condition that the PWT lengths are known and to be the same, they are not available for more practical problems that the PWT lengths and depths are generally both unknown. In this research, we focus on deriving a more useful method that can quantitatively evaluate the PWT degrees without knowing the PWT lengths.

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As a result, through analyzing the relationship between the PWT length and degree, and by introducing a geometric approximation, the PWT volumes containing information of both the lengths and degrees are quantitatively evaluated. The basic microwave detection theory is the same as what has been described in our previous works [9,12], it can be described as that the wavelength of microwave in the pipe is a function of the frequency and the inner diameter of the pipe after the working mode of microwave for certain frequencies has been known. Therefore, after tracing the route that microwaves propagate in the pipe and building up the resonance condition of microwaves, and then by solving the resonance equations, a method to evaluate the PWT volumes remotely and quantitatively is established.

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 distance between the two ports of the sensor is $d_0 = 6.0$ mm). The photograph of the instrument is shown in Fig. 1. The T&R coaxial-line sensor has a simple structure and was designed using standard coaxial-line cables (K118) and connectors (K101F), and its schematic diagram is shown in Fig. 2. The schematic diagram of the inspected pipe is shown in Fig. 3.

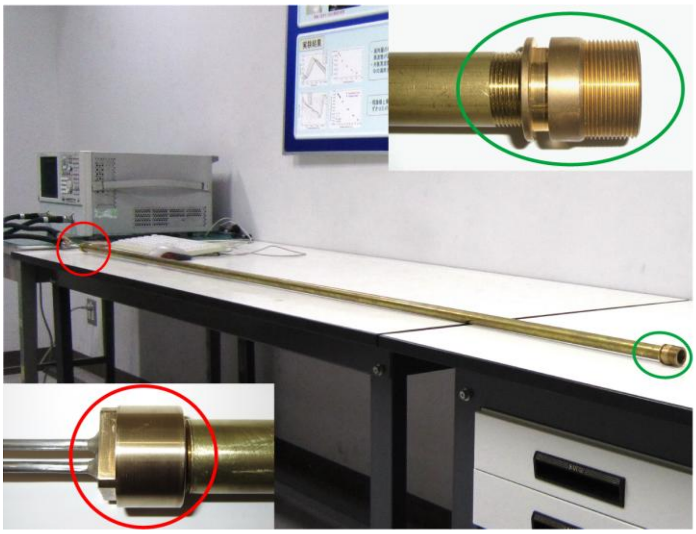

Fig. 1. Overall photograph of the microwave network analyzer, pipe, sensor, and joints

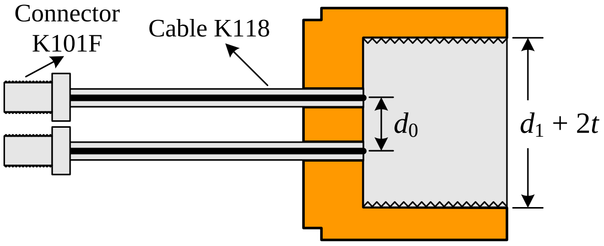

Fig. 2. Schematic diagram of the self-designed T&R coaxial-line sensor

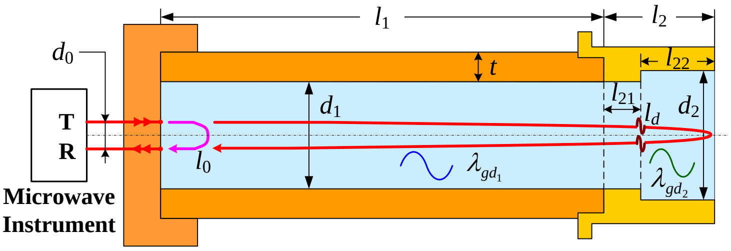

Fig. 3. Schematic diagram of resonance structure in the pipe connected with PWT joint

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 is 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 is also composed of three joints and their PWT part having a length of 12.0 mm. The third group is 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. 3. It should be noted that all the introduced PWTs here are axisymmetric and full-circumferential.

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

In Fig. 3, 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.

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.

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 [12],

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

with

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

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 $(m+x)$ 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 $(n+y)\lambda_{gd_2}$ is the length of roundabout trip along which microwave propagates in the pipe at the part having PWT.

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

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

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

$$q = (m+n+x+y) \in N \tag{4}$$

From Eqs. (4) and (2), the resonance condition can also be written in a simpler form as

$$x + y = 1 \tag{5}$$

Eqs. (4) and (5) 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 $2\pi q$.

Therefore, when the wall thinning degree is expressed as $s = (d_2 - d_1)/2$, based on Eq. (3), Eq. (1) can be written in function of PWT length and degree as

$$2l_{Total} - l_0(f_q) + 2l_d(f_q) = q \cdot \lambda_{gd_1} - P(f_q, l_{22}, s) \tag{6}$$

where

$$P(f_q, l_{22}, s) = (n+y)(\lambda_{gd_1} - \lambda_{gd_2}) \tag{7}$$

Symbol $P(f_q, l_{22}, s)$ is an undetermined composite function of the resonance frequency f_q and the PWT length l_{22} and degree s. While using V to express the PWT volume, it can be expressed as

$$V = \pi[(s + d_1/2)^2 - (d_1/2)^2]l_{22} = \pi(d_1 s + s^2)l_{22} \tag{8}$$

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

$$V \approx V_{\mathrm{appr}} = \pi d_1 s l_{22} \tag{9}$$

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

In Eq. (7), $(n+y)$ at the right part has a proportional relation with the PWT length l_{22}, i.e., $(n+y) \propto l_{22}$. While $(\lambda_{gd_1} - \lambda_{gd_2})$ is function of the applied frequencies f_q and the pipe's diameters d_1 and d_2. To expand the right part of Eq. (7), 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]

$$\lambda_g = 1\Big/\sqrt{\mu\varepsilon f^2 - \left[p_{nm}/(\pi d)\right]^2} \tag{10}$$

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 *m*th 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 frequency range including the dominant TM_{01}-mode is used, for which we have $p_{nm} = p_{01} = 2.4048$.

From Eq. (10), it can be derived that

$$\lambda_{gd_1} - \lambda_{gd_2} = (U_2 - U_1)\big/(U_1U_2) \tag{11}$$

where $U_i = \sqrt{\mu\varepsilon f_q^2 - \left[p_{01}/(\pi d_i)\right]^2}$, ($i = 1$ or 2).

While the numerator of the right part of Eq. (11) can be written as

$$U_2 - U_1 = (U_2^2 - U_1^2)/(U_2 + U_1) = (d_2^2 - d_1^2)[p_{01}/(\pi d_1 d_2)]^2/(U_2 + U_1) = sD/(U_2 + U_1) \tag{12}$$

where $D = 2(d_1 + d_2)[p_{01}/(\pi d_1 d_2)]^2$.

Therefore, the difference of wavelengths can be written from Eqs. (11) and (12) as

$$\lambda_{gd_1} - \lambda_{gd_2} = sD\big/[(U_1U_2)(U_1 + U_2)] \tag{13}$$

Eq. (7) can be written as

$$P(f_q, l_{22}, s) \propto s l_{22} D\big/[(U_1U_2)(U_1 + U_2)] \tag{14}$$

At the condition that satisfies the approximate PWT volume expressed in Eq. (9), Eq. (14) can be expressed as

$$P(f_q, l_{22}, s) \approx P(f_q, V) \propto V\big/[(U_1U_2)(U_1 + U_2)] \tag{15}$$

where $(U_1U_2)(U_1 + U_2)$ has an approximately proportional relation with f_q^3. Therefore, it is approximately

$$P(f_q, l_{22}, s) \approx P(f_q, V) \propto V\big/ f_q^3 \tag{16}$$

In this meaning, Eq. (16) can be written in the separate form as

$$P(f_q, l_{22}, s) \approx p(f_q) \cdot V \tag{17}$$

where $p(f_q)$ is an undetermined function of f_q^3, and it will be calibrated using a PWT joint whose PWT volume is known in the next section.

When using joint No. 0, the joint without PWT, only omitting the parameter l_d taking account for the fictitious path at the interface of discontinuity in Eq. (1), 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,

$$2l_{Total} - l_0(f'_q) = q \cdot \lambda_{gd_1}(f'_q) \tag{18}$$

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 is Eqs. (6) and (10) for pipe with PWT, the another is Eq. (18) for pipe without PWT, the resonance conditions are both expressed in Eq. (4).

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. (18) to construct and solve l_0 and to solve q simultaneously, and the second step is to using l_0 and q to solve Eqs. (6) and (17).

The inhomogeneity of the inner diameter of the pipe will aggravate the evaluation precision. Therefore, before carrying out the calculation and evaluation, a high-precision method to detect the average of the inner diameter of a pipe is derived from the cut-off frequency of TM_{01}-mode measured in the experiment and the expression is shown as follows [13],

$$d_{\mathrm{E}} = p_{01} \Big/ \left(\pi f_{cTM_{01}} \sqrt{\mu\varepsilon}\right) \tag{19}$$

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

In our previous research [12], a method to determine l_0 and q has been established and demonstrated in detail.

In Eq. (6), $l_d(f_q)$ 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 degree of the pipe and of the applied frequencies. For simplification, l_d can be expressed as $l_d = a_0(f_q)V/2$.

When considering Eq. (17) and the simplified expression of l_d shown above, Eq. (6) describing the PWT condition can be written as follows,

$$2l_{Total} - l_0(f_q) = q\lambda_{gd_1} - p'(f_q)V \tag{20}$$

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

Eq. (20) also satisfies the limit condition that when the pipe is without PWT, then V equals 0 and f_q becomes f'_q, and then Eq. (20) degenerates to Eq. (18).

Based on Eqs. (16) and (17), $p'(f_q)$ can be written as $a_1 f_q^{-3} + a_0(f_q)$. Because the less joints are needed for calibration, the easier use of the method, for simplification and easy to calibrate, taking

$$p'(f_q) = a_2 f_q^{-3} \tag{21}$$

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. (20), and then from Eq. (21), 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. (20), the PWT volume is evaluated to be as follows,

$$V_{\mathrm{eval}} = [q\lambda_{gd_1} + l_0(f_q) - 2l_{Total}] / p'(f_q) \tag{22}$$

4. Results Analysis and Conclusion

When calibrating l_0 using the method described in detail in previous work [12], the microwave signals at the frequency range from 14.00 to 14.21 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 14.08 to 14.12 GHz are presented here.

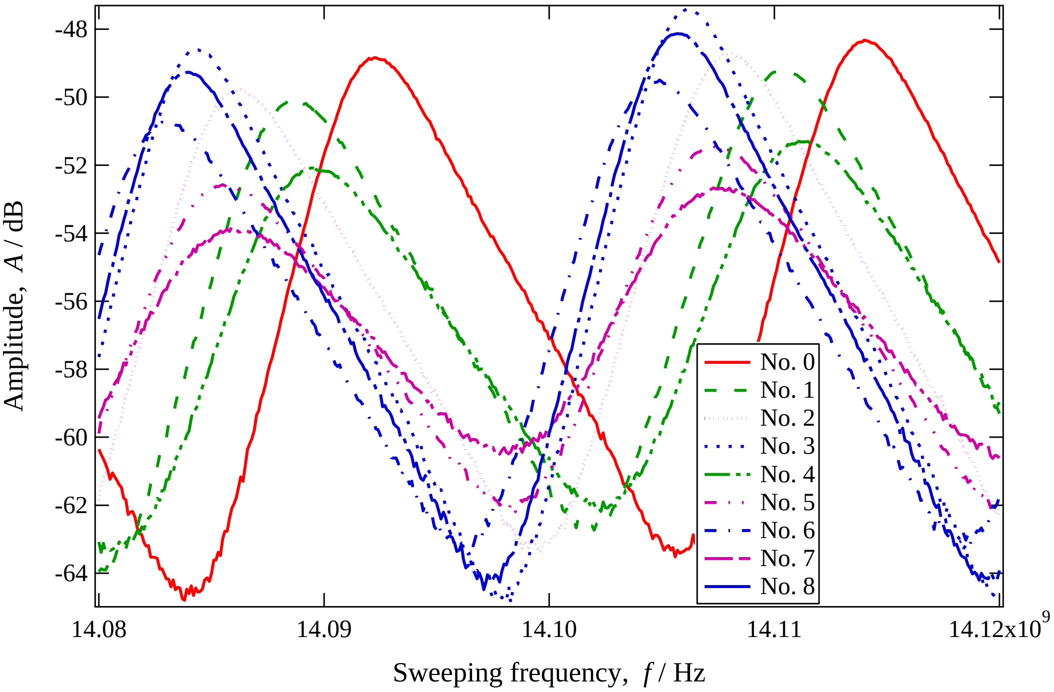

Fig. 4. Experimental results of amplitudes versus sweeping frequencies of microwaves when the pipe is connected with different PWT joints

Fig. 4 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 guided 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, the cut-off frequency for TM$_{01}$-mode is found to be between 13.47670 and 13.476775 GHz from 4 times of repetitive measurement (disassemble and reassemble the pipe and sensor for each time), and then from Eq. (19), 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 Eq. (10), 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. 5 in form of blue triangle markers. In Fig. 5, using Least Square method, linear curve-fitting is used, and the linear curve-fitting results matches well with the experimental ones.

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

$$l_0 = a_1 \lambda_{gd_1} + b_1 \tag{23}$$

By using the linear curve-fitting in Fig. 5, the a_1, b_1 are solved to be $a_1 = 3.6122392 \times 10^{-3}$ and $b_1 = -7.5125426 \times 10^{-5}$, and then the expression of l_0 is achieved.

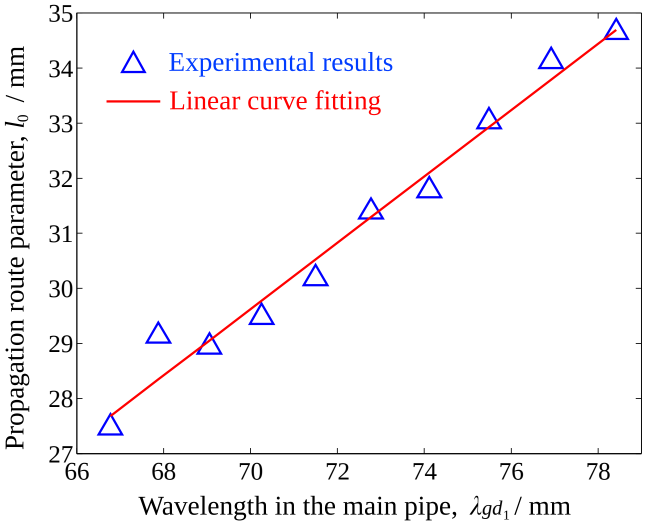

Fig. 5. Experimental method to determine the path length l_0 using neighboring resonance frequencies

As described in Section 3.2, to solve the a_2 in Eq. (21), joint No. 2 (with known PWT volume of 358.9 mm^3, see Table 1) is used for calibration. It is solved as $a_2 = 1.57942 \times 10^{26}\ (\mathrm{m}^{-2} \cdot \mathrm{s}^{-3})$.

q are $q_0 + 4$ and $q_0 + 5$ for the two groups of resonance frequencies shown in Fig. 4. To the comparatively lower frequency results at range 14.08 ~ 14.10 GHz shown in Fig. 4, the PWT volumes are evaluated by using the resonance frequencies extracted from Fig. 4 and Eqs. (21), (22) and the parameters a_1, b_1, a_2, q solved above. Fig. 6 shows the evaluated PWT volumes in comparison with the nominal ones of the 9 joints shown in Table 1.

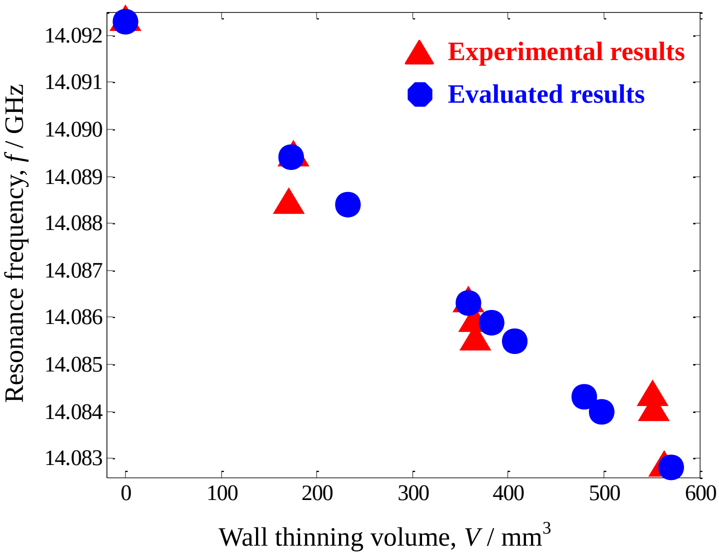

Fig. 6. The evaluated results comparing with the experimental ones of the comparatively lower frequency results in Fig. 4

The triangle markers in Fig. 6 show the relationship of the resonance frequencies 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 frequency decreases step by step. The PWT volumes of the experimental results shown in Fig. 6 are in correspondence with the ones shown in Table 1, the corresponding numbers of the data for the joints can be confirmed by comparing the volume values.

The circle markers in Fig. 6 show the evaluated results when using the same resonance frequencies obtained from the experiment, i.e., the resonance frequencies used for obtaining the evaluated results are completely the same to that of the experimental ones.

From Fig. 6, for pipe having 17.03 mm inner diameter, it is found that most of the evaluated results agree well with the experimental ones, and the maximum evaluation error is less than 13.0% except for only one joint (joint No. 1). It indicates that this method can be used for remote detection and quantitative evaluation of PWT volumes. It is estimated that the evaluation errors mainly come from the approximations approached in solving the resonance equations derived in this method.

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