Application of Microwaves on Remote and Nondestructive Testing of both Biofouling and Wall Thinning inside a Metal Pipe

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Abstract: The authors have already proposed microwave nondestructive testing (NDT) method on detecting both location and degree of a pipe wall thinning (PWT) inside a metal pipe. However, problems caused by biofouling inside metal pipes are also frequently reported in recent years. As the existence of biofilm inside a waveguide will change its wave impedance and also cause microwave reflections, the characteristic signals of biofilm defects are studied here to distinguish the biofilm and PWT defects. A pair of coaxial line probes is designed and utilized for the microwave NDT testing. This paper reports the experimental results on this research, and it presents not only the detected reflection signals according to both the PWT and biofilm, but also the detected resonance frequencies for both of them during the experiment. This work is a preliminary and original attempt that aims to remote detect and distinguish the defect types inside a metal pipe using microwaves.

Keywords: Microwave, Nondestructive testing, Remote detection, Wall thinning, Biofilm and biofouling.

1. Introduction

Metal pipes are widely used in modern industries, such as oil and gas transportation, chemical industry, water supply system, and power plants. Many pipes have been in service for more than tens of years, and accidents took place often on the ageing pipes. Pipe wall thinning (PWT) is one of the most common and serious defects that caused the problems, which has been studied by lots of scientists and also our former work [1-7]. As the industrial pipes are generally composed of a complicated piping system, efficient detection and quantitative evaluation of the PWT location and degree are important issues for effective maintenance (safety guarantee) and lifetime prediction of pipes so as to economically avoid severe accidents.

Since metal pipes can be taken as circular waveguide of microwaves, microwave NDT has been utilized to solve the PWT problems in our approaches [1,2,4-7]. However, biofouling also exists inside many long-time used pipes especially in most ageing oil transportation and water supply systems. The existence of biofoulings also causes reflections and thereby hampers the PWT detection.

Biofouling and biofilm are assemblage of the microbial cells that is irreversibly associated with a surface and usually enclosed in a matrix of polysaccharide material [8], and they are composed primarily of microbial cells and extracellular polymeric substances (EPS) [8-10]. The presence of biofouling on a metal surface, as well as its metabolic activities, can also cause potential problems such as microbiologically influenced corrosion (MIC) [11], which is not an actual form of corrosion but a process involving micro-organisms that may initiate or otherwise contribute to the propagation of corrosion and typically accelerate the existing corrosion form [12]. Previous researches on biofilm corrosion effect of drinking water distribution system (DWDS) mainly made of cast iron pipes also shown that the accelerated corrosion will also bring consequences such as unpleasant color, lowering the pressure resistance, engendering water supply accident and thereby accelerating water quality deterioration and aggrandizing the threat to human health [13,14]. Moreover, other researchers also showed that biofilm formulation and multiplication can also develop on stainless steel, copper, and some other kinds of metal pipes [15,16]. Therefore, the existence of biofilm is a general condition in metal pipes and its potential effect cannot be ignored.

In this work, we focus on analyzing the more practical condition with considering reflections caused by both biofilm and PWT defects, and we aim to present this method not only for remotely and nondestructively detecting both biofilm and PWT defects but also on distinguishing them through analyzing their characteristic signals. This work is a preliminary and original attempt to not only remotely detect defects inside a metal pipe but also to qualitatively or even qualitatively characterize and classify the defect types using microwaves.

2. Experimental Approach

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During our research, a vector network analyzer (VNA), E8383B (Agilent Technologies, Inc., California, USA) is utilized for generating and receiving microwave signals, and a pair of T&R coaxial line adaptors is used separately at S11 (for the single coaxial line probe) or S21 mode (for the double coaxial line probe) as a bridge to introduce the signals to the pipe under test (PUT) [4-6]. The overall schematic diagram of the experimental approach is shown in Fig. 1. In this figure, two defect-free pipes, VNA, a pair of flexible coaxial line cables, self-designed coaxial-line probes, and three joints are shown together in detail. All of specimens are made of brass. PUTs have different wall thinning values are realized through connecting a joint that has inner diameter larger than the two pipes between the two defect-free pipe specimens. The inner diameter of the defect-free pipes is 19.0 mm, and the wall thickness is 3.0 mm, and the lengths of them are 750.0 and 1000.0 mm. The mentioned joints have different inner diameters and the same outer diameter of 25.0 mm, and the detailed geometrical parameters of the joints are shown in Table 1.

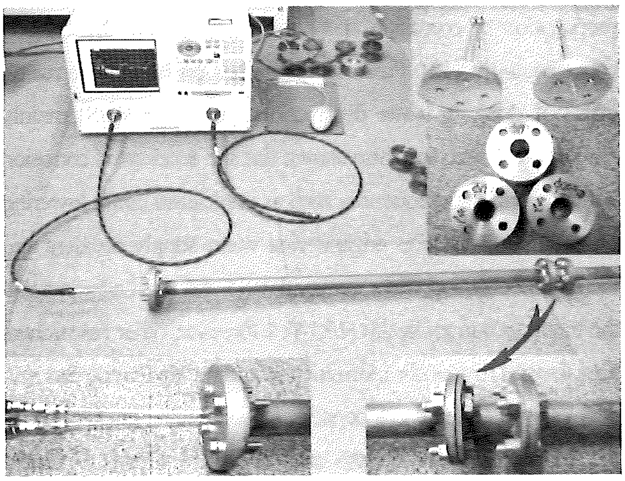


Fig.1 Overall schematic diagram of experimental approach

Table 1 Geometrical parameters of the brass joints

No.	1	2	3
Inner diameter (mm)	19.00	19.40	20.00
Equivalent PWT depth (mm)	0.00	0.20	0.50
PWT length (mm)	40.0	40.0	40.0

It is reported that generally the relative dielectric constants of biofilms are 2 ~ 6, and the conductivities are around 0.1 ~ 0.5 S/m [17-19]. For a primary attempt, a frequently used PET based double-sided adhesive tape whose composing material is not only comparatively homogeneous but also has a dielectric constant of 2.5 ~ 3.4 is adopted here to simulate a biofilm. Different thickness can be obtained from using different layers of the tapes. The PET based tape possesses a relative dielectric constant of 3.2 ~ 3.4 around 60 ~ 1,000 Hz, 3.0 ~ 3.3 around 1 MHz, 2.7 around 1 GHz, and 2.6 ~ 3.0 around 10 ~ 20 GHz [20-22]. The thickness of a single layer tape used in experiment is approximately 0.12 mm, and each layer of biofilm is simulated through making the inside surface of the no wall thinning joint No. 1 be fully covered of a single layer tape. As a result, all of the simulated biofilms are axially symmetrical and have a axial length of 40.0 mm.

It is the same as our former research that the frequency range between the cutoff frequency of the dominant TM_{01} mode and the first high-order TM_{11} mode is adopted in the experiment [4-6]. Considering the diameter of 19.0 mm of the circular waveguide, the frequency range is calculated to be from 12.1 to 19.2 GHz. During which, the dielectric constant of the tape is around 3.0.

During the experimental approach, both S11 and S21 parameters are measured for both PWT specimens and pipes having different thickness of biofilms are measured through utilizing the VNA after calibration.

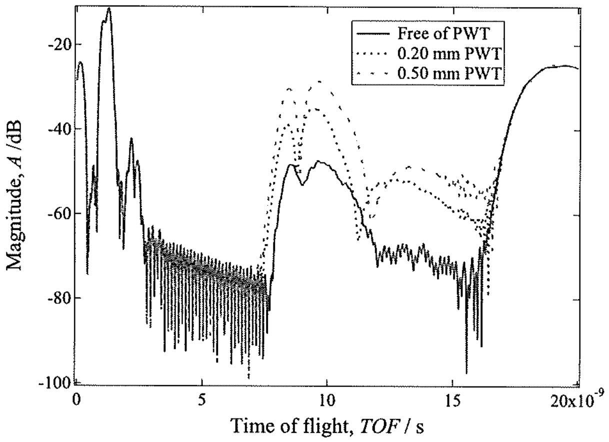
For microwave engineering, either a PWT or a biofilm defect can be taken as a discontinuity along the circular waveguide [6]. When microwave propagates to a discontinuity, reflection will happen and thereby some of the propagation energy will be reflected to the transmitting port. Based on this fact, we can easily evaluate the defect location by extracting and analyzing the reflected signals [6]. Time of flight (TOF) means the time passed though when microwave signals reaching and reflected from a target. TOF is also used here for locating the defects.

The frequency range for the single dominant TM_{01} mode, 12.1 ~ 19.2 GHz, is utilized for measuring the S11 parameters of microwave signals, and the S21 parameters at frequency range 13.3 ~ 13.7 GHz are also measured.

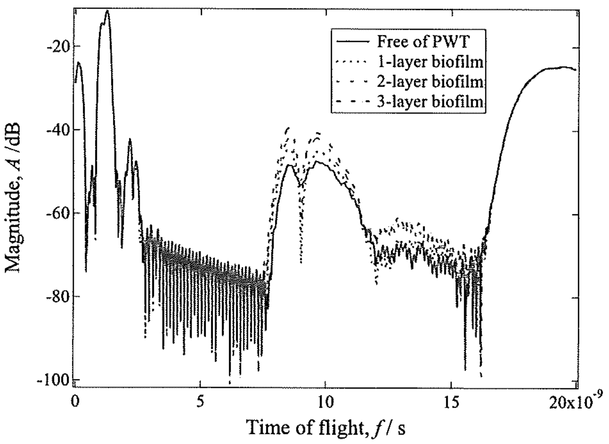
3. Results and Analysis

3.1 Reflection detection for locating defects

Utilizing the method described similar as shown in Ref. [6], S11 parameters at frequency range 12.1 ~ 19.2 GHz are measured, and the experimental results for both pipes having different PWT degrees and different biofilm thicknesses are shown together in Fig. 2. The "Free of PWT" shown in the figures means that the No. 1 joint (that has a PWT depth of 0) is utilized in the PUTs. It should be no reflection when no wall thinning, however, two most shallow peaks also appears during the experimental results. It is assumed to be mainly caused by the connection between the joint and the two pipes, and the connections act as a pair of closed cracks inside the pipe.



(a) Time domain results of PUTs having different PWT degrees



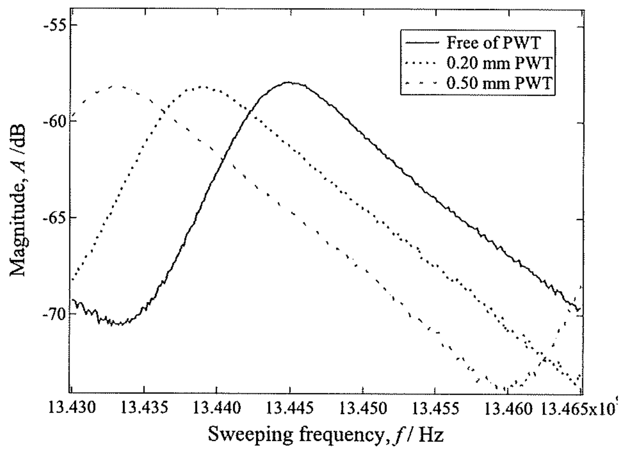
(b) Time domain results of PUTs having different biofilm thicknesses

Fig.2 Time domain results for both PWT and biofilm testing

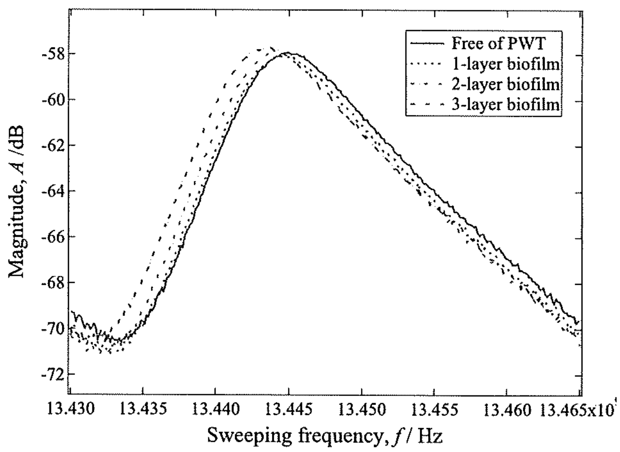
From the calibrated group velocity and the values of their TOF, the locations for both the PWT and the biofilm can be easily evaluated. It can be seen from the experimental results shown in Fig. 2 that peaks located at quite similar locations (have same values of TOF), which enables the stable of method. However, it should be noted that we still cannot obtain enough information to distinguish the types of defects only from the time domain measurement results although it offers a stable and quantitative way for efficiently evaluating the defect locations.

3.2 Resonance testing for distinguishing defect types

In order to supply more information to combine with the time domain measurement for distinguishing defect types, frequency domain measurement based on resonance testing and resonance analysis is also carried out. Our former research on resonance analysis has shown the peaks of resonance frequencies will shift for pipes having different wall thinning degrees [4,5].



(a) Frequency domain results of PUTs having different PWT degrees



(b) Frequency domain results of PUTs with different biofilm thicknesses

Fig. 3 Frequency domain results for PWT and biofilm testing

Utilizing the method described similar as shown in Ref. [4,5], S21 parameters at frequency range 13.3 ~ 13.7 GHz are measured, and the experimental results for both pipes having different PWT degrees and different biofilm thicknesses at frequency range

13.430 ~ 13.465 GHz are shown in Fig. 3. The "Free of PWT" shown here also means during which the No. 1 joint (that has a PWT depth of 0) is utilized in the PUTs. For the same reflection (having the same values of both TOF and magnitude) in time domain measurement as shown in the similar way of Fig. 2, if their peak shifts of resonance frequencies are different as shown in the similar way of Fig. 3, they should be different types of defects. It should be quite significant to establish a remote testing method to distinguish defect types.

4. Conclusion

In this research, we have demonstrated a remote, efficient and quantitative way to nondestructively detect both wall thinning and biofilm inside a long-distance metal pipe, during which a pair of coaxial line probes is designed and utilized to measure both the S11 and S21 parameters, and all of the measurement is implemented by testing the pipes at open-ended condition. Since pipes under open-ended condition are the most common case in the practice, this will enable the method to be easy to carry out and bring into popular use.

In addition, this research aims to study on the more practical condition with considering reflections caused by both biofilm and PWT defects. This work is a creative and original attempt to not only remotely detect defects inside a metal pipe but also to qualitatively or even qualitatively characterize and classify the defect types using microwaves, and the authors hope this work can show some hints for other researchers to think out of better ideas to carry out more detailed research on such a topic.

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