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Corrosion Induced Roughness Characterization by Ultrasonic Attenuation Measurement

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ABSTRACT

Corrosion and erosion lead to partial wear inside pipes. This wear induces some roughness of the inner pipe wall and decreases its thickness. This could cause a fatal accident in nuclear and thermal power plants. In general, nondestructive inspection by ultrasonic devices measures only the thickness, not the roughness. When reflected on a rough surface ultrasonic waves scatter and attenuate. Then this study aims to estimate the surface roughness of the pipe wall from ultrasonic attenuation estimation, based on the analysis of the acquired waveforms on several specimens that have been machined in order to simulated a corroded rough surface. The experimental data exhibit a clear relationship between the roughness and the ultrasonic attenuation, in good agreement with theoretical models available in the literature, for both bulk longitudinal and shear waves.

KEYWORDS

Nondestructive testing, corrosion, surface roughness, wave attenuation, longitudinal and shear-horizontal wave

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1. Introduction

Piping system in nuclear and thermal power plants is a major and essential component. Mechanical and chemical interactions between pipes and flowing liquid induce corrosion and erosion on the inner wall of a pipe [1-3]. Corrosion and erosion lead to partial wear inside pipes. This wear induces some roughness of the inner pipe wall and decreases its thickness. They could cause a fatal accident. To prevent accidents, periodic nondestructive inspections are performed on the piping system.

The inspection generally measures the representative thickness of the measurement area. The pipe-wall thickness has been used to estimate the healthy state of the pipe [4]. However, the inside surface of the corroded pipe is not flat and has a roughness due to corrosion and erosion phenomena. Deep pits might increase the risk of breaking a pipe. If we obtain the thickness and the roughness, it is expected to correctly estimate the cause of corrosion and the breaking risk in comparison with only the thickness. Several papers reported models for ultrasonic reflection on rough surfaces [5,6]. Nagy derived a theoretical model of surface roughness induced attenuation. The model is limited to a low surface roughness and a plane wave. Vasudevan reported reflection coefficients of an SH wave on a rough interface by numerical simulation [7]. Regarding actual measurement on back surface roughness, Benstock et al. presented an effect of surface roughness on ultrasonic thickness measurement [8]. Wang et al. reported an influence of surface roughness on ultrasonic testing to detect a crack on a back-surface roughness [9]. They focused on thickness measurement and crack detection based on reflection signals from back surface roughness. Choi et al. proposed a rough surface reconstruction method by a digital filter [10]. Their method required much measurement data and calculation.

The final goal of this study is the development of a measurement method of surface roughness inside pipes by ultrasonic attenuation. An ultrasonic wave scatters and attenuates at the reflection on a

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rough surface. From the acquired waveforms one can obtain the amplitudes of the attenuated wave and estimate the surface roughness. In this study, we derive an attenuation variable based on the acquired waveforms. The experiments have been carried out on model specimens with machined periodic surfaces that simulate the corrosion. The experimental data show clearly a relationship between the roughness and the attenuation, that will be discussed in comparison with a theoretical model.

2. Surface Roughness Induced Attenuation

2.1. Theory

When an ultrasonic wave reflects on a rough surface, the wave scatters and is attenuated. The following theory is based on Nagy's work [4]. We consider a randomly solid rough surface expressed by $h(x,y)$. The $h(x,y)$ is positioned in the $z=0$ plane of an x,y,z coordinate system as shown in Fig. 1. The rough surface is supposed to be geometrically an area A, and the surface quality is characterized by a roughness parameter h:

$$h^2 = \frac{1}{A}\int_A \int h^2(x,y)dxdy, \tag{1}$$

where h is a root-mean-squared roughness parameter. When a plane wave transmitted on the flat surface propagates and reflects at the rough surface on the opposite side, the wave is perturbed by the random phase modulation $\phi_r(x,y)$. The amplitude of the reflected wave R is given as

$$R = \frac{R_0}{A}\int_A \int e^{i\phi_r(x,y)}dxdy, \tag{2}$$

where R_0 is the amplitude of the wave reflected on a flat surface, used as a reference. According to the phase perturbation approximation, the roughness induced phase modulation is expressed by

$$\phi_r(x,y) = -2h(x,y)k, \tag{3}$$

where k denotes the wavenumber in the carbon steel. Here, we presumed that the correlation length of the rough surface is high with respect to the wavelength. In addition, presuming that the surface profile is an ergodic random process, we obtain the following equation by the probability density function $p(\phi)$ of the random phase modulation.

$$R = R_0\int_{-\infty}^{\infty} e^{i\phi}p(\phi)d\phi, \tag{4}$$

where

$$p(\phi) = \frac{1}{\sqrt{2\pi}\phi_r}e^{-\phi^2/2\phi_r^2}. \tag{5}$$

In this case, the solution of Eq. (4) is given by

$$\begin{aligned} R &= R_0 e^{\frac{-\phi_r^2}{2}} \\ &= R_0 e^{-2k^2h^2}. \end{aligned} \tag{6}$$

We can estimate the roughness parameter h from R, R_0 and k by Eq. (6). Nagy derived the equation for longitudinal plane waves.

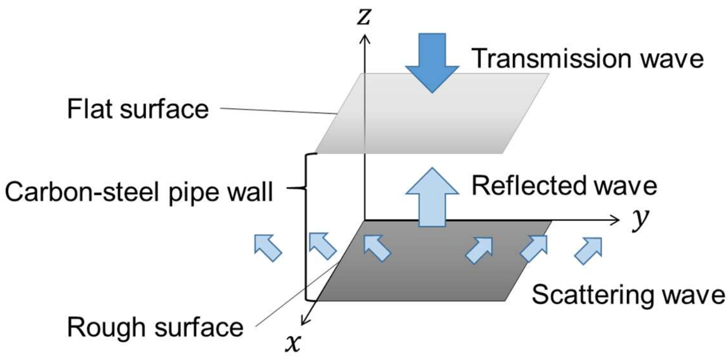


Fig. 1. Transmitted wave to rough surface and reflected wave.

2.2. Attenuation calculated from experimental data

In a very general manner, and also in agreement with Nagy model, we will assume that the attenuation is given by a decreasing exponential law as follows:

$$r = r_0 e^{-f(h)}, \tag{7}$$

where r_0 and r are the amplitude reflection coefficients at the flat and rough bottom surfaces, respectively, and $f(h)$ is an attenuation function to be determined in relation with the roughness parameter of the studied surface.

Let us consider the reflections at the flat and rough bottom surfaces as shown in Fig. 2. The flat bottom sample is for the reference sample. If we assume the amplitude of the incident wave on the top surface of the sample to be A, the amplitude of the first reflection from the back face is given by

$$R_0^{1st} = At_{in}r_0t_{out}e^{-2\alpha d}e^{-2\alpha_c d_{c0}} \tag{8}$$

for the reference sample, where t_{in} and t_{out} are the amplitude transmission coefficients at the first and second interface respectively, α is the attenuation in carbon steel, α_c is the attenuation in couplant, d is the sample thickness and d_{c0} is the couplant thickness of the reference sample.

$$R^{1st} = At_{in}rt_{out}e^{-2\alpha d}e^{-2\alpha_c d_c} \tag{9}$$

for the rough sample, where d_c is the couplant thickness which might be slightly different form d_{c0}. The second reflections are then given by

$$R_0^{2nd} = At_{in}r_0^2 r_{t0}t_{out}e^{-4\alpha d}e^{-2\alpha_c d_{c0}} \tag{10}$$

for the reference sample, where r_{t0} is the reflection coefficient at the top surface between the sample and the transducer, and

$$R^{2nd} = At_{in}r^2 r_t t_{out}e^{-4\alpha d}e^{-2\alpha_c d_c} \tag{11}$$

for the rough sample. In the time interval between the first and the second echoes, we assume that the thickness of the couplant is constant. All the terms R_0^{1st}, R_0^{2nd}, R^{1st} and R^{2nd} account for the amplitude losses due to the reflections and transmissions at the interfaces and also for the intrinsic attenuation in the steel or in the couplant. Then

$$\frac{R_0^{2n}}{R_0^{1st}} = r_0 r_{t0} e^{-2\alpha d} \tag{12}$$

and

$$\frac{R^{2nd}}{R^{1st}} = r r_t e^{-2\alpha} \ , \tag{13}$$

so

$$\frac{\frac{R^{2nd}}{R^{1st}}}{\frac{R_0^{2nd}}{R_0^{1st}}} = \frac{r}{r_0}\frac{r_t}{r_{t0}}. \tag{14}$$

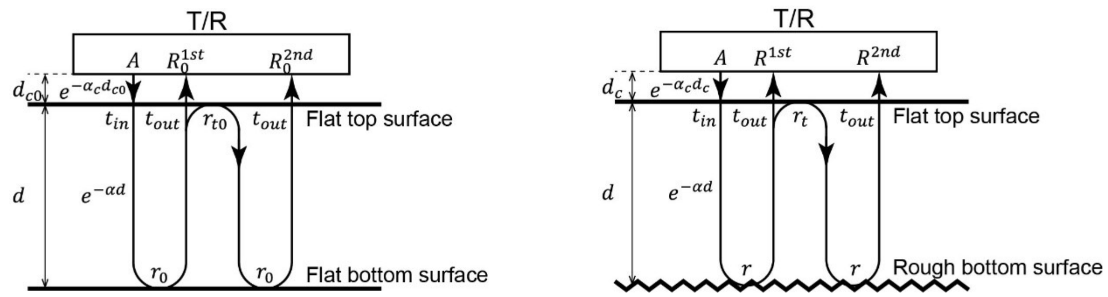
We can assume that the reflection coefficient at the top surface and on the reference and rough samples are very close so $\frac{r_t}{r_{t0}} \approx 1$ and finally, that

$$\frac{\frac{R^{2nd}}{R^{1s}}}{\frac{R_0^{2nd}}{R_0^{1st}}} \approx \frac{r}{r_0} = e^{-f(h)}. \tag{15}$$

Hence,

$$\beta = \ln\left(\frac{\frac{R^{2nd}}{R^{1st}}}{\frac{R_0^{2nd}}{R_0^{1s}}}\right) = \ -f(h). \tag{16}$$

In this study, the regression analysis using the experimental data estimates the attenuation function $f(h)$, which has the roughness parameter h and the experimental attenuation variable β as an explanatory variable and an objective variable, respectively. The attenuation function $f(h)$ is compared with the theoretical model.



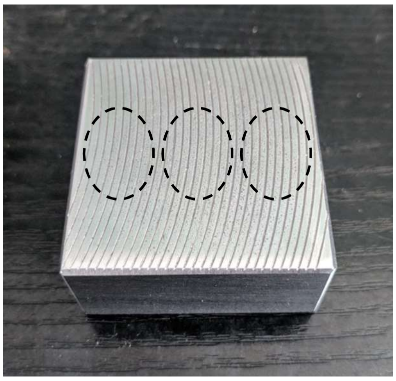
(a) Flat bottom surface. **(b) Rough bottom surface.**

Fig. 2. Two reflections at the flat and rough bottom surface.

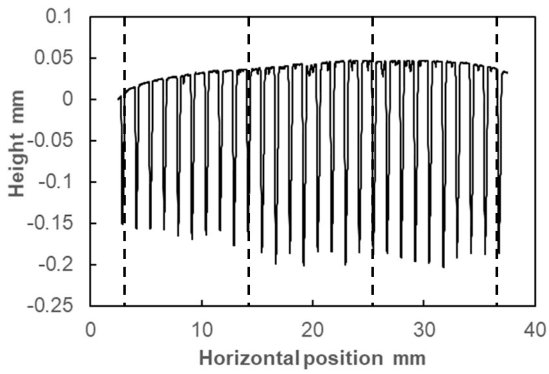
3. Experiments

3.1. Specimens

Specimens were 9 carbon steel blocks which had 20 mm in thickness and an area of 40×40 mm2. The specimens were given different periodic flaws, simulating roughness, on one side by a machining process. A typical specimen is shown in Fig. 3(a). A surface profile meter measured the specimens. Fig. 3(b) shows a typical profile of the central line of the rough surface. We separated each specimen into three measurement zones as shown in Fig. 3(a) and (b) with dashed lines. Each zone in Fig. 3 (a) has a width of 11 mm. We determined the roughness parameter h for each zone by the root mean square averaging of the profile height deviations. In addition, a specimen without flaws was used to obtain the amplitudes of the reflected wave on a flat surface.



(a) Example of specimen.



(b) Profile of specimen (a).

Fig. 3. Specimen.

3.2. Experiments by L-wave probe

The experimental conditions are as follows:

- Pulser and receiver, data acquisition: prisma (Sonatest Ltd)
- Probe: Phased-array 1D with wedge (contact area: 25×23 mm, Sonatest Ltd)
- Gain: 20.0 dB
- Wave frequency: 5 MHz (actual value: 4.88 MHz)
- L-Wave velocity: 5610 m/s

Only one element of the phased-array probe was used for experiments as the transmitter and receiver of ultrasonic waves. The wave is spherical. The amplitudes are obtained by averaging 10 measurements.

An example of received echoes is shown in Fig. 4. Fig. 4 includes the first and second echoes from rough surfaces with roughness parameter h = 22.7 and h = 59.5 μm. As expected the amplitudes of the first and second echoes from the surface with $h = 22.7$ are higher than those from the surface with $h = 59.5$.

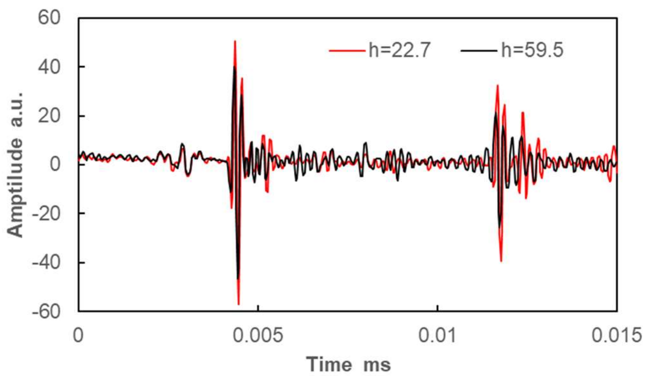


Fig. 4. An example of the first and second echoes. h is roughness parameter and its unit is μm.

The experimental data of the attenuation expressed by Eq. (10) are shown in Fig. 5. Fig. 5 also shows fitting curves by the regression analysis using the experimental data. The analysis included the terms up to the fourth order of h. The functions of $ah + bh^2$ and ch^2 had low root-mean-squared errors (RMSEs). The RMSEs and the coefficients are shown in Table 1, which also includes the coefficient $-2k^2$ of Nagy's theoretical model.

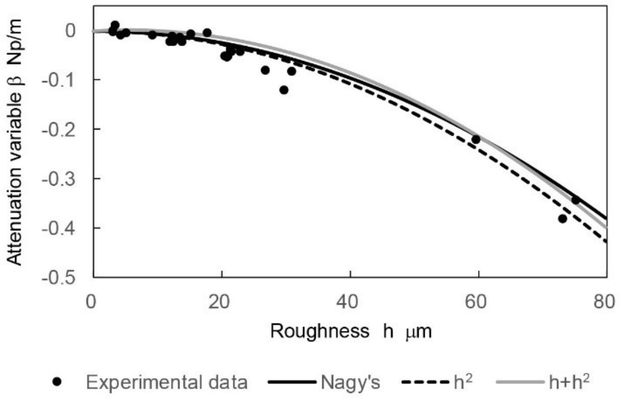


Fig. 5. Experimental data of L-wave and fitting curves.

Table 1. RMSEs and coefficients of the models for L-wave.

Model	$h + h^2$	h^2	Nagy's
RMSEs	0.016	0.020	0.023
Coefficient of h^2	-5.12×10^{-5}	-6.72×10^{-5}	-5.97×10^{-5}
Coefficient of h	-1.04×10^{-3}	-	-

3.3. Experiments by SH-wave probe

The conditions of the experiments using a SH-wave probe are as follows:

- Pulser and receiver: 5072PR (Olympus Co.)
- Data acquisition: WaveRunner HRO 64Zi (Teledyne LeCroy Co.)
- Probe: SF-051 (diameter: 13 mm, CTS Co.)
- Gain: 15.0 dB
- Wave frequency: 5 MHz (actual value: 4.0 MHz)
- Wave velocity: 3239 m/s

In the same manner as the experiments of the L-wave probe, the first and second amplitudes were determined by averaging 10 measurements. The experimental data are shown in Fig. 6. The regression analysis showed that the function of $h + h^2$ had the lowest RMSE of 0.035. Table 2 shows the RMSEs and the coefficients.

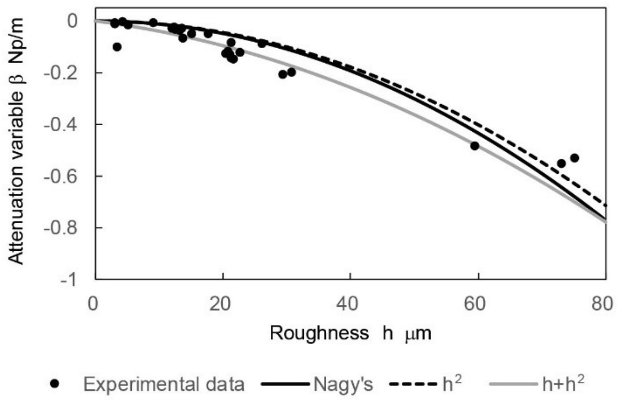


Fig. 6. Experimental data of SH-wave and fitting curves.

Table 2. RMSEs and coefficients of the models for SH-wave.

Model	$h + h^2$	h^2	Nagy's
RMSEs	0.035	0.060	0.061
Coefficient of h^2	-4.56×10^{-5}	-1.11×10^{-4}	-1.20×10^{-4}
Coefficient of h	-1.11×10^{-4}	-	-

4. Discussion

In Fig. 4, the rougher surface scattered and attenuated the ultrasonic waves more. This result indicates that the echoes have a potential to estimate both the thickness and roughness of the carbon steel block simultaneously. The thickness is estimated from the time of flight between the two echoes. The roughness is estimated from the amplitudes of the two echoes. Since the amplitudes are sensitive to factors except for the surface roughness the reflection, Eq. (16) cancels their effects.

In agreement with Nagy model, the results of the regression analysis showed that the term of h^2 is a major factor for the attenuation of the ultrasonic wave. Regarding the L-wave, the coefficient of h^2 was almost coincident with the coefficient $-2k^2$ of Nagy's model. Nagy's model assumes the random rough surface. In the experiments, the simulated flaws were not random but periodic. The results indicate that the roughness is also estimated from the amplitudes of the ultrasonic wave reflected on the periodic rough surface. Nagy's model also assumes that the correlation length of the roughness is much larger than the wavelength. In the experiments, there was not a large difference between these lengths. The model might have a potential to be applied to the wide range of the wavelength. In addition, Nagy's model only deals with the plane L-wave scattering. However, even in the cases of the spherical L-wave and the SH-wave, the coefficients of h^2 were almost coincident with the coefficient $-2k^2$ of Nagy's model, too. Although we considered that the SH-waves were attenuated due to the polarization with respect to the flaws shapes, Nagy's model fits qualitatively the behavior of the experimental data of the SH-wave. Nagy's model assumed that the back surface had a randomly rough surface. It is possible to improve the model based on other rough surfaces such as periodic roughness. The function $f(h)$ in Eq. (16) would be also identified from the theoretical model. If the probe transmits the ultrasonic wave on the surface with curvature, the relationship between the diameter of the probe and the curvature affects the measurement data. The relationship should be considered to identify the function $f(h)$.

5. Conclusion

This paper assumed the relationship between the surface roughness induced attenuation and the amplitudes of ultrasonic waves reflected on the rough surface. We derived the attenuation variable based on the acquired waveforms. The experiments using the simulated periodic corrosion obtained the amplitudes of the first and second echoes of the L- and SH- waves. The regression analysis identified the attenuation function with the roughness parameter. The experimental data and the regression analysis indicated that both L- and SH-waves had a potential to estimate the roughness. In addition, the behaviors of the experimental data of the L- and SH-waves fitted Nagy's theoretical model.

The objective of this study is characterization of corrosion inside pipes. In future works, we will make pipe-shaped specimens and verify the effectiveness of the characterization.

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