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Experimental Verification of a TE_{01} Mode Converter to Locate a Crack in a Metal Pipe

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Abstract. In this study, a TE_{01} mode converter was developed to locate an axial crack on the inner surface of a metal pipe. Three-dimensional finite element simulation was conducted to evaluate the effect of inserted coaxial cables on the transmission characteristic of the mode converter. The result showed that the energy of TE mode microwaves leaned to transmit to one side when the cables penetrated with inclination. To demonstrate the effectiveness of the mode converter, experimental verification was conducted. The mode converter was fabricated based on the simulation result. Microwaves were emitted through the pipe wall of the converter to propagate on both sides ('right side' and 'left side') of a pipe with an artificial slit. Compared with the signals from each side, the reflection from the slit on the right side was more significant than that on the left side. This result is consistent with the numerical simulation result.

Keywords: nondestructive testing, metal pipe, surface crack, microwave, time-of-flight, TE_{01} mode, mode conversion

1. Introduction

Precise maintenance activities are essential to ensuring the safety of nuclear power plants. The piping system is one of the most crucial components of the plants, thus, various nondestructive inspection methods such as eddy current and ultrasonic testing have been applied. However, these highly sensitive methods consume a significant amount of time because of their narrow inspection range. To make the inspection efficient, a nondestructive microwave testing method has been proposed to implement a quick inspection [1-3].

The basic principle of this method is to propagate microwaves and locate flaws by evaluating their time-of-flight (TOF). In previous study, its applicability to the detection of small-scale flaws such as cracks has been demonstrated: propagation of circular TM modes and circular TE modes are adequate to detect circumferential and axial cracks on the inner wall of a pipe, respectively [4]. Therefore, various mode conversion methods are essential to propagate specific modes into a metal pipe. In previous studies, various methods have been proposed to convert microwaves [4-7]. Although a mode converter has been developed to enter TE modes by introducing microwaves from the side wall [4], it cannot be determined on which side the reflection generated because microwaves traveled to both ends of the pipe equally.

To address this issue, a mode converter was designed to focus on propagating TE modes in one direction of a straight metal pipe. The numerical simulation was conducted to evaluate and optimize the transmission characteristic of the mode conversion. A mode converter was fabricated based on the result of the simulation, and its effectiveness was demonstrated via experiment.

2. Numerical simulation

2.1. Simulation model

Figure 1 shows the numerical analysis model designed in this study. This model simulates a circular pipe with a diameter of 19 mm with four semi-rigid coaxial cables inserted. These cables have even intervals in the circumferential direction and a tilt to the cross-section with the angle of θ. The core wires are exposed inside the pipe and point to the right side with the length of l_e. These coaxial cables carry TEM mode microwaves with the same amplitude and phase for each cable. Then the transmitted electro-

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magnetic waves are evaluated as energy ratios to the excitation energy for each mode on 'Evaluating planes' at both pipe ends.

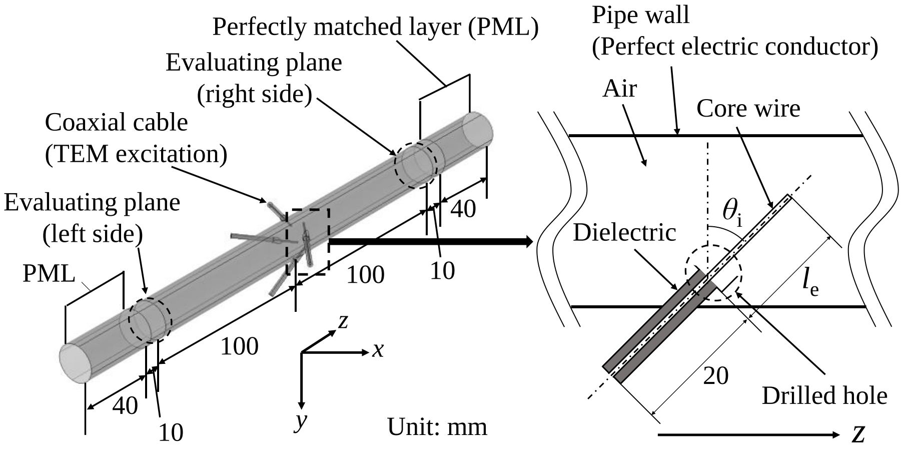


Fig. 1 Simulation model

The numerical analysis was conducted in the frequency domain by the three-dimensional finite element method using the commercial software, COMSOL Multiphysics v5.2a with its RF module. The governing equation is as follows:

$$\mathrm{rot}\left(\mu_{\mathrm{r}}^{-1}\mathrm{rot}\,\boldsymbol{E}\right)-k_0^2\left(\varepsilon_{\mathrm{r}}-\frac{\mathrm{j}\sigma}{\omega\varepsilon_0}\right)\boldsymbol{E}=0 \tag{1}$$

$$k_0=\omega\sqrt{\varepsilon_0\mu_0} \tag{2}$$

where $\boldsymbol{E}$ denotes the electric field, ε_0 the permittivity of vacuum, μ_0 the permeability of vacuum, ε_{r} the relative permittivity, μ_{r} the relative permeability, σ the electrical conductivity, j the imaginary unit, and ω the angular frequency, respectively. In the analysis, these values are set to be $\mu_{\mathrm{r}} = 1$, $\varepsilon_{\mathrm{r}} = 1.687$ [8], $\sigma = 0$ for the dielectric and $\mu_{\mathrm{r}} = 1$, $\varepsilon_{\mathrm{r}} = 1.000$, $\sigma = 0$ for the air. The properties of the pipe wall and the surface of the cables are defined as the perfect electric conductor, whose boundary condition is $\boldsymbol{n}\times\boldsymbol{E}=0$. Here, $\boldsymbol{n}$ denotes the normal unit vector of the surface. The frequency range was 20-40 GHz with a step of 0.5 GHz, which is above the cutoff frequency of TE_{01} mode for a pipe with a diameter of 19 mm, 19.3 GHz. The transmission characteristics were calculated for each combination of the inclination angle θ and the exposition length l_{e} of the cables that were set, as Table 1 shows. The maximum l_{e} vary depending on θ because of the geometrical restriction. The geometry is plane-symmetric in the cases of $\theta = 0$ deg, which is the same as in a previous study [4].

Table 1. Cable conditions in the simulation

Inclination angle θ [deg]	Exposition length l_{e} [mm]
0	8, 12
15	8, 12, 16
30	8, 12, 16
45	8, 12, 16, 20
60	8, 12, 16, 20, 24

2.2. Simulation results

The frequency characteristics of the transmitted energy ratio of the microwave for each side of the pipe were obtained by numerical simulation. The characteristic in the case of $\theta = 0$ deg, $l_{\mathrm{e}} = 8$ mm, right side is shown in Figure 2, and $\theta = 45$ deg, $l_{\mathrm{e}} = 16$ mm in Figure 3. The characteristic in Figure 2 is the same as that of the left side because of the symmetric geometry and boundary conditions as mentioned above. On the other hand, TE_{01} and TE_{41} mode microwaves were more propagated to the right side of the pipe in comparison with the left side in Figure 3. This result implies that each side of the pipe can be inspected in turn by emitting microwaves through inclining cables.

Generally, precise inspection using a pulse in the time domain requires providing a wide bandwidth in the frequency domain. On the other hand, multiple modes can propagate into a waveguide such as a metal pipe in the higher frequency region, which makes signals complicated due to their individual dispersibilities. Therefore, the frequency range should be limited to avoid this matter. In this simulation, the frequency span of 20-26 GHz is suitable for propagating TE_{01} mode microwaves appropriately.

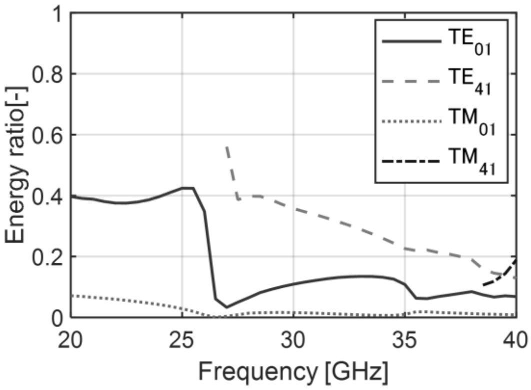
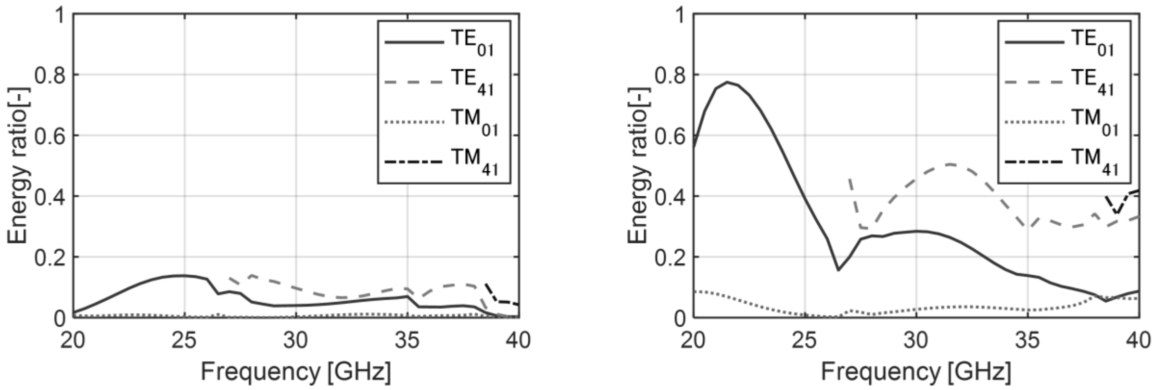


Fig. 2. Transmission characteristic (θ = 0 deg, l_e = 8 mm, right side)



(a) Left side (b) Right side

Fig. 3 Transmission characteristic (θ = 45 deg, l_e = 16 mm)

To optimize the characteristic of the mode converter, the amplitude for the right side and the left side, A_{right} and A_{left}, were estimated in the following steps:

1. Approximate the energy ratio of TE_{01}-mode from 20 to 26 GHz by a cubic curve.
2. Discretize the curve in step 1 into 1,921 points.
3. Multiply the curve in step 2 by a 6-order Kaiser window.
4. Integrate the curve in step 3.

Finally, the estimated amplitude ratio A_{right} / A_{left} to inclining angle θ was obtained, as shown in Figure 4. The ratio became the maximum in the case of θ = 45 deg, l_e = 16 mm. This case was the most suitable condition to transmit the TE mode microwaves to the right side.

3. Experimental verification

3.1. Experimental set-up

A mode converter was fabricated based on the simulation model to demonstrate its effectiveness. This converter was made of a straight brass pipe with flange joints, which had an inner diameter of 19 mm and a length of 0.2m. Four semi-rigid coaxial cables (Anritsu, K118) with cable connectors (Anritsu, K101F-R) were inserted with an inclination, as Figure 5a shows, and were bonded with conductive epoxy resin (Chemtronics, CW2400). The geometry of the cable was set to θ = 45 deg, l_e = 16 mm, which is the best condition in this study, as discussed in section 2.2.

Figure 6 shows an overview of the experimental system. This measuring system was set up to propagate microwaves inside metal pipes through the tube wall. Straight brass pipes were used for testing as well as the mode converter, which had an inner diameter of 19.0 mm, a wall thickness of 3 mm and a total length of 11.2 m. Two 5.5-m pipes were connected by the flange joints on the left and right sides of the converter. A slit with an axial length of l_a and a width of 1.0 mm penetrated the tube wall of the measuring pipe and was covered by a copper foil to simulate a non-penetrating crack. A network analyzer (Agilent Technologies, E8363B) emitted microwaves and measured reflections as scattering parameters (S_{11}) in the frequency domain. The amplitude and phase of microwaves were calibrated to be considered that a pulse was emitted from the tip of the coaxial cable (Junkosha, MWX051) connected to the network analyzer. A power divider (ET industries, D-640-4) split the microwaves four ways and summed up reflections from the coaxial cables (Junkosha, MWX241) connected to the mode converter.

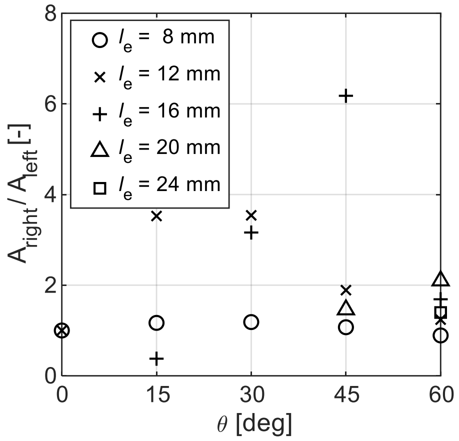
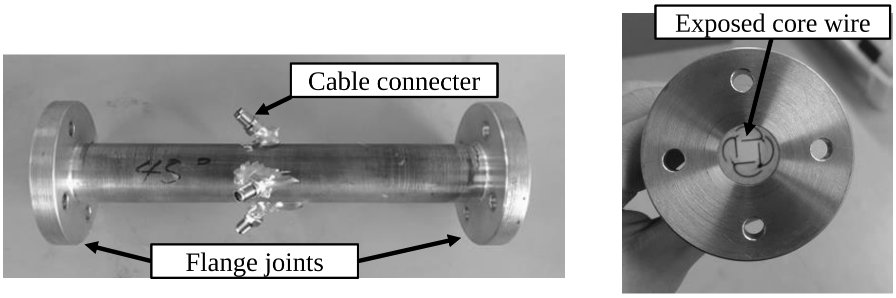


Fig. 4 θ vs. amplitude ratio



(a) Overall view (b) Inside

Fig. 5 TE_{01} mode converter

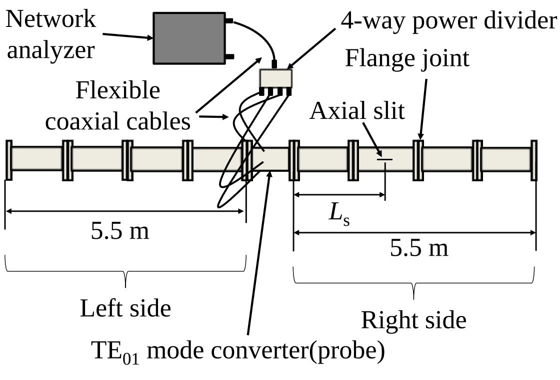


Fig. 6 Experimental system

The position of the axial slit was deployed at a distance L_s from the end of the converter on either the right or left side, as described in Figure 6. The slit condition is described in Table 2. The reflections were measured for each condition. The frequency range in the measurement was from 20 to 26 GHz (3,201 points), which was based on the characteristic of the converter.

Table 2. Slit conditions in the measurement

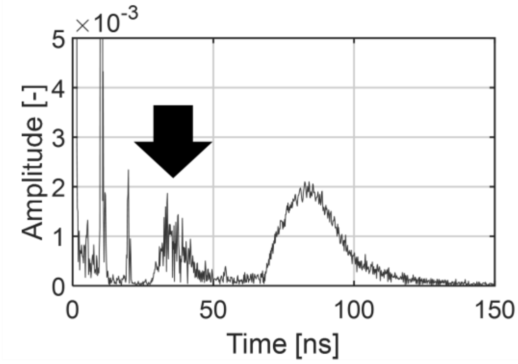
Slit location L_s [m]	Slit length l_a [mm]
2.0, 3.5, 5.0	10, 20, 30

Generally, a pulse decays due to the dispersion of circular-mode microwaves. Firstly, the measured signals in the frequency domain were converted to evaluate in the time domain processing the inverse fast Fourier transform (IFFT) with multiplying by a 6-order Kaiser window. Furthermore, a signal processing method called dispersion compensation [9] was applied to the original reflections in the frequency domain to evaluate TOF and the peak value without dispersion. Since the accurate location of the reflection source was unknown, the peak value was evaluated while sweeping the predicted distance.

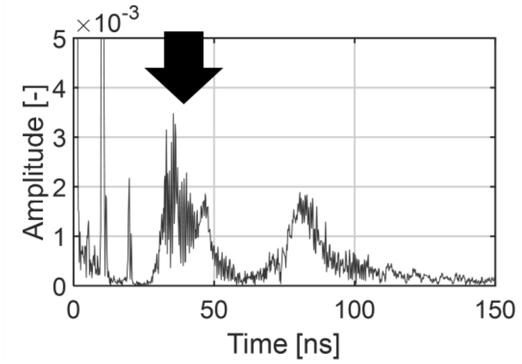
3.2. Results and discussion

3.2.1. Signal comparison in the time domain

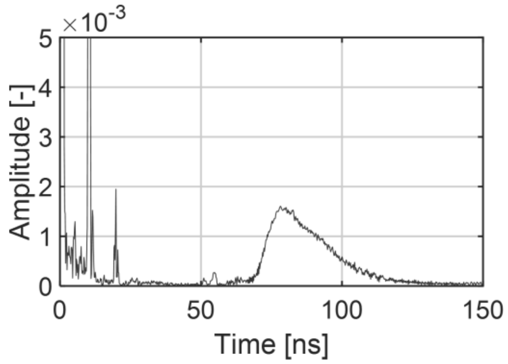
Figure 7 shows the signals measured with and without the slit under L_s = 2.0 m and l_a = 30 mm in the time domain. In Figure 7c, peaks at 0 ns and 10 ns were considered to be the first reflection at the tip of the coaxial cable connected to the divider and the tip of the semi-rigid cable of the converter, respectively; a peak at 20 ns was the second reflection at the tip of the semi-rigid cable. Since these reflections were induced inside the coaxial cable that TEM-mode microwaves can propagate, these peaks showed almost no dispersion. On the other hand, a reflection from the pipe ends around 70-120 ns showed dispersion, which was due to the propagation of the TE_{01} mode microwaves.



(a) With slit (L_s = 2.0 m, l_a = 30 mm, left side)



(b) With slit (L_s = 2.0 m, l_a = 30 mm, right side)



(c) Without slit

Fig. 7 Signals in the time domain

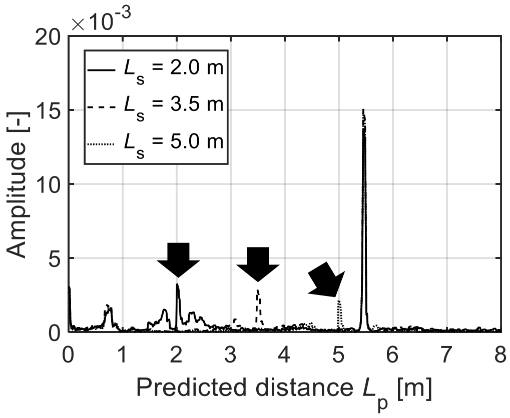
The signal from the slit was obtained around 30–50ns as shown by the arrows, which also formed a bell-shaped curve rather than a pulse due to the dispersion of the TE_{01} mode microwaves. Given that the signal at 10 ns was due to the reflections from around the probe, the TOF was calculated at 20–50 ns. This value agrees with the theoretical TOF calculated from the group velocity of the TE_{01} mode. Furthermore, the signal from the slit on the right side of the pipe was more significant than that on the left side. This result qualitatively agrees with the claim in the numerical simulation.

3.2.2. Peak evaluation

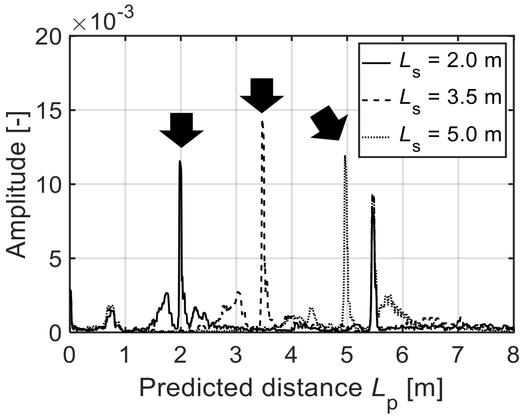
The peak value was evaluated using dispersion compensation on the assumption that microwaves went and returned as TE_{01} mode. Figures 8a and 8b show the results of the prediction in the cases of l_a = 30 mm. Peaks at 5.5 m were the reflection from the pipe ends. As the arrows show, peaks due to the reflections from the slit were observed when the predicted distances L_p approximately agreed with the actual position L_s. The locating error, namely the difference between L_p and L_s was at most 10 mm and 40 mm in the case of the left and right side, respectively.

Signals besides those mentioned above were also observed, which were due to the propagation of other modes, such as TM_{01} and TE_{21} mode microwaves.

Applying the signal processing, the peak value could be quantitatively evaluated. The peak value ratio of the right side to the left side was calculated, as shown in Figure 9. Explicit dependency on neither l_a or L_s was observed, however, the amplitude ratios were around 3-6 in any of the slit conditions. Accordingly, the efficacy of the new mode converter was substantiated.



(a) Slit on left side



(b) Slit on right side

Fig. 8 Peak evaluation

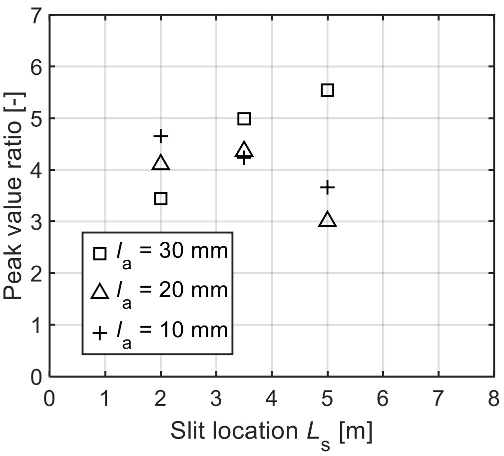


Fig. 9 Peak value comparison

4. Conclusion

In this study, a TE_{01} mode converter was designed to locate an axial crack on the inner surface of a metal pipe. Both the result of the numerical simulation and experimental verification showed that the transmitted energy of TE mode microwaves leaned to one side of the pipe when the cables were penetrated into the mode converter with inclination to the pipe axis. The experimental result showed that it could be determined on which side the axial crack existed even if microwaves entered through the tube wall. Furthermore, the maximum location error was 40 mm (0.8 %).

Acknowledgments

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