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In-pipe Crack Detection for Multiple Diameters Using TE_{11} Mode Microwaves

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Abstract. This study evaluated the effect of pipe diameter on the applicability of a technique using TE_{11} mode microwaves for in-pipe crack detection. Three TE_{11} mode converters of different inner diameters were designed based on theoretical calculations and verified via numerical simulations. The working bandwidths of these mode converters were 7.0, 4.0, and 1.9 GHz. Experimental verification was carried out using brass pipes with the corresponding three inner diameters, and with pipe lengths up to 21–25.5 m. An axial and a circumferential slit were introduced to simulate cracks and deployed at multiple positions along the pipes under test. The results showed that both axial and circumferential slits could be detected and located for an inner pipe diameter up to 39 mm and at a distance of 15 m – 24 m.

Keywords: Microwaves, TE11, NDT, mode converter, crack

1. Introduction

Metallic pipes are crucial components of power plants, oil refineries, and many other industrial facilities. To ensure the safe operation of piping systems, some conventional non-destructive testing (NDT) methods, such as eddy current testing [1] and ultrasonic testing [2], have been put into practical use for the inspection and maintenance of piping systems. However, despite the high detection precision, these methods require surface preparation or probe scans, which consume time and labor thus decrease the inspection efficiency.

A state-of-the-art NDT method using microwaves [3,4] has been proposed for rapid pipe inspections. Microwaves of certain mode(s) are emitted into a metal pipe and propagated inside the pipe with a low attenuation and a high propagation speed. A defect located on the inner surface of the pipe disrupts the microwaves' propagation and generates a reflection. By measuring this reflection and evaluating its time-of-flight, the existence as well as positional information of the defect can be acquired. Former studies on this method have demonstrated its detectability of pipe wall thinning [5], cracks [6,7], and corrosion under an insulator [8], while a detection range of 26.5 m has also been achieved [9].

Our previous study [10] has revealed that using TE_{11} mode microwaves with two orthogonal linear polarizations can effectively detect both axial and circumferential slits. However, only one pipe (diameter) was tested in that study, while the pipe length was only 7 m. Therefore, more experimental verification should be carried out to further confirm its detection capability under different conditions (e.g. variations of the pipe's inner diameter, length, etc.).

This paper studied the effect of pipe inner diameter on the applicability of a technique using TE_{11} mode microwaves for in-pipe crack detection. Three TE_{11} mode converters of different inner diameters were designed via theoretical calculations and numerical simulations. Experimental verification was implemented by detecting an axial and a circumferential slit deployed at multiple longitudinal positions in pipes whose lengths ranged from 21 to 25.5 m.

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2. Design of TE_{11} mode converter

Figure 1 (a) illustrates the structure of the TE_{11} mode converter, comprising a TEM-TM_{01} mode converter [11] and a dual-bend TM_{01}-TE_{11} mode converter [12]. TE_{11} mode converters for inner pipe diameters D =11, 19, and 39 mm were designed following a systematic method [10] proposed by the authors, and the procedure is briefly interpreted as follows: (1) Design a TEM-TM_{01} mode converter for a certain D by changing the exposure length of a semi-rigid cable's core wire l_P using numerical simulation, and determine the operational frequency range of TM_{01} mode; (2) Over the obtained frequency range, compute the mode conversion when TM_{01} mode propagates through two inversely connected bends (TM_{01}-TE_{11} mode converter), based on the theory of mode coupling due to a bend [13]; (3) Alter the dimension of the bend (curvature radius r and bend angle α) to obtain an optimum conversion characteristic from TM_{01} to TE_{11} mode in the frequency domain. In this study, the curvature radii and bend angles of two bends were set to identical for simplification. A detailed computational procedure and simulation model are given in the preceding study [10]. Table 1 summarizes the optimized values of l_P, r, and α for three TE_{11} mode converters, and their working frequency spans f_W were obtained accordingly, over which the energy ratio of TE_{11} mode was greater than or equal to 90%.

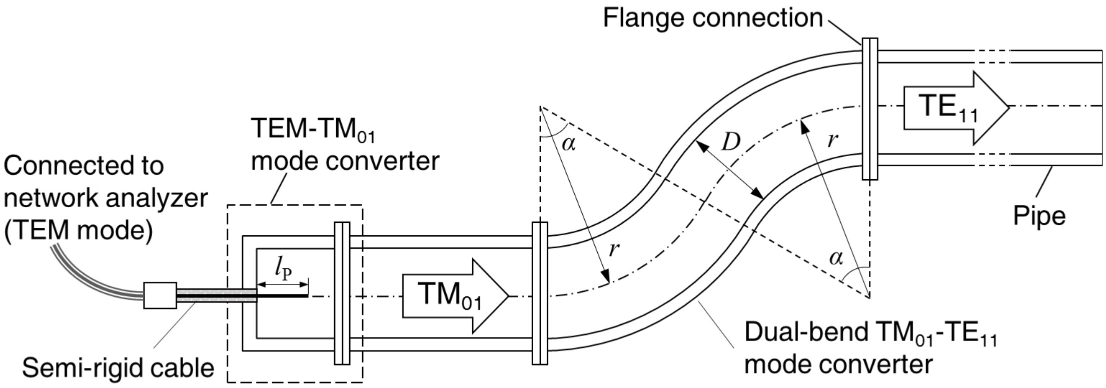
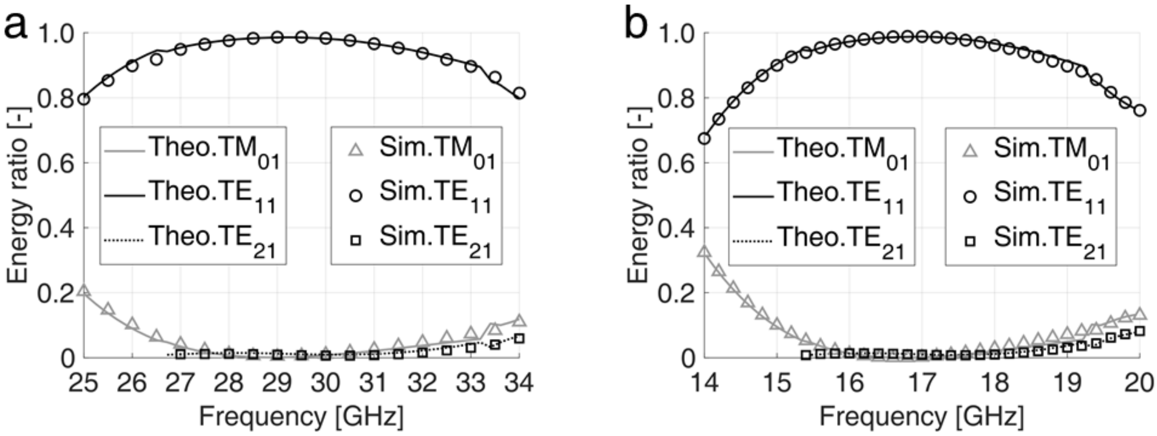


Fig. 1. Structure of the TE11 mode converter.

Comparisons between theoretical and numerical results of the optimized fractional energy are displayed in Fig. 2 (a), (b), and (c), for the three TE_{11} mode converters. Good consistency is observed for each scenario, and the working bandwidths of the three mode converters were 7.0, 4.0, and 1.9 GHz. It can be seen that the working bandwidth of the TE_{11} mode converter decreases when D becomes larger, which is not preferable because the time domain resolution is inversely proportional to the frequency bandwidth [14]. However, this problem can be resolved in the future by applying an optimized design of the TEM-TM_{01} mode converter [11] to widen the operational frequency range of the TM_{01} mode, or by selecting different r and α for the two bends of the TM_{01}-TE_{11} mode converter to improve the conversion efficiency from the TM_{01} to TE_{11} mode.



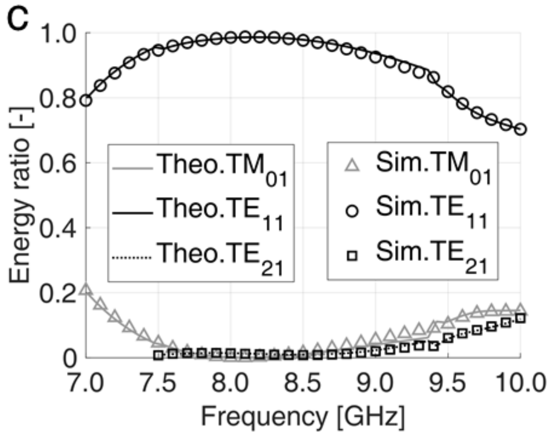


Fig. 2. Conversion characteristics of the three TE_{11} mode converters, (a) D =11 mm, (b) D =19 mm, (c) D =39 mm.

Table 1 Parameters of the three mode converters

D (mm)	r (mm)	r/D (-)	α (deg.)	l_P (mm)	f_W (GHz)
11	30	2.73	48	3	26–33
19	50	2.63	50	5	15–19
39	100	2.56	51	9	7.3–9.2

3. Experiment

3.1. Experimental setup

Figure 3 (a) shows the experimental system. A network analyzer (Agilent Technologies, E8363B) was employed to generate TEM mode microwaves, which propagated through a flexible cable (Junkosha. Inc., MWX051) and were converted into circular TM_{01} mode by the TEM-TM_{01} mode converter. The converted TM_{01} mode microwaves were subsequently converted into TE_{11} mode by the TM_{01}-TE_{11} mode converter and entered the pipes under test. The three TE_{11} mode converters were fabricated based on the results given in Table 1 and portrayed in Fig. 3 (b).

Brass pipes of the same three inner diameters and lengths over 20 m were prepared for the experiment, by connecting several short pipes (1.0, 1.5 or 2.0 m in length each) with flange pipe fittings. An axial or a circumferential slit was machined in the middle of a short pipe (200 mm in length, D =11, 19, and 39 mm) to simulate a crack, and their dimensions are displayed in Fig. 3 (c). Moreover, to each D, another short pipe of the same length but with no fabricated slit was used for reference. The short pipes were longitudinally situated at different positions (L_S) along the pipes under test. According to the analysis in our previous study, the sensitive areas of linearly-polarized TE_{11} mode microwaves against slits in a circumferential direction are dependent on the polarization (horizontal or vertical), whereas an orthogonal deployment of the TE_{11} mode converter can eliminate the dead detection zones of each polarization and thus implement a thorough inspection of the inner surface of the pipe. Therefore, in this experiment, reflection signals were measured only under a state of horizontal polarization, and the slits were deployed at the corresponding sensitive areas in the circumferential direction. Table 2 summarizes the experimental parameters. It should be noted that: due to the precision limit of the mechanical fabrication, the inner diameter of the TM_{01}-TE_{11} mode converter for D =19 mm was actually 18.7 mm, and the 0.3 mm difference in diameter between the mode converter and the pipe resulted in a 0.4 GHz frequency span shift, compared with the frequency span f_W given in Table 1. The reflection signals were measured as S-parameters in the frequency domain at 3201 evenly spaced sampling points, and were further processed using a dispersion-compensation method [15] to predicate the location of the flaw in a pipe.

Table 2 Experimental parameters

Parameter (unit)	Inner pipe diameter, D (mm)		
	11	19	39
Frequency span, f (GHz)	26 – 33	15.4 – 19.4	7.3 – 9.2
Pipe length, L (m)	21	22.5	25.5
Short pipe position, L_S (m)	5, 10, 15, 20	4, 8, 12, 16, 20	4, 8, 12, 16, 21, 24

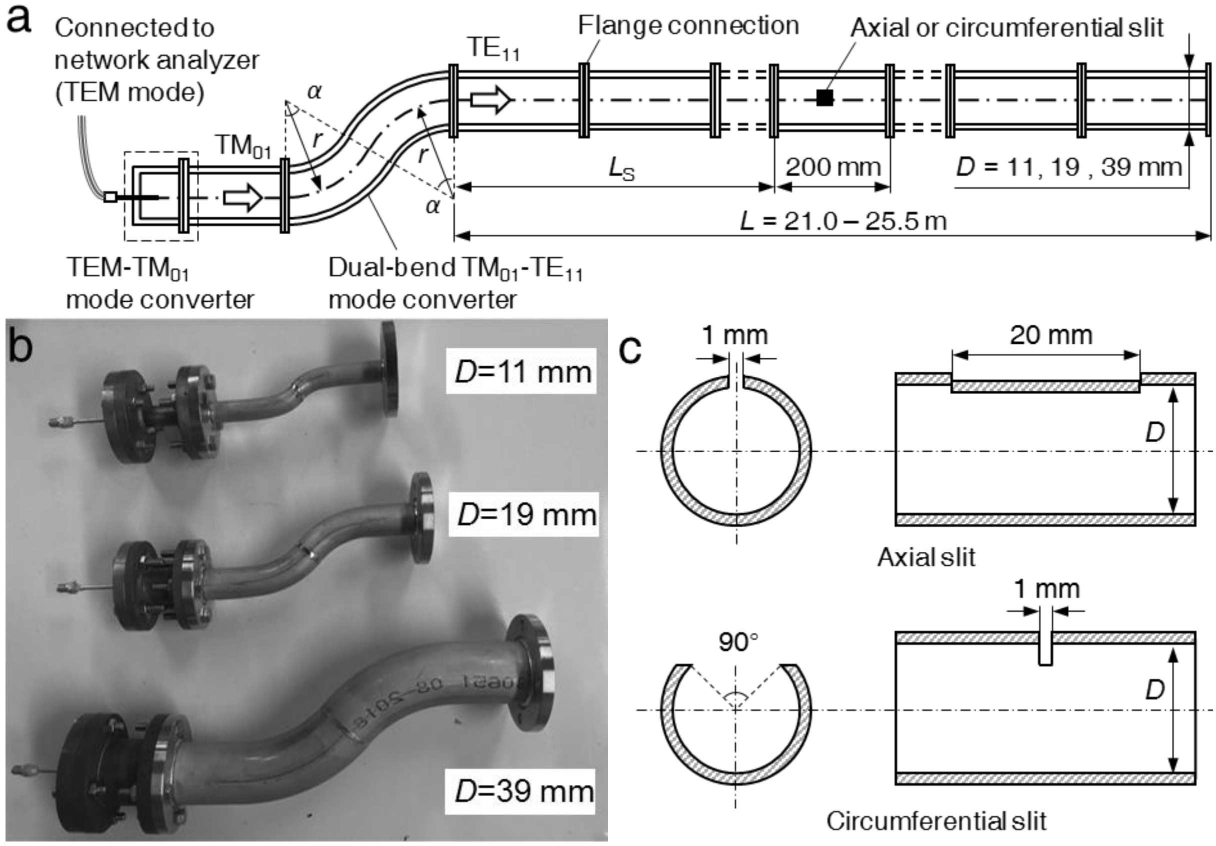


Fig. 3. Experimental setup, (a) overview of the experimental system (not to scale), (b) three TE_{11} mode converters, (c) dimensions of the axial and circumferential slits (D = 11, 19, and 39 mm, not to scale).

3.2. Results and discussions

The experimental results for three different D values are depicted in Figures 4, 5, and 6. In the case D = 39 mm, shown in Fig. 4 (a) and (b), the clear reflection peaks appearing at L_S = 4, 8, …, 24 m indicate that both the axial and circumferential slits were detected at each location in the pipe. Small reflection peaks whose amplitudes were smaller than 0.002 were mainly due to the flange connections, while the reflection at 25.5 m corresponds to the pipe end. It should be noted that the results of D = 39 mm exhibit clear pulses even though the working bandwidth was not so wide. This implies that this method is prospectively applicable to the inspections of pipes of larger diameters, after further optimizing the designs of the TEM-TM_{01} and TM_{01}-TE_{11} mode converters. Similarly, when D = 19 mm as shown in Fig. 5, explicit reflection signals can be observed where the axial and circumferential slits were deployed. When D = 11 mm, the sharp and steep reflection peaks shown in Fig. 6 (a) reveal that the axial slit can be detected with a high sensitivity. However, the result of the circumferential slit, shown in Fig. 6 (b), is more complicated: the reflection from the circumferential slit became smaller, meanwhile, some unknown reflections (highlighted with the dashed-line box) occurred at positions in which neither slit nor flange connections existed. After comparing the reflection signal of the circumferential slit with that obtained using the reference pipe (with no slit) shown in Fig. 6 (c), it can be seen that the reflections from the circumferential slits (highlighted with solid-line box) at L_S = 5, 10 and 15 m are still discernible for detection, while the unknown reflections may result from some hidden corrosion inside a 2 m long pipe. Moreover, it should be noted that: when the pipe diameter becomes smaller, the working bandwidth increases accordingly, while the reflection signal tends to decay faster because the sweeping frequency also increases.

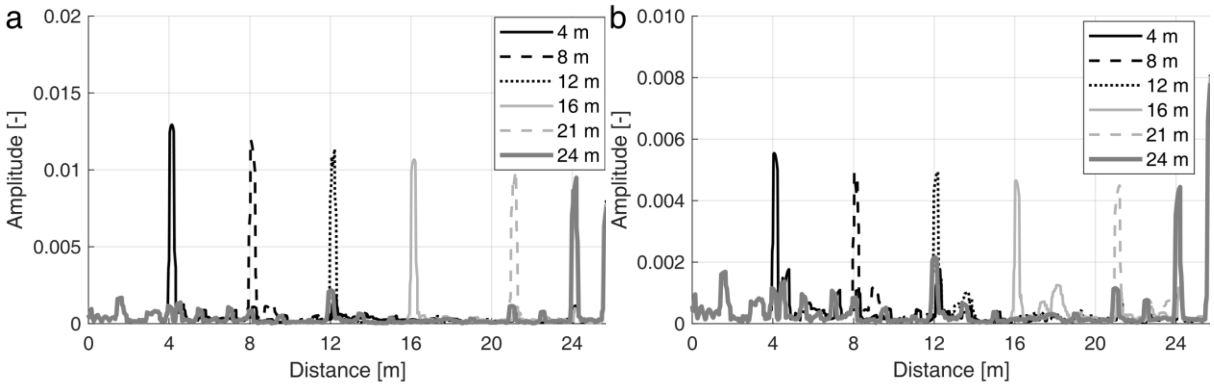


Fig. 4. Processed reflection signals (*D*=39 mm) from two slits situated at L_S= 4, 8, 12, 16, 21 and 24 m, (a) axial slit, (b) circumferential slit.

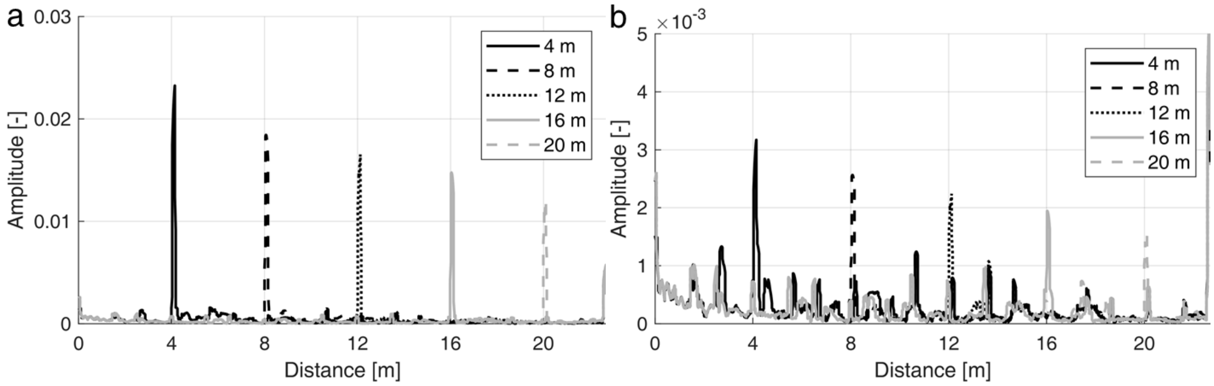


Fig. 5. Processed reflection signals (*D*=19 mm) from two slits situated at L_S= 4, 8, 12, 16 and 20 m, (a) axial slit, (b) circumferential slit.

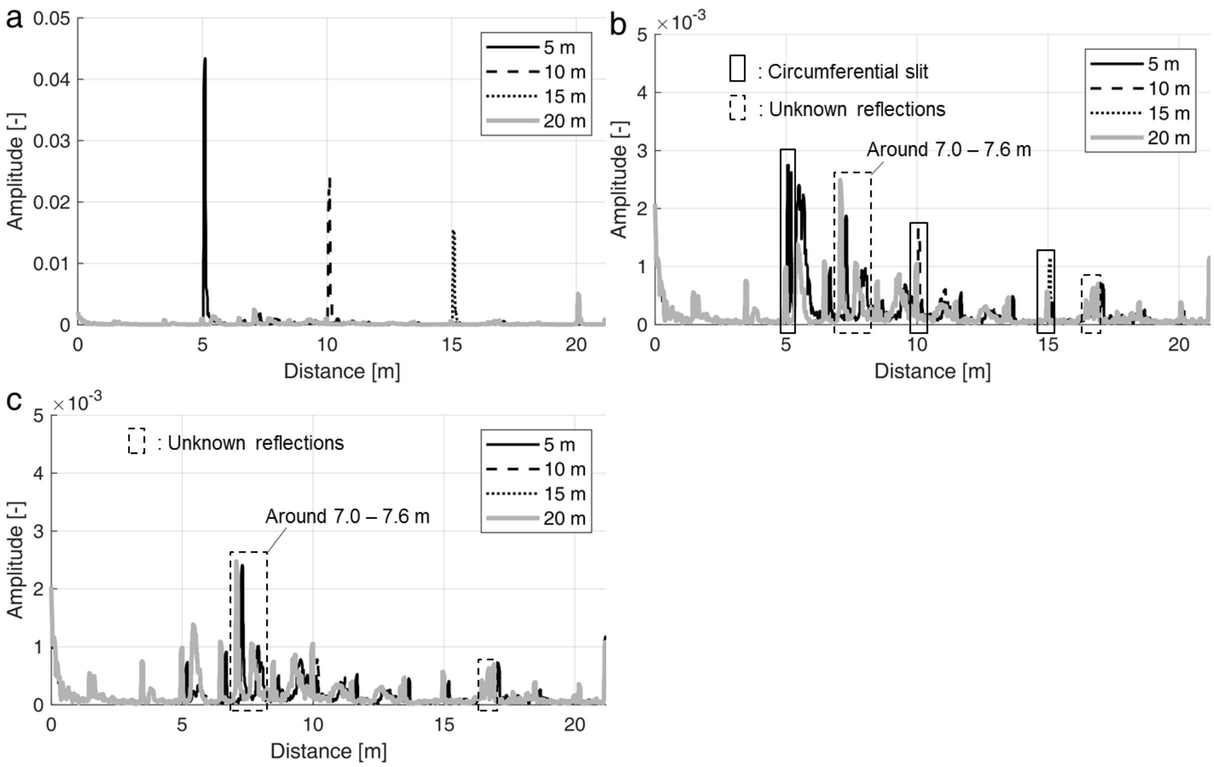


Fig. 6. Processed reflection signals (*D* = 11mm) from two slits situated at L_S= 5, 10, 15 and 20 m, (a) axial slit, (b) circumferential slit, (c) reference signal.

4. Conclusion

This study evaluated the effect of pipe inner diameter on the applicability of a technique using TE_{11} mode microwaves for crack detection. Three mode converters of three different inner diameters were designed using theoretical calculations and numerical simulations, and these two results accord well with each other. The experimental verification was carried out using pipes of the corresponding three inner diameters and two artificial slits (axial & circumferential), while the results showed that both two types of slits were detectable in each pipe, at a distance of 15–24 m. Furthermore, the influence of pipe diameter on the detection capability of this method was discussed to evaluate its viability for the inspection of larger or smaller diameter pipes.

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