Study on Improvement of Microwave Non-destructive Testing Technology for Inspection of Piping Systems with Bends

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学 位 論 文 題 目　Study on Improvement of Microwave Non-destructive Testing Technology for Inspection of Piping Systems with Bends (曲がり部を有する配管に対する電磁波非破壊検査手法の高度化に関する研究)
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論文内容要約

Metal pipes are extensively employed in various industrial facilities for substance transportation. During pi operation, degradations occur on account for fatigue, corrosion, etc., which may result in pipe failure and thus cau catastrophic consequences. Conventional non-destructive testing (NDT) methods such as ultrasonic testing and ed current testing are of high precision but request probe scans or surface preparations, which are time&labor consumir Ergo, an NDT technology using microwave has been proposed to implement rapid and long-range pipe inspectic Microwaves are propagated inside a pipe as guided waves, while reflection from a flaw is measured and time-of-flight is evaluated for location.

Former studies have demonstrated that flaws such as pipe wall thinning and cracks can be detected and located a long distance. Nevertheless, these studies mainly focused on inspection of straight pipes, while the application to be pipes, which are also widely used, has not been studied deeply. This study targets the inspection of piping systems with bends using microwave NDT, and three aspects of works are carried out: 1. Clarify the effect of a bend on microwave transmission and reflection; 2. Develop a crack-detection method using a TE_{11} mode microwave probe for inspection of bent pipes with open-end; 3. Design a dual-port, side-incident microwave probe for directional inspection of closed piping systems. This thesis is organized as below:

Chapter 1 gives basic introductions to the background, former studies, and objective of this study;

Chapter 2 introduces the research methods, including the theory of microwave in a circular waveguide, numerical simulation method, experimental equipment, and signal-processing method.

Chapter 3 investigates the effect of a bend on microwave transmission and reflection. The factors affecting the mode conversion of microwaves due to a bend were studied theoretically and verified by numerical simulation. Both theoretical and numerical results reveal that the mode conversion at a bend depends on the three factors: the frequency normalized by the cut-off frequency of an arbitrary mode (f/f_c), the ratio of the curvature radius to the inner diameter of the pipe (r/D) and the bend angle (α). Moreover, the polarization of non-axisymmetric mode like TE_{11} mode also influences the mode conversion, while the polarization itself is not affected by the bend. Experiment was performed to evaluate the effect of a bend microwave reflection, by quantitatively comparing the reflection signals from pipe wall thinning in a straight pipe with those in a bent pipe. The results show that the presence of a bend leads to a decrease in the reflection signal behind the bend, and the extent of decrease is also correlated with the mode conversion at the bend, i.e., r/D, α and f/f_c. Furthermore, the flaw size does not noticeably influence the decrease in reflection signal when the bend's dimensions are certain. To two bends with different inner diameters D but identical or similar r/D and α, given the same range of f/f_c, the effects of them on reflection are also consistent.

Chapter 4 presents a crack-detection approach using a TE_{11} mode microwave probe. The linearly-polarized TE_{11} mode is proved to be sensitive to both axial and circumferential cracks in the light of the analysis on surface current density. A systematic method was proposed to design a TE_{11} mode microwave probe (comprising a TEM-TM_{01} and a dual-bend TM_{01}-TE_{11} mode converter) for an arbitrary inner pipe diameter D using theoretical and numerical analysis. A 3.5 GHz working bandwidth was achieved for D = 23 mm. Experimental verification was conducted by detecting an axial and a circumferential slit situated at different longitudinal and circumferential positions in a 7 m long stainless-steel pipe. The results show that both axial and circumferential slits were detected at arbitrary positions in a pipe by jointly analyzing the reflection signals of TE_{11} mode under horizontal and vertical polarizations. Subsequently, this method was applied for detecting cracks in a bent pipe. The results show that: given the impact of TE_{11} mode's polarization on mode conversion at the bend, the detectability against axial crack was still significant, whereas that against circumferential crack could be largely influenced if the bend imposes too much effect. The problem can be addressed by utilizing the TM_{01} mode 'integrated' in the probe to detect circumferential cracks. Moreover, the application to long-range detection and multiple inner pipe diameters has also been validated experimentally, and a detection range up to 15 – 24 m for D = 11, 19, and 39 mm has been confirmed. Besides, an improved TE_{11} mode microwave probe design was proposed to achieve wide working bandwidth and apply to larger pipe diameters. In addition, this method was applied for inspecting bend-region cracks. The detection capability has been preliminarily confirmed, as both axial and circumferential slits at variant angular positions of a bend were successfully detected, with positional information specified by the peak locations of reflections. Finally, additional tests were made to examine the detectability of TE_{11} mode microwaves towards pipe wall thinning and non-penetrant slit.

Chapter 5 proposes a dual-port, side-incident microwave probe that realizes directional pipe inspections of closed piping systems. Two types of side-incident probes (LJ and JL) are proposed to transmit TM_{01} or TM_{02} mode microwaves into the pipe under test, and each type of probe has two ports utilized for inspections of two opposite directions. Numerical simulations were conducted to study the dimensional parameters affecting the transmission characteristic of the probe and thus optimize the probe to obtain better mode purity and transmission directivity. The simulation results also suggest that the optimal probe dimensions for one inner pipe diameter can be applied to another diameter according to the proportional relationship between the optimal dimensional parameters of the probe and the pipe diameter. Two LJ-type, side-incident probes with an inner diameter of 19 or 39 mm, were fabricated based on the simulation results. The experimental verification was subsequently carried out to test the detection directivity of the probes by detecting the pipe wall thinning situated on both sides of each probe. The results show that the proposed dual-port, side-incident microwave probes can effectively detect the pipe wall thinning on either side of each probe using the corresponding port, and thereby realize the directional pipe inspection. Furthermore, this method shows the prospect of being applied to various inner pipe diameters.

Chapter 6 summarizes the works carried out in this study and proposes some future tasks for further improvement and practical use of this technique.