Long Range Inspection of Wall Reduction of Tank Utilizing Zero-th Order Symmetric Mode Lamb Wave

—Performance Demonstration of the Method Proposed—

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We developed a new long range inspection method of corrosion-induced wall reduction of storage tanks. The method utilizes the zero-th order symmetric mode (So-mode) Lamb waves excited and monitored by a specially designed rectangular compression type PZT transducer mounted on the edge of the annular plate and side wall. The system can measure both the location and damage depth from the arrival time and amplitude of the So-mode reflected by the defects, respectively. We first measured attenuation of the So-mode wave and then the depth of dish-shaped wall reduction on single carbon steel plate. Amplitude of the So-mode wave reflected by the defects was found to increase proportionally with the defect depth less than 15% of the plate thickness (10 mm). Amplitude of the reflected So-mode Lamb wave from the shallow dish-shaped defects with depth of 0.6 mm or 7.5% to the plate thickness was detected. We also detected the So-mode waves from corrosion-induced dish-shaped wall reduction with 1.45 mm depth in 10 mm plate. Artificial groove of 1 mm depth on the step-weld 8 mm plates could be detected by the proposed method. [doi:10.2320/matertrans.I-MRA2007843]

(Received September 4, 2006; Accepted February 14, 2007; Published May 25, 2007)

Keywords: symmetrical mode Lamb wave, corrosion, residual wall thickness, plate structure

1. Introduction

Oil storage tanks in Japan have been used for past 30 years or more. Both bottom and side plates of these tanks have been suffering corrosion and, in the worse case, leading to oil leakage. Wall reduction of the side wall by external corrosion under thermal insulation is now becoming an important problem in addition to the corrosion damage of the bottom plates. Wall thickness of the bottom plates (both of the annular plate and floor plate) must be inspected, according to the regulation by the Fire and Disaster Management Agency, at every seven or twelve years depending on the tank size. The regulation allows a wall reduction less than 20% of the designed wall thickness, when the plates were inspected by a point-to-point UT inspection.1) This inspection requires both tank opening and cleaning and inevitably expensive cost and time. There is a strong need for non-expensive and in-service inspection method of wall reduction of the plates.

Lamb wave has been utilized for the long range inspection of plate structure.2) It possesses two wave modes, i.e., symmetrical (S) and anti-symmetrical (A) modes, with dispersive nature. These mode waves also have higher order modes. However, at low frequency range, two zero-th order or fundamental modes of S- and A-modes are dominant. These mode waves are designated as So- and Ao-modes in this paper.

In the conventional inspection methods utilizing the Lamb waves and PZT transducer, the Ao-mode has been mainly utilized because of easily generation and detection due to its large out-of-plane motion. Large attenuation of the wave due to energy leakage into polymer coating, sludge and oil-sand on the plates makes the long distance inspection difficult. Contrary to this, the So-mode wave at low frequency range is less dispersive and shows lower attenuation. Here it is noted that strong So-mode wave can be excited by striking at the center of edge plane of the plate. For the inspection of the bottom plates or side walls, we can produce strong and directional So-mode wave by using a special transducer on the edge plane of plates and monitor the So-mode reflected by the defects. Location of the defect can be easily estimated from the arrival time of the reflected So-mode using constant group velocity. Shear horizontal (SH) waves only have in-plane motion or motion normal to propagation direction and have feasibility for inspecting wall reduction of plates.3) As both the generation and detection of SH mode wave need a shear-type PZT transducer, efficiency of generation and detection is relatively low.

In this paper, we introduce an estimation accuracy of both the location and depth of dish-shaped artificial and corrosion-induced defects utilizing the reflected So-mode Lamb wave. We also report the detection limit of the defects in angular-weld plates by the proposed method.

2. Nature of So-Mode Lamb Wave and Transducer Developed

Nature of the So-mode at low frequency range was first studied for useful utilization and effective detection. Figure 1 compares distribution of out-of-plane (broken line) and in-plane (solid line) amplitudes of the So-mode at 100 kHz across a 10 mm thick steel plate. These are calculated with commercial software of DISPERSE.4) The amplitude of the in-plane component shows the same phase and approximately uniform, while the amplitude of the out-of-plane component is much smaller. These natures also imply that the So-mode wave can be effectively excited by an impact to the edge plane (distal plane) of the plate and also that the reflected So-mode wave can be monitored by the receiver mounted on the edge plane. Figure 2 shows the velocity dispersions of the So-mode waves in the frequency range from 0 to 200 kHz for a steel plate of 6, 8 and 10 mm thickness. The velocity at frequency zero is independent from
wall thickness and 5410 m/s for the steel plates. Though the velocity decreases with increasing the frequency, depending on the wall thickness, but can be taken as 5250 m/s at 100 kHz.

We developed a special transducer for generating and receiving the plane So-mode Lamb waves propagating in one direction. The shape of the transducer is 100 mm length, 10 mm width and 40 mm height. The center frequency is designed as 100 kHz/30 kHz (at 6 dB drop). Figure 3 shows amplitude distribution (length of arrows) of the So-mode wave as a function of propagation angle. Here the So-mode wave was generated by the transducer mounted on the straight edge plane of a semi-circular aluminum plate of 10 mm thickness, and detected by small PZT-type acoustic emission sensor (PAC, Type-PICO with 5 mm diameter) mounted on the semi-circular edge from 0° to 75° to detect the in-plane motion. The amplitudes are normalized by the maximum amplitude of the So-mode wave detected at 0°.

The transducer was found to produce plane So-mode Lamb wave with high directionality to the normal direction of the transducer. Wave amplitude within ±20° is higher than the half of the maximum amplitude at 0°. Shown in Fig. 4 are the detected Lamb wave at 0° and its frequency component by FFT. Only the So-mode Lamb wave with center frequency of 100 kHz was successfully excited and detected.

3. Attenuation of the So-Mode Lamb Wave

Attenuation of the So-mode wave by sludge and oil sand is hazard for the long distance inspection of defects. In this section, we compared the attenuations of both So- and Ao-mode waves. The So-mode wave was generated and detected by the transducer mounted on the edge plane of 500 mm square carbon steel plate of 8 mm thickness, while the Ao-mode wave by the transducer mounted on the plate surface. Attenuations were compared for both mode waves detected for the plate with and without high viscous grease of 10 mm thickness. The grease is used as an attenuator since our previous study revealed the grease gives the highest attenuation and can simulate the sludge. Figure 5 compares the waveforms. First burst wave indicated leak current from the signal generator. We detected only the So-mode wave at
200 μs for both plates, as shown in Fig. 5(a) and (b). The amplitude of the So-mode wave for the plate with the grease decreased compared to that for the plate without grease. Attenuation coefficient by the grease was measured as 3.7 dB/m. Contrary to this, we detected both the weak So-mode at 200 μs and strong Ao-mode Lamb waves at 320 μs in the wave(d), when the Lamb waves were excited by the transducer mounted on the plate surface as shown in (c) and (d). Attenuation coefficient of the Ao-mode wave by the grease was measured as 10 dB/m and approximately three times large that of the So-mode.

4. Depth Estimation of Defects by the So-Mode Wave

4.1 Dish-shaped defects in single plain plate

We prepared eight dish-shaped defects with depth from 0.6 mm to 2.0 mm in a steel plate (SS400) of 1000 mm length, 500 mm width and 8 mm thickness as shown in Fig. 6. Elliptical dish-shaped defects were produced by hand-grinding at 750 mm from the right edge to which the transducer was mounted. The major axis of the defect was machined as 50 mm and the minor axis as 30 mm. The transducers, mounted on the edge or surface of the plate, were driven by a chirp input signal to improve S/N ratio utilizing a pulse-compression processing. Here the chirp signal consists of frequency sweeping from 80 kHz to 120 kHz. Figure 7 shows the waveform of the So-mode wave excited and detected by the transducer on the edge plane for the plate with defects of 0.6 mm, 1.0 mm and 1.4 mm depth (the upper) and their enveloped waveforms processed by the pulse-compression technique. There observed two peak waves in original waveforms. Strong peak waves at approximately 400 μs correspond to the So-mode wave reflected by the opposite edge of the plate. Weak peak waves at approximately 320 μs correspond to the So-mode wave reflected by the defects. The amplitudes of the reflected So-mode wave increased with the depth of the defects, while the amplitude of the wave reflected by the edge was kept constant. These characteristic features were apparent both in the original waveform and enveloped pulse-compressed waveform.

Figure 8 shows the Lamb waveform excited and detected by the transducer mounted on the plate surface with the defects of 1.0 mm and 1.6 mm depth. We observed no
reflected Ao-mode from the shallow defects with depth less than 1.0 mm, but detected the weak So-mode and strong Ao-mode waves reflected by the opposite edge at approximately 380 µs and 600 µs, respectively. These waves are denoted as the So-edge and Ao-edge in the figure. The Ao-mode wave from the defect was detected for only the plate with deep defect of 1.6 mm depth, as denoted as the Ao-defect at approximately 600 µs in (b). As the waveform of the Ao-mode from the defects resembles that of the So-mode from the opposite edge, these two waves can be hardly classified. This is the most troublesome problem which we experience using the Ao-mode Lamb wave.

Figure 9 shows a relationship between the normalized amplitude of reflected wave and defect depth. Here the amplitude of the reflected wave was normalized to that of the reflected wave by the opposite edge and also the defect depth was normalized to the plate thickness. Solid triangles designate the measured data and the linear line the relation was normalized to the plate thickness. The normalized amplitude of the wave was measured as 14.0%. This amplitude gives normalized damage depth of 1.12 mm based on Fig. 9. The estimated damage depth (1.12 mm) agreed fairly well with the actual depth (1.25 mm).

4.2 Defect detection in step-weld plates with different thicknesses

Storage tank is generally constructed by step- or angular-welding of the steel plates, except the annular plates. Side wall was constructed by step-welding of plates with different thicknesses, i.e., thicker plates in the bottom portion and thinner plates in the top portion of the tank. Study of this section aims to examine whether the defects can be monitored crossover the step-weld. We then prepared step-weld plates of 10 mm and 8 mm thickness as shown in Fig. 11 for simulating the side wall. We induced rectangular grooves of 0 mm (no defect), 1 mm and 2 mm depth in a 10 mm thick plate by grinding. The So-mode waves were excited and received by the transducer mounted on the edge plane of 8 mm plate. Figure 12 shows the So-mode waves for the plate without defect and with two types of defects. For the defect free plate (a), we detected only the So-mode wave from weld line at around 210 µs. Amplitude of this wave is smaller than that of the wave from the opposite end edge. For the plates with defects (b,c), we detected the So-mode wave from the defects at around 320 µs in addition to the waves from the weld line and end edge. It is noted that the wave amplitudes
The overlapped weld samples. We observed four wave packets at approximately 200, 275, 330 and 400 μs. First two packets appear to be the reflected waves from the weld line accompanying the mode conversion. First packet corresponds to the reflected So-mode wave and the second the reflected Ao-mode wave. The So-mode wave from the defects was clearly detected at approximately 340 μs. We found that the defect with 0.8 mm depth (10% reduction of a 8 mm thick plate) could be detected for the overlapped weld plates. As the wave attenuation due to the overlapped weld is estimated as 7 dB, the So-mode waves cannot be detected for plates with two or more step welds.

5. Conclusions

With the aim of monitoring the wall reduction of storage tank in service, an estimation method of defect depth and location was attempted utilizing the So-mode Lamb wave. Performance of the developed method was studied for artificial and corrosion-induced damages in single plate and step-weld plates. Results are summarized below.

1) A rectangular transducer (transmitter and receiver) with center frequency of 100 kHz was developed and mounted on the edge plane of the plate for exciting and receiving the zero-th order symmetrical mode Lamb waves (So-mode). The transducer show strong directivity and its full width at half maximum was ±20 degree. Attenuation of the So-mode wave via the plate with thick grease was measured as 3.7 dB/m and three times small that of the Ao-mode wave.

2) We detected the So-mode waves reflected by elliptical dish-shaped defect with depth of 0.6 mm in a 8 mm steel plate. Amplitudes of the reflected So-mode from the defects were found to increase linearly with the depth below 15.6% to the plate thickness. The system could detect corrosion-induced wall reduction of 1.25 mm in a 8 mm thick plate.

3) Experiments for step-weld plates demonstrated that the system could detect the So-mode Lamb waves reflected by the artificial defect with depth of 1 mm. Due to the wave attenuation by step-welds, detection of So-mode wave from the defects appear to be difficult for two or more step-welds plates.

REFERENCES

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