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3D Analysis of interaction of Lamb waves with defects in loaded steel plates

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Abstract

The objective of the research presented here is the investigation of the interaction of guided waves with welds, defects and other non-uniformities in steel plates loaded by liquid. The investigation has been performed using numerical simulation for 2D and 3D cases by the finite differences method, finite element method and measurement of 3D distributions of acoustic fields. Propagation of the S_0 mode in a steel plate and its interaction with non-uniformities was investigated. It was shown that using the measured leaky wave signals in the water loading of the steel plate and by application of signal processing, the 3D ultrasonic field structure inside and outside of the plate can be reconstructed. The presence of leaky wave signals over the defect caused by the mode conversion of Lamb waves has been proved using the numerical modelling and experimental investigations. The developed signal and data processing enables to visualise dynamics of ultrasonic fields over the plate, and also to estimate spatial positions of defects inside the steel plates.

Keywords: Ultrasonic guided waves; Numerical simulation; Ultrasonic NDT

1. Introduction

In the petrochemical industry, corrosion of fuel tank floor plates is an object of ultrasonic non-destructive testing (NDT). The problems of long range inspection of such structures are due to large diameter of the tanks (up to 100 m) and intention to test the steel floor without emptying the tank. The bottom of the tanks is made of 6–8 mm thick steel plates, which are interconnected by welded lap joints. The floor of a filled ground storage tank is impossible to inspect without emptying using conventional methods, therefore one possibility is to use ultrasonic guided waves. Attenuation of the Lamb waves propagating in the floor is caused by a few reasons: leakage of the Lamb wave to the liquid, losses in the welded lap joints and etc [1–4]. For analysis, the low frequency S_0 mode was selected due to lower leakage losses and a longer distance which the wave may propagate in the floor of a fuel tank [1,5].

The main objective of the presented research is to investigate interaction of guided wave with non-uniformities in a steel plate and to reconstruct the structure of ultrasonic fields scattered by these non-uniformities.

2. Investigation of propagation of S_0 mode Lamb waves through a lap joint

Investigation of the Lamb waves propagation across adhesively bonded lap joints and weld seams of the pipes is presented in [4,5]. Interaction of individual Lamb wave modes with discontinuity in a plate was analyzed by calculating the reflection and transmission coefficients for varying incident Lamb wave modes, frequency and discontinuity shape. It was found that reflection and transmission coefficients are frequency dependent [6]. To analyze propagation of guided ultrasonic waves through welded floor plates a numerical model for 2D case was developed using the Wave2000 software [7,8]. The parameters used in the model are presented in Table 1 and are the following [2]: ρ is the density, c_L is the longitudinal wave velocity, c_T is the shear wave velocity, λ and μ are the first and the second

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Table 1
Acoustical properties of the materials used in the models

Material	ρ (kg/m^3)	c_L (m/s)	c_T (m/s)	λ (MPa)	μ (MPa)	γ	E (MPa)
Diesel	800	1250	–	1250	0	0.50	0
Steel	7800	5900	3190	112,771	79,373	0.29	205,332
Moist sand	1980	1656	–	5430.58	0	0.5	0

Lame constants, γ is the Poisson ratio, E is the Young modulus. To clear up the dependence between the overlap zone width and attenuation of the signal, simulations of the welded 8 mm steel plates loaded by diesel from the top side and by moist sand from the bottom side were performed (Fig. 1). In the steel plate virtual receivers (Rc1 – before weld, Rc2 – behind weld) are inserted which do not interact with the propagating wave, but are only used to pick up the ultrasonic signal. The S_0 mode Lamb wave was excited from the left end of the top plate by an ultrasonic transducer mounted on the plate edge (Fig. 1). The steel plates are welded to each other with an overlap zone, the width of which for the presented case was 80 mm. There was no acoustical contact between the plates in the overlap zone except for the weld seam. Attenuation of the guided wave can be calculated from the spectra ratio of the signals picked by the receivers Rc1 and Rc2. In order to obtain a reliable estimation of the attenuation in a wide frequency range, a set of simulations was performed at different frequencies in the frequency range from 20 kHz to 100 kHz with the 10 kHz step.

Due to large required computational resources it is impossible to simulate propagation of ultrasonic waves through the whole bottom of the petroleum tank. Therefore the computational task was decomposed into separate subtasks, like analysis of the signal propagation through the loaded steel plate without welds and the signal propagation through a weld seam of two welded plates. In the case of a tank filled with diesel and resting on moist sand, the attenuation due to wave leakage at the 50 kHz is less than 1 dB/m (Fig. 2, dashed line). Such attenuation corresponds to "slip" boundary conditions between these materials [2].

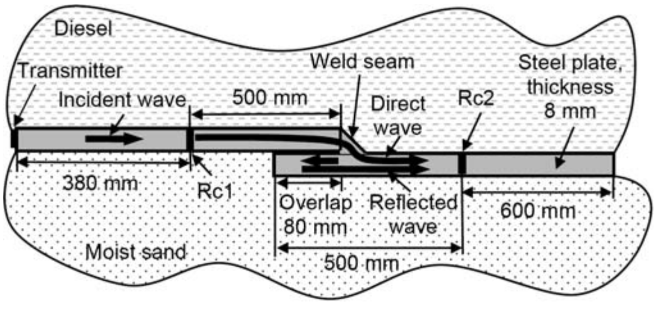

Fig. 1. Model of overlapping welded plates.

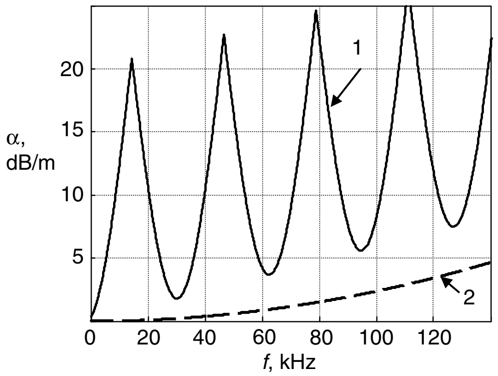

Fig. 2. Attenuation of ultrasonic waves in the welded lap joint: (1) attenuation coefficient of the single weld obtained by numerical simulations using the finite difference model, (2) attenuation coefficient only due to leakage to moist sand and diesel (calculated by the global matrix method).

The attenuation of the ultrasonic wave transmitted through the welded lap joint is given by

$$\alpha(\omega) = -20 \cdot \lg\left(\frac{U_1(\omega)}{U_0(\omega)}\right), \tag{1}$$

where $U_0(\omega)$ is the amplitude spectra of the reference signal (picked up by the virtual receiver Rc1) and $U_1(\omega)$ is the spectra of the signal transmitted through the weld (picked up by the virtual receiver Rc2). From the set of the modelling results obtained at different excitation frequencies the calculated attenuation function is presented in Fig. 2 by the solid line. For comparison, the attenuation coefficient due to leakage of the S_0 mode wave to moist sand and diesel calculated by the global matrix method is also presented (Fig. 2, dashed line). From the results presented it is possible to see that the overlapping zone influences attenuation of the signal, which deviates from 5 up to 25 dB/weld. It was determined that the attenuation in the lap joints is additive in the direction perpendicular to the weld seams [2]. The oscillations of the attenuation coefficient which are presented in Fig. 2 may be explained by interference of two signals: the signal transmitted through the weld and the signal reflected from the left end of the bottom plate.

3. Interaction of the S_0 mode Lamb waves with artificial defect

The aim of the presented modeling is to investigate the properties of S_0 mode Lamb waves interaction with a circular defect having limited lateral dimensions and to estimate spatial position of the leakage into the surrounding media using 3D approach. The only means to obtain solutions close to the physical situation is a finite element simulation by using 3D solid or coupled solid-acoustic models [6]. The 3D finite element computational model composed of linear elastic elements has been built by using ANSYS and LSDYNA finite element codes. ANSYS has been used to generate the geometry and to perform the meshing of the fully parametric model. Further the problem is solved in LSDYNA environment. The model of the unconstrained floor plate (250 × 500 × 6 mm) with an artificial circular

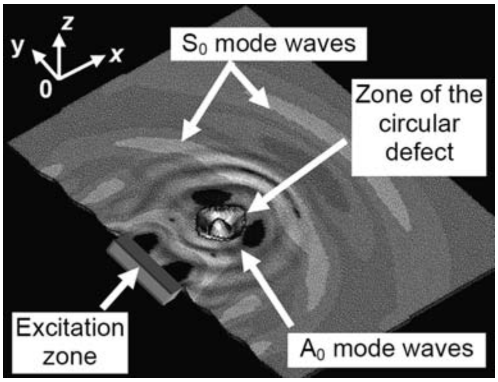

Fig. 3. Interaction of the S_0 mode Lamb wave with the circular defect, whose diameter is 50 mm and depth 0.5 wall thickness.

defect has been investigated. The diameter of the defect was 50 mm. In the defect region, the plate thickness was 0.5 of the nominal one. The bottom plate was assumed to be a homogeneous elastic steel structure. The acoustical properties of the materials were used from Table 1. During analysis it was assumed that the Lamb waves were excited by a thickness mode of 50 kHz transducer, lateral dimension of which was 50 mm.

The results of the simulation are presented in Fig. 3. It is possible to see the transformation of the S_0 mode into A_0 mode, which propagates almost uniformly in all directions. The vertical particle displacement and particle velocity vector in the defect region have a much higher amplitude, so it can be assumed that the defect acts as some kind of a virtual transmitter of the A_0 mode wave. The wavelength of S_0 mode is almost twice the diameter of the defect, therefore part of the S_0 mode is diffracted around the defect (Fig. 3). If the plate was covered by some liquid medium, this defect would radiate acoustic waves into the liquid.

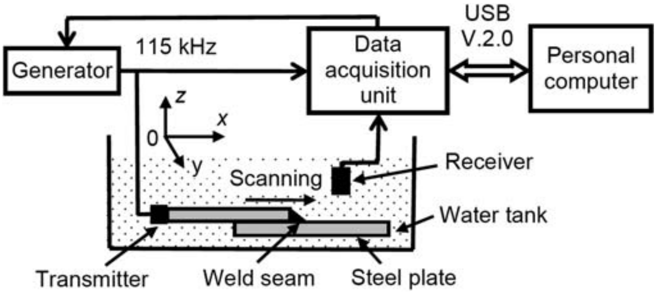

Fig. 4. Measurement set-up used for investigation of the waves leakage to the loading liquid. The zero point of the coordinates ($x = 0$ mm, $y = 0$ mm) correspond to the place on the plate edge where the transmitter is mounted, $z = 0$ mm correspond to the surface of the plate.

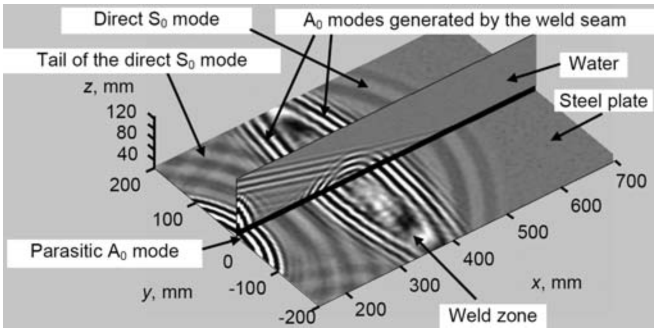

Fig. 5. The ultrasonic field measured over the weld in two perpendicular planes. The receiving transducer was placed at the distance over the plate $z = 25$ mm and oriented at a 90° angle with respect to the horizontal plane. Scanning along x–y directions was performed in the range $x = (150{:}5{:}700)$ mm, $y = (-200{:}5{:}200)$ mm. Scanning along x–z directions was performed in the range $x = (150{:}5{:}700)$ mm, $z = (25{:}1{:}125)$ mm.

4. Experimental verification of modelling results

The objective of the presented part was experimental verification of the modelling results, obtained by the finite element model. Since the dimensions of real size plates were too large to perform investigations in a laboratory, a scaled down size structure 625 × 1100 × 3 mm of the two welded steel plates with an overlap zone width of 30 mm was selected. For estimation of the wave leakage the immersion experimental set-up was used (Fig. 4). The transmitting thickness mode ultrasonic transducer was mounted on the edge of the plate and the receiving transducer was scanned over the plates interconnected by weld seams. Data acquisition was performed by the measurement system developed in the Ultrasound Institute. The excitation pulse frequency was 115 kHz, the number of the rectangular burst cycles was three. The transducer attached to the edge of the plate effectively excited the S_0 mode, but due to non-ideal parallelism between the transmitter and the edge of the plate, the parasitic A_0 mode also was excited. The use of the transmitter in a resonance mode resulted in the tail of the S_0 mode. The excitation voltage of the transmitter was 20 V and the gain of the receiver was 20 dB. Projections of the ultrasonic field, which were measured along the x–y and along x–z directions at the particular time instant $t_1 = 132\ \mu s$ are presented in Fig. 5. The results indicate that at the weld seams mode transformation of the S_0 mode to the A_0 mode occurs. The A_0 mode waves propagate in forward and backward directions and radiate leaky waves into water.

Scanning of the drilled circular defect at the bottom of the plate was performed in the x–y directions. The projection of the ultrasonic field which was measured at the particular time instant $t_2 = 106\ \mu s$ is presented in Fig. 6. It corresponds to the simulation results obtained using the finite element model.

Note that in Figs. 5 and 6 the parasitic A_0 mode and the tail of the main S_0 mode due to non-ideal excitation of the plate are clearly seen.

5. Conclusions

It was estimated that the frequency dependent attenuation of the signal transmitted through a welded lap joint

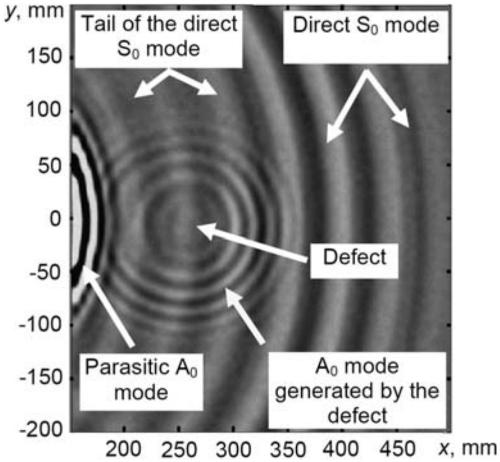

Fig. 6. The ultrasonic field measured over the circular defect at the bottom of the plate: diameter 12 mm, depth 0.5 wall thickness. The receiving transducer was placed at the distance over the plate $z = 35$ mm and oriented at a 90° angle with respect to the horizontal plane. Scanning of the ultrasonic transducer over the plate along x–y directions was performed in the range $x = (150{:}5{:}500)$ mm, $y = (-200{:}5{:}200)$ mm.

is a function of the plates overlap width. In each weld due to the mode conversion, the two A_0 mode waves are generated, which propagate in opposite directions from the weld. A similar phenomenon was found when the guided wave interacts with a defect, which acts as the virtual source, therefore a part of the acoustic energy is radiated into the loading liquid. It was verified by experiments and numerical simulation. Using a set of ultrasonic receivers this energy can be picked up and it is possible to locate the coordinates of the defect in a tank floor.

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