Long-range Ultrasonic Non-destructive Testing of Fuel Tanks

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Abstract.
The inspection of a storage tank floor is a time consuming and expensive procedure, mainly due to necessity to empty and to clean the tank before an inspection. For this purpose a long range ultrasonic technique based on Lamb waves may be applied. Such an approach is used for inspection of pipes and can cover the distances up 100m. However the storage tanks are much more complicated structures from the point of view of ultrasonic inspection due to presence of multiple lap joint welds.

In order to propose an efficient testing technique regularities of Lamb wave propagation in tank floor plates and welds loaded by sand from a bottom side and by fuel (diesel) on the top side have been investigated. It was found that each of non-uniformities in the floor, such as welds and defects act as sources of leaky waves, propagating in the liquid loading the tank floor. For a tank floor inspection two different ultrasonic techniques were proposed. The first one is based on the through transmission tomography of Lamb waves propagating in a tank floor. The second one is based on a spatial analysis of the leaky waves picked up in the liquid, loading the tank floor. Performance of the proposed techniques was tested on a scaled model of a tank and *in situ* experiments.

Introduction

In petrochemical industry corrosion of fuel tank floor plates is an object of ultrasonic non-destructive testing (NDT). The inspection of storage tanks is a time consuming and expensive procedure, mainly due to necessity to empty and clean the tank before the inspection using conventional NDT methods. Therefore, the objective of this study was to develop an ultrasonic technique, suitable for tanks inspection without emptying and cleaning the tank. The most promising technique which enables inspection at a relatively long range and can be used for inspection of a tank floor from an outside perimeter is based on ultrasonic guided waves. The guided waves can propagate long distances in planar and tubular structures and already are used for inspection of pipes [1, 2]. The main differences of the tank floor inspection case is the complexity of the object containing multiple lap joint welds along the large diameter of the tank (up to 100 m) and necessity to reconstruct 2D distribution of defects from the information obtained at the edges of a tank floor or external vertical walls. To reach this goal it is necessary to solve at least two tasks. The first one is application of the ultrasonic transmission tomography for localization of non-uniformities inside tank floor, taking into account ultrasonic signal losses due loading of a tank floor by the liquid in a tank and a basement (sand) on which the floor is laid down. The second task is to develop a reconstruction technique enabling to obtain spatial location of non-uniformities in a tank floor from the leaky waves picked up in the liquid, loading the tank floor.

1. Selection of the Lamb wave mode suitable for tank floor inspection

The tank floor consists of the set of steel plates having thickness 6-8 mm joined together using lap welds and may have the diameter up to 100 m (Fig. 1(a, b)). The guided waves propagate in planar structures such as plates or sheets and may possess unlimited number of modes. Mainly the symmetric S_0 or asymmetric A_0 modes are used for inspection. The transmission, reflection and mode conversion of these waves takes place on each non-uniformity of the floor, including welds and defects. Each of these phenomena causes energy losses of propagating waves. On the other hand that enables to detect defects using reflection or transmission technique [1, 3].

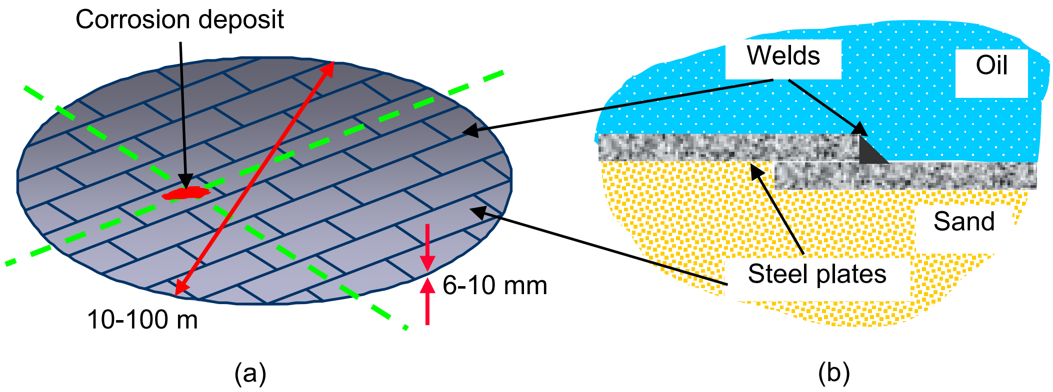

Fig. 1. The typical geometry of a tank floor (a) and the model of a lap joint weld (b)

In order to develop an efficient testing technique regularities of Lamb wave propagation through tank floor plates and welds loaded by the sand from a bottom side and by the fuel (diesel) on the top side have been investigated. The theoretical investigation was carried out to estimate the losses of the Lamb waves propagating in a tank floor using the global matrix and the finite difference methods. The obtained regularities have been verified experimentally. It was found that the losses of the S_0 mode guided wave in the tank floor loaded by diesel from one side and wet sand from another side at the 50 kHz are 0.5 dB/m approximately. Such attenuation corresponds to “slip” boundary conditions between these materials [4]. In the case of a medium size tank with the diameter 30 m this leads to 15 dB attenuation. The losses of the A_0 mode wave are more than 1 dB/m under the same conditions, so, taking into account possible diameters of the tank this mode is less attractive for a long range inspection. It was determined also that the most critical parameters determining losses of the S_0 mode are the boundary conditions between the steel plate and a supporting medium, for example, wet sand. The simulation and experiments have shown that the contact between the mentioned media is a slip, that is, the shear component of the waves is not transmitted into another medium. In the case of a “solid” contact, like gluing, the losses of the S_0 mode can increase up to 10dB/m.

Numerical simulation and experimental investigations also have shown that the transmission losses of the S_0 mode wave are 8 dB per weld and are additive in the direction perpendicular to the weld seams [4]. The mentioned effect can by 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. There can be tens of welds across diameter of the tank floor, so the total losses can exceed 100 dB.

2. Reconstruction of the distribution of non-uniformities on the tank floor using transmission tomography

For reconstruction of the distribution of non-uniformities on the tank floor from the measurements performed only outside perimeter of the tank, the through transmission tomography of Lamb waves propagating in a tank floor was proposed. The basic principle of it are the multiple measurements across the object at different angles using fan type or linear beams in such a way obtaining multiple so called projections. In the second step the back-projection according special algorithms is performed, after which the spatial distribution of the investigated parameter in a tank floor is obtained. There are many versions of the ultrasonic tomography, but the transmission tomography was selected as the most promising one [2, 5]. In this case the physical parameter, the spatial distribution of which should be reconstructed, is attenuation of the S_0 mode Lamb wave. In order to estimate the performance of the reconstruction algorithm, the tank floor with the diameter 10 m and the weld geometry as shown in Fig. 2 was simulated. The tomographic projections were obtained calculating the total attenuation along different chords of the tank floor. It was assumed that there is the 0.5 dB/m attenuation caused by leakage and 8 dB losses in each weld. The total losses across the tank vary in the range 75-100 dB depending on a chord angle. The artificial circular defect with the diameter 10 mm was inserted close to the tank floor centre. It was assumed that it causes the 4dB losses of the Lamb waves. The reconstructed image of the tank floor with the circular defect is presented in Fig. 2.

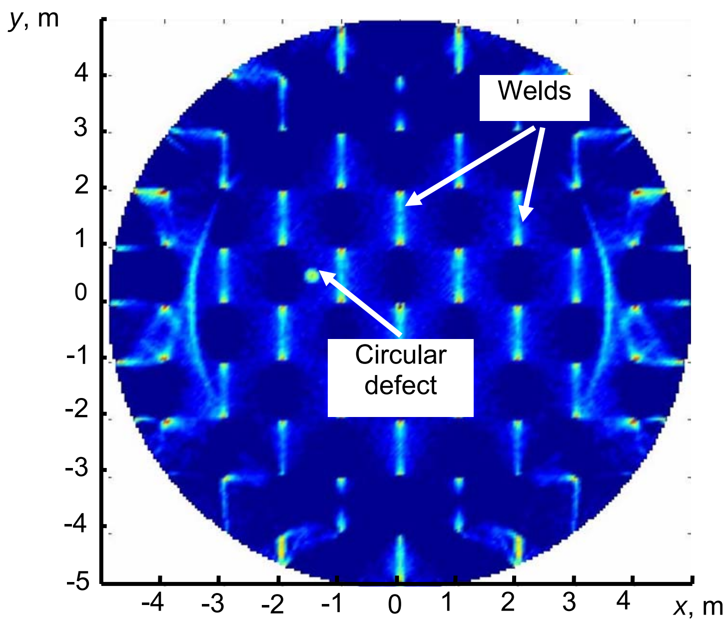

Fig. 2. Reconstructed ultrasonic image of the petroleum tank floor with a circular defect (from simulated data) using the through transmission tomography technique

3. Spatial localization of defects on the tank floor from the analysis of the leaky waves

The second ultrasonic technique suitable for localization of defects on the tank floor is based on a spatial analysis of the leaky waves picked up in the liquid, loading the tank floor. For experimental investigation the scaled down size tank mock-up (scaling factor 8:1) placed on wet sand and filled with water was selected (Fig.3a). The internal diameter of the tank was 1 m, the height 1.1 m, the thickness of the floor plate was 1 mm. The experimental set-up used in the investigation is presented in Fig. 3b.

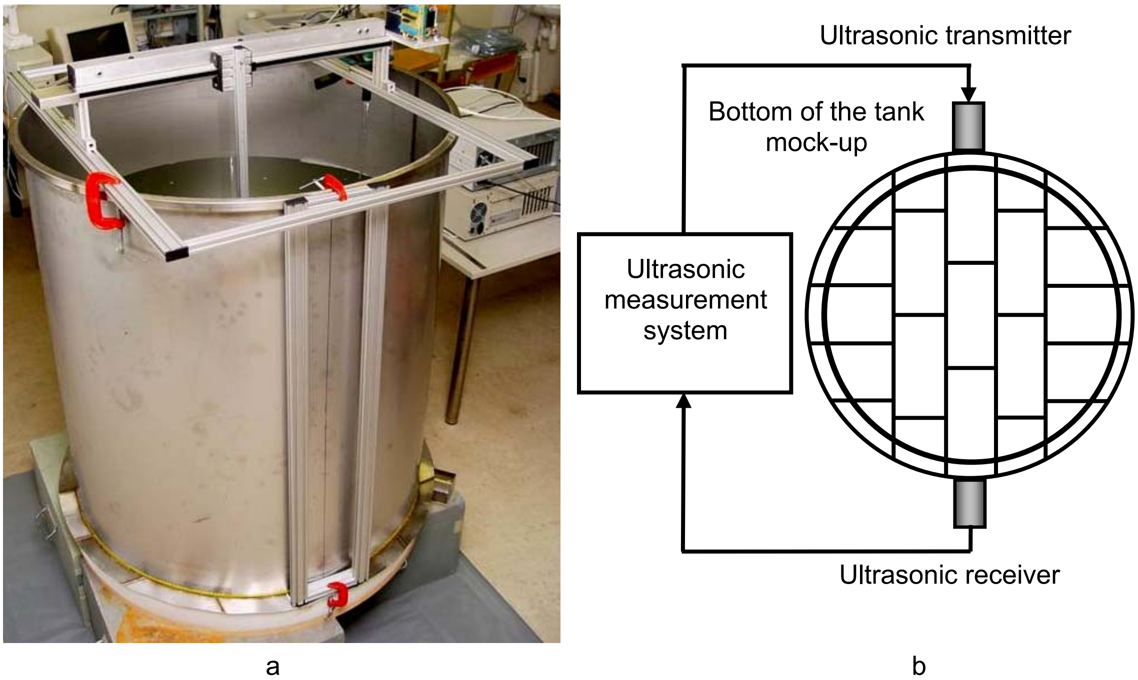

Fig. 3. Photo of the 1:8 scaled down size tank mock-up (a) and the measurement set-up (b) used for investigation

The transmitting ultrasonic transducer was mounted on the edge of the plate. Data acquisition was performed by the measurement system developed in the Ultrasound Institute of Kaunas University of Technology. The excitation pulse frequency was 400 kHz, the number of the rectangular burst cycles was 3. 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 excitation voltage of the transmitter was 200 V and the gain of the receiver was 50 dB.

The receiving transducer was mounted on the edge of the tank floor (flange). The signals propagating through the tank floor were recorded. The S_0 and A_0 Lamb wave modes can be recognized in the signal using the known propagation velocity (Fig. 4). The multiple mode conversion signals can be observed also. The mode conversion (A_0 mode to S_0 and opposite) take place at each weld of the bottom plate and on the weld between the floor and wall plates.

The leakage losses of the S_0 mode in the floor of the scaled down size tank mock-up (diameter 1m), which was resting on moist sand and loaded by water from the top side are the following:

- Measured: (5.5 ± 0.6) dB (at 400 kHz).
- Calculated using the global matrix method [4]: 4.7 dB (at 50 kHz).
- Calculated using the finite difference method [4]: 6.1 dB (at 50 kHz).

The measured transmission losses of the S_0 mode in a single weld are (7.4±0.7)dB. That corresponds very well to the results (7.8 dB) obtained by modeling using the finite difference method [4].

In order to analyze leaky waves, which were radiated into liquid by non-uniformities inside the tank floor, the immersion type receiving transducer was scanned over the specially prepared segment of the tank floor plates, joined by weld seams. The mentioned segment was also affected by a natural corrosion. The projection of the leaky ultrasonic field which was measured over the segment of tank floor with the single weld at the time instant *t* = 85 μs after the excitation of the transmitting transducer is presented in Fig. 5. It is possible to observe the transformations of the S_0 mode into A_0 mode, propagating almost uniformly in all directions. Therefore, it can be assumed that the non-uniformity inside tank floor acts as some kind of a virtual transmitter of the A_0 mode wave. Due to this, it was shown that the two A_0 mode waves, propagating in opposite directions are generated by the mode conversion phenomenon at each weld (Fig. 5). It can be seen that the weld is a source of the leaky waves into the liquid, contacting with a steel plate.

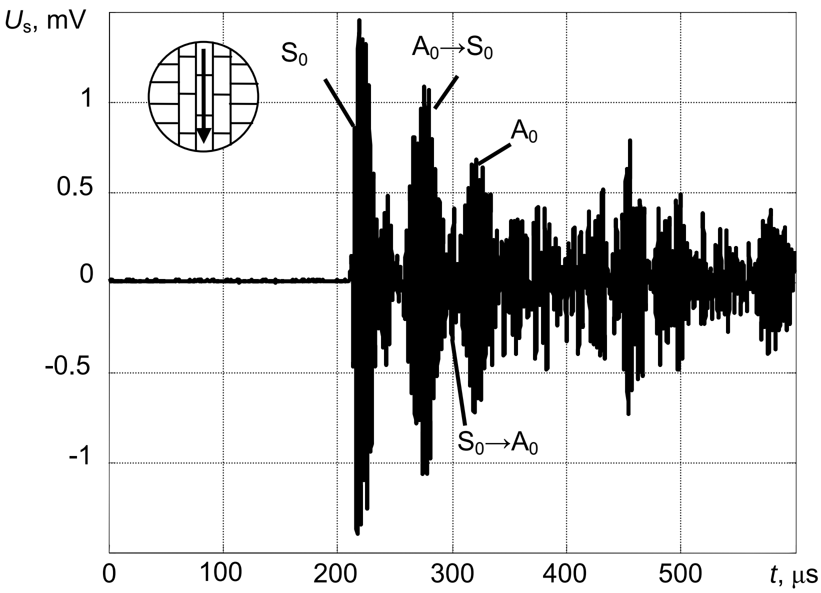

Fig. 4. Signal transmitted through the loaded floor of the tank mock-up, when transmitting and receiving transducers were mounted on the edges of the tank floor (flanges)

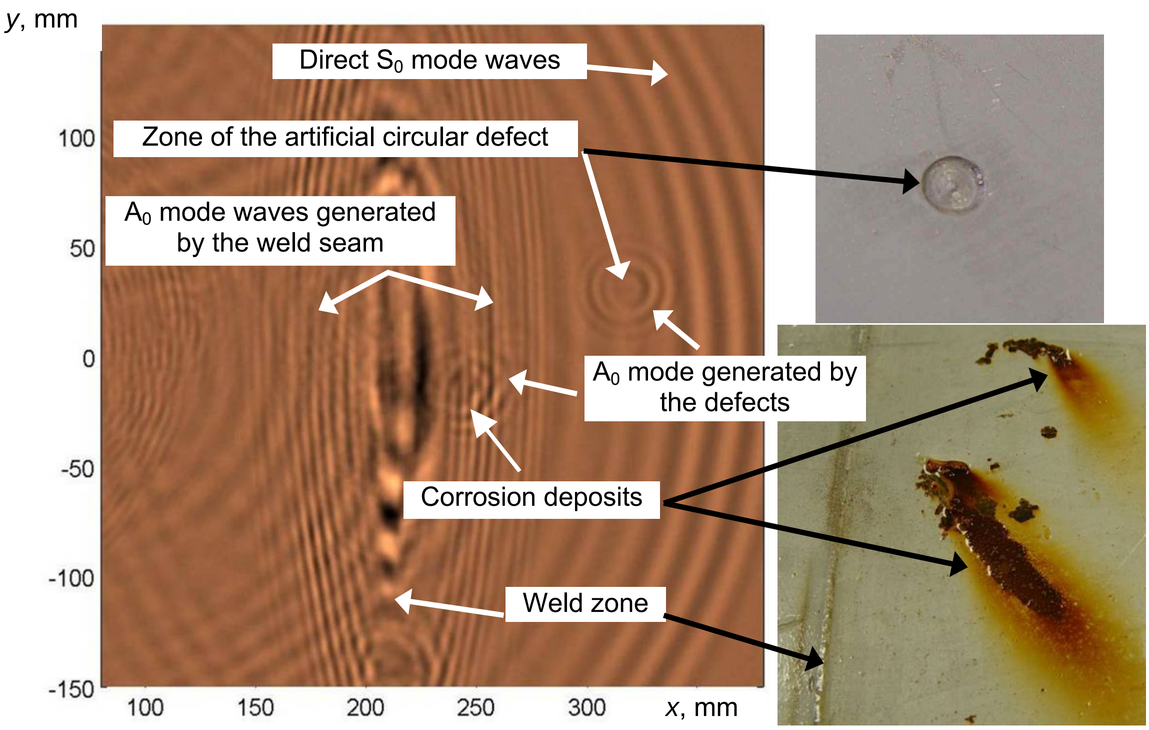

Fig. 5. The horizontal cross-section (at time instance t = 85 µs) of the measured leaky ultrasonic field over the weld and the defects at the segment of the tank bottom plate, one of them was artificially drilled (diameter 5mm, depth 0.5 wall thickness) and another was caused by natural corrosion. The receiving transducer was placed at the distance over the plate z = 15 mm and oriented at the 90° angle with respect to the horizontal plane.

Investigation of the welded plate has shown that the artificial defect of 5 mm diameter generates a spherical leaky wave, which can be observed clearly in Fig. 5 as circular waves in the image. The shorter length of these waves (comparing to the direct S_0 wave) demonstrates, that mainly the asymmetric mode A_0 of Lamb waves is generated due to mode conversion on the defect. The similar spherical wave generated by the presence of the natural corrosion deposits on plate can be observed also.

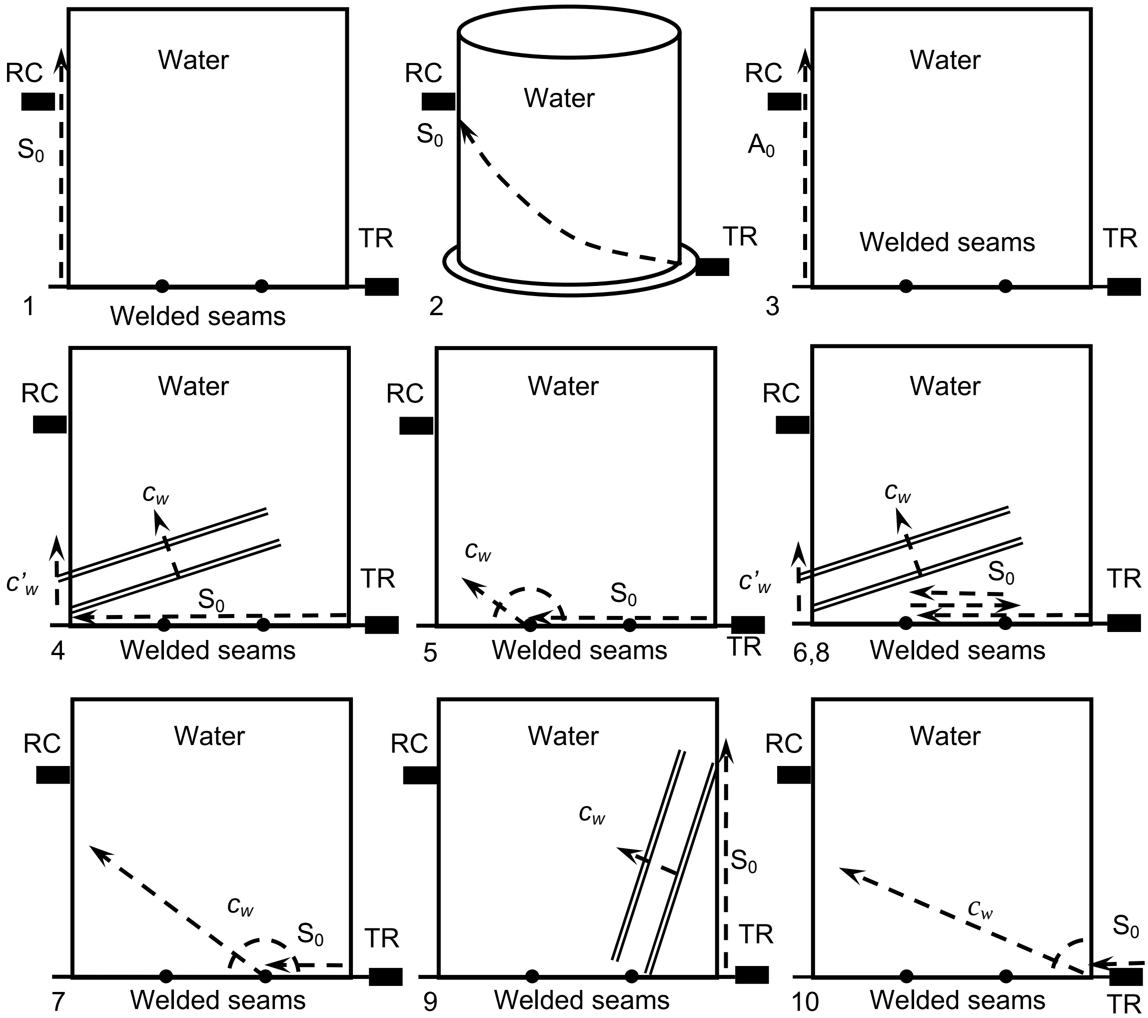

Fig 6. The explanation of different acoustic paths of the Lamb waves radiated into the liquid and picked-up on the vertical wall of the tank, TR denotes the transmitter and RC denotes the receiver, which was scanned vertically on the tank wall

For more detailed analysis measurements of the ultrasonic waves propagating in the tank mock-up were performed. For this purpose the S_0 type Lamb wave was excited in a tank floor. The ultrasonic signals were picked-up on the vertical wall of the tank by a mechanically scanned contact type transducer with liquid coupling (Fig. 3). The explanation of possible wave propagation paths is presented in Fig. 6. The experimental B-scan image with the calculated curves of different types of waves is shown in Fig. 7. The interpretation of the obtained image is the following:

- The S_0 mode propagates in the tank floor and then in the vertical tank wall. The estimated propagation velocity from the B-scan data is 5300 m/s (Fig. 6, case 1).
- The S_0 mode propagates around the tank wall directly to the measurement point, where the receiving transducer is placed (Fig. 6, case 2).

- The S_0 mode, propagating in the tank floor at the junction of the bottom plate with the vertical wall, converts into another mode, which propagates in this wall. The estimated velocity of this converted mode is 1850 m/s. Probably, it is not A_0 mode, because the velocity is relatively low and it is not essentially attenuated when it propagates inside the tank wall loaded by liquid (Fig. 6, case 3).
- The S_0 mode propagating in the tank floor creates the leaky wave in water. The wave front of these waves creates a pattern on the vertical tank wall. The calculated wave front pattern velocity on the vertical wall is 1553 m/s (Fig. 6, case 4).
- The mode conversion of the S_0 mode on the weld seam causes generation of the leaky wave into the loading liquid. Using propagation time of this wave is possible to estimate the position of the seam. The estimated position of the weld seam is at the distance 320 mm away from the vertical tank wall on which the receiving transducer was mounted (Fig. 6, case 5).
- The additional leaky waves are radiated by the S_0 mode once reflected between neighbouring welds (Fig. 6, case 6).
- This is similar case as the case 5, only signals correspond to the mode conversion waves on the other weld. The estimated distance to the weld is 640 mm away from the tank wall on which the receiving transducer is mounted (Fig. 6, case 7).
- The additional leaky wave is caused by the S_0 mode, which has been twice reflected between neighbouring welds (Fig. 6, case 8).
- The leaky wave in the liquid is caused also by the S_0 mode propagating in the vertical tank wall on which the transmitting transducer was mounted (Fig. 6, case 9).
- This is also similar case as the cases 5 and 7. The estimated distance to the weld is 1000 mm away from the vertical tank wall on which the receiving transducer was placed. In this case the source of the leaky wave is the T-joint weld between the tank floor and the vertical wall (Fig. 6, case 10).

Conclusions

In order to develop efficient NDT technique regularities of Lamb wave propagation through tank floor plates and welds loaded by the sand from a bottom side and by the liquid (diesel) on the top side have been investigated. The most significant signal losses occur due the loading and welds. Also it was found that all non-uniformities in the plate, such as welds and defects act as sources of leaky waves, propagating in the liquid loading the tank floor. It was shown that using the measured leaky wave signals in the water loading the steel plate and application of signal processing the 2D ultrasonic field structure inside and outside the plate can be reconstructed.

For spatial localization of the defects in a tank floor two different ultrasonic techniques were proposed. The first one is based on the through transmission tomography of Lamb waves propagating in a tank floor. The second one is based on a spatial analysis of the leaky waves picked up in the liquid, loading the tank floor. Performance of the proposed techniques was experimentally investigated on a scaled down size model of a tank.

The investigation carried out demonstrates that it is possible to detect the non-uniformities of the tank floor by ultrasonic technique having access only from the outside perimeter of the tank.

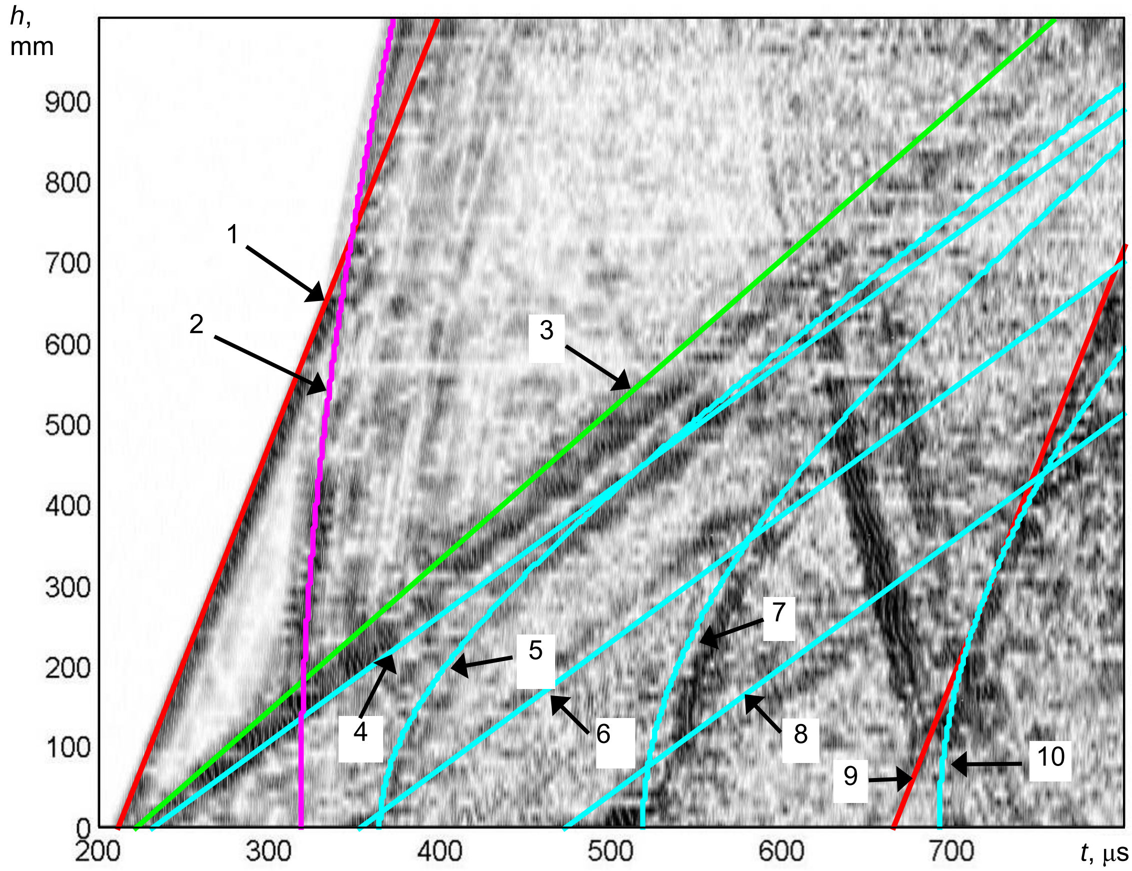

Fig 7. Identification of the experimentally measured waves, which were picked-up on the vertical wall of the tank. The numbers 1 - 10 correspond to the numbers in Fig.7.

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