Assessment of Long-Range Guided-Wave Active Testing of Storage Tanks

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Abstract. Guided Wave Testing (GWT) is now increasingly being used for the non-destructive testing of large structures. Petrochemical tank bottoms are particularly subject to corrosion. Today, the monitoring of corrosion in storage tanks is probably one of the most challenging applications of GWT because of the size and the complexity of such medium. This article deals with the main physical issues of this application, in particular, the prediction of the elastic field propagating in the tank wall and bottom, and the prediction of guided wave scattering by joints. Drawing on current research work, a representative numerical configuration is defined. The global diffusive effect and the local diffraction effect of the lap joints are studied. The methodology have led us to focus on the low ultrasound frequency range: from 10 to 50 kHz. A quantitative evaluation of the scattering by lap joint is carried out by means of simulations and experiments on elementary reduced scale joints. Dynamic range computations make it possible to get prior knowledge about the minimum signal-to-noise ratio (SNR) required to get information about the tank bottom, for a given configuration, leading to a SNR–resolution trade-off. The method can be extended to larger tanks. The results confirm that the use of GWT technology for long-range active testing and imaging of storage tanks is promising.

1. Introduction

1.1. Context and Purpose

Guided Wave Testing (GWT) is now increasingly being used for the non-destructive testing of large structures, such as storage tanks and pipelines. Petrochemical storage tank bottoms are particularly subject to corrosion. Liquid loading, chemical reactions, the presence of welded joints and strong ambient conditions increase the risk of defect occurrence. The design of large storage tanks imposes a minimum acceptable thickness that needs to be inspected. Today, storage tank corrosion monitoring is probably one of the most challenging applications of GWT because of the size and the complexity of such structures. Tank bottoms are most often inspected by using conventional NDT techniques after emptying the tank. The use of GWT technology seems to be promising for performing inspection without emptying and cleaning the tank. More specifically, it could make long-range active testing and imaging possible. This could be a significant advantage over existing methods, such as Acoustical Emission, conventional Ultrasound Testing, often considered superficial or imprecise, or over invasive solutions. The main physical issues identified for the GWT of storage tanks are: (i) the attenuation caused by large propagation distances, (ii) the attenuation caused by fluid loading, (iii) the scattering by
joints, (iv) the complexity of signals due to the multimodal nature of elastic guided waves. Other constraints specific to particular ambient conditions may be added to this list. Fortunately, the recent technological advances, in terms of instrumentation and digital processing, are encouraging for this purpose, as shown in the following paragraph.

1.2. Background
Research has been carried out for the evaluation of the long-range guided-wave imaging of tank bottoms. Mažeika et al. proposed attempts at using fan-beam tomography on a tank bottom 8 m in diameter [1, 2, 3]. The basic idea consists in exciting the tank from the tank wall or from the annular chime using piezoelectric transducers to generate a wavefront in the tank bottom. The commonly used frequency range is 20 to 100 kHz. More advanced research, led by TWI (The Welding Institute), has been carried out [4]. Propagation simulations through lap welds showed that it is possible to propagate the $S_0$ and $SH_0$ modes over distances up to 100 m [5]. A feasibility study of the method for tanks without geometric discontinuities such as lap joints has been carried out [6]. In a recent article, Lowe et al. have assessed the possibility of exciting the tank from the wall to generate $S_0$ propagation in the bottom [7]. Indeed, the majority of storage tanks in use have no annular chime, or when it is the case, the chime is often strongly corroded, and the surface is too rough for contact transducers to be used. Tanks with a diameter greater than 12.5 m must have an annular chime [8]. This outer ring, on which the bottom is fixed, can be partitioned into several edge welded sectors called annular plates. The cited authors highlighted the influence of the excitation technique on the dynamic range and signal-to-noise ratio (SNR). More generally, understanding acoustical phenomena in such complex media is challenging. Although the cited studies have presented serious investigation in this domain, improvement of the comprehension of the acoustical phenomena is needed.

1.3. Content
The work reported in this article has been particularly influenced by Lowe et al. contribution. A priori methodology related to the issues raised by the authors is still lacking. This work is based on an improved methodology aiming at giving more precise prior information about the physical phenomena related to GWT of storage tanks. This information is crucial in selecting frequency, assessing detection performance, and assessing the potential for imaging. An elementary tank numerical configuration has been defined. The same simplified tank geometry as the one defined by Lowe et al. has been chosen. First, the description of the configuration is given. Considerations about technical aspects of the numerical model are given. Then, the joint modelling, divided into a local approach and a global approach, is presented. Experimental results of guided wave transmission through lap joint are presented. The considerations about scattering by joints have led us to focus on the 10 to 50 kHz frequency range. Numerical results obtained for this frequency range are presented, analysed and discussed.

2. Methods
2.1. Configuration
Different tank designs exist depending mainly on the tank size and the fluid load. The elementary tank numerical configuration defined by Lowe et al. is a relevant representative model. A common lap joint assembly configuration has been added to this model. The geometry is given in figure [1]. Construction designs follow European design and construction standards such as EN 14015 [9]. According to this standard, the bottom thickness of most large storage tanks is 8 to 10 mm. The wall thickness is usually greater than the bottom thickness, and depends on the liquid load. To simplify the model, the thickness $h$ of the all the plates constituting the tank is set to 8 mm. The tank is assumed to be made of construction steel whose properties are given in table A1. As studied by Lowe et al., the excitation of the structure can be performed on the
tank wall or on the annular chime, see figure 1. As previously noted in the background section, these two possibilities are a trade-off between the correct $S_0$ mode polarisation excitation in the bottom and the possibility of sending more energy in the bottom by means of more accessible surface.

![Figure 1: Studied tank reference geometry.](image)

2.2. Finite Element Model
A finite element method (FEM) was implemented in order to deal with the elastodynamic behaviour of the structure. The FEM is known to be a relevant method for dealing with the prediction of complex propagation and/or scattering transient phenomena. More specifically, it makes it possible to predict the long-range propagation and the scattering of guided waves, as well as elastic waves in volumes, by considering their multimodal and vectorial nature, (see e.g. [10]). The main practical limitation of the FEM is the computational cost for a large characteristic wavenumber $ka$, where $a$ stands for the propagation length and $k$ the largest wavenumber at a given frequency, for which the dimension of the problem may be beyond the computational resources. Consequently, the discretisation of the geometry was selected according to this constraint, added to the common sampling constraint that depends on the wavelength. The mean element size was set to 6 mm. In order to reduce the dimension, and to tackle the lap joint geometry complexity, we decided to select a 2D model. Thus, it was no longer relevant to model geometrically the thickness of the plates using 3D elements, which Lowe et al. did. Two-dimensional plate-membrane quadrangle linear elements were used. The formulation is based on the first order shear approximation. Considering a finite element of a plate $P$ defined by

$$ P := [-h/2, h/2] \times \mathbb{R}^2, \tag{1} $$

where a point of the plate is defined by the following coordinates

$$ (x, y) \in \mathbb{R}^2, z \in [-h/2, h/2], \tag{2} $$

the displacement vector $\mathbf{u}$ at a point of the plate is approximated by its first order Taylor series at the mid-plane $z = 0$ in the direction normal to the plate:
\[ u(x, y, z) \approx u(x, y) + z \xi(x, y). \] (3)

The following notations are used for the components of \( u \) and \( \xi \) in the system \((x, y, z)\)
\[ u := [u, v, w]^T, \xi := [\theta, \vartheta, \phi]^T, u := [u, v]^T, \theta := [\theta, \vartheta]^T. \] (4)

The elastodynamic equilibrium equations for an isotropic material of parameters \((\rho, \lambda, \mu, \kappa)\) lead to the following expressions of potential energy \(U\) and kinetic energy \(T\) involved in the variational formulation.
\[ U = I_2 \sigma(\theta) : \epsilon(\theta) + I_0 \kappa \mu (\nabla w - \theta)^2 + I_0 \sigma(u) : \epsilon(u) + I_0 c(\epsilon(u) + \phi I) + I_2 (\nabla \phi)^2, \] (5)

where \(\sigma\) denotes the stiffness tensor, \(\epsilon\) denotes the strain tensor, and \(c\) denotes the elastic constant tensor
\[ T = I_0 \rho \dot{u}^2 + I_0 \rho \dot{w}^2 + I_2 \rho \dot{\theta}^2 + I_2 \rho \dot{\phi}^2, \] (6)
integrated in space over the finite element. This formulation involves the plate moments defined by
\[ I_n := \int_{-h/2}^{h/2} z^n \, dz. \] (7)

For an isotropic symmetric plate
\[ I_0 = h, I_1 = 0, I_2 = \frac{h^3}{12}. \] (8)

This model leads to 3 fundamental propagating modes, and 3 evanescent/propagating modes, which are approximations of Lamb modes \(S_0, SH_0, A_0, S_1, SH_1, \) and \( A_1. \) The dispersion relations for these modes, which are divided into symmetric, antisymmetric and shear horizontal modes, for \( h = 8 \) mm, are given in figure 2.

![Image of dispersion relations for symmetric, shear horizontal, and antisymmetric modes.]

(a) Symmetric modes. (b) Shear Horizontal modes. (c) Antisymmetric modes.

Figure 2: Dispersion relations for an 8 mm thick steel plate for the first order shear deformation approximation (plain curves) compared with exact Lamb wave solutions (dotted curves). The low-frequency range is highlighted in blue. The vertical dashed lines in (a) and (c) denote the propagation regime bounds.
As shown in figure 2a, there exist three propagation regimes for the $S_0$ mode, depending on group velocity, which one can call: (i) membrane, (ii) dispersive, and (iii) asymptotic. For the frequency range studied, that is $[0, 100 \text{ kHz}]$, the $S_0$ mode propagates in the membrane regime. One can verify that the Taylor series at $\omega = 0$ of the analytical dispersion relation of the associated plate-membrane mode gives

$$k^2(\omega) = \frac{\rho \omega^2}{E'} + \ldots$$

where

$$E' := \frac{E}{(1 - \nu^2)} = \frac{4\mu(\lambda + \mu)}{\lambda + 2\mu}.$$  

The membrane speed $c_M$ is thus defined by

$$c_M := \sqrt{\frac{E'}{\rho}}.$$  

In the dispersive and asymptotic regimes, which are beyond the frequency range studied, the first order shear approximation suffers the well known discrepancy compared with actual $S_0$ Lamb mode, see e.g. [11]. The $A_0$ mode is strongly dispersive in the low-frequency range. This has a significant effect on the numerical behaviour. Indeed, the flexural mode is known to be sensitive to the numerical anisotropy, see e.g. [12]. To avoid this effect, which may have consequences for the correct evaluation of the times of arrival, the correct isotropic propagation of the $A_0$ mode was checked for the selected mesh and frequency range. The $SH$ plate-membrane modes are exact representations of associated Lamb modes. The characteristic velocities derived from the chosen isotropic material parameters are given in table A1. For the selected mesh and frequency range, the attenuation of $S_0$ for the selected configuration is given in figure 3. At 20 kHz, the exponential attenuation parameter is around 0.03 dB/m, which corresponds to -0.12 dB for a 4 m propagation. Thinking in terms of order of magnitude, one can conclude that the $S_0$ mode attenuation due to fluid loading is negligible in front of the $A_0$ mode attenuation due to fluid loading.
2.4. Lap joint modelling

The whole structure of a tank consists of metallic plates assembled by the mean of lap joints and T joints. The common lap length is about five times the plate’s thickness [9]. The lap joint modelling was divided into two approaches: (i) a local approach, aiming at modelling the local scattering effect of the joint geometry, (ii) a global approach, aiming at modelling the global diffusive effect of a given tank bottom dense assembly configuration.

2.4.1. Local approach  In this part, we considered a long joint illuminated by a plane wave in normal incidence. The problem is thus reduced to a one-dimensional propagation/scattering problem. The transmission transfer function \( t_{\text{joint}} \) of the joint of given geometry relates the transmitted field through a joint \( U_{\text{joint}} \) to the transmitted field through a reference plate without joint \( U_{\text{ref}} \).

\[
t(\omega) := \frac{U_{\text{joint}}(\omega)}{U_{\text{ref}}(\omega)}.
\] (12)

We focused on the \( S_0 \) transmission transfer function, \( S_0 \) being the mode of interest. The transmission coefficient is identified to the modulus of the transmission transfer function. Finite element computations in the frequency domain, using absorbing regions at guide ends to deal with the scattering problem, were carried out for the geometries shown in figure 4. The scattering of guided wave by joints was expected to be sensitive to continuity at plate and weld interfaces.
Experiments were carried out on similar reduced scale geometries. The tested samples were: a T joint and a two-sided lap joint, see figure 5b. The thickness of each sample was 2 mm, and so the scale factor was 1:4. The experimental setup consisted of a pair of immersion transducers. Two pairs of transducers with two different frequencies were used: 250 kHz and 500 kHz. The sample was maintained in water by nylon wires so that the plate was in stress-free conditions. A photograph of the experimental setup is given in figure 5a.

We were not able to perform measurement at lower frequencies because of the following reasons: (i) manufacturing samples less than 2 mm in thickness with common welding instruments would have been complicated and unrepresentative; (ii) we did not yet have transducers with a frequency lower than 250 kHz. Consequently, the main aim of the local approach was to give conclusions about the mid low-frequency range, which corresponds to $[50 \text{ kHz}, 100 \text{ kHz}]$, in which the scattering by joint is expected to be more significant than the low frequency ultrasound range $[10 \text{ kHz}, 50 \text{ kHz}]$.

2.4.2. Global approach Modelling the 3D geometry of a given complex and large joint configuration is complicated. This is partly due to the fact that it would require modelling...
each lap joint and each three-plate joint geometry. The 2D model makes easier implementation possible. Thus, let us assume that a T joint is modelled by connecting two perpendicular plate elements, and that a lap joint is modelled by a perpendicular break of height $h$ in the plate’s plane. Contrary to the local model, this 2D model neglects diffraction effects associated with the real joint ‘volumic’ geometry (lap length, weld thickness). Because the wavelength is much larger than the lap joint characteristic geometry, which is about the plate’s thickness, these diffraction effects are negligible. In order to perform fast lap joint numerical implementation, thus to avoid complex geometric modelling, we assumed that the break in the plate’s plane can be reduced to an interface producing a similar scattering effect. The method consisted in affecting to a given interface at the place of the joint, the elementary stiffness and mass matrices of the associated lap joint, see figure 6. Consequently, this neglects the small delay caused by the break, which is clearly negligible in front of the total propagation time. For the validation of the method, a qualitative comparison between the field scattered by different modelling methods: geometrical joint, approximated interface joint, and 3D joint is given in figure 7. The 3D simulation was performed by using hexahedral linear elements, and with two elements in thickness. It highlights the fact that the lap joint does not only produce a reflection of the incident mode, but also an in-plane/out-of-plane mode conversion, which is accurately reproduced by the interface approximation in the 2D case. Discrepancy is observed for the out-of-plane displacement by comparing with the 3D simulation. Indeed a $A_0$ wavefront from mode conversion is scattered by the joint. The reason for that is that the methods do not behave the same with regard to flexion that occurs in the joint. One can expect that the 3D modelling better describes the phenomena locally, but the lap joint interface model is still a good approximation which makes it possible easier implementation.

![Illustration of the finite element interface approximation for lap joint modelling.](image)

Figure 6: Illustration of the finite element interface approximation for lap joint modelling.
Figure 7: Qualitative comparison of the displacement field diffracted by different lap joint modellings: (a.) geometrical joint, (b.) interface approximation, (c.) 3D lap joint.

A more quantitative validation focusing on the $S_0$ plane wave normal transmission through the joint was performed, see figure 8. A time domain Fourier transform method was used. Figure 8a shows that the transmission coefficient of the approximated interface joint is higher than the geometrical joint. This is also shown by the amplitude of a transmitted 20 kHz Ricker wave in figure 8b. Thus, to be more conservative and closer to the geometrical joint, one can increase the scattering effect by increasing the stiffness of the interface joint by an empirical factor, see figure 8a. The factor was set to 1.5.
2.5. Real tank bottom sample experiment

Experiments were carried out on a real tank bottom sample. The sample consisted of a lap joint assembly of 6 mm steel plates, extracted from a real storage tank, see figure 9. In similar manner to the reduced scale setup, the aim was to measure the $S_0$ amplitude drop due to the lap joint, in real testing conditions. Transmission of the first $S_0$ echo through healthy plate, and plate with lap joint were compared. The propagation distance was 2 m. Two instrumental configurations were tested. The first configuration consisted of a pair of 200 kHz General Electrics™ transducers. We noticed that we could excite the transducers in a band around 40 kHz using burst excitation. At higher frequencies, the transmission through the lap joint would have been to weak. The purpose of this configuration was to highlight the limitations of conventional transducers and frequency for tank bottom inspection. For the second instrumentation, the excitation was performed using a Wilcoxon™ high power portable shaker. The receiver was an acoustic emission transducer with high sensitivity at 12 kHz. This instrumentation is illustrated in figure 9. The excitation was a 12 kHz two-periods tone burst. Due to high power generation, high SNR was obtained.
For both configurations, the excitation was performed on the sides of the plate. The main issue in such configuration is coupling. The sides of the plate were flattened for a better coupling. To take into account coupling uncertainty, several measurements (8 to 32), associated with different excitation positions, (by slightly displacing the transducers), were performed for each cases: without lap joint and with lap joint. A statistical representation of the measurements were done. Although deviation is expected to be high, the mean behaviour of the lap joint could be estimated.

3. Results

3.1. Transmission through joint in the mid low-frequency range

The results of the lap joint experiment are given in figure 10. The results of the T joint experiment are given in figure 11. Transducer or plate positioning error is expected. Thus, perfect normal incidence is not expected. We evaluated that this error could affect the measured amplitudes at the worst for about ±10%. Bounds corresponding to the farthest measurements from the mean of all measurements have been added to the graph. The converted frequency scale for $h = 8$ mm is given in the upper part of the graph.

Figure 9: Tank bottom sample (left), 12 kHz excitation configuration (right).
(a) Transmission coefficient in the frequency domain from experimental signals, compared with finite element results.

Figure 10: Transmission of $S_0$ mode through a lap joint in the mid low-frequency range.

(b) Measured signals normalized with respect to the reference plate signal.

Figure 11: Transmission of $S_0$ mode through a T joint in the mid low-frequency range.
3.2. Transmission through joint in the low-frequency range

The results of the real tank bottom sample experiment are exposed in this paragraph. The two sets of signals associated with the two frequencies 40 kHz and 12 kHz, that consist of the first $S_0$ for the cases with and without lap joint, are plotted in figure 12. This representation shows an overview of the repeatability of the coupling. In spite of the variations in signal absolute amplitude, one can observe the effect of lap joint on the amplitude drop of the echo. Please note that, for this representation, the delay was compensated for each signals. Figure 13 shows the average transmission coefficient in frequency domain for the two configurations. The $1\sigma$ (conventional standard deviation) bounds are plotted on the graphs.

![Figures 12 and 13](image)

Figure 12: Gated transmitted $S_0$ echoes through a 2 m plate with and without lap joint.

Figure 13: Estimation of a 6 mm steel plate lap joint $S_0$ transmission coefficient in the tested frequency ranges, using coupling uncertainty averaging.

3.3. Estimation of lap joint transmission spectrum

By exploiting the results obtained at different frequencies, and assuming scale independence behaviour of the lap joint, we reached the estimation of the lap joint transmission spectrum, in the frequency-thickness scale, that is given in figure 14. The measurements are compared to the one-sided lap joint FEM prediction. The comparison with the prediction confirms the general behaviour of the lap joint. The grey scale of the crosses corresponds to the band of each transducer.
3.4. Prediction of the propagation in the tank

The field results of the FEM simulation of the propagation in the tank are given for a 20 kHz Ricker wave punctual radial excitation at the tank wall. A view of the field corresponding to the amplitude of displacement $|u(x)|$ at $t = 0.6$ ms is given in figure 15. The field is analysed as follows: $S_0$ and $SH_0$ wavefronts propagate in the bottom. The $A_0$ mode is highly scattered by joints in the bottom, and thus no clear wavefront can be defined. The strong $A_0$ wavefront in the wall produced by the excitation is reflected at the top and follow a circumferential path. The $S_0$ head waves, caused by the mode conversion at the circular T joint, follow a circumferential path in the wall. The sinogram corresponding to the set of signals recorded at the wall in the radial direction is given in figure 17. For clarity of signal analysis, the sinogram of the simulation without the lap joints is given in figure 16. In this figure, the dashed lines indicate the analytical times of arrival from group velocity values given in table A1. The transmitted signal, corresponding to $\theta = 0$°, for this simulation, is given in figure 18.

The spatial fields of the $S_0$ beam for the case of the tank without lap joints and the tank with lap joints are given in figure 19. The axial section of the field, corresponding to the direction $\theta = 0$°, is given in figure 20. A power law fit of the type $A = A_0(x/x_0)^m$ was done for three cases: (i) tank without lap joints, (ii) tank with standard interface lap joints, and (iii) tank with conservative $\times 1.5$ interface lap joints. The corresponding values of $m$ appear in the graph. The theoretical spatial rate of decrease for a wave expanding in a plane is $m = -1/2$. For the cases of bottom with joints, the value of $m$ includes the global diffusive effect of lap joints. Finally, the results are analysed in terms of dynamic range, in table 1, for different excitation frequencies: 10, 20, 30, 40 kHz, different types of joints, and for the two possible excitation types (tank wall, annular chime). The dynamic range (DR) was defined as the ratio the amplitude of the transmitted $S_0$ echo at $\theta = 0$°, see figure 18, and the maximum amplitude of the displacement (in the excitation range). It is given in dB using the following convention:

$$DR := 20 \log_{10} \left( \frac{|u_{r,S_0,transmitted}|}{|u_{excitation}|} \right).$$  \hspace{1cm} (13)

The attenuation due to the scattering by joints is defined as the difference between the DR of the tank-without-joint simulation and the DR of the tank-with-joint simulation. Figure 21 shows the attenuation due to joints for the tested frequencies. One can compute this attenuation by summing $N$ independent local contributions of each joint using the previously measured transmission coefficient $|t(\omega)|$, in the low-frequency range as well as in the mid low-frequency range.

$$DR(\omega) \approx N20 \log_{10}(|t(\omega)|)$$  \hspace{1cm} (14)
For the selected geometry, a direct path has a maximum of $N = 10$.

Figure 15: Tank response to a 20 kHz Ricker punctual excitation at the tank wall, at $t = 0.6$ ms, amplitude of displacement in linear scale.
Figure 16: Sinogram without lap joints.

Figure 17: Sinogram with lap joints.
Figure 18: Transmitted signal at $\theta = 0^\circ$ for a 20 kHz Ricker wave tank wall excitation, in normalized linear scale.

Figure 19: $S_0$ wavefront field, corresponding to the maximum of absolute amplitude of displacement, for a 20 kHz Ricker wave tank wall excitation, in normalized linear scale.
Figure 20: $S_0$ Beam decrease at $\theta = 0^\circ$ for the 20 kHz tank wall excitation, in normalised linear scale.

| Frequency (Ricker) | Type of excitation | Lap joint type | Dynamic Range |
|--------------------|--------------------|----------------|---------------|
| 10 kHz             | tank wall          | no joint       | -44.8 dB      |
| 10 kHz             | tank wall          | standard       | -47.1 dB      |
| 20 kHz             | tank wall          | no joint       | -47.7 dB      |
| 20 kHz             | tank wall          | standard       | -56.3 dB      |
| 20 kHz             | tank wall          | conservative   | -60.4 dB      |
| 20 kHz             | annular chime      | standard       | -32.3 dB      |
| 30 kHz             | tank wall          | no joint       | -46.3 dB      |
| 30 kHz             | tank wall          | standard       | -62.4 dB      |
| 40 kHz             | tank wall          | no joint       | -45.6 dB      |
| 40 kHz             | tank wall          | standard       | -66.8 dB      |

Table 1: Dynamic Range for different simulated configurations.
4. Discussion

The results obtained from joint scattering measurements highlight two main phenomena: (i) the diffraction patterns specific to the joint geometry, (ii) the decrease in the transmission coefficient with frequency. The diffraction effect is well predicted by the FEM results. One can assume that error is expected due to the fact that the actual joint geometry, which contains imperfections, does not match the ideal geometry. As expected, the T joint results show a better agreement with the disconnected plates model compared with the connected plates model. Similarly, the lap joint results show a better agreement with the one-sided lap joint plates model compared with the two-sided joint plates model. Overall, one can conclude that transmission through a joint is highly dependent on: (i) the geometry of the joint, (ii) the cohesion between the plates. Indeed, it is expected in practice that lap joints are not homogeneous, and suffer different kinds of defects due to localised corrosion caused by the discontinuities inherent to the metallic structure. Secondly, defects in joint may be caused by deficient welding process. The order of magnitude of the measured transmission coefficients is not that far from the prediction. Thinking in terms of the echo’s amplitude ratio, the local attenuation due to a lap joint measured is about 0.55 (−5.2 dB) at 250 kHz, and 0.45 (−7 dB). For the case of significant joint density, it is clear that the transmitted guided wave would be too attenuated at these frequencies. The associated frequency range is about 50 to 160 kHz for a 8 mm thick plate, and 40 to 130 kHz for a 10 mm thick plate. Consequently, the low frequency ultrasound range around 20 kHz would be a solution to the trade-off between SNR and resolution. The real tank bottom sample experiment confirmed this prediction. The 40 kHz signal is relatively perturbed compared with the 12 kHz signal. The analysis of the signals demonstrates the behaviour of transmission with respect to frequency. The statistical representation of the signals makes it possible to quantify coupling uncertainty. The results showed that the computed averages make sense. In the fundamental regime, transmission coefficient goes down with frequency. The transmission coefficient is about 60 % at 40 kHz, whereas it is about 80 % at 12 kHz. This comparison demonstrates the irrelevancy of conventional ultrasonic testing instrumentation. The high SNR provided by the high power excitation is very promising for long range applications. Using this
kind of low-frequency high power instrumentation, propagation over tens of meters is achievable.

As demonstrated, the selected approach provides a helpful analysis of the elastic field that propagates in a storage tank. The echoes related to the three fundamental modes are identified. These echoes can be identified by means of analytical times of arrival. The dynamic range results show that the transmission of guided waves in the bottom is strongly sensitive to frequency. Within the selected framework, the effect of scattering by joints is about $-2.3$ dB at 10 kHz, $-8.5$ dB at 20 kHz, $-16.1$ dB at 30 kHz, and $-21.2$ dB at 40 kHz. This effect is demonstrated by a significant decrease in the wavefront amplitude. Local multiple scattering effects are observed. The annular chime excitation leads to a better dynamic range because of the polarisation of the $S_0$ mode in the bottom. However, as demonstrated by Lowe et al., a smaller surface is available for excitation compared with the tank wall. The noise level should be considered and compared with the dynamic range for a given excitation method. These observations lead to the trade-off between spatial resolution and SNR.

5. Conclusion
Guided wave testing of storage tank involves complex guided wave phenomena. A storage tank bottom can be considered as a strongly inhomogeneous medium, because of the presence of lap joints. Thanks to the proposed prediction method, it is possible to get prior knowledge of the propagation in such medium. The method is relevant for interpreting the signals, thanks to the elastic field analysis. The effect of joints has to be taken into consideration for the selection of the inspection centre frequency. Experiment carried out on reduced scale joints and real storage tank sample allowed to estimate transmission of guided waves in such structure. GWT of storage tank in the low ultrasound frequency range has great potential. High power low-frequency instrumentation is promising. The method can be extended to larger tanks for which a greater dynamic range may be required. The trade-off between SNR and resolution has to be considered. Assessing detectability of defects in tank bottoms using the $S_0$ mode is challenging. In this sense, a study of the scattering of the $S_0$ mode by defects is needed to get to a conclusion on this detection issue. Further work needs to be carried out to assess the possibility of long range imaging and tomography for storage tanks.

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**Appendix A. Parameters**

| Parameter                          | Value | Unit  |
|-----------------------------------|-------|-------|
| **Plate parameters**              |       |       |
| Plate thickness                   | 8     | mm    |
| Young’s modulus                   | 210   | GPa   |
| Poisson’s ratio                   | 0.3   |       |
| Density                           | 7850  | kg.m$^{-3}$ |
| Shear correction factor $\kappa$  | 0.83  |       |
| Membrane wave velocity            | 5422  | m.s$^{-1}$ |
| Shear wave velocity               | 3208  | m.s$^{-1}$ |
| Rayleigh wave velocity            | 2928  | m.s$^{-1}$ |
| **Leaky guided wave parameters** |       |       |
| Water density                     | 1000  | kg.m$^{-3}$ |
| Water speed of sound              | 1480  | m.s$^{-1}$ |
| Fuel density                      | 875   | kg.m$^{-3}$ |
| Fuel speed of sound               | 1425  | m.s$^{-1}$ |
| Soil Young’s modulus              | 20    | GPa   |
| Soil Poisson’s ratio              | 0.2   |       |
| Soil density                      | 2200  | kg.m$^{-3}$ |

Table A1: Simulation parameters.
| Parameter                  | Value  | Unit   |
|---------------------------|--------|--------|
| Plate density             | 7812.5 | kg.m$^{-3}$ |
| Plate thickness           | 2      | mm     |
| Pressure wave velocity    | 6015   | m.s$^{-1}$ |
| Membrane wave velocity    | 5400   | m.s$^{-1}$ |
| Young’s modulus           | 196.8  | GPa    |
| Poisson’s ratio           | 0.3    |        |
| Plate size                | 320 $\times$ 320 | mm |

Table A2: Measured experimental setup parameters.