Autonomous Robotic Inspection and Maintenance on Ship Hulls and Storage Tanks

Deliverable report – D3.2

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Author(s)	A. SAIDOUN, H. WALASZEK, J. THABOUREY, Q.A.VU, N. SAMET, E. NDIAYE, A. VALENTIN
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HISTORY OF CHANGES

Date	Written by	Description of change	Approver	Version No.

REFERENCED DOCUMENTS

- D3.1 Simulation localisation and geometry inference on a metal plate

Executive summary

This document corresponds to deliverable D3.2 entitled Defect localisation by ultrasonic guided wave imaging, planned for month 33 of the project. The work carried out in this phase of the project aims to validate the methodology based on ultrasonic guided waves (GW) (developed in D3.1 Simulation localisation and geometry inference on a metal plate) for the detection and localisation of corrosion patches.

Application of ultrasonic guided waves imaging to detect and localise defects

1. Introduction

Based on the conclusions of deliverable D3.1, the candidate sensor for our application should meet the following requirements:

- modal selectivity on transmission and detection: generate/detect properly the SH_0 mode with the best possible SNR
- omnidirectional transmission and reception
- the echo mode will be preferred (transmitter and receiver probe at the same location)

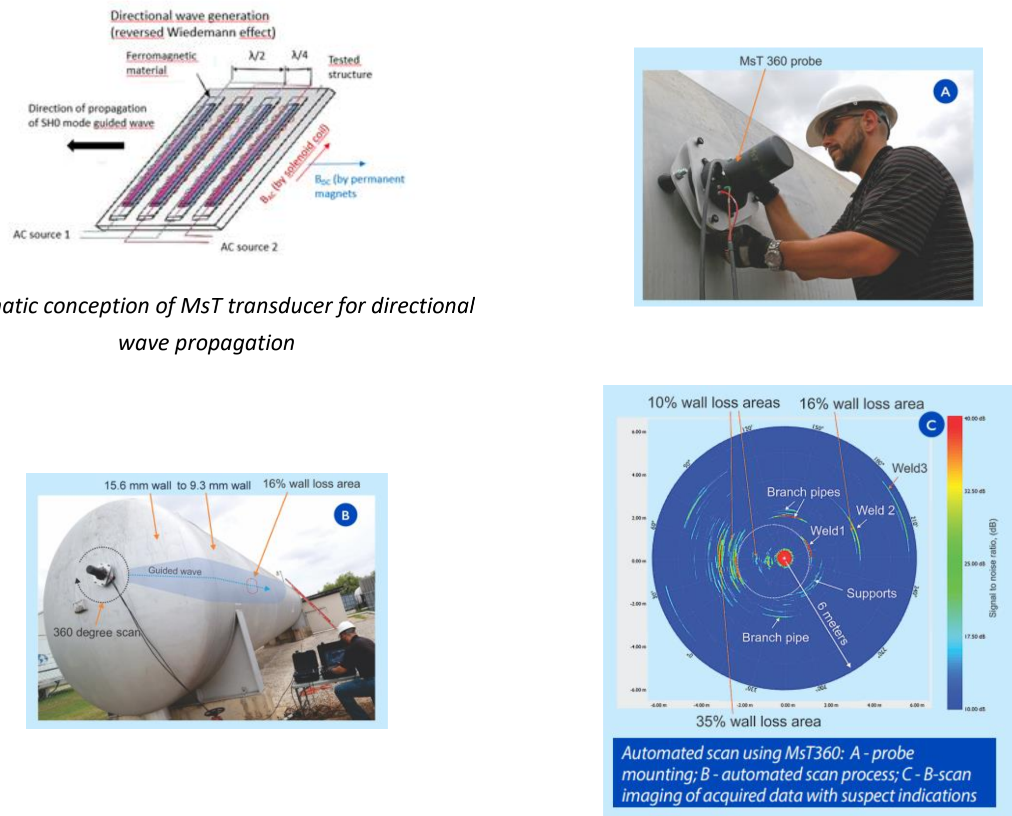
In the present report, the two solutions previously proposed in D3.1 (PZT omnidirectional sensors and Magnetostrictive omnidirectional sensors) have been tested in order to establish their performances first on the defect-free mock-up and then on a plate with representative defects of thickness losses.

2. Numerical and experimental methodology

2.1. Magnetostrictive solution (MsT 360°)

The probe MsT360 developed by Southwest Research Institute (SWRI, s.d.)(Figure **1**) has the ability to inspect large plate surfaces from a single location, and precisely locate reflectors (possible stiffeners, butt-welds, defects). The MsT360 includes a plate MsT probe, being highly directional ultrasound emitter, connected to a software-driven servo motor that rotates the probe over the structure surface. The latter permits a 360° inspection in all direction of the plates (360° at every 5°). The result of the control is a large map of radius up to 7-8 meters, in which the position of the eventual reflectors is stated. The different reflectors can be distinguished by the intensity of the detection (amplitude of reflection ultrasound from the reflector). The probe can be attached to a tank wall using magnets or suction cups.

The wave generation by the MsT360 bases on magnetostrictive mechanism. The ultrasound is first generated on the patch – a part of the probe by the combination of a permanent magnetic field (imposed by small magnets polarised in plane) and an alternative one (generated by a coil and alternative current at desired frequency). This configuration, with benefit of the high magnetic permeability of the patch, permits the generation of highly energetic and in plane polarisation ultrasound. Then, with help of a shear-wave coupling, the ultrasound displacements are transmitted to the structure for the generation of shear horizontal guided wave modes (SH waves). The fundamental SH_0 mode is used due to its low dispersion rate, which allows high accuracy in defect location.



Schematic conception of MsT transducer for directional wave propagation

Automated scan using MsT360: A - probe mounting; B - automated scan process; C - B-scan imaging of acquired data with suspect indications

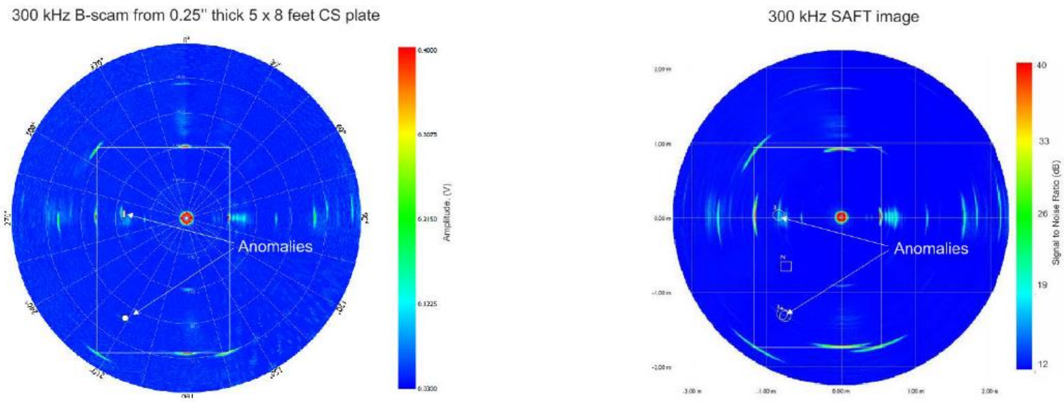
Figure 1: The MsT360 probe: illustrative installation and imaging result (SWRI, s.d.)

The probe can be used on plates with thicknesses up to 30 mm (due to wide frequency range) and bends. Additionally, custom versions of the probe could be used for structural health monitoring (SHM) of shells with a temperature up to 250°C. This probe use a dry coupling method with materials standing a high temperature.

2.1.1. Imaging algorithm

The measurement consists of an automated scan of every 5 degrees up to 360 degrees. All the single time signals can be presented as a circular B-scan (Figure **2**-a). Then, a synthetic aperture focusing (SAFT) algorithm is used to process data and obtain improvement of the image resolution (Figure **2**-b). A graphical user interface is dedicated for the data analysis and image presentation.

More accurate results can be obtained by using two probes that cover dead zones and confirms relevant indications.



a/ B-scan imaging

b/ Imaging with SAFT

Figure 2: Comparison between data presentation using B-scan imaging and SAFT

2.1.2. Experimental set-up

Testing includes mounting the probe, running an automated scan, and compiling an inspection report.

The probe can be fixed on the structure surface using magnets or suction cups. To ensure the wave transmission from the probe to the structure, a shear-wave coupling can be used and/or by application of pressure.

The measurement can be monitored from the control unit. The connection with the probe is ensured by cable of type usb 2.0, with length of 20 m and longer if needed. For the current version, there is an external battery used for motor rotation.

The user interface can be used for measurement setting, launch/stop the automated scan and data acquisition. Below are given the characteristics of the probe:

- Standard frequencies of 20-250 kHz
- High-frequency package includes frequencies from 250-500 kHz
- Up to three frequencies can be acquired at a time
- Probe rotated in 0.2-to-5.0-degree increments
- With five-degree increments, the time needed for one scan is reduced to about 10 minutes
- The area of probe coverage could be in the 10-100 square meters range, depending on the geometry and condition of the structure.

a/ Utilisation of high viscosity coupling (sugar-based solution) for a good wave transmission to the structure

b/ The probe installed on the mock-up, fixed by magnets

Figure 3: Experimental set-up using the MsT 360° probe

2.1.3. Results

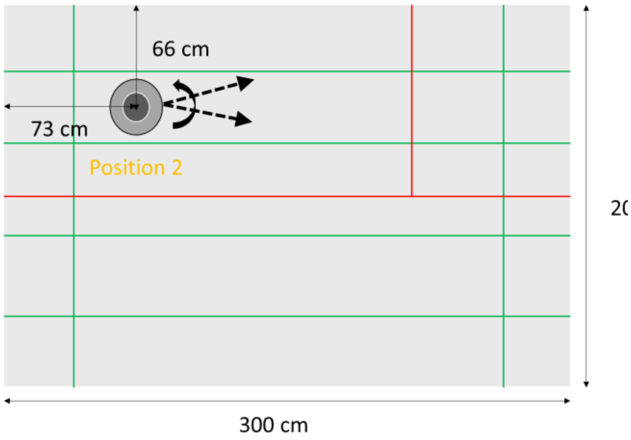
In this chapter, two types of tests have been carried out:

- Tests on mock-up: in order to detect discontinuities (edges, welds, stiffeners)
- Tests on plate containing defects: in order to detect and localise the defects

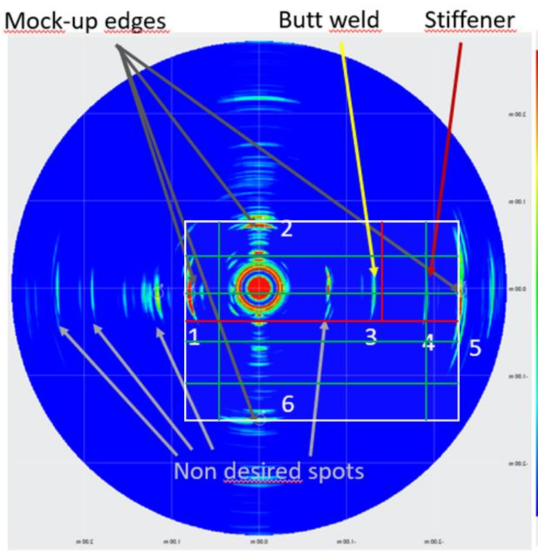
The first testing results are about the detection of the reflectors on the mock-up. Indeed, in the Figure **4**, following the relative position of the probe, all the edges, also a butt weld and a stiffener are detected.

The circle around the probe position represent the dead zone (the area just below the surface of a test object that cannot be inspected because of the transducer is still ringing down and not yet ready to receive signals). The radius of this zone is about ten centimetres (it depend on the frequency).

The “non-desired” spots indicated in the Figure **4**-b, are related to the probe. Indeed, at one single angle of scan, the MsT360 generates 80% of the wave energy in the main direction of the scan, and 20% in the opposite direction which explains symmetric spots (the main spot is the most energetic).



a/ Experimental plan of tests on the mock-up (steel plate of 8 mm with ~400 µm painting thick)



b/ SAFT imaging result at 100 kHz

ID	Feature	X Pos. (m)	Y Pos. (m)	Amplitude	SNR (dB)
1	Indication	0.8000	0.0000	2.1835	NA
2	Indication	0.0000	0.7120	1.6229	NA
3	Indication	-1.3120	-0.0320	0.5704	NA
4	Indication	-1.9200	-0.0480	0.4765	NA
5	Indication	-2.3120	-0.0240	0.9275	NA
6	Indication	-0.0080	-1.5120	0.7139	NA

c/ List of reflectors identified, available in the inspection rapport

Figure 4: Experimental results on the mock-up by using the MsT 360° probe
(detection of the detection of the plate boundaries)

We can see that all reflectors are visible. Edges, stiffeners and even the butt weld which are very difficult to observe but thanks to SAFT reconstruction, the 2 butt welds are visible. As expected, the signal coming from welds are weaker than those from stiffeners.

We can see also that a problem of symmetry artefact occurs which is especially due to the 20% of the excitation energy in the opposite direction and the SAFT algorithm reconstruction principle.

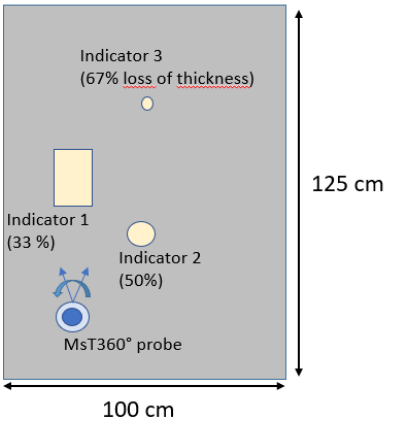
The second test was carried out on a steel plate 1000x1250x6 mm containing artificial thickness losses (Figure **5**):

- Reflector 1: rectangle shape, 92 x 184 mm^2 and 2 mm depth (33% of loss)
- Reflector 2: circular shape, Ø= 46 mm, and 3 mm depth (50% of loss)
- Reflector 3: circular shape, Ø= 30 mm, and 4 mm depth (67% of loss)

Based on the results shown in Figure **5**-c:

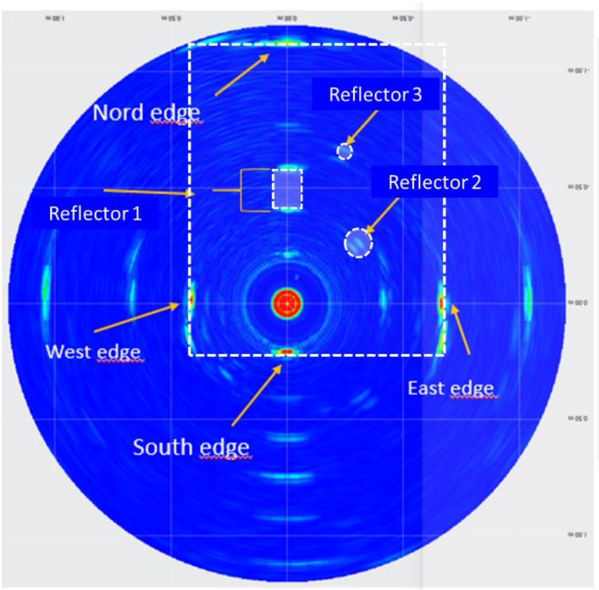
- The edges of the plate were well detected with high resolution
- At 220 kHz, the dimension of the dead zone is smaller than the previous case (at a lower frequency, 100 kHz)

- The problem of non-desired spots still remains, related to the 20% of wave generated in the non-desired direction.
- The defects were detected with an acceptable signal/noise ratio:
    - signal/noise ratio (edge) = 30 dB
    - signal/noise ratio (defect 1) = 20 dB
    - signal/noise ratio (defect 2) = 11 dB,
    - signal/noise ratio (defect 3) = 8 dB



a/ Position of the probe and of the artificial defects (indicators/reflectors)

b/ a steel plate of thickness 6 mm and 1000x1250 mm size



c/ SAFT imaging result at 220 kHz

Figure 5: Experimental result on a steel plate with artificial defects

2.1.4. Summary of MsT 360° results

According to the first results obtained by the MsT 360° probe, it is possible to note that:

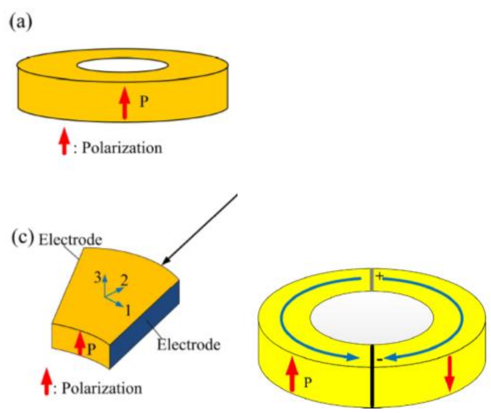
- the probe meets the two conditions, generation of the SH_0 mode as well as omnidirectional reception thanks to the 360° scan

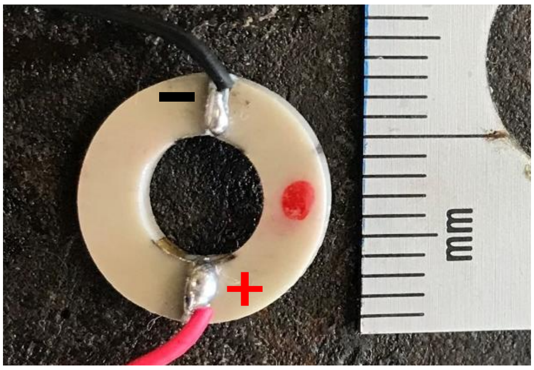
- the imaging algorithm used (SAFT) offers simplified visualization of reflectors (edges, welds, stiffeners) and also thickness losses
- symmetric artefacts are present at each scan which are related to 20% of the excitation energy in the opposite direction and the SAFT algorithm reconstruction. It would be possible to reduce or even eliminate these artefacts through costly technical development of the probe
- The remaining work consists, first, of the associating of signatures to each reflector shape (edges, welds, defects, etc.) and second, the determination of the limits of detection and localisation according to the dimensions of the defects (extent and loss of thickness)

2.2. Piezoectric solution

Huan (Huan, 2019) demonstrated the interest of using a new concept of sensor to generate SH0 waves without being disturbed by other modes. Indeed, all the sensors based on piezoelectric discs have the particularity to generate several types of modes when they are excited, which makes the interpretation of the received signals difficult.

In order to avoid this limitation, Huan has developed a sensor composed of half rings polarised in the direction of thickness. The half rings are then bonded in the opposite direction of polarization to compose a single circular ring. When the ring is assembled, the polarization directions of adjacent elements are opposite, so they can share common side electrodes (Figure 6). This sensor has been called omnidirectional SH wave piezoelectric transducer (OSH-PT).





a- Plan of the sensor made by Huan (Huan, 2019)

b- Sensor made by Cetim

Figure 6: Omnidirectional SH wave piezoelectric transducer (OSH-PT). The PZT ring is first polarized in the thickness direction (red arrow). After polarization, the ring is cut into 2 elements along its diameter. Then, the lateral electrodes are installed to generate a circumferential field (Huan, 2019). (a) sensor made by Huan (b) sensor made by Cetim

When the sensor is excited, it generates shear in the circumferential direction while minimizing other displacements in the other directions. In this case, the SH_0 mode is favoured when the sensor is coupled to a waveguide such as a plate.

This sensor seems to be very interesting for industrial applications since the SH_0 mode is non-dispersive, and the sensor is omnidirectional. Coupled with the TFM imaging technique, the industrial applications become very interesting. It is for all these reasons that Cetim chose to integrate this technology in order to evaluate its relevance.

In order to set up the qualification tests we used a multi-channel system developed by Cetim, which allows using 64 channels in excitation and 64 in reception. This system allows selecting the amplitude, the frequency, and the shape of the excitation signal (pulse, burst etc.).

Its sampling frequency is fixed on the system at 14MHz.

The system has 3 amplifications levels at the reception on all channels 20, 40 and 60 dB.

The system is controlled by a computer which hosts a software from PnenX company.

Figure 7: Acquisition system

We first worked on the coupling of the sensors to find the optimal coupling. The objective here is to recover a signal emitted by the sensor without knowing which mode was generated.

We tried in this case the following coupling mean:

- High viscosity coupling for shear waves transmission
- Solid coupling by bonding with salol (Phenyl salicylate), which has the advantage to be removed by heating

Longitudinal modes are not generated has the transducers are not designed for it.

Figure 8: Example of OSH-PT sensor coupling with Salol

In order to carry out these tests we used an OSH-PT sensor in transmission and another one in reception. The transducer are spaced of 400 mm (Figure **9**).

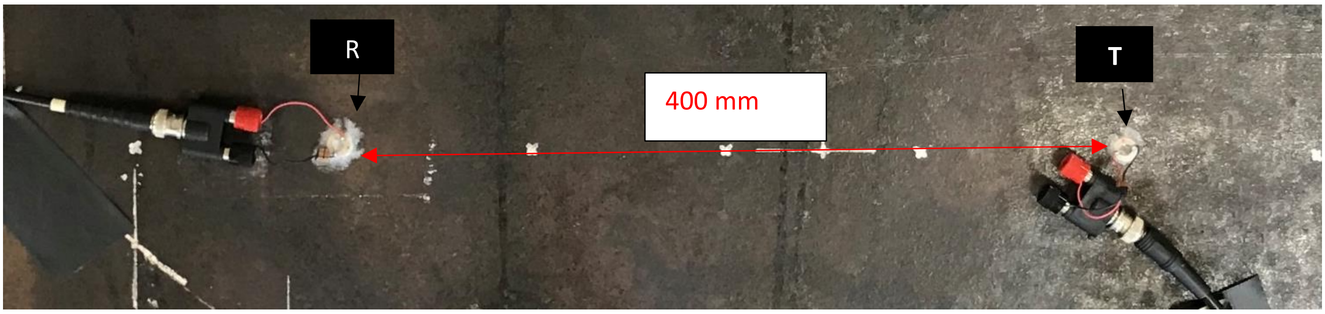
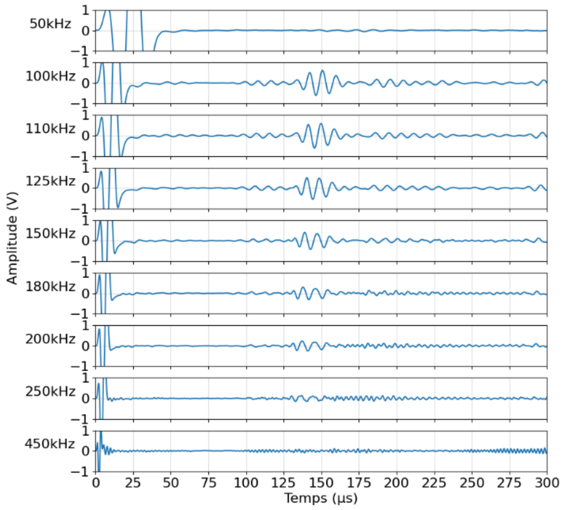


Figure 9: Experimental configuration to test the OSH-PT sensor coupling

The coupling with the shear wave coupling agent appeared to be poor since the signal to noise ratio was insufficient to distinguish the received signal. On the other hand, with the solid coupling "Salol", the signal to noise ratio was sufficient, around 17 dB. In all the following, we have used salol as a coupling agent.

Several frequencies between 50 and 450 kHz were tried in transmission in order to find the centre frequency of the wave generated in the 8 mm thick model. A Fourier transform of the signal of interest located between 125 µs and 175 µs was also calculated to determine the centre frequency and bandwidth of the sensor, as well as a continuous wavelet transform (CWT). The results are shown in Figure **10**.

(a)



(b)

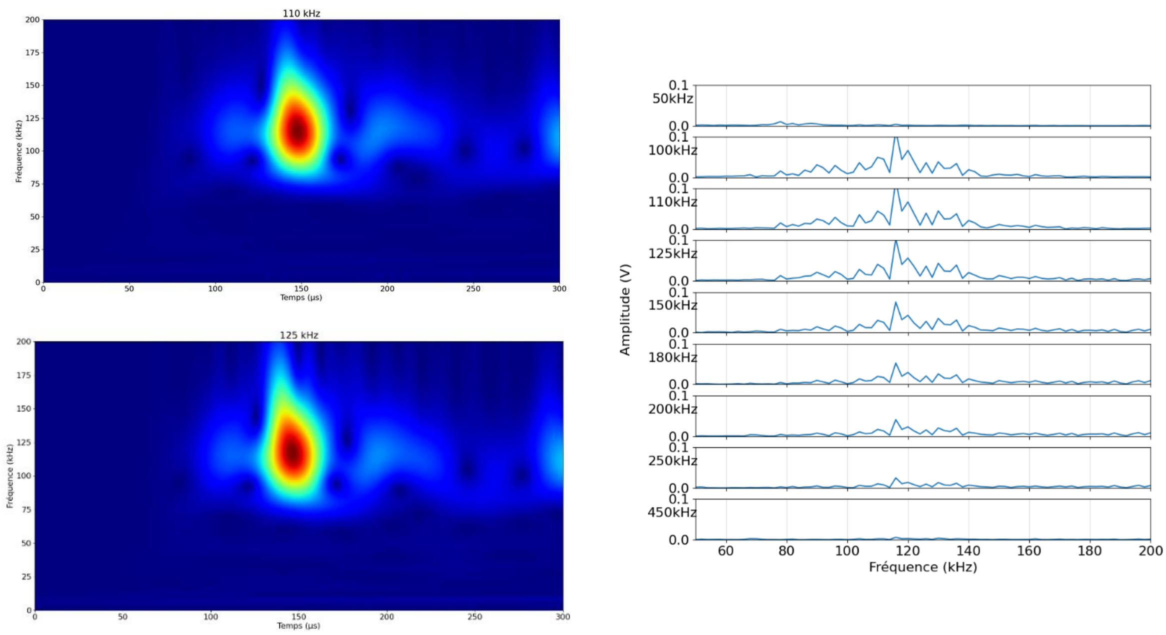


Figure 10: Search for the optimal excitation frequency of OSH-PT sensors (a) signals (b) CWT and FFT of the signals

We can see that the largest amplitudes are obtained around 125 µs (which corresponds to 400 mm of propagation at speed 3200m/s), for frequencies between 100 and 150 kHz.

Looking more closely (Figure **11**), we can see that the best signal to noise ratio is obtained for the 110 kHz frequency.

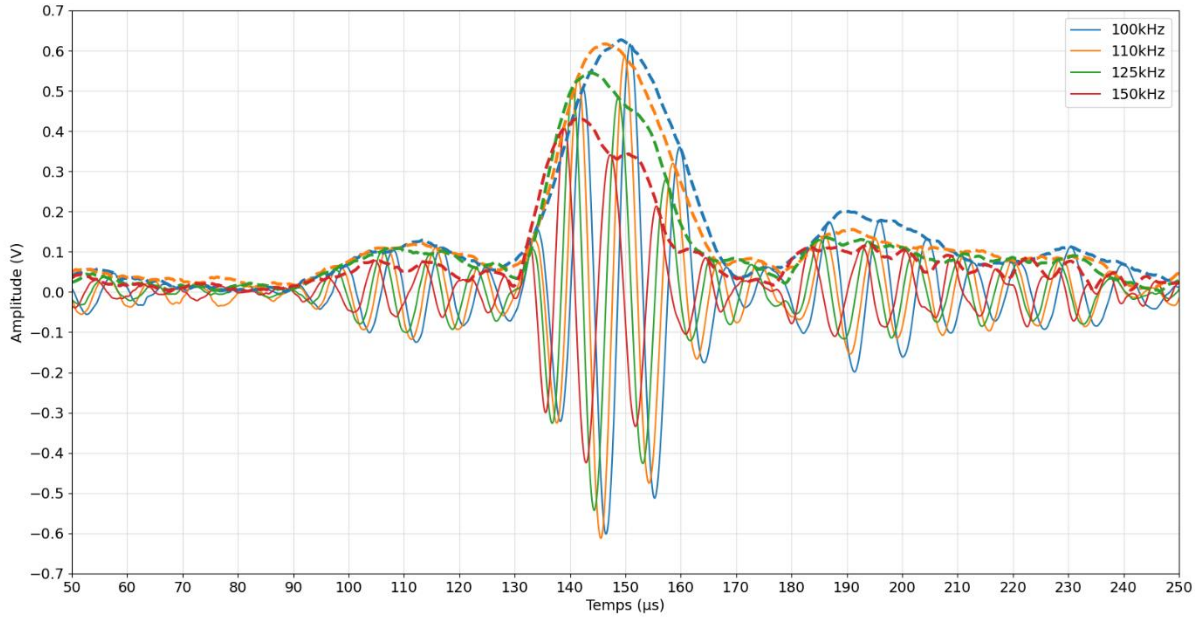


Figure 11: Search for the optimal excitation frequency of OSH-PT sensors

By observing the FFT and the CWT of the signals at all excitation frequencies, we can see that the central frequency of the received signal is between 110 and 115 kHz.

In the following, the frequency used for excitation will be 110 kHz.

In reception, we tried the 3 amplification levels that the system offers, i.e. 20, 40 and 60 dB. We also averaged the signal over 8acquisitions. We can see on the figure below that at 20 dB gain the signal to noise ratio is low, at 60 the signal is distorted and at 40 we obtain the best signal to noise ratio.

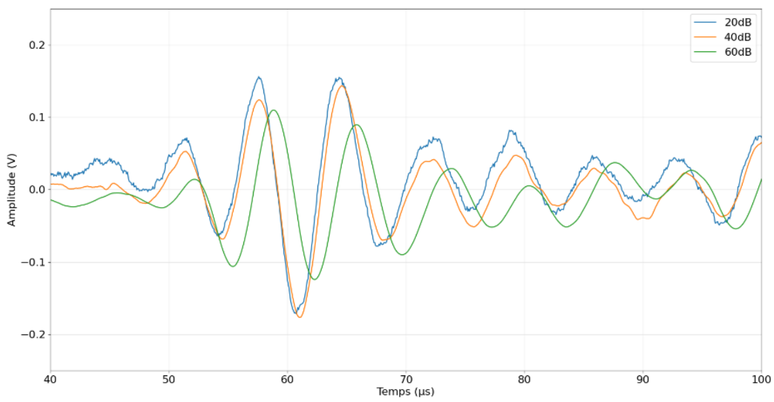


Figure 12: Result of the amplification at the reception

For the following, we have chosen the 40 dB amplification in reception.

Among the most important criteria of this sensor is the generated mode. Huan was able to generate an SH_0 mode without completely cancelling the A_0 mode. On the other hand, he was able to maximize the SH_0 signal to A_0 noise ratio at 20 dB.

In what follows we will demonstrate that the mode generated by the sensor is indeed the SH_0 mode. To do this, we conducted a test in transmission with an OSH-PT sensor in transmission and in reception a T-wave sensor capable of receiving any type of SH wave. The sensor is broadband with a bandwidth between 50 and 1500 KHz at -6dB. We then moved the receiver on a straight line on a distance between 150 and 300 mm from the transmitter with a step of 0.5 mm.

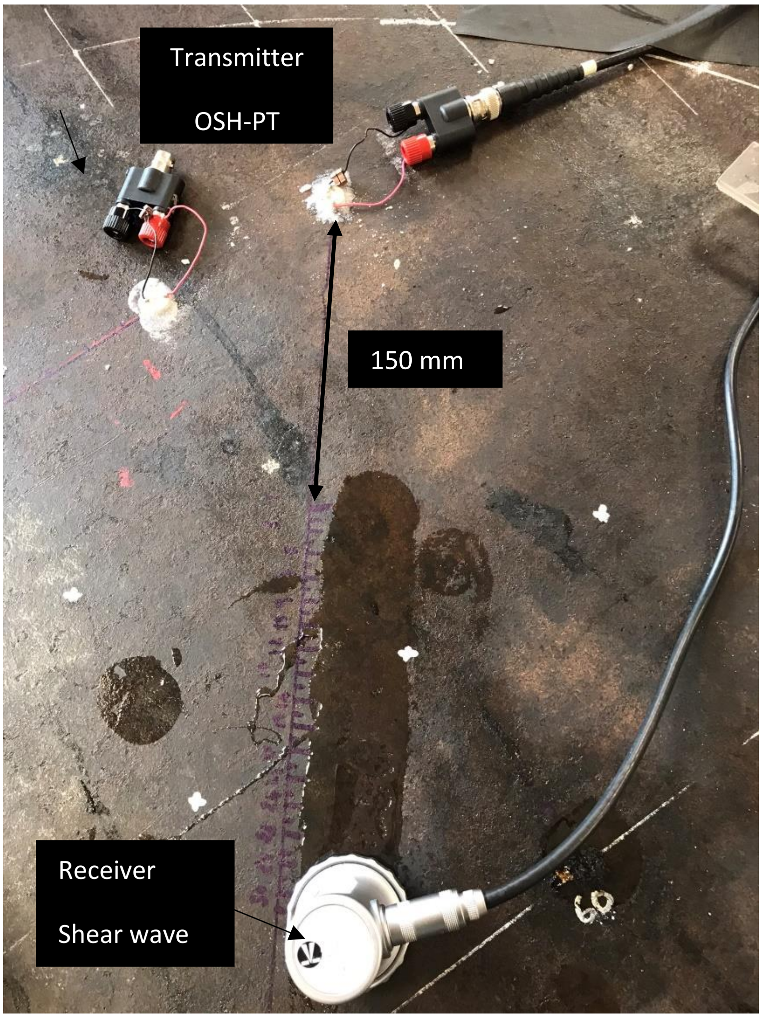


Figure 13: Distance scanning between the OSH-PT transmitter and the OS receiver

The results of this test are presented as Bscan in the figure below.

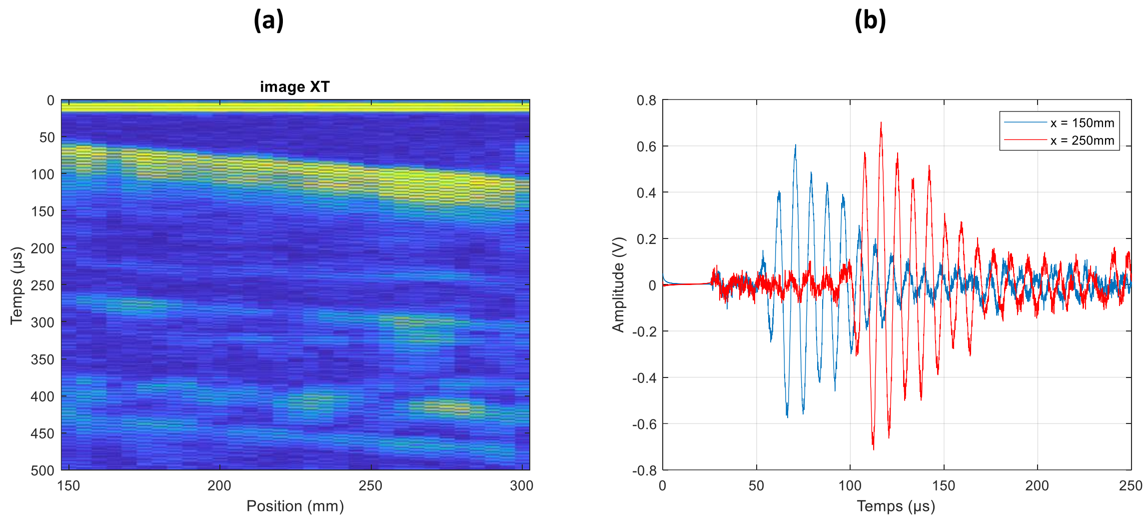


Figure 14: A Bscan in distance between OSH-PT and OS. b- signals at 150 and 250mm

An example of the signal obtained at the beginning and end of the scan is given in the Figure 14.

We can see that the signal of interest starts around 48 µs and ends 96 µs on the scan line. The signal is not disturbed by other modes and the velocity corresponds well to SH_0 wave speed i.e. around 3200 m/s.

In order to be sure of this observation we have performed a 2D FFT and have superimposed the dispersion curves of the SH waves.

We can observe that the mode corresponds well to the SH_0 mode and that it is well obtained at a frequency around 110 kHz (Figure **15**).

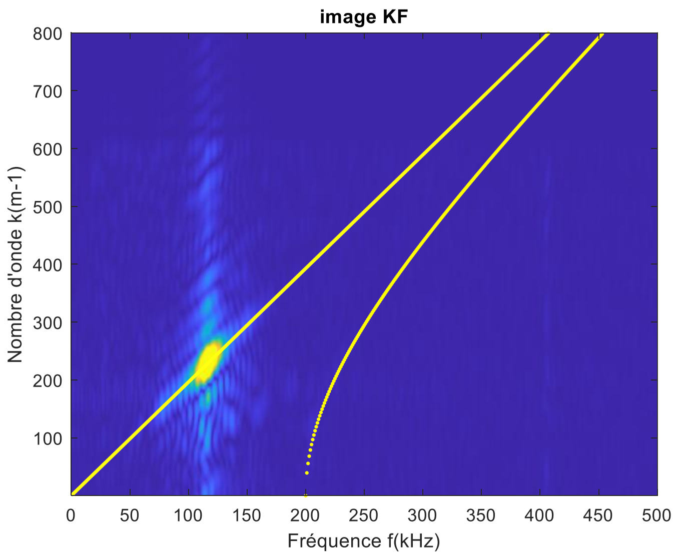


Figure 15: 2D FFT and dispersion curves

The OSH-PT sensor is omnidirectional. In this phase we are going to demonstrate that the sensors realized by Cetim correctly fulfils the need.

For this reason, we set-up a measurement protocol which allow to demonstrate the omnidirectionality of the latter.

The protocol consists in putting an OSH-PT sensor in the centre of a circle of 200 mm of radius and to receive the wave emitted with the T wave sensor on various angles on this circle (Figure **16**).

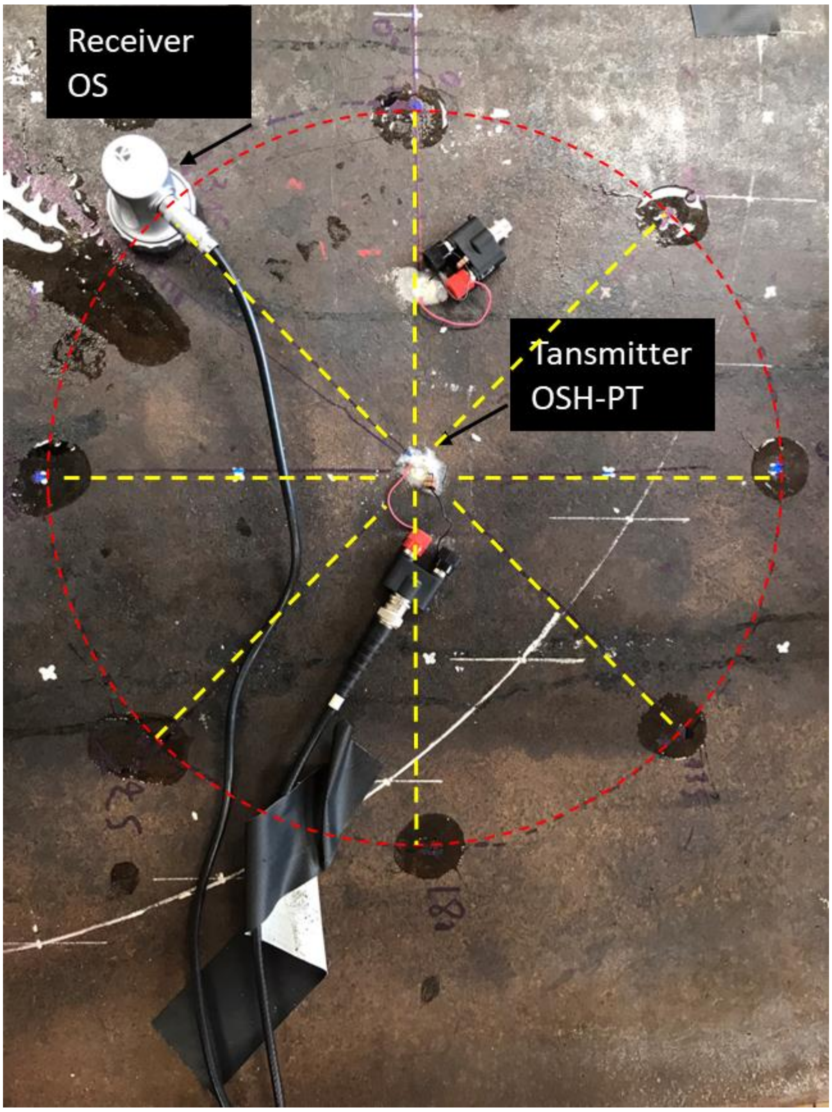


Figure 16: OSH-PT sensor directivity measurement protocol

The result is shown in Figure **17**. We can observe that depending on the angle (from 0 to 315) the amplitudes obtained are of the same order of magnitude, which means that the sensor generates SH_0 waves in all the directions.

In this chapter, we could set up several protocols to qualify the OSH-PT sensors carried out by Cetim. We were able to set up an acquisition chain to use these sensors easily. The parameters of excitation and reception of the acquisition chain were optimized in order to correctly qualify the technical characteristics of the sensors. We were able to verify that the OSH-PT sensor generates the SH_0 mode with a sufficient signal to noise ratio (A_0 mode) close to 17dB. We also checked that the sensor is omnidirectional.

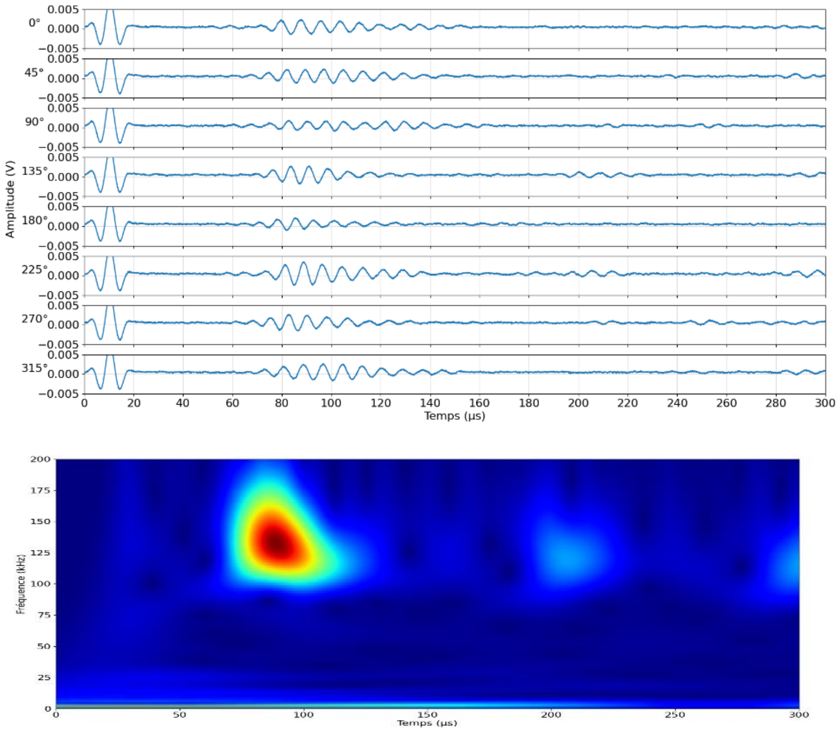


Figure 17: Result of the directivity and CWT of a signal

2.2.1. Imaging algorithm update

The objective of this chapter is to set up a mapping method, based on guided waves to allow the detection of stiffeners and welds in order to locate them on the structure.

To study the use of TFM algorithm for detecting discontinuities, experiments are carried out on the representative mock-up.

By using TFM algorithm for each pixel (x, z) of a given image, the intensity is given by the following formula (Holmes, 2005.):

$$I(x,z) = \left| \sum_{\text{for all tx, rx}} h_{tx,rx}\left(\frac{\sqrt{(x_{tx}-x)^2+z^2}+\sqrt{(x_{rx}-x)^2+z^2}}{c_l}\right) \right|$$

with t_x the transmitter and r_x the receiver, x_{rx} and x_{tx} their abscissas, $h_{tx,rx}$ the Hilbert transform of the emitted signal by t_x and received by r_x and c_l the propagation velocity of the wave.

Since the waves used here are guided waves, so $z_{rx} = z_{tx} = 0$, and the formula becomes

$$I(x,y) = \left| \sum_{\text{for all tx, rx}} h_{tx,rx}\left(\frac{\sqrt{(x_{tx}-x)^2+(y_{tx}-y)^2}+\sqrt{(x_{rx}-x)^2+(y_{tx}-y)^2}}{c_l}\right) \right|$$

with y_{rx} and y_{tx} the ordinates of the transmitters and receivers.

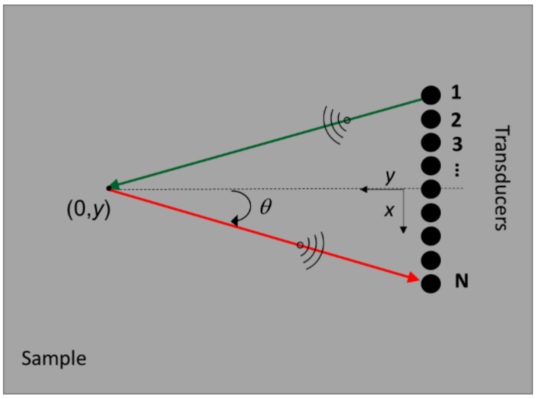


Figure 18: Explanation of the resolution of the TFM (in green the emission and in red the reception, to see the whole sequence refer to the video at the following address here)

We put the transducers in a circle and not aligned to avoid a problem that occurred previously with the TFM processing, which consisted in the apparition of an unexpected of artefact symmetry of the mapping with respect to the sensor line (see D3.1).

2.2.2. Experimental set-up

To perform the TFM, we arranged 16 OSH-PT sensors in a circle on the mock-up as it can be seen in the figure below. Each transducer transmits in turn, and the other transducers receive the signal.

Figure 19: Configuration of the transducers

2.2.3. Results

The results are shown in the figure below (where the free edges are in white, the welds in red, the stiffeners in green and the sensors are the white circles). First of all, we can see that the cartography obtained is not symmetrical, so the inclusion of the sensors in a circle was effective. Even if the resolution is not optimal due to the small number of sensors used (32 should be better), we can clearly see the free edges on the TFM mapping. Most stiffeners seem also to be visible, except for the bottom horizontal one and the two-horizontal hidden by the blind zone. However, the two welds are more difficult to distinguish: the horizontal one is hidden by the blind zone, and the other is not really visible due to the fact that welds reflects back less wave amplitude than stiffeners and free edges.

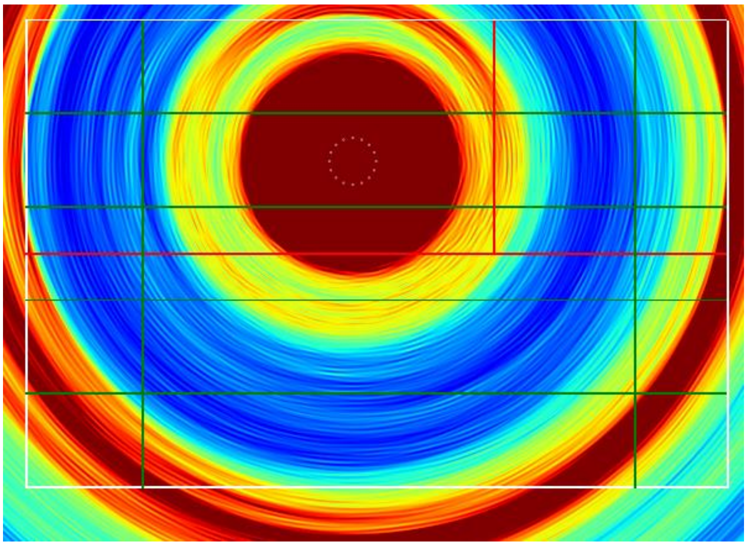


Figure 20: Result of TFM mapping

2.2.4. Summary of Piezoectric results

According to the first results obtained by piezoelectric probes, it is possible to note that:

- the probes meets the two conditions, generation of the SH_0 mode as well as omnidirectional reception
- by using the TFM imaging algorithm, the circular configuration of the sensors allows to attenuate or even completely eliminate the effect of symmetry of the reflectors on the image
- the obtained results allow to validate the detection of the discontinuities on the mock-up (edges, welds, stiffeners). The resolution can still be improved by increasing the number of sensors (32 or 64 instead of 16)
- the sensors should be conditioned to be more handy and easier to use without gluing them. The conditioning will consist of protect them with housing that allow to use them with shear wave coupling agent.

3. Global summary of results

This report summarizes the work carried out with the two types of sensors (MsT 360° and PZT-OSH):

- MsT 360°:
  - mock-up tests: the objective is to validate the detection of discontinuities (edges, welds, stiffeners)
  - tests on the plate with defects (loss of thickness): the objective is to detect and localize the thickness loss
- PZT-OSH:
  - mock-up tests: the objective is to validate the detection of discontinuities (edges, welds, stiffeners)
  - tests on the plate with defects (loss of thickness): ongoing (the results will be presented in the next deliverable D3.3)

- The two sensors fulfil the condition of SH_0 mode generation. in terms of directivity, the PZT-OSH is more omnidirectional than the MsT probe.
- Concerning the experimental set-up, for the moment the two types of probes depend strongly on the coupling used, a good coupling whether mechanical or by a shear wave coupling is essential. this point requires special attention in the robotisation stage.
- the results obtained show that the MsT 360° probe meets the objectives of task 3.2, the detection and location of thickness losses. Additional work remains to be done in order to determine the limits of this detection as well as to deepen the identification of the different signatures (weld, loss of thickness, etc.)
- PZT-OSH probes have clearly improved the resolution of TFM imaging due to their modal selectivity (SH_0) but also their good S/N ratio. Images on the thickness losses will be presented in the next deliverable D3.3 Defect Localisation from a robot team, planned at M45, in order to be able to compare the two types of probes.

4. Conclusion

The main conclusions are as follow:

- the two types of sensors (MsT 360° and PZT-OSH) used in the present work confirm their suitability for the requirements set in the previous task 3.1, explicitly the generation of the SH_0 mode and its omnidirectional reception;
- the obtained results show the improvement in the imaging resolution of the discontinuities on the mock-up (edges, welds, stiffeners) whether by the TFM algorithm (for the PZT-OSH probes) or the SAFT algorithm (for the MsT 360° probe);
- the first imaging results on the detection and localisation of artificial thickness losses obtained by the MST 360° probe show its potential for this type of defect. It now remains to define the limits of this detection and localisation as well as the calibration of the echoes in order to trace more quantitative information on the loss of thickness;
- tests will be carried out using the PZT-OSH probes in parallel with the MsT 360° probe on the same defects in order to decide on the sensor solution for the BUGWRIGHT2 project;
- the experimental implementation of the two types of solution will also be a point to be considered in the final choice. For the moment, the two types of sensors strongly depend on a coupling partially or totally not adapted to the following stage which will concern the robotisation of the control. An improvement of this point is envisaged.

5. REFERENCES

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