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Development of a portable measuring system using ultrasound guided and surface waves to characterize concrete structures

Jean-Marie HENAUT^{1*}, Rafik MOULOUEL¹, Thilakson RAVEENDRAN¹, Yves DENOS², Alexandre BOULE³, Philippe BISARAH³, Jean-Paul BALAYSSAC⁴, Jean-François CHAIX⁵, Vincent GARNIER⁵, Jean MAILHE⁵, Arnaud RECOQUILLAY⁶

¹ EDF R&D PRISME, Chatou, France

² EDF R&D MMC, Moret-sur-Loing, France

³ EDF DI TEGG, Aix-en-Provence, France

⁴ LMDC, Toulouse, France

⁵ LMA, Université d'Aix-Marseille, CNRS, Ecole Centrale, UMR7031, Aix-en-Provence, France

⁶ CEA, Saclay, France

*Corresponding author, e-mail address: jean-marie.henault@edf.fr

Abstract

Multi-channel Analysis of Surface Waves is a well-known acoustic Non-Destructive Technique used in geophysics to characterize layered structures. The measuring system consists of an active source and several receivers equally spaced. The data is processed and inverted to get a shear wave profile along depth. Two French academic laboratories adapted this technique to characterize concrete structures in the ultrasound domain. We decided to develop a new measuring system, aiming to be portable, easy-to-use, fast and with a reduced cost, by combining the advantages of the two academic systems to bring the technique to an industrial stage. The system is composed by 61 dry point contact sensors and an acquisition unit, commercially available, and a specific electronic card to multiplex the receivers. The data are processed with open-source tools. The system was used in lab and on site for different applications. Examples of results are given related to concrete leaching, concrete carbonation and steel corrosion.

Keywords: non-destructive technique, ultrasound, surface wave, guided wave, concrete

1 Introduction

Realizing the diagnosis of concrete civil engineering structures is a major issue to optimize their maintenance and increase their operating lifetime. To complete the analysis performed in laboratory on a few drilled samples, it is important to get efficient Non-Destructive Techniques (NDT) which can be widely used on site to get a more exhaustive view of the structure. NDT based on ultrasounds are sensitive to mechanical properties of the inspected medium. For many years, operating ultrasound products have been available to image concrete structures. But there is no such device for concrete cover characterisation. In France, two academic laboratories have been developing specific instrumentations which fit that need. Their systems are based on the same principles which is a well-known technique in geophysics called Multi-channel Analysis of Surface Waves (MASW). Our goal is to develop a new measuring system with a high Technology Readiness Level by transferring the technology from the academic labs to an industrial company.

After reminding the principles of the MASW technique, we will present the main characteristics of the systems developed by these two academic labs. Then we will present the prototype that we designed and built and finally we will show examples of applications.



2 Principles of the MASW technique

The Multi-channel Analysis of Surface Waves (MASW) is a well-known non-destructive acoustic technique used in geophysics to characterize layered media.

The general principle is illustrated in Figure 1. The measuring system is composed of an active source and N receivers, with Δx_1 the source-receiver distance, Δx the distance between receivers and L the total length of the receiving part which is equal to $(N-1) \cdot \Delta x$. In geophysics, the active source is generally a hammer and receivers are geophones. Δx_1 is often equal to Δx which could induce near field effects but which enables to maximize the number of measurements in attenuated media.

In geophysics, measurements are called seismograms. They are presented in a time-distance domain, which can help to identify the different waves propagating in the media, P waves, Rayleigh waves, reflected waves...

The next step transposes measurements in the time-distance domain to a dispersion image in the frequency-phase velocity domain. This can be done by a p-w Transform which is equivalent to a 2D-FFT [1]. The dispersion image indicates maxima which correspond to the experimental dispersion curves. The range of the experimental dispersion curves are deduced from the measuring configuration. The maximum wavelength is defined by $(L/2)$ and the minimum wavelength by $(2 \cdot \Delta x)$ [2]. As the relation between velocity, v , frequency, f , and wavelength, λ , is $v = \lambda \cdot f$, then these wavelength limits are represented by two lines in the frequency-velocity domain and the validity domain of the experimental dispersion curves is included between these two lines. In this zone, experimental curves can be compared to theoretical ones which can be calculated with several available tools. These tools assume that the structure is defined by layers for which at least Young's modulus, Poisson's coefficient and density or pressure velocity, shear velocity and density properties must be defined. For instance, in geophysics, GPDC from the open source Geopsy suite can be used [3]. It assumes that the structure is a semi-infinite medium. The guided wave module of CIVA from CEA [4] or Disperse tool from Imperial College [5][6] are more versatile as they offer more options to define the structure (flat plate or cylindrical geometries, arbitrary numbers of layers, elastic or damped isotropic or anisotropic solid, structure in vacuum, immersed in a fluid, ...).

Finally, dispersion curves can be inverted to estimate properties of the layered medium of the inspected structure, for instance with the Dinver tool in the Geopsy suite [3][7]. In geophysics, the dispersion curve from the surface wave is often inverted to estimate the shear velocity profile with depth. This last information is of interest for the user as it characterizes the depth and the properties of the different layers of the structure.

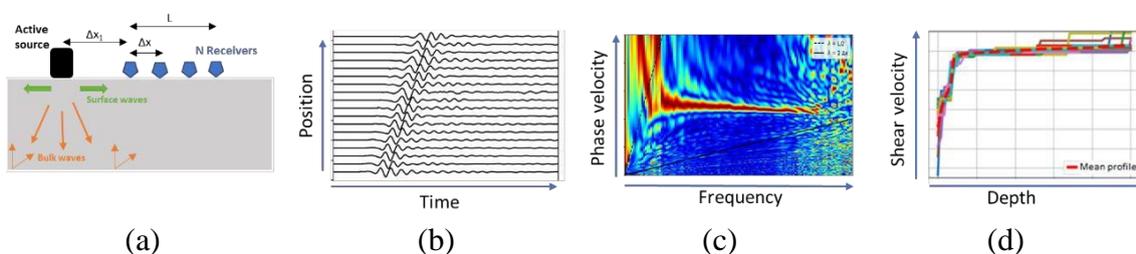


Figure 1: General principle of MASW technique: (a) measuring configuration, (b) measurements in the time-distance domain, (c) dispersion image in the frequency-phase velocity domain with the validity zone between the two lines and (d) shear velocity profile obtained after inversion of the dispersion curve corresponding to the maxima in the dispersion image

3 Existing MASW systems for concrete inspection

Two French laboratories, Ecole Centrale de Lille (ECL) and Université Gustave Eiffel (UGE), have been developing MASW systems dedicated to concrete inspection and especially to concrete cover characterization. Their systems are based on the same principles but they made different technological choices.

ECL has been developing a system based on air-coupled sources and receiver [8]. ECL identified different active sources with complementary frequency bandwidth. To cover a very large bandwidth of [40kHz; 300kHz], ECL uses 3 different sources: [40kHz; 100kHz], [50kHz; 150kHz] and [100kHz; 300kHz]. ECL selected a very large frequency bandwidth sensor for the receiver, [5kHz; 1MHz]. The active source and the rail supporting the receiver are fixed on the structure. The receiver moves automatically from a measuring location to the next one, spaced by a distance of $\Delta x=0.25\text{cm}$, over a spread length $L=15\text{cm}$, corresponding to $N=60$ receiving locations. This way, this system has very close measurement points, independently of the size of the sensors. After the acquisition of all the receiving locations, the active source is manually changed for another one and the acquisition sequence is launched again. In practice, it takes several minutes to cover the total measuring bandwidth.

UGE has been developing a system based on dry point contact sensors [9][10]. UGE selected Acsys P-wave S1803 transducers with a nominal frequency of 100kHz. UGE developed an array of 13 sensors, one is used as the active source and the others as receivers spaced by 5cm. The array is positioned manually on the structure. An acquisition sequence is launched consisting of emitting with the active source and receiving successively with all receivers. One acquisition sequence only takes about ten seconds. The user can repeat the acquisitions after moving the array on the same inspection zone. This enables to perform spatial data averaging so as to increase the coherent part and to decrease the incoherent part of the signal coming from multi-scattering of the wave on the concrete aggregates.

In both cases, specific electronics and computing units were developed. UGE packaged the electronic part in a 1m^3 acquisition rack and recently made a substantial effort to miniaturize the electronic unit producing a new electronic card called Ondulys resulting in size reduction factor of 25. This new electronic device could be used to perform MASW measurements but it is also more versatile because the card has 8 channels which could be used in emission and in reception. Combining the sensors array and the Ondulys module enables to get a portable system which can be used on field.

Both of these two labs process the data in a similar way [11]. They estimate dispersion images. Then, maxima are extracted to define dispersion curves. Inversion is finally processed to get a velocity profile.

ECL and UGE have been using their systems to inspect different concrete samples and structures in different projects. They obtained very positive results in different studies proving that this technique is an efficient non-destructive tool to characterize concrete structures.

4 New measuring system

The aim of our work was to develop our own measuring system which had to be adapted to on-site concrete inspection. It had to be portable, easy to use, fast and with a reduced cost.

We led our developments by combining the advantages of the two systems described in the previous paragraph.

We decided to select the P-wave dry point contact S1803 Acsys transducers as they are adapted to concrete surface. They have a nominal frequency of 100kHz and have a large bandwidth from 10kHz to 160kHz.

One sensor is used as the active source. The first source-receiver distance is equal to $\Delta x=7\text{cm}$ to minimize near field effect. 60 sensors are used as receivers with a space interval of $\Delta x=0.5\text{cm}$ and a spread length $L=29.5\text{cm}$. This configuration enables to get a large validity zone on the dispersion images, limited by $\lambda_{\min}=2.\Delta x=1\text{cm}$ and $\lambda_{\max}=L/2\approx 15\text{cm}$.

As the sensor packaging diameter exceeds the distance between 2 successive receivers, the sensors can't be aligned on the sensor holder. We hence decided to locate them on circular arcs so that the spacing between sensors along the axis of propagation remains as $\Delta x=0.5\text{cm}$ but the inter-sensor distance can be higher. Indeed, as the source is a point-like sensor and the targeted medium is supposed isotropic, measurements at a given distance of the source along any direction should give equivalent signals. This solution was validated by comparing measurements acquired on different samples (concrete samples, steel plate, glass plate) with one sensor fixed at a location as the active source and a second sensor used as the receiver successively moved from a location to another, with a space interval of $\Delta x=0.5\text{cm}$, with the receiver locations first in line and then on circular arcs.

The 61 sensors are mounted with springs in an adapted holder with a dimension of 45cm x 15cm x 15cm that was specifically designed and 3D printed.

We decided not to develop the whole electronic part. We selected the ultrasonic low frequency acquisition unit Acsys A1560 Sonic-LF because it is adapted to the interrogation of dry point contact sensors, it can be remotely controlled and it is autonomous with a built-in battery. This device has 2 channels: one for the emitter and the second for the receiver. As a consequence, we had to develop the multiplexing solution for the 60 receivers. Among the different available multiplexing technologies, we selected 16-channel analog multiplexers. A specific electronic card was designed with 4 multiplexers. A Raspberry-pi (R-pi) unit controls the multiplexing sequence. A tablet computer is used to control the A1560 unit and the R-pi. The computer programs installed on the tablet and on the R-pi were coded in Python. The electronic card and the R-pi are positioned in the sensors holder which is also equipped with two handles and a button to launch and stop the data acquisition process. An acquisition sequence on the 60 receiving sensors lasts about 20s and could still be optimized.

The programs enable not only to perform data acquisitions but also to compute the dispersion image, to extract the maxima and to calculate by inversion a shear velocity profile with Dinver. The A1560 unit and the tablet computer can be installed on the sensor holder but they can also be separated if needed. For instance, the A1560 unit can be installed in a backpack to decrease the weight of the device handled by the user which is around 5kg in total. The weight of the sensor holder could still be optimized.

It took us less than one year from summer 2020 to summer 2021, during the Covid period, to achieve our goal of producing 2 prototypes: the first one to test solutions in lab (TRL 4) and the second one more optimized and integrated which was used in lab and on site (TRL 7).

The Acsys products, S1803 sensors and A1560 unit, were supplied by Acsys through Ralf Demmer. The total cost of the device is less than 16k€ (2020 economic conditions). Figure 2 presents pictures of the final prototype.

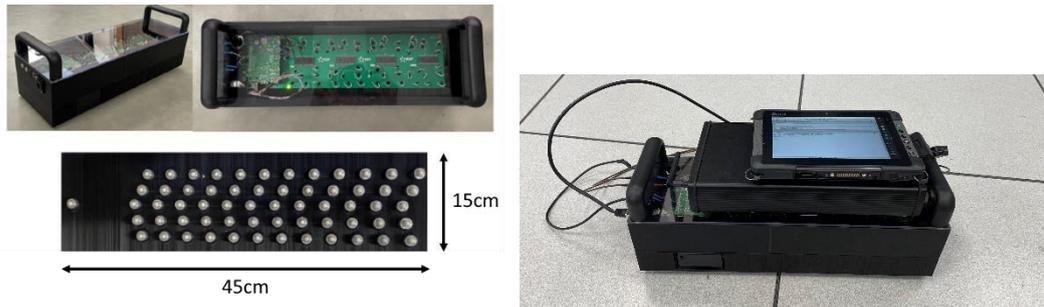


Figure 2: Pictures of the developed measuring system

5 Examples of applications

In the next paragraphs, we will present examples of applications of the measuring system concerning concrete leaching, concrete carbonation and steel corrosion for which the measurements were performed in laboratory.

We also used the system during a multi-technique NDT campaign on a dike which proves that it is adapted to field conditions (cf. Figure 3).



Figure 3: Picture of the measuring system used on field on a dike

5.1 Leached concrete

In specific environmental conditions, concrete can be damaged by leaching effect which causes an important degradation of the surface concrete.

During the PhD of Charles Ciccarone in ECL [12], co-financed by EDF and the French Ministry of Research through the ANR/PIA ENDE project, ECL made some concrete samples leached with a NH_4NO_3 solution. At the end of the PhD, EDF got from ECL 2 leached samples with a dimension of 50cm x 25cm x 12cm. Results obtained with our measuring system are shown in Figure 4. The dispersion curve extracted from the dispersion image calculated by a p-w transform from the measurements was inversed with Dinver. The shear velocity profile shows

a gradient up to a depth of about 1cm which corresponds to the leaching depth determined by ECL.

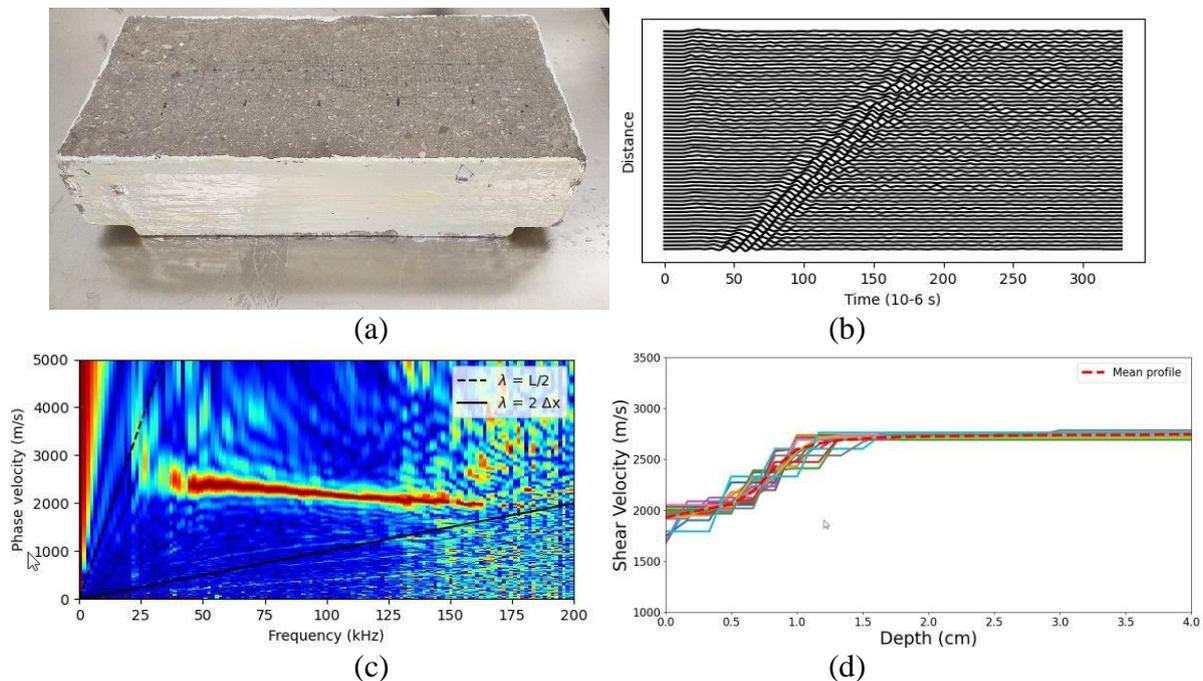


Figure 4: (a) Picture of a leached concrete sample, (b) example of measurements, (c) corresponding dispersion image and (d) shear velocity profile

5.2 Carbonated concrete

In common environmental conditions, concrete is affected by carbonation the depth of which is traditionally measured by drilling and a chemical pH indicator testing. As ultrasound velocity is sensitive to concrete carbonation, a first assumption could be that ultrasound techniques and especially surface waves techniques could be used to estimate the carbonation depth. Unfortunately, this sensitivity is small: velocities in sound and carbonated concrete only differ by a few %, for instance a maximum of 5.5% was observed in [13]. Moreover, ultrasound velocity is also sensitive to concrete water content with a sensitivity of more than 10% [14]. On this basis, it is realistic to assume that a unique ultrasound NDT technique can't assess carbonation depth. But combining different NDT techniques could be a better solution which is investigated through a partnership between EDF and the French laboratory, Laboratoire Matériaux et Durabilité des Constructions (LMDC).

The new measuring system was used to characterize sound and carbonated concrete samples made by LMDC with different carbonation depths varying from 0mm to 33mm. Their dimensions were 50cm x 25cm x 12cm. Examples of results are shown in Figure 5. They correspond to measurements made on samples of sound concrete and 33mm carbonated concrete made with the same formulation. The samples have a global water saturation of less than 20% after spending about 4 months in a heat chamber at 80°C.

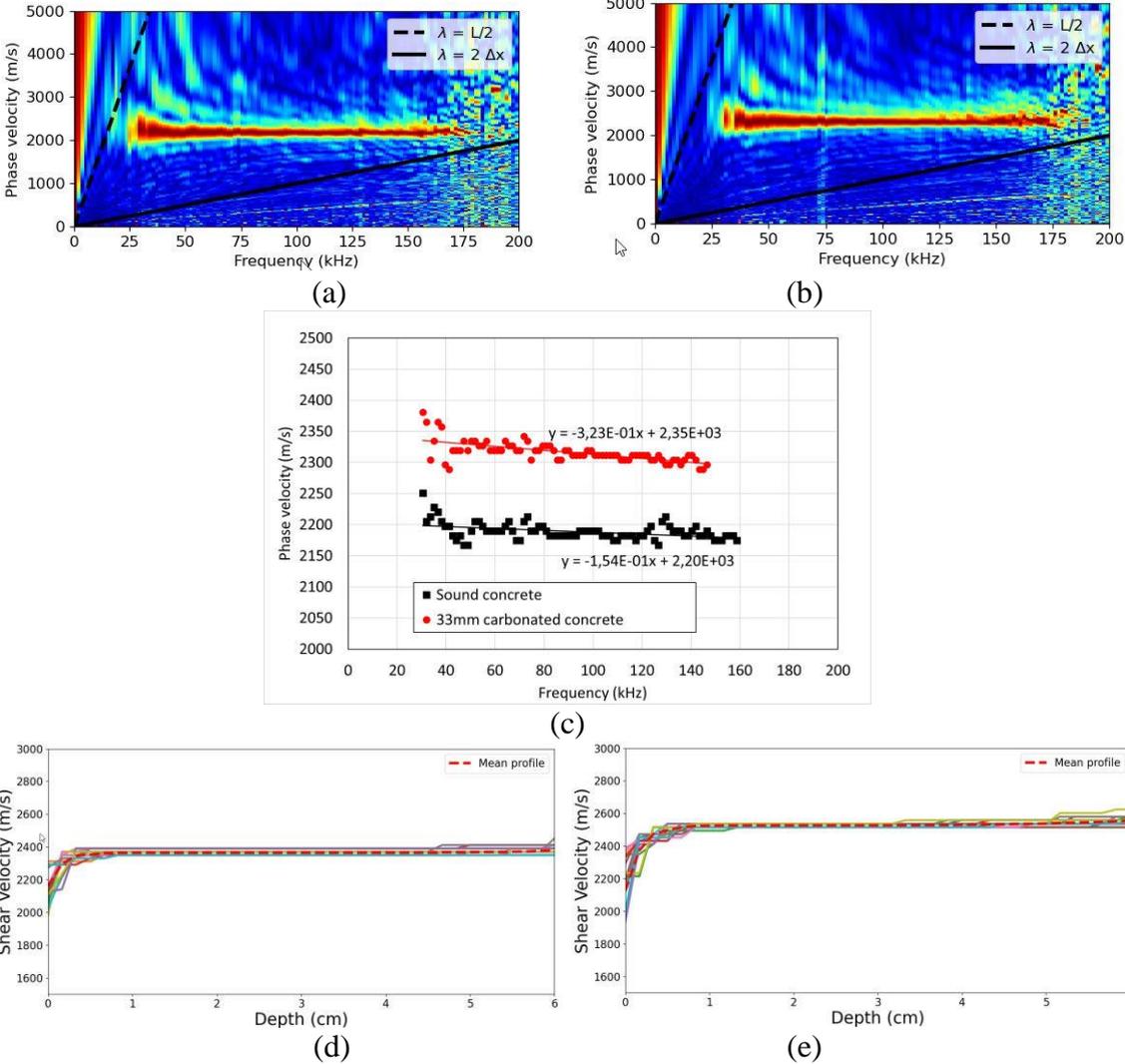


Figure 5: Experimental dispersion images for (a) sound concrete and (b) 33mm carbonated concrete, (c) comparison of the dispersion curves, and shear velocity profiles for (d) sound concrete and (e) 33mm carbonated concrete

Figure 5.c shows the comparison of the dispersion curves corresponding to the maxima extracted from the dispersion images shown in Figures 5.a and 5.b. We observe that phase velocity values for the 33mm carbonated concrete are greater than for the sound concrete, whereas the concrete formulation is the same for the two samples. The two dispersion curves can be approximated by linear functions the equations of which are given in Figure 5.c. The slope value for the sound concrete is small which is coherent with a homogenous media. The absolute value of the slope for the carbonated concrete is greater which is coherent with an inhomogeneous media. Inversion of the dispersion curves in terms of shear velocity profile was performed with Dinver. The results are shown in Figure 5.d for the sound concrete and in Figure 5.e for the carbonated concrete. For the sound concrete, the shear velocity profile shows a gradient over the first 3 millimeters and then a constant value which is coherent with a sound concrete with a slight modification over the first millimeters. For the carbonated concrete, the

shear velocity profile shows a gradient over the first centimeter which doesn't correspond to the carbonated depth of 33mm.

This result confirms that this technique can't be used alone to assess carbonation depth.

The study is on going. Other samples with different carbonation depths and different water saturation values are analyzed not only with this ultrasound technique but also with an electromagnetic technique.

5.3 Guided waves in a corroded steel pipe

Steel corrosion is a major issue in concrete civil engineering as it can affect steel elements embedded in concrete like rebars and liners which contribute to the tightness and the mechanical strength of the structure. Concrete/steel/concrete pipes are used in nuclear power plants to transport water. For sites located near the sea, chlorides in the water diffuse through concrete and can provoke the corrosion of the steel layer. Through a partnership between EDF, CEA and the French laboratory Laboratoire de Mécanique et d'Acoustique (LMA), we are developing NDT techniques to detect perforations in the steel layer and estimate the remaining steel thickness. Ultrasound techniques are studied using bulk and guided waves. One question concerns the ultrasound characteristics of corrosion products as they are filled with air or water.

To bring answers to this question, we had an opportunity to make some measurements on a steel pipe coming from a site by the sea which has transported seawater during several months. As can be seen on Figure 6, the steel pipe is corroded. The corrosion at the outer side is negligible whereas the corrosion at the inner side is very important.



Figure 6: Pictures of a steel pipe affected by corrosion

The pipe was transported on a EDF R&D site for analysis. Bulk and guided wave ultrasound measurements were performed as the pipe was filled with air and spring water. Then some samples were cut to remove the corroded layer and to measure the remaining steel thickness. Results obtained with our measuring system inspecting the same zone in a linear part of the pipe are shown on Figure 7.

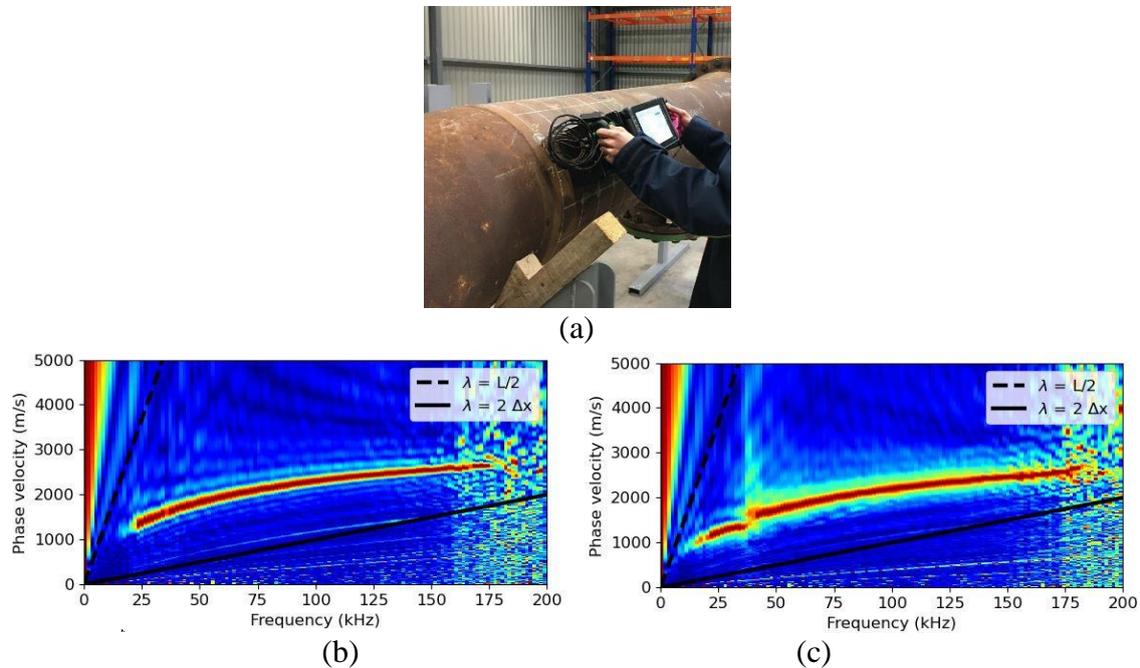


Figure 7: (a) Picture of the measurement and dispersion images as the pipe is filled with (b) air and (c) water

Experimental dispersion curves coming from the extraction of the maxima of the dispersion images are compared in Figure 8. They show discrepancies up to 40 kHz and they are overlapped for upper frequencies. To understand these differences, theoretical curves were calculated with Disperse. As the pipe diameter is far greater than the pipe thickness, the system was modeled by a flat plate configuration. Dispersion curves were calculated for a 1mm steel plate in air and in water (cf. Figure 9). When the steel plate is in water, a specific mode called Scholte mode exists corresponding to a leaky wave mode. For both configurations, A0 mode curves overlapped above 400kHz.mm.

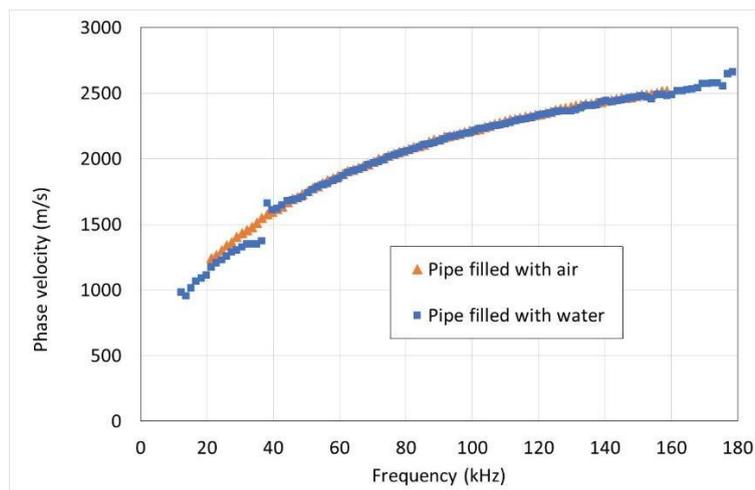


Figure 8: Experimental dispersion curves for the pipe filled with air and water

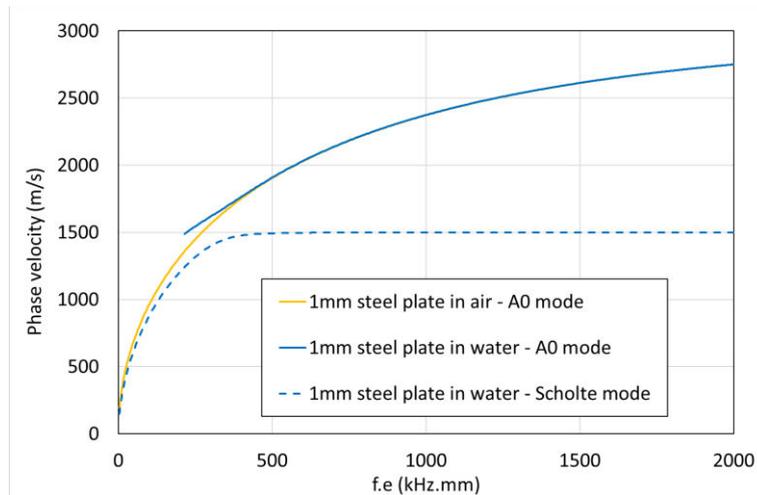


Figure 9: Theoretical dispersion curves for a 1mm steel plate in air and water

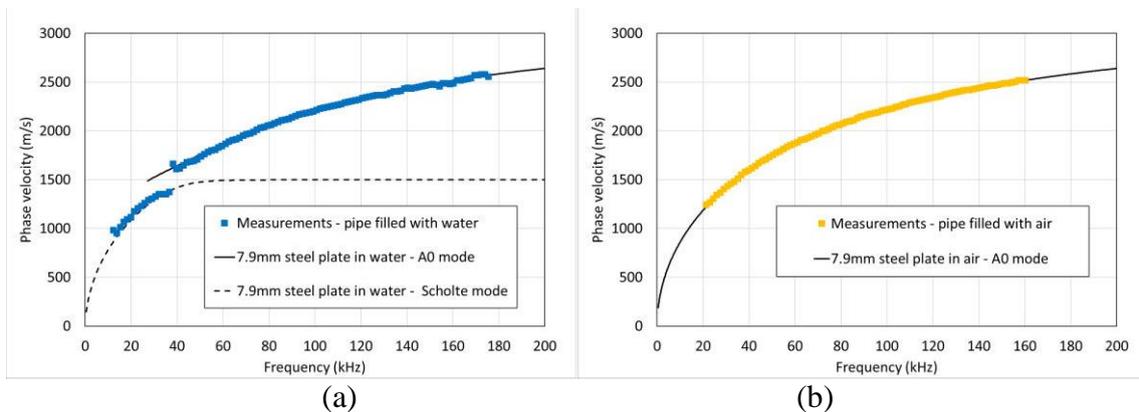


Figure 10: Comparison between experimental and theoretical dispersion curves for the pipe filled with (a) air and (b) water

Optimizing the steel thickness, A0 and Scholte modes explain the experimental results obtained in air and water with a common steel thickness of 7.9mm (cf. Figure 10). This value was coherent with pulse echo ultrasound measurements made on the same location with a 10MHz transducer when the pipe was filled with air and water. Moreover, this steel thickness value was confirmed by destructive analysis. The corrosion product layer has a thickness of several millimeters.

These results confirm that, in the described conditions, ultrasounds are not sensitive to corrosion products. They could be replaced by air or water for modeling purposes.

6 Conclusion and perspectives

A new NDT system was developed to measure surface and guided ultrasound waves to characterize concrete structures. It combines technical advantages of two systems developed by French academic laboratories with the aim of being portable, easy-to-use, fast and with a reduced cost. The designed prototype was already successfully used for different applications on lab and on field. In the future, it could be optimized by, for instance, reducing its weight and its cost.

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