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Università Politecnica delle Marche

Extended summary

Development and testing of an ultrasonic system for non-destructive testing of composite materials with complex shape

Curriculum: Ingegneria Meccanica e Gestionale

Author

Alfonso Cavuto

Tutor(s)

Prof. Enrico Primo Tomasini

Prof. Gian Marco Revel

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Abstract. In this work the problem of Non-Destructive Testing (NDT) on composite components with complex shapes for civil constructions and transport infrastructures was analyzed. In such applications at the state of the art main challenges are related to the inspection of thick sandwiches with low density cores (below 80 kg/m^3) and curved panels. After a review of suitable NDT techniques, an original set-up for low frequency (100 kHz) ultrasonic inspection is proposed, which combines different solutions in through transmission mode. The set-up is based on a hybrid configuration coupling a contact emitting probe with a non-contact air-coupled receiver. The use of a contact probe in emission is necessary to have enough energy to analyze thick components with low density core. The contact between probe and surface is made punctual and smooth using an appropriate spherical cap interface which is inserted over the contact transducer to increase lateral resolution at low frequency and to allow scan on irregular surfaces. The non-contact probe in reception allows a better inspection flexibility on curved and thick components, where pulse echo is not feasible at all. The system is mainly developed for inspection after production in an industrialized production process, where through transmission testing is possible. The analysis of results on two different samples (one thick sandwich with low density 40 kg/m^3, 50 mm thick PUR core and one curved laminate panel) shows that the proposed methods can efficiently inspect construction composites of complex shape with satisfactory Signal-to-Noise Ratio (usually SNR > 15 dB) and lateral resolution (2-3 mm). This paper proposes also an evaluation of an alternative set-up for this particular inspection configuration using a finite element numerical model. The numerical model is used to simulate a rolling ball contact adapter of the emitting transducers in such a way as to evaluate potential improvement of the set-up to generate higher energy transmission. The experimental reconstruction of the pressure field generated from the transducer, achieved by a 3D imaging interferometric measurements, has been used to validate the model of the ultrasonic transducer. The numerical simulation and the preliminary experimental results show the effectiveness of the proposed approach.

Keywords. Comsol Multiphysics, Hybrid Configuration, Mobile Sphere, Tomography, Ultrasound.

1 Problem statement and objectives

Several European projects (such as HP FUTURE-Bridge [1], Safefloor [2] and MEgawind [3]) on the fiber-reinforced polymers for applications in the construction field have shown that the use of these components is very promising with regard to quality requirements, technical and economic feasibility and the favourable impact that they have in terms of sustainability, security and quality of life.
The increase in FRP applications, and the need to satisfy the economic and social constraints, now require a new process of industrialization, which allows the production of composite parts in a flexible infrastructure that covers the entire supply chain .
The research is part of the Trans-IND European Project whose general aims is the development of a new process for the realization of industrialization, through the use of composite materials, the transport infrastructure.
Within this project, the experimental work performed has focused on integration in the off-site production process of a special measurement system for non-destructive testing of the prefabricated elements in composite, ready to be assembled.
Attention has been focused on the detection of defects in composite structureswith innovative flexible and efficient methods. FRP composite components can develop subsurface defects (e.g., cracks, voids, delaminations, disbonds) during the manufacturing process, transportation, construction and/or during the service life, therefore a reliable inspection method is necessary to guarantee a secure application. For in-service evaluation of structural integrity, the current trend is to use embedded sensors (e.g. Fiber Bragg Grating) for Structural Health Monitoring (SHM), but for the inspections after production and on the assembly site a non-destructive testing technique must be developed and used.
Different techniques have been developed and applied to inspect FRP components in the aeronautic [4], automotive and wind turbine fields, as thermography, shearography, ultrasonic phased array, air-coupled ultrasonic, etc.
However, the use of many of these techniques on composite structures for applications in the construction field can be difficult, because of the substantial thickness and complex shapes.
In this work the focus will be on the control of structural elements made of composite materials with complex shapes, such as sandwich panels with a thick core of low density (40 kg/m^3) and curved FRP panels, state of the art elements constitute a limitation for many inspection techniques.
The development of themes in this field leads to a significant step forward in the inspection of sandwich components and the means to optimize and characterize the inspection systems.
Main achievements are:

- the development of an original set-up capable of measuring ultrasonic inspection of thick sandwich elements and low-density core with easily automated systems;
- an alternative configuration to improve flexibility of movement and to increase the energy transmitted ;
- quantitative characterization of transducers and validation of numerical models by laser interferometry tomography.

2 Research planning and activities

After a careful review of the state of the art on nondestructive testing of composite structural components for civil applications and specific defects that characterize them, in the first part of the work different measurement techniques have been compared, highlighting their limitations and the possibilities to use them on these materials. This study has led to the development of an original set-up of measurement constituted by the combination between ultrasonic contact probes in emission and non-contact air-coupled probe in reception (hybrid configuration) and by a dedicated device (spherical cap), to be placed in front of the emission probe in order to make punctual contact with the component to be inspected and allowing an improvement of lateral resolution. The experimental tests have been performed both in Through Transmission mode and in Pulse-Echo mode with and without the use of the spherical cap (see Figure 1).

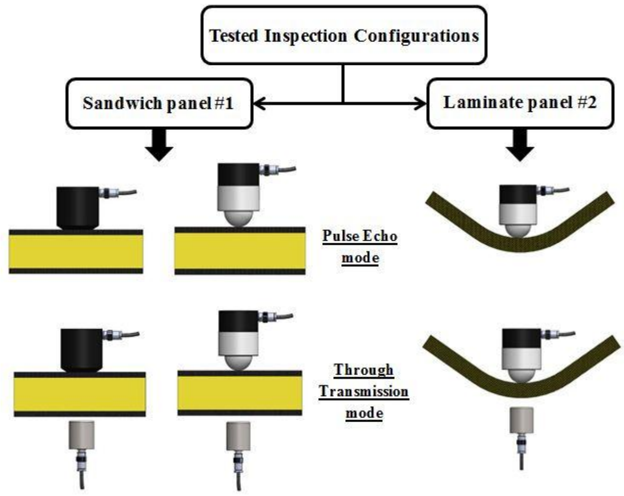

Figure 1. Configurations of inspection

The investigated test samples are fully representative of real structural elements used in civil infrastructures. The tests performed on two of them are here reported, each of them having a specific inspection challenge.

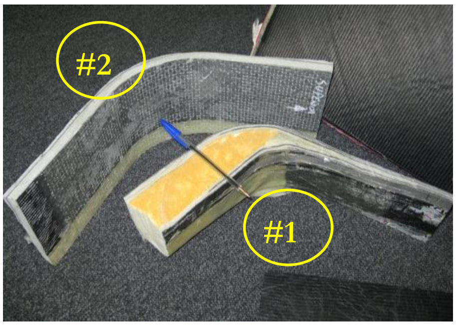

Figure 2. The two test samples

The sample #1 in Figure 2 is a sandwich element with a very low density (40 kg/m^3) of PUR core 50 mm thick and two skins of CFRP and GFRP with about 8 mm of thickness each. In this case the attention is focused on the inspection of the sandwich element and the core at its maximum thickness, which is impossible with techniques as thermography or shearography. This element is very difficult to be inspected also with ultrasonic techniques (in particular to detect delaminations between skins and core) because of the very high thickness, attenuation at the interfaces and irregular surfaces (here surface oscillations can reach some millimeters).
The sample #2 is a laminate curve element with a mix of CFRP and GFRP fibers, the thickness is about 24 mm. In practice this sample is used to evaluate if the proposed hybrid set-up for sample #1 can be used for all parts of the same complex component.
In the sample #1 two simulated defects have been produced by drilling, one defect on the skin (10x2.5x30 mm) and one defect on the core (10x3x30 mm), Figure3. The skin defect starts at 6 mm depth from the planar surface and finished at 2 mm depth and the core defect is 22.5 mm depth from the planar surface.

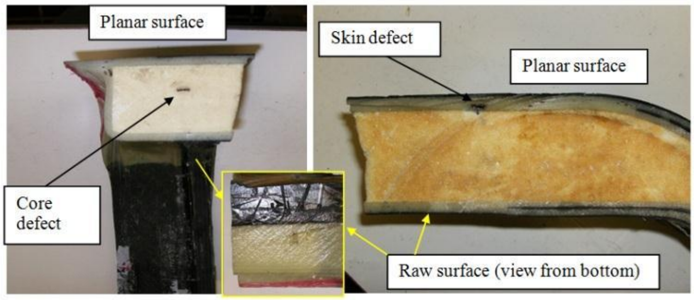

Figure 3. Left, core defect; right, skin defect

In sample #2 a defect with size 11x2x28 mm has been realized in the curved part of the panel at about 12 mm from the top surface, Figure 4.

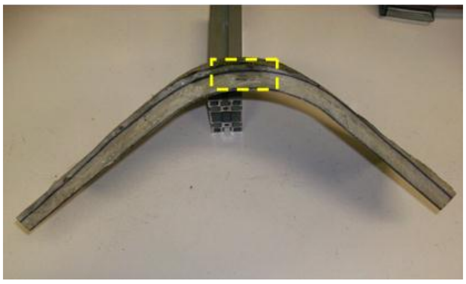

Figure 4. Laminate sample

In a second phase of the research work a finite element numerical model has been developed through the software Comsol Multiphysics. In a first approach the model has been calibrated in the simulation of the pressure field in the air generated by a non-contact ultrasound transducer. Using a finite element approach it is possible to study the interaction of ultrasonic waves with materials and defects, but this requires the observance of very strict rules on the spatial and temporal discretization [5,6,7]. If the dimensions of the component are significant and the used frequencies high, the number of degrees of freedom of the model tends to increase strongly, often making it impossible to solve real problems of propagation [8]. An analysis was performed to determine the maximum dimensions of the elements of the mesh to be used in the model in order to obtain accurate results with acceptable computations times in the desired frequency range. It was made a comparison between two different solvers, one with implicit scheme and the other with explicit. The numerical model was validated through an innovative quantitative comparison with the values obtained from 3D reconstruction of the pressure field using a technique based on Interferometry Laser Tomography [9]. The proposed procedure for the characterization of the acoustic field of the transducer (and model calibration) can be summarized as follows:

1. Laser interferometric measurement of the optical phase shift in time sensed by the interferometer because the refraction index fluctuates along the laser beam path (z direction) from different directions of view;

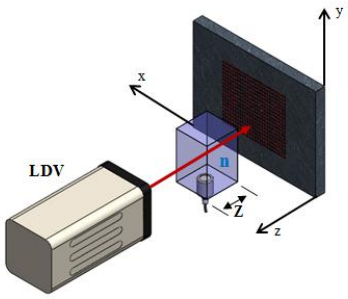

Figure 5. Mach-Zender interferometer configuration

2. Calculation of the optical phase shift volumetric distribution (at each volume position (x,y,z)), from the integral measured over the optical path, by a tomographic algorithm;
3. Determination of the refraction index volumetric distribution as a function of the measured optical phase shift;
4. Derivation of the fluid density and relative acoustic pressure oscillation at each voxel of the measurement volume.

In the last part of the work an alternative improved configuration of the hybrid set-up was studied by using the implemented and validated FE Model. A device with mobile spherical contact has been proposed with the aim of:

- further focusing the ultrasound beam;
- improving flexibility of movement with the possibility to investigate curvilinear profiles.

3 Analysis and discussion of main results

3.1 Results of tests performed with the proposed hybrid set-up

Here the results of experiments performed on the Trans-IND samples are reported highlighting the applicability of the developed hybrid system for inspection of thick and curved composites and sandwiches.

3.1.1 Results on the thick sandwich structures (sample #1)

Pulse-Echo mode: the C-scan maps obtained in pulse echo mode using the contact transducer with and without spherical cap applied on the upper skin are compared in Figure 6. The maps report the RMS (Root Mean Square) signal amplitude, which is thus proportional to attenuation. A gain of 70 dB is used for the acquisition whit and without spherical cap.
In both the maps the presence of the defect on the skin (white area) is easily detectable, in fact the signal amplitude is maximum in the defected area. It is interesting to note how in the right map of Figure 6 the defect is better defined with dimensions closer to real ones. This improvement is due to the addition of the spherical cap which allows to have punctual measurement area with increased spatial resolution.

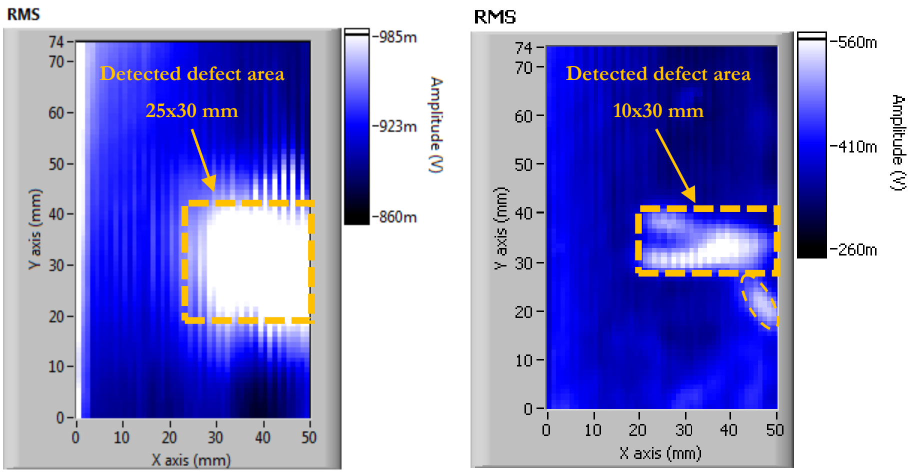

Figure 6. C-scan map, pulse echo mode; left, 100 kHz probe without spherical cap; right, 100 kHz probe with spherical cap

Through Transmission mode: in Figure 7 the maps obtained on the same panel with the hybrid contact/non-contact through transmission configuration are compared for the set-ups with and without the spherical cap (gain 70 dB).
In this configuration, where the signal amplitude at the receiver is attenuated in correspondence to the defects, both damages (core defect and skin defect) have been found with a fast and flexible scan. The size of the two defects are very similar between the maps with and without spherical cap. There is however a clear improvement in the map with spherical cap, where the edge effects are much less evident and artefacts are reduced, thanks to the punctual contact in the emitting probe. Also in this case it is confirmed that the SNR decreases with the spherical cap (from 19 dB without cap to 13 dB with cap), but it is still good enough to detect defects both in the skin and the core.

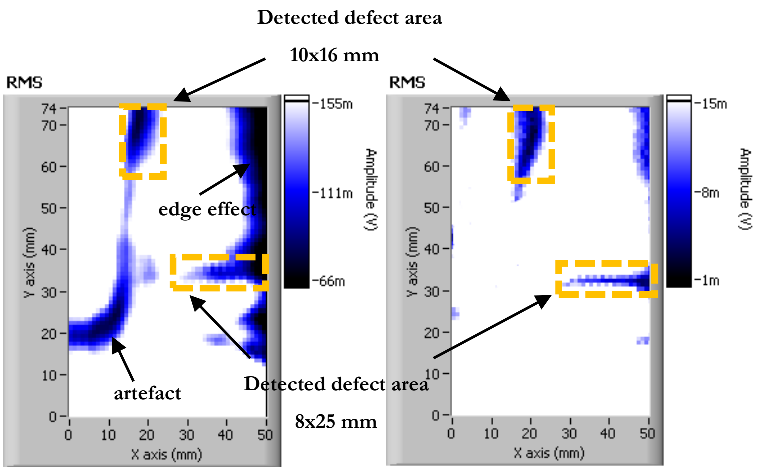

Figure 7. C-Scan map, through transmission mode 100 kHz probes; left, 100 kHz probe without spherical cap; right, 100 kHz probe with spherical cap

3.1.2 Results on the laminate curved panel (sample #2)

Through Transmission mode: the inspection was performed with a step resolution of 1 mm; the inspected area was 30x40 mm. This component could be easily inspected with roller dry-coupled or phased-array probes, but the aim is to assesses suitability for application on curved components with the same approach used for the thick sandwich, so as to have a unique flexible inspection system. The scans were performed in semiautomatic mode since the used system allows only two degrees of freedom in a plane (along x and y axis) so, after each scan line along the y axis, the transducer was manually moved along z and rotated to keep perpendicularity between the probe and the sample surface. A calibrated pre-loaded spring on the probe seat can be easily used to keep the contact pressure constant. Figure 8 shows the plot of both RMS amplitude and Time of Flight (TOF), where the defect is clearly well detected, with the TOF the defect seems even more definite with improved lateral resolution. In this case the average SNR increases up to about 25 dB.

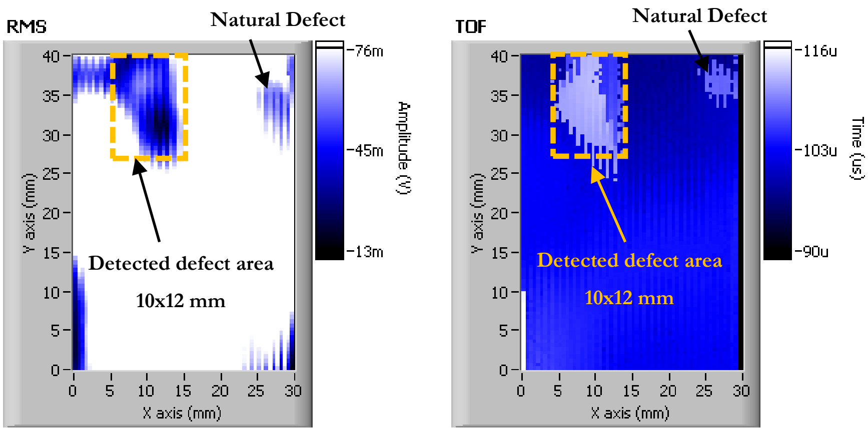

Figure 8. C-scan map, through transmission mode, left map of RMS; right, map of Time of Flight

3.2 Validation of numerical model and simulation of the improved measurement set-up

The maps below show the distribution of the pressure field generated in the air by an ultrasound non-contact transducer with working frequency of 140kHz. Figure 9 shows the 3D reconstruction of the pressure field by means of tomographic measurements and algorithms, while in Figure 10 the pressure 2D field determined respectively by means of tomographic reconstruction (vertical section of the pressure 3D field) and numerical simulation are compared.

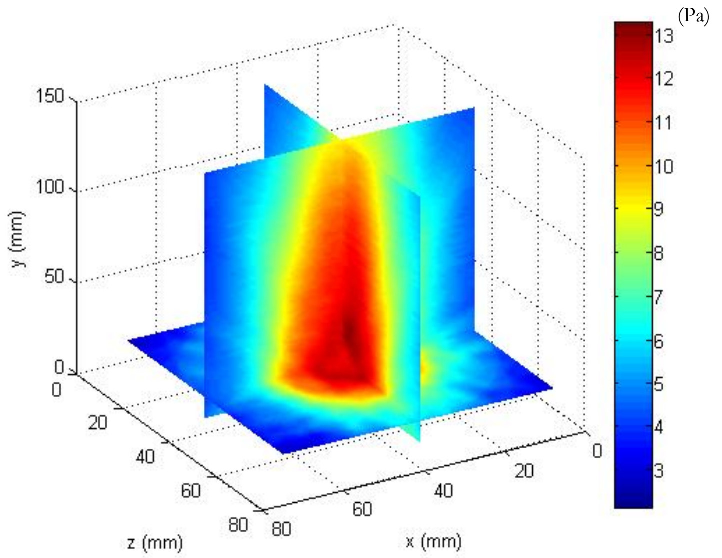

Figure 9. 3D reconstruction of the pressure field by tomographic algorithm

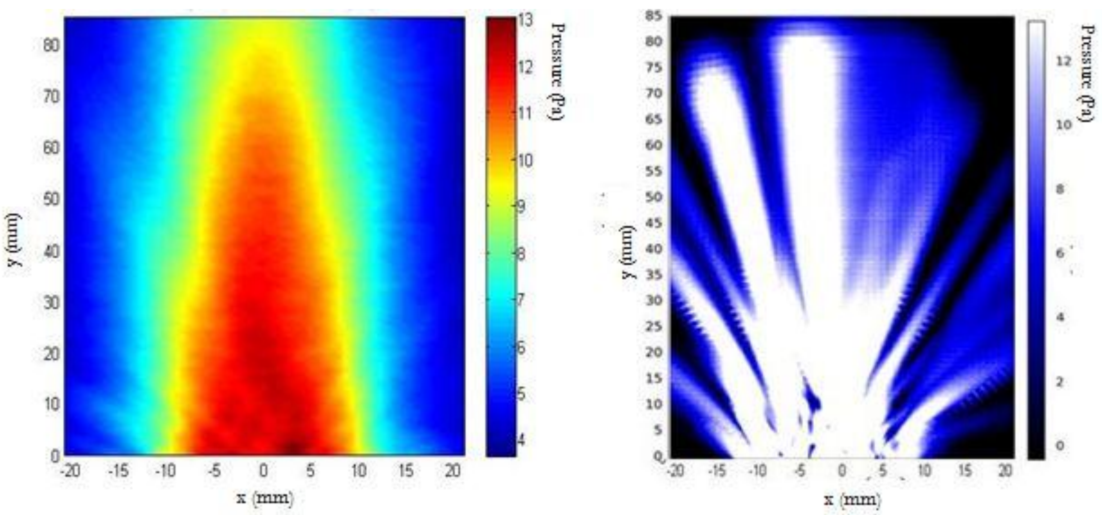

Figure 10. Comparison of 2D pressure fields obtained through: left, tomographic algorithm; right, FEM simulation

However, in 2D simulations only the constructive and destructive interactions that take place on the plane are considered, leaving out the contributions coming from other directions of space. This brings to loose information about the directionality of the beam. To take into account such interactions a 3D model has been realized (Figure 11).

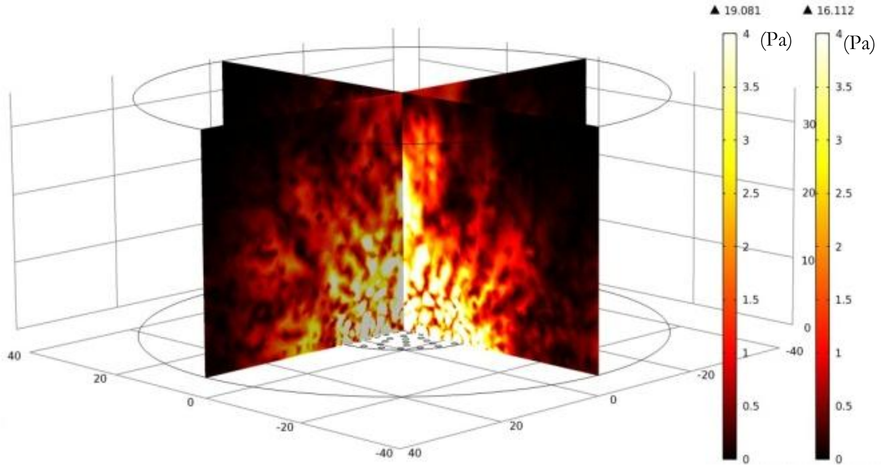

Figure 11. Projection of the pressure field in two orthogonal planes located inside the simulated volume

Using the validated FE Model, an alternative configuration has been studied for the hybrid measurements set-up. In particular it was designed a device with a mobile sphere to be coupled with the contacting emitting probe (instead of the spherical cap). The aim was to improve both the flexibility of movement and the energy transmitted to the component to be inspected. The model allowed to design and investigate a configuration with improved performances, as shown in Figure 12 and 13. In particular it was possible to increase the transmitted pressure of about 25 %.

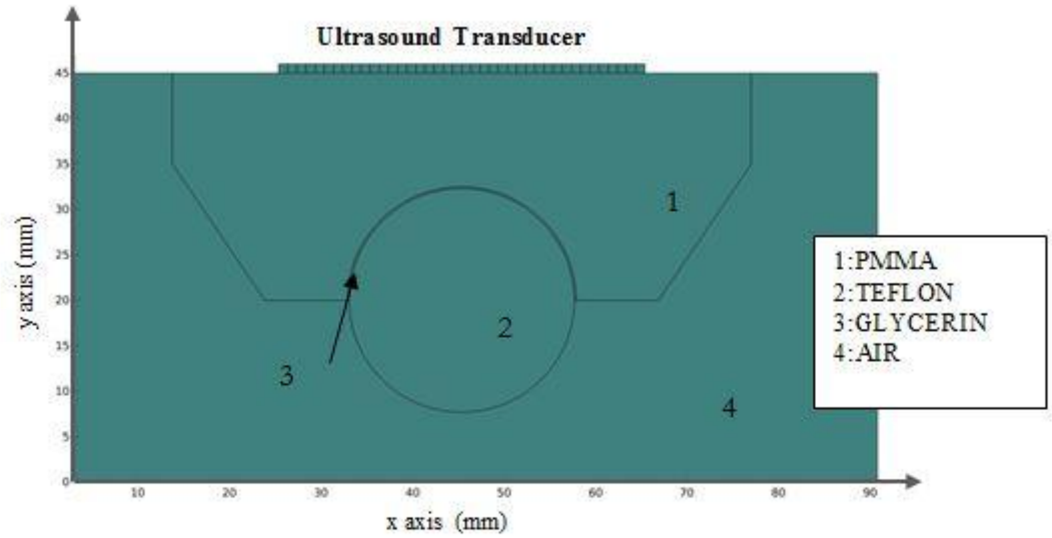

Figure 12. Geometric model

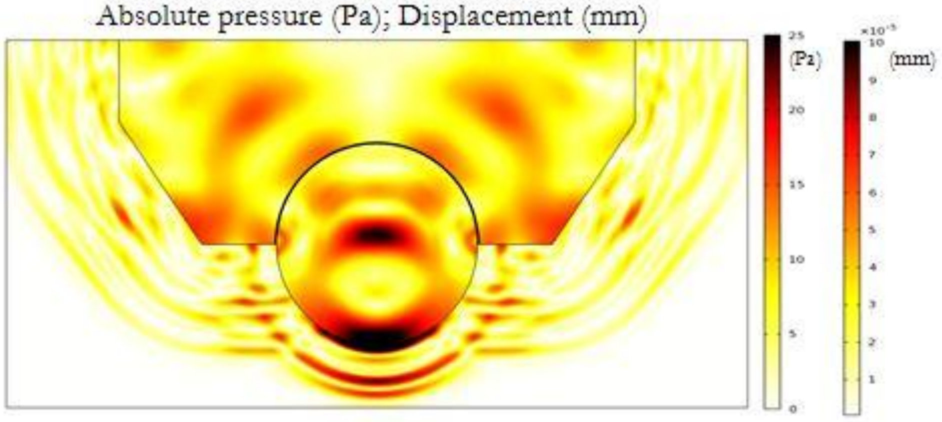

Figure 13. Device with mobile sphere

4 Conclusions

In order to exploit the high penetration of a contact method and the inspection flexibility of a non-contact approach, an innovative combination between contact and non-contact probes (*hybrid configuration*) has been proposed in this work The emitter contact probe allows to have a high ultrasound energy injected trough the material and the non-contact receiver probe allows to have more degrees of freedom to follow up the panel profile, usable with a low weight receive-side manipulator without the need of a squirter water supply, heavy pneumatics or rollers for the contact.
The creation of a dedicated device (spherical cap) to be placed in front of the ultrasound contact transducer has reduced the area of contact with the component to be inspected while maintaining a satisfactory signal to noise ratio (SNR> 15 dB) and a significant improvement of spatial resolution (2-3 mm).
The analysis of simulations of the alternative device with the mobile sphere highlight how , varying the configuration, the geometrical point of view, the materials used, etc.. you get different results. Using materials such as PMMA, Teflon and Glycerin it is possible to increase the value of the pressure transmitted to the air by 25% compared to that with spherical cap. In the future optimization algorithms can be used to make the system more efficient, e.g. introducing objective functions that optimize the geometry. Increments of a few Pascal of acoustic field downstream of the device can be crucial to the detection of the acoustic wave in the core components such as sandwich with low-density (40 kg/m^3).
The comparison between the values of pressure obtained by simulating the pressure field generated downstream of the non-contact air-coupled ultrasound probe, using as input to the model, the velocity values of the membrane measured with a scanning laser vibrometer, with those obtained by experimental method based on interferometry laser tomography have showed the consistency of the results, validating the models adopted in the simulations.
The convergence of the results obtained with the experimental ones allow then to use the models developed in the Comsol Multiphysics to characterize not only qualitative but also quantitative ultrasound beam within the means of propagation, having thus a powerful means of analysis for a preliminary study on the applicability of the transducers on the components to be inspected.

In fact , knowing the pressure values of the ultrasonic wave output from the probe and the values of pressure downstream of the piece to be inspected, it is possible to model the dispersion of the wave in its path and estimate for a given material the maximum thickness inspectable, fundamental information for a company that must choose to install the sensors according to the variety of its production.
Moreover, the characterization of a transducer associated with simulation systems make users more aware of the potential available in order to take into account when designing of the component inspectionability.

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