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PHONONIC CRYSTAL DEVICE AS A SELF-COLLIMATOR FOR LASER INDUCED ULTRASOUND

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ABSTRACT

LASER GENERATED ULTRASOUND HAS GAINED INTEREST AS AN ALTERNATIVE SOURCE OF ULTRASOUND THANKS TO ITS REMOTE OPERATION , HIGH RESOLUTION IN THE EXCITATION AREA AND BROAD FREQUENCY BAND. HOWEVER, ONE OF ITS DRAWBACKS IS THE WIDE-ANGLE DIRECTIVITY. WE PRESENT A NUMERICAL STUDY WHERE THE DIRECTIVITY OF ULTRASOUND PROPAGATION IS CONTROLLED BY THE INSERTION OF A PHONONIC CRYSTAL IN THE ULTRASOUND PROPAGATION PATH. THIS CRYSTAL COLLIMATES THE LASER GENERATED ULTRASOUND AT THE DESIRED FREQUENCY BAND IN METALLIC STRUCTURES AND REDUCES PERTURBATIONS IN THE DETECTED WAVEFRONT, FOR MORE ACCURATE SIGNAL PROCESSING.

RESUMEN

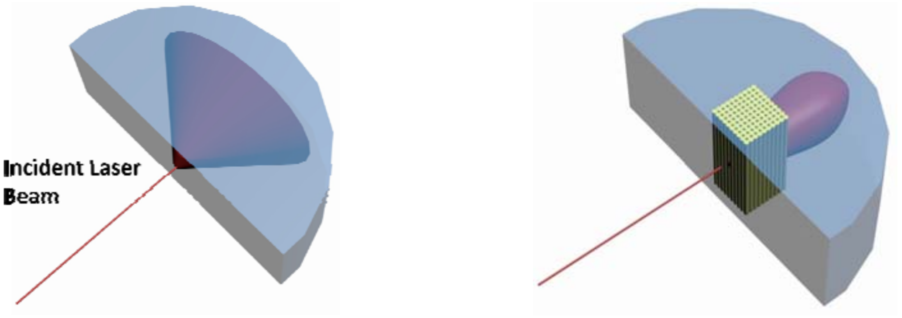
LA GENERACIÓN DE ULTRASONIDOS UTILIZANDO UN LASER SE HA CONSIDERA COMO UNA FUENTE ALTERNATIVA DE ULTRASONIDOS GRACIAS A LA POSIBILIDAD DE CONTROL REMOTO, UNA ALTA RESOLUCIÓN ESPACIAL DE EXCITACIÓN Y UNA BANDA ANCHA DE FRECUENCIAS. UNO DE LOS PRINCIPALES INCONVENIENTES ES SU PROPAGACIÓN CON UN GRAN ÁNGULO DE DIVERGENCIA. EN ESTE TRABAJO PRESENTAMOS UN ESTUDIO NUMERICO DEL POSIBLE CONTROL DE LA DIRECCIÓN DE PROPAGACIÓN DE LOS ULTRASONIDOS MEDIANTE EL USO DE UN CRISTAL FONÓNICO. EL CRISTAL PUEDE COLIMAR EL ULTRASONIDO A UNA FRECUENCIA DETERMINADA, EN UNA ESTUCTURA METÁLICA Y REDUCE ASÍ LAS PERTURBACIONES EN LA DETECCIÓN DEL FRENTE DE ONDA.

INTRODUCTION

A pulsed laser incident onto a solid material may generate ultrasound that could be used, for example, for remote nondestructive testing (NDT) applications as an alternative to typical ultrasound transudcers being used as exciters. As important advantages, with respect to the classical transducer-induced ultradsound, the laser generated ultrasound (LGU) has a more flexible and accurate targeting of the excitation, it is very broadband in frequency, it is noncontact and can be remotelly controlled. However, LGU directivity is difficult to control as it depends on many factors such as the intensity of the laser pulse, the wavelenght, the interaction regime and the material [1–4].

Once the ultrasound is generated in thermo-elastic or ablation regimes, its directivity pattern is broad and wave energy is spread at different angles inside the material in which it propagates. Those diverging waves cause major problems in NDT studies for crack detection due to their interference with the reflections from boundaries of the object under test. As a consequence the signal detected corresponds to a complex wave containing various components that could hide the information of interest or make it difficult to interpret the recorded data. The ability to direct these ultrasound waves at certain angles, for instance far from boundaries or to propagate in a direct path towards the receiving transducer would be a good enhancement to the performance of LGU. The recorded signal would be potentially easier to interpret thanks to the removal of the interfering scattered and reflected components from boundaries. Dispersion relations for propagation modes are modified in Phononic Crystals (PC) in such a way that ultrasound waves can propagate without diffraction broadening [5,6]. This phenomenon is known as self-collimation and can be used to control the propagation of ultrasound waves and directivity of sources [7]. PC properties have been extensively studied in the past two decades and a lot of interesting results have been discussed in literature [8–11]. In this work we design, and conceive a PC for the control of the directivity of LGU propagating in a solid media (aluminium). We aim to generate an enhanced spatial wave-front profile, propagating at the desired direction.

In our study we consider a 2D PC, consisting in a periodic distribution of cylindrical holes (air) drilled in an aluminium block arranged in a square periodic lattice. Fig.1 shows a scheme of the directivity pattern control by the insertion of the PC (fig 1b) in comparison to the reference case of LGU freely propagating in the material (fig 1a). In order to achieve the self-colimation regime [12], we design the PC parameters (filling factor and radius of the scatterers) to provide near zero-diffraction at a specific working frequency.



a) b)

Fig.1: Schematic representation of the metal structure under test where ultrasound waves are excited by laser a) freely propagating in the medium and b) self-collimated by an embedded PC.

Here we present a theoretical simulation of the wave propagation in the solid material due to the presence of PC using Finite Element Method (FEM) via Comsol and Matlab software.

Numerical simulation and PC design

We consider aluminium as the elastic media where ultrasound is excited by a punctual source representing the laser pulse excitation. The PC is designed to be embedded in the sample, consisting in cylindrical holes (air) drilled into the aluminium. The lattice symmetry is square, as can be seen in Fig. 2 where the unit cell is shown. We solve the elastic equations in the solid by discretizing with simulations based on the finite element method. The aim is to design an appropriate two-dimensional PC in order to achieve self-collimation. In the analysis, a study of the effect of the filling factor on the mode shapes in the unit cell is considered. Different PC with scatterers varying between 2.5mm and 3.5mm are considered and its dispersion curves, and equifrequency contours are calculated.

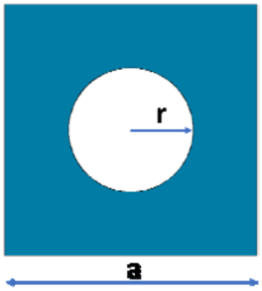
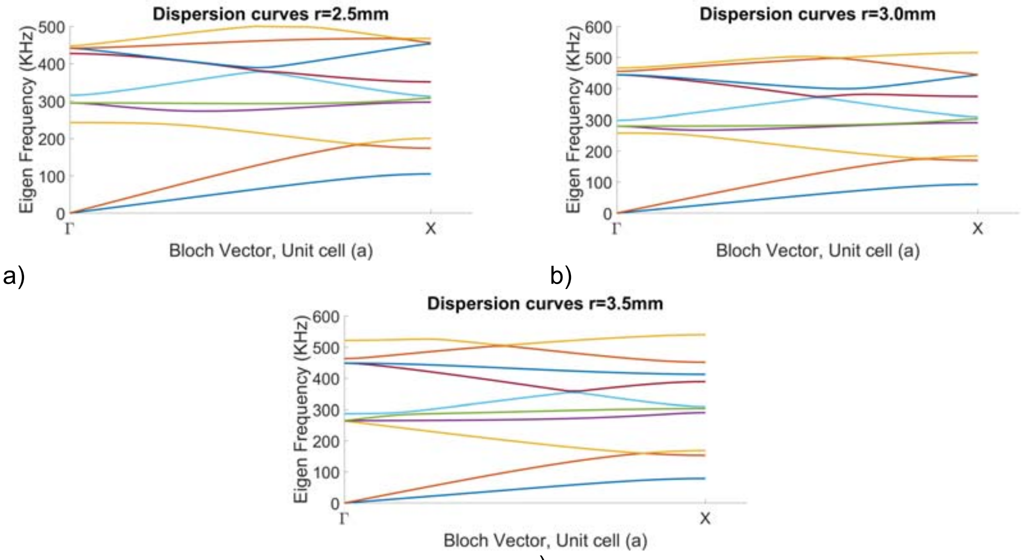


Fig.2: Unit cell of the 2D PC.

A dispersion diagram contains the propagating frequencies at a certain wave number k_x, or k_y. This shows the nature of propagation at the Brillouin zone. Equifrequency contour maps are plots that identify the intersection of a specific frequecny with a dispersion surface, by applying this plot strategy to all allowed frequencies of propagation, we get a complete equifrequency contour maps across all wavevectors.The importance of these equifrequency contours is their ability to determine the direction of propagation of the wave corresponding to a wave vector. Any flat contour line would mean that all these wave vectors are going to pass without suffering any diffractions, hence the concept of self-collimation [12–14]. We create a frequency domain analysis for the selected filling factors.

The dispersion relationship in a PC is considering all propagating frequencies at a specific wave number k. by scanning across all wavenumbers inside the Brillouin zone, we can find that the dispersion relationship is composed of discrete bands formed due to the periodicity of the medium. Depending on the dimensions and shape of the PC, some frequencies are forbidden to propagate in certain wave vector directions. This feature is referred to as Bragg gaps. They appear due to the destructive interference of scattering waves because of the inclusions. If all frequencies are forbiddien to propagate at all directions, it is called band gaps. If they are prevented to propagate at specific directions, they are called band stops [15]. The dispersion relationship calculations for three different radii are shown in Fig.3. It is found that large complete bandgap is available at r=2.5mm at bragg frequency band 250-280KHz.

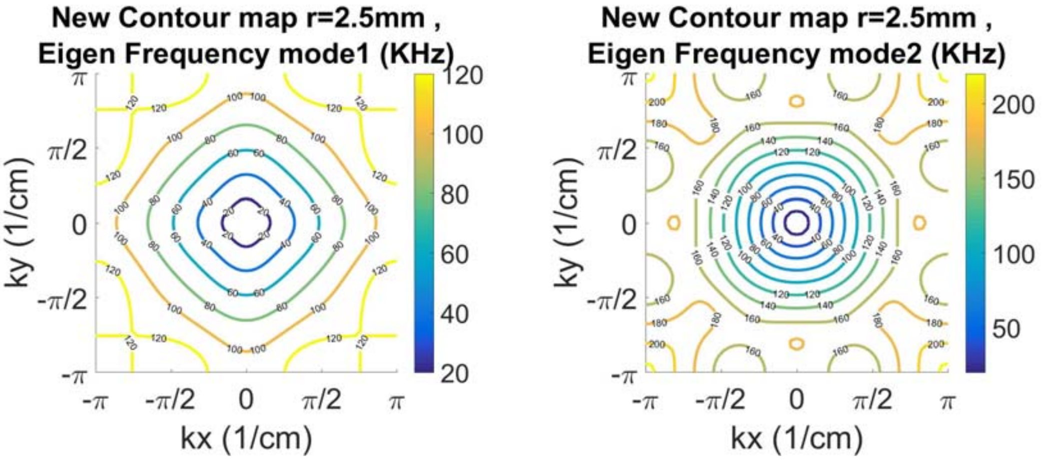


a) b)

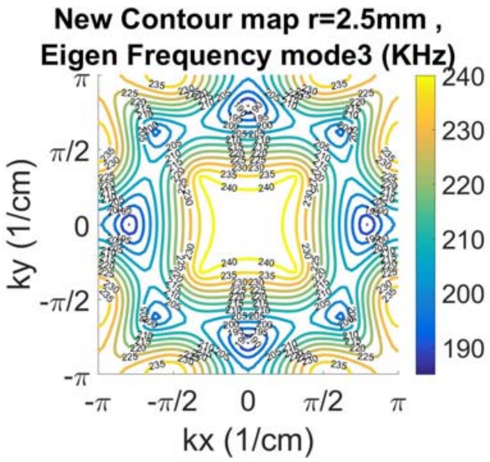
c)

Fig.3: Dispersion curves for the various radii of the unit cell a) 2.5mm b) 3.0mm c) 3.5mm.

We calculate the equifrequency contours for the selected 3 filling factors (r=2.5,3.0,3.5mm). It is found that the best self-collimation conditions are at 2nd and 3rd modes with radius r=2.5mm compared to the other cases. Fig.4 shows equifrequency calculations.



a) b)


New Contour map r=2.5mm , Eigen Frequency mode3 (KHz)

c)

Fig.4: Equifrequency mode calculations for selected radii a) mode 1 b) mode 2 c) mode 3.

We analyze the frequency response of a configuration where the laser excitation in the medium is represented by a harmonic displacement punctual excitation source in x direction and the crystal is a finite periodic arragement of 20x20 elements embedded in the medium as shown in Fig. 5. Scatterers are circles of radius r= 2.5mm and the lattice constant a is 10mm. The filling factor is: ff=0.2 where:

$$\mathit{fillingfactor}(ff) = \frac{\pi r^2}{a^2} \tag{1}$$

A displacement point is placed between the source and the crystal and a displacement point behind crystal for the analysis.

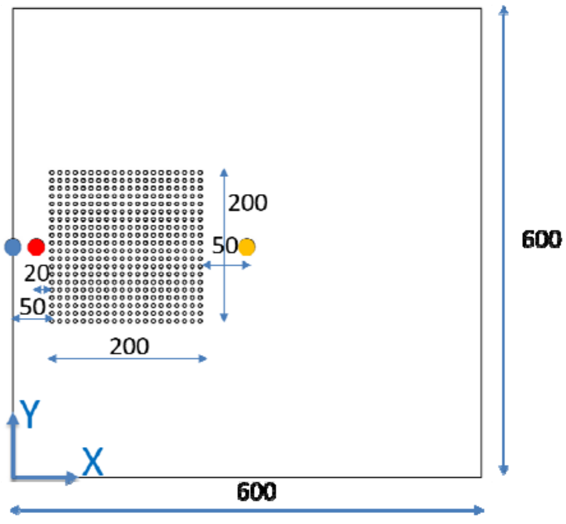
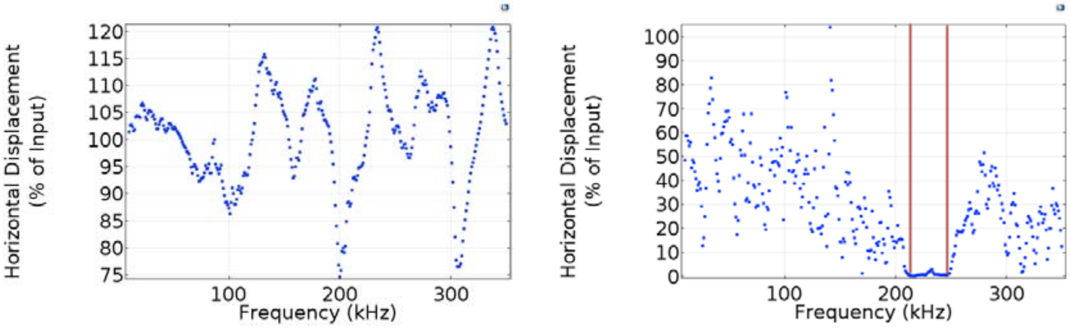


Fig.5: Numerical scheme used for the frequency analysis, including a point source (blue circle), displacement measurement point before crystal (red circle) and displacement output point behind the crystal (orange circle), all dimensions are in mm.

The frequency spectrum of the horizontal displacement propagation is shown in Fig.6 at positions before and behind crystal with an input horizontal displacement where the band gap appears clearly between the two red lines. A bandgap appears between the two red lines in the frequency spectrum after the crystal in Fig.6b. The points where the measurements taken after the crystal were at a distance of 50mm as shown in Fig.5 (orange circle) while the point of measurement before the crystal was at 20mm distance as shown in Fig.5 (red circle). By comparing these resutls of Fig.6b and Fig.3a we can see the agrrement of the band gap frequencies.



a) b)

Fig.6: frequency spectrum a) at 20mm before the crystal and b) at 50mm after crystal of the horizontal displacement propagation with an input horizontal displacement.

Free propagation of waves in the medium is shown in Fig.7. The X Displacement Propagation after the insertion of the PC in the wave path of propagation at various frequencies is shown in Fig.8. It is also shown for frequency 110KHz, in Fig.8a, a relatively high signal amplitude is available at the propagation path after crystal. This high amplitude gets higher at frequency 140KHz in Fig8b and is reduced significantly until it reaches the complete bandgap. This is shown in Fig.8c at frequency 240KHz. Later the wave exits the bandgap and we can see again propagation at higher frequency modes where a lot of transverse and longitudonal waves combine and the problem gets more complicated. This is shown in Fig.8d at frequency 330KHz. However; we are not concerned with these high frequency modes. Our main focus is on the first 3 frequency modes. These amplitude fluctuations are in agreement with the frequency spectrum in Fig.6b.

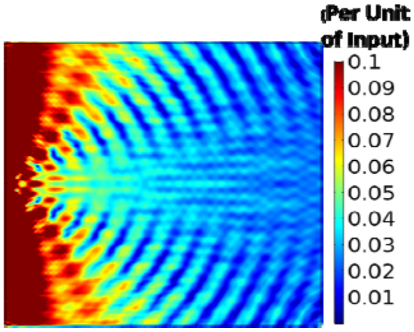


Fig.7: Horizontal input displacement propagation without phononic crystal.

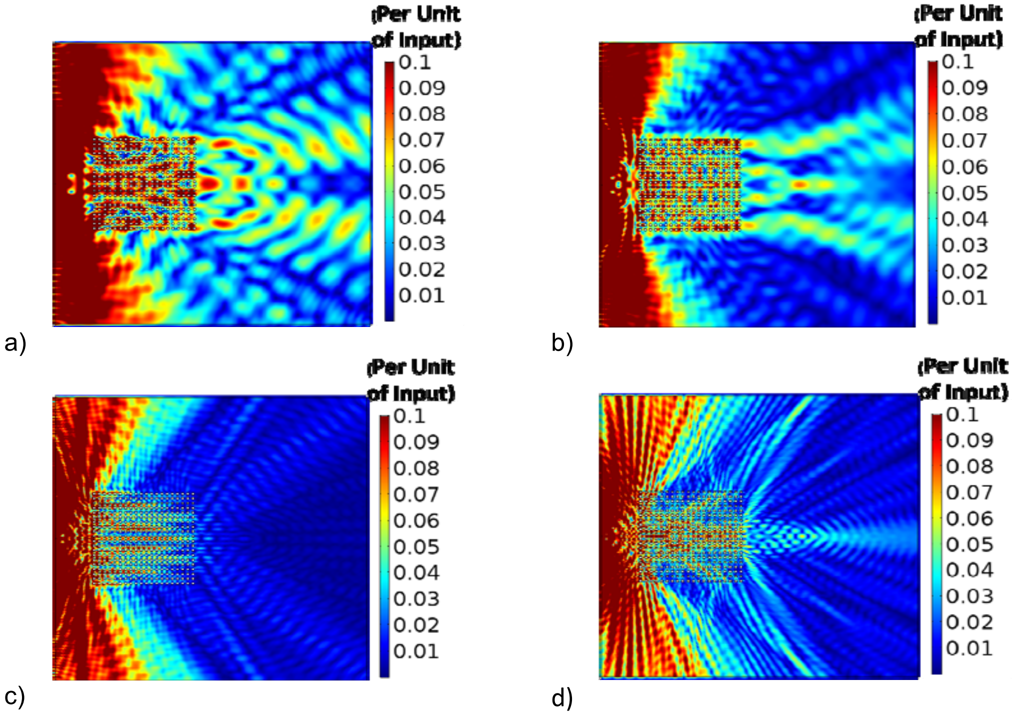


Fig.8: Horizontal displacement surface propagation at frequency a) 110KHz b) 140KHz c) 240KHz and d) 330KHz.

By comparison of both cases, with and without the addition of the PC, we can see that the waves propagates in spherical shape without any wave directivity guidance, in Fig.7 and in Fig.8 it is shown clearly that the directivity of the propagating signal is controlled by the PC and the self-collimation condition is achieved.

CONCLUSION

In this study, a strategy based on the dispersion of waves in periodic media for the control of laser generated ultrasound waves on an aluminum sample is proposed. Numerical simuations show that the directivity of the source is enhanced by concentrating ultrasound energy in a certain angle at a specific frequency range. Controlling the directivity of the LGU and generating an enhanced spatial wave front profile can be very useful for NDT purposes for the purpose of crack detection. These applications of NDT are facing difficulties to analyze the received ultrasound signals containing mixture of the useful signals representing the cracks buried with a lot of unuseful signals due to the perturbations from boundary conditions and multiple reflections.

ACKNOWLEDGEMENTS

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