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Selective mode focusing in a plate of arbitrary shape applying time reversal mirrors

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Abstract
In this paper, a time reversal mirror is used to remotely focus symmetric or antisymmetric modes in a plate of arbitrary shape without the need of precise knowledge about material properties and geometry. The addition or subtraction of the forward motions recorded by two laser beams located on both sides of the plate allows, respectively, to focus a symmetric or an antisymmetric mode. The concept is validated using experimental and numerical analysis on an aluminum plate of complex machined geometry which exhibits various thicknesses as well as a bi-materials zone. The limitations and possible ways to overcome them are then presented.

I. Introduction
Time reversal is based on the invariance of the wave equation by time inversion. A pulse wave propagating from an emitter to a receiver can be time reversed (t → -t) and sent back from the receiver. Even if this wave has been reflected several times by eventual scatterers and boundaries, the time reversed waves will follow backward the forward path, producing a focalization (reconstruction of the initial pulse) at the exact location of the initial source. This physical principle has been widely employed and developed for medical applications [1] but also in various fields of material physics. For example, it is employed to focalize highly localized energy in time and space probe or locate material elastic nonlinearities [2-4]. Lamb waves [5] are produced in plane plates depending on the frequency and the thickness of the plate. Two different kinds of mode exist, namely symmetric and anti-symmetric. Symmetric modes refer to an opposite out-of-plane displacement of both sides of the plate while an antisymmetric one refers to bending or shear motions. The study of their propagation is of interest in a wide range of topics including material science, metamaterials, [6] with applications to several fields such as aeronautics [7]. Most of them are related to Non Destructive Evaluation (NDE) [8] with the goal to evaluate plate properties, detect and locate defects [9,10]. The main advantage is that these guided waves can propagate over tens of wavelengths from the source with very low energy losses compared to bulk ones. However, from a practical point of view, due to their dispersive nature, as soon as the geometry departs from an infinite plate with constant thickness, it is difficult to predict which kind of Lamb wave is going to propagate through a localized geometry change. Park investigated the possibility of selective generation [11] of symmetric and antisymmetric mode using two transducers glued on each side of the plate to generate only in phase (S0) or out of phase (A0) waves. This approach succeeded in a homogenous plate of constant thickness.
The aim of this paper is to make use of the properties of time reversal to focus, at a prescribed location, a symmetric or an antisymmetric mode on a plate of arbitrary shape without precise requirements on the knowledge of the thickness or dispersion curves using simple signal processing. Focusing of antisymmetric or symmetric modes is achieved by a subtraction or addition of forward out of plane motions recorded on both sides of the plate. The following details the experimental procedure, shows the validity of the method using experimental data and numerical simulation.

II. Materials and methods

An aluminum plate is arbitrarily machined to produce a complex shape with various thicknesses (Fig.1). The bi-material is labeled Z3, where a plexiglass plate is glued on side 2. Four piezoelectric transducers glued on the plate are driven by a multichannel system connected to high voltage amplifiers (TEGAM 2350 with a ×50 gain). Thanks to the reciprocity principle [12], the focalization can be achieved even if the time-reversed signals are sent back to the sample from the initial sources. This principle is employed here using two laser vibrometers (Polytec OFV 5000, 1.5 MHz bandwidth) as receivers to record the out-of-plane component of the particle velocity at the same location on both sides (surfaces) of the plate. In order to scan the zones of interest, the plate is mounted on a Newport synchronized motion controller allowing to move on the (x,y) plane (Fig.1). The forward signals recorded on both sides are subtracted or added to produce, respectively, an antisymmetric or a symmetric mode. Note that for each laser, a positive sign of the particle velocity corresponds to the outward-pointing normal surface. At generation, the maximum reachable sampling frequency by the multichannel system is 750kHz. According to the Shannon principle, the maximum frequency employed in this study is set to 350kHz. Within such a frequency range, regarding the thicknesses of the plate (5 to 10 mm), the higher frequency-thickness product ranges from fd = 3.5 MHz.mm to 1.7 MHz.mm. It is worth noticing that the out-of-plane displacement is dominant for antisymmetric modes. However, for symmetric modes, especially the S0 mode [13], the out of plane displacement becomes dominant from fd = 1.5 to 2 MHz.mm. At lower values of fd, the in-plane displacement is noticeably larger. For that reason, using a chirp coded procedure, the 10kHz-175kHz range is selected to focus antisymmetric mode, and 175kHz-350kHz is used to favor symmetric ones.

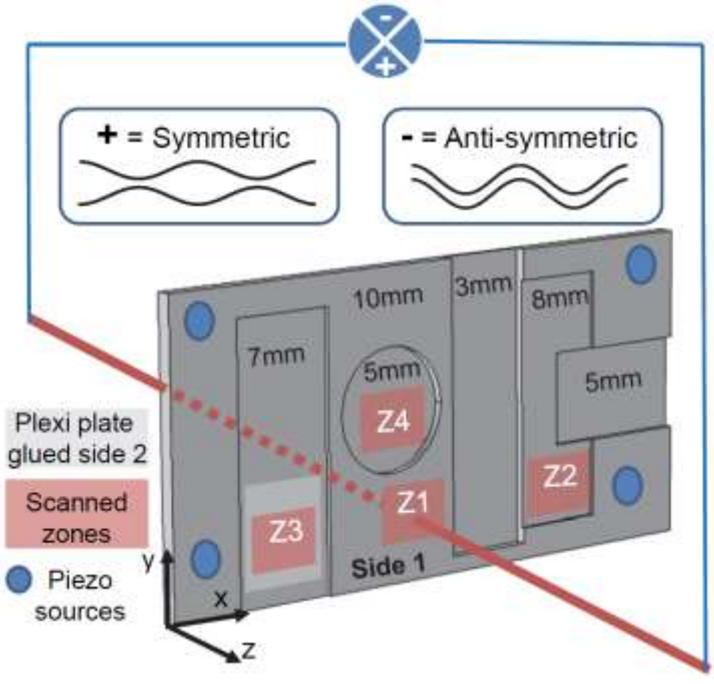

Fig. 1. (Color online) Experimental and numerical scheme.

III. Results and discussions

The validity of the proposed approach was first demonstrated by numerical simulations using an approach similar to that described by Remillieux et al. [14]. Simulations were carried out in the time domain and in 3D using the "Structural Mechanics" module of the commercial finite-element software package COMSOL Multiphysics 5.2a. The geometry file used to machine the plate was imported into

COMSOL using the built in mechanical properties of aluminum and plexiglass (acrylic plastic). That leads respectively to a Young modulus of 70 and 3.2 GPa, a density of 2700 and 1190 kg/m^3, a Poisson ration of 0.33 and 0.35. The computational domain was discretized into quadratic tetrahedral elements with a maximum element size of 1.5 mm, which ensured at least 6 elements per smallest wavelength for the highest frequencies involved in this study. The numerical solutions are integrated in time with a time step of 100 ns using the Generalized-α method [15], which is a fully implicit, unconditionally stable, and second-order accurate method with control over the dissipation of spurious high-frequency modes. The time step is small enough to satisfy the Courant–Friedrichs–Lewy stability condition. Four individual forward problems were simulated for each of the four source positions depicted in Fig. 1. For each source, a normal load with the time history of a Ricker wavelet centered on a frequency of interest f_0 (the frequencies considered in the experiments) is applied on the source region (blue disks in Fig. 1). As the disturbance generated in the source region propagates throughout the plate in the form of elastic waves, the normal component of the particle velocity is recorded on the top and bottom surfaces of the plate, at the center of the Z1 region. The forward propagation is recorder during 1ms. For each source, the complex responses recorded in the zone of interest on the top and bottom surfaces are i) summed or subtracted depending on which type of mode needs to be focused, ii) time reversed (this operation will be indicated as TR in the text), iii) and emitted from the source. During the TR step, all four sources are activated at the same time. The TR propagation is recorded during 1.1 ms in order to ensure that the full focus is recorded. The comparison of numerical simulation and experiments at the Z1 zone is shown Fig.2 (a-b). A very good agreement is found, which validates the approach. Moreover, the S0 wave structure shown Fig.2 (c), is very similar to those described by Rose [13] for an S0 mode at high fd product. It is worth noticing that a broadband signal is used in numerical simulations, unlike the theoretical wave structures in [13] given for a single frequency.

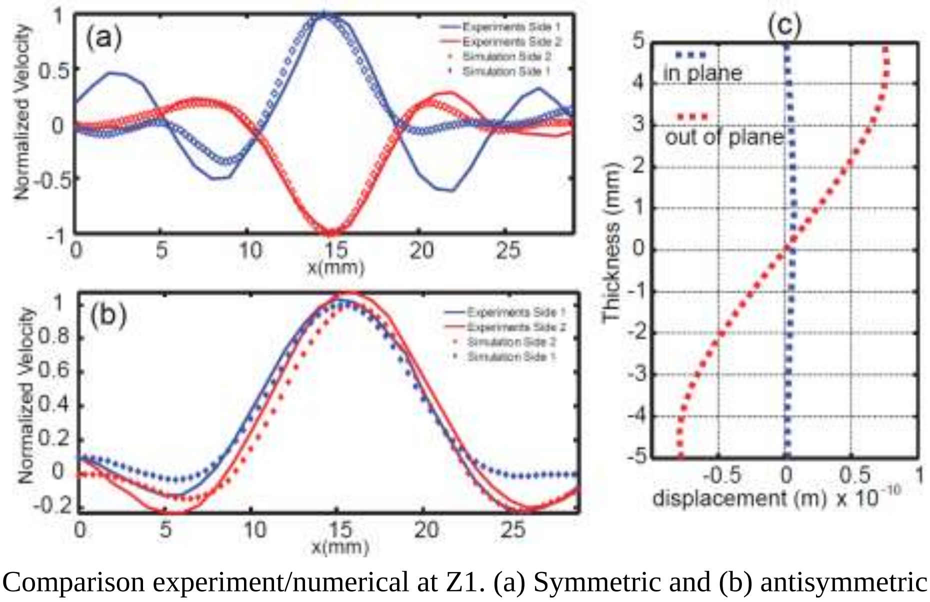

Fig.2. Comparison experiment/numerical at Z1. (a) Symmetric and (b) antisymmetric mode focusing. (c) Numerical wave structure (displacements) over the thickness of the plate for the symmetric mode.

The full set of experimental results are shown from Fig.3 to Fig.6 for zones Z1 to Z4 respectively. The surface map of the particle velocity on both sides of the plate (labelled b and d) as well as a slice along the x axis (labelled a and c) are shown for both symmetric (left panel) and antisymmetric (right panel)

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modes. In every case, the antisymmetric mode is successfully focused. For Z1 and Z2, the fd product is sufficiently high to focus the S0 mode.

For Z3 (Fig.5), where a 3mm plexiglass plate is glued on side 2, the S0 mode is also well focused. The amplitude difference is mainly due to the fact that the lasers measure the particle velocity. Under the plane wave propagating in a three-dimensional infinite medium approximation, one can approximate the strain amplitude as the particle velocity divided by the speed of sound. The ratio three found between particle velocities amplitude side 1 and side 2 corresponds to the speed of sound ratio between the aluminum (about 6000m/s) and plexiglass (about 2000m/s). An antisymmetric mode is also well focused without amplitude variation because the bending or shear motion is dominated by aluminum which drives the plexiglass plate.

For Z4 (Fig.6), the antisymmetric mode is successfully focused. However, in that case, the fd product is 0.9 MHz.mm at central frequency. Within such a frequency range, the maximum amplitude difference at focal point is produced for two neighboring antisymmetric modes with high out of plane displacement (Fig.6).

Even if the experimental setup employed in this study does not allow to focus any mode anywhere in that plate, these results suggest possible improvements. The first one is of course a higher frequency generation system. The second is the adjunction of a differential laser, or the use of a three-dimensional laser, to simultaneously probe in plane and out of plane motions. Knowing precisely the ratio between the two motions for a given fd product, one could focus the S0 mode with a single side access to the plate.

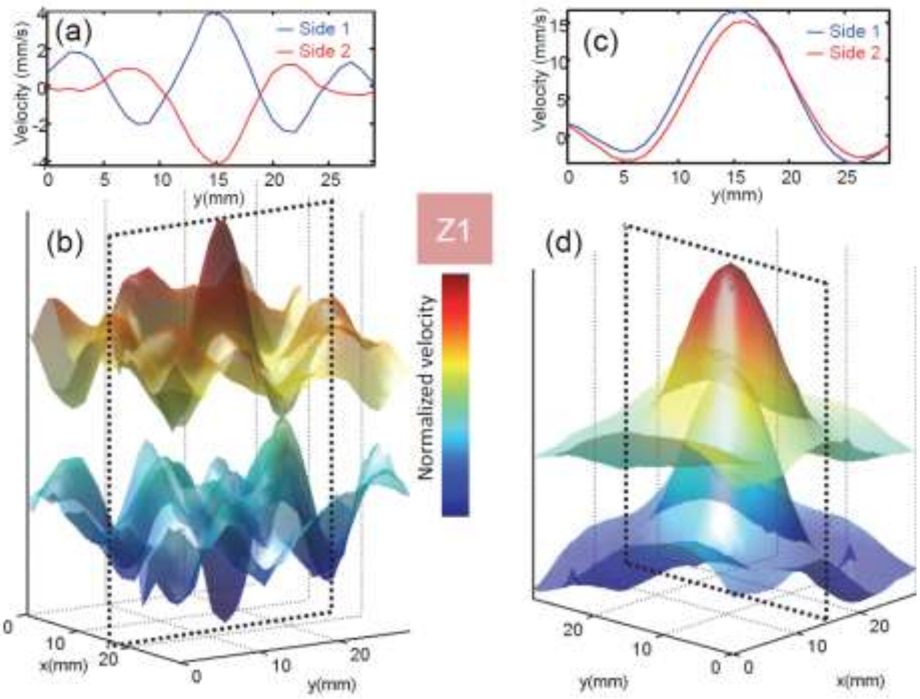

Fig. 3. Experimental focusing in Z1 zone. Left panel: Symmetric mode focusing, with the particle velocity map on the bottom and a slice on the top. Right panel: Antisymmetric mode focusing, with the particle velocity map on the bottom and a slice on the top.

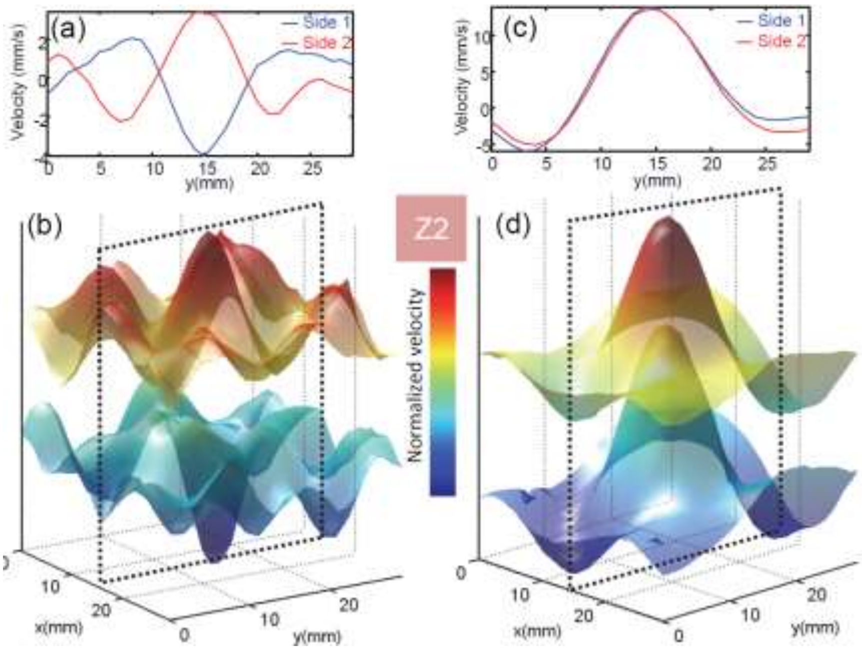

Fig. 4. Experimental focusing in Z2 zone. Left panel: Symmetric mode focusing, with the particle velocity map on the bottom and a slice on the top. Right panel: Antisymmetric mode focusing, with the particle velocity map on the bottom and a slice on the top.

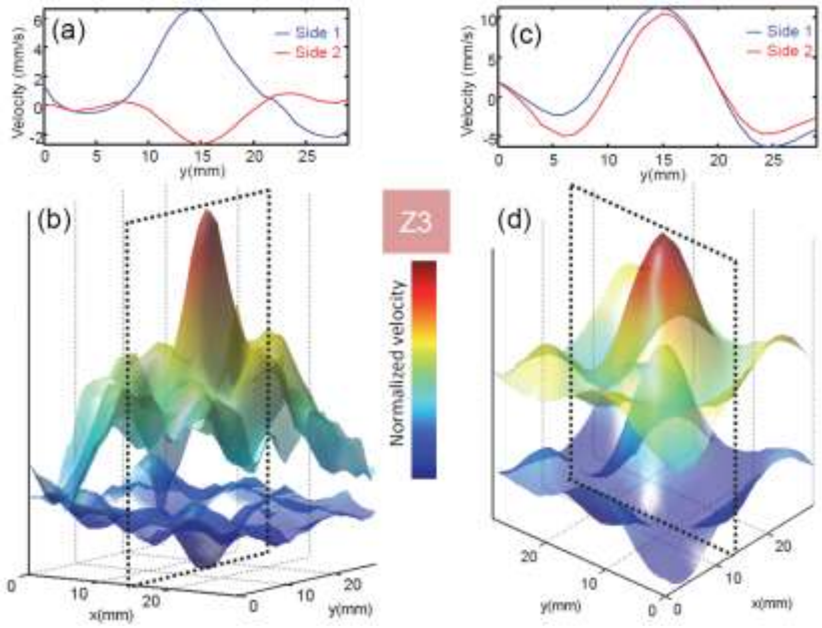

Fig. 5. Experimental focusing in Z3 zone. Left panel: Symmetric mode focusing, with the particle velocity map on the bottom and a slice on the top. Right panel: Antisymmetric mode focusing, with the particle velocity map on the bottom and a slice on the top.

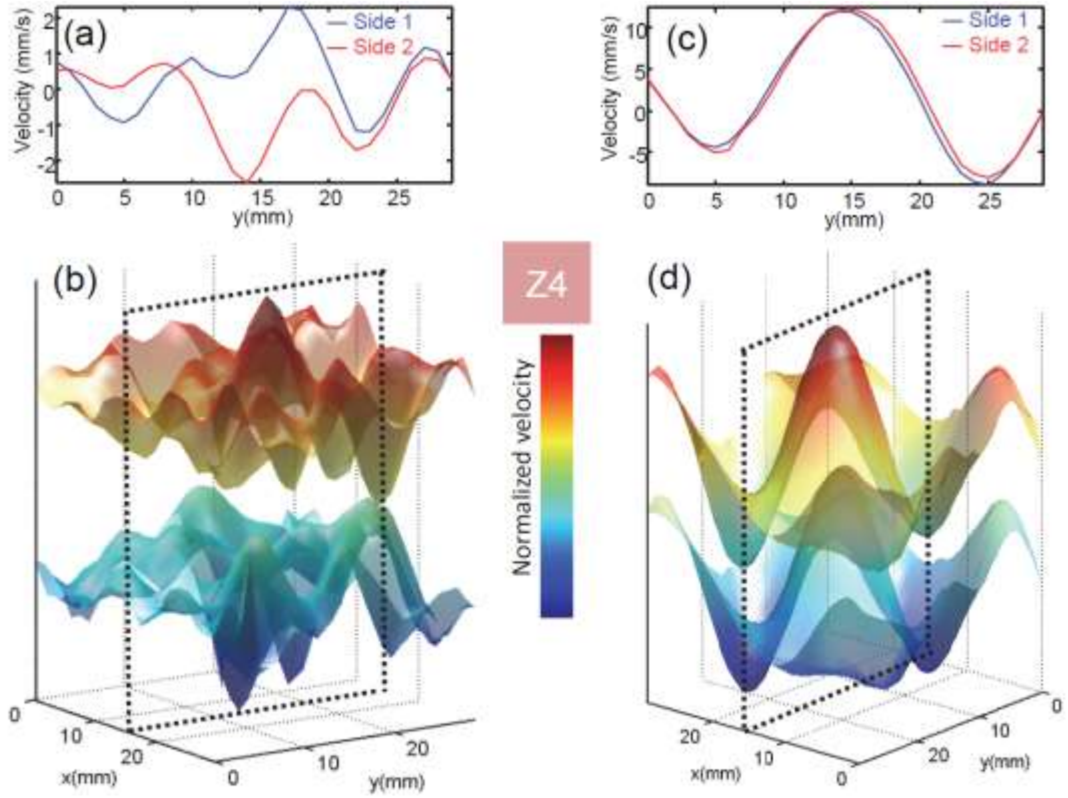

Fig. 6. Experimental focusing in Z4 zone. Left panel: Symmetric mode focusing, with the particle velocity map on the bottom and a slice on the top. Right panel: Antisymmetric mode focusing, with the particle velocity map on the bottom and a slice on the top.

IV. Conclusion

This paper shows the possibility of selectively focusing a symmetric or antisymmetric mode in a plate of arbitrary geometry without the need of precise knowledge about the mechanical characteristics nor the thickness of the plate. The method is based on time reversal, using a simple addition or subtraction of forward signals on both sides of the plate. The proposed approach is validated experimentally and numerically using a machined plate of complex shape. Even if the equipment employed here is limited, possible improvements are detailed. Future studies will aim to take advantage of these possibilities to locally probe nonlinear behavior in bounded assemblies. Ultimately, this method could allow to focus enough energy to replace laser shock, known to be a possible destructive method, as a fully nondestructive tool for adhesion characterization.

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