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Chladni Plate in Anechoic Chamber: Symmetry in Vibrational and Acoustic Response

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Abstract: A square metal plate (Chladni plate) is excited harmonically by a vibration shaker, while the whole system is set in an anechoic chamber to stop reflections, isolate the system from sound entering from the surroundings, and deal with direct sounds only. As far as the authors are aware, such an arrangement has not been achieved so far. Vibration modes are visualized by using poppy grains scattered over the upper surface of the plate and are also recorded by a camera located above it, inserted among the acoustic wedges on the roof of the chamber, which made it possible to record the patterns and avoid unpleasant sounds associated with some of them. Four distinctive vibration modes of the plate are then originally identified using vibrational and acoustic mode identification. These responses from the plate are measured both by an accelerometer attached to the central point of the plate and by a microphone set on the same vertical line as the accelerometer but above it, measuring the direct sound. The signals from the accelerometer and the microphone are then compared in two experimental arrangements, and their forms and the frequency contents are found to be equivalent. It is shown that the existing symmetry, i.e., the exact correspondence between vibrational and acoustic responses, can be used as the identifier of the patterns formed on the plate and the associated modal frequency.

Keywords: Chladni plate; vibration modes; acoustic response; accelerometer; microphone; frequency

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1. Introduction

Ernst Florens Friedrich Chladni (1756–1827) was a German-born physicist and musician of Hungarian and Slovak origin, who is perhaps best known for inventing a technique to demonstrate the various vibration modes on a surface [1,2]. He published this technique in 1787 in his book *Entdeckungen über die Theorie des Klanges* ('Discoveries in the Theory of Sound') [3], which consisted of drawing a bow over a piece of metal whose surface was lightly covered with sand; the plate was bowed until it reached modal resonance when the vibration caused the sand to move and concentrate along the nodal lines, along which the surface was motionless as the vibration amplitude was zero, causing the sand to create mode shapes as beautiful patterns. The patterns formed by nodal lines are named after him and are now called Chladni figures or Chladni patterns, although Chladni was building on earlier experiments performed by Robert Hooke. In 1680, Hooke applied a bow to a glass plate that had flour on it and noticed the emergence of nodal patterns. But even half a century before Hooke, in 1632, patterns displayed on an oscillating body were described by Galileo Galilei. Galilei wrote: 'As I was scraping a brass plate with a sharp iron chisel to remove some spots from it and was running the chisel rather rapidly over it, I once or twice, during many strokes, heard the plate emit a rather strong and clear whistling sound: on looking at the plate more carefully, I noticed a long row of fine streaks parallel and equidistant from one another. Scraping with the chisel repeatedly, I noticed that it was only when the plate emitted this hissing noise that any marks were left upon it; when the scraping was not accomplished by this sibilant note there was not the least trace of such marks.' However, the first person to record this phenomenon in writing is thought to have been Leonardo da Vinci. After noticing how the dust on his worktable moved as he vibrated the table in the late 1400s, he wrote: 'I say that when a table is struck along diverse lines, the dust on it is concentrates in various shapes of hills and small mountains... The dust which divides itself into various mountains on the struck table descends from the hypotenuse of these hillocks, enters beneath their bases, and raises again around the axis of the region under the top of the mountain.'

Chladni's techniques and patterns have been applied in various fields of research, such as musical instruments [4–6], seismology [7], nanomechanics [8,9], theoretical and applied mechanics [10–12], etc. Woodhouse and co-workers [10–12] developed a simple and effective procedure for evaluating the four elastic constants of a thin orthotropic rectangular plate based on the experimental results: Young's moduli in two orthogonal directions, in-plane shear modulus, and Poisson's ratio.

Numerical investigations in different types of software have been carried out to visualize and quantify them so widely that even a graphical user interface *NumChladni* currently exists [13], as well as an open access Chladni plate simulation application [14].

Researchers also examined various shapes of the plates and the corresponding Chladni patterns [15–18]. Chladni's patterns have been obtained, including their inversions [19]. It has become more common to use a loudspeaker driven by an electronic signal generator or a vibrating shaker to produce vibration modes with interesting nodal lines. Regarding the driving source, experimental evidence suggests that the resonant frequencies and eigenfrequencies may differ greatly due to the tight coupling between the driving source and the vibrating system. [20–22].

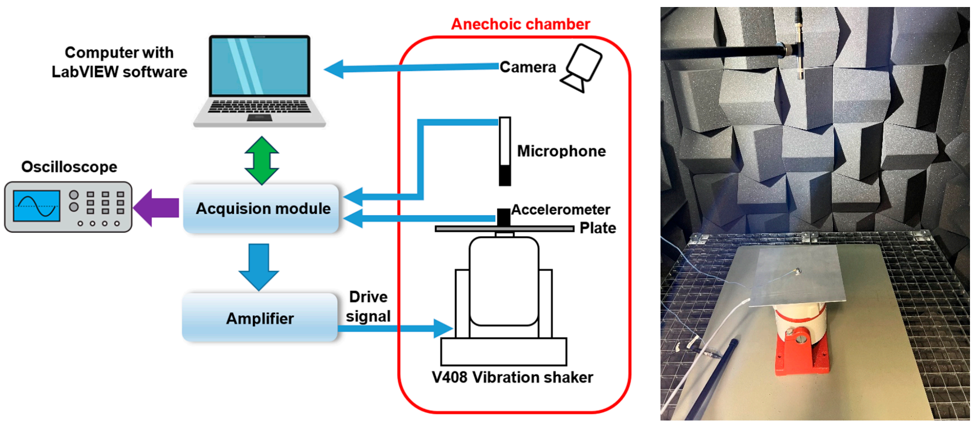
The influence of the environment in which the Chladni plates are placed was investigated as well. It was experimentally confirmed in [15] that the Chladni patterns are not affected by the ambient air and remain almost undisturbed if the extra masses are placed at the nodal lines or at the central excitation point. It was concluded in [23] that when the plate was submerged in water, the water currents caused by the displacement of the plate guided the solid particles towards the circles with no transverse acoustic velocities. When very light particles were utilized, they exhibited behavior different from that seen in air-induced inverse Chladni patterns that produce antinodes. The authors of [24] created a vibrating drum by suspending polystyrene microbeads in water, injecting the suspension into a microfluidic device, and stretching a polysilicone membrane across a circular aperture at the base. This method is an alternative to scattering sand on metal plates. Then, using a camera mounted on a microscope, they captured the positions of the microbeads. The beads arranged themselves at the antinodes as a result of the plate vibration and acoustic streaming in the fluid. It was demonstrated in [25] how unconventional Chladni patterns might emerge in cylindrical fluid channels, with the patterns being produced by the vibrations of the walls of the tubes and related to the resonant modes of the fluid channels.

In [26], the authors considered a structure that had two panels with coupling elements between them, but no mechanical coupling with the excitation. Based on their research, it was concluded that Chladni figures would be a useful tool for examining the mode forms of a structure during rapid temperature changes and for detecting small amplitude changes on the structure's surface. Coupling was also of interest in [27]. It was demonstrated therein that the coupling strength considerably affects the amplitude and nodal-line patterns of the eigenfunctions. It was established that using point-driven Chladni plates can produce a clear demonstration of the nodal-line pattern's dependence on the coupling strength. In [28], the impact of applying a stiffener at the plate's antinode locations was taken into consideration. For the plate with the stiffener, the Chladni designs were obtained at a higher frequency than those for the plate without the stiffener.

In this work, an original approach is taken as follows: a vibrating plate is placed in an anechoic chamber to deal with the direct sound only, and the focus is both on vibrations and acoustics. As far as the authors are aware, this arrangement and the associated measurements have not been performed so far. The plate is centrally attached to the top of a shaker, which produces a vertical harmonic excitation with a known and controlled frequency. The vibrational response is measured using an accelerometer attached to the central point of the plate. The acoustic response is measured using a microphone placed above the accelerometer. Two approaches are experimentally taken to compare the vibrations and acoustic responses. The details of the experiments are provided in Section 2, and the results obtained are presented in Section 3. A discussion is presented in Section 4. There is also an Appendix A that is related to Section 2 and shows a carefully and thoughtfully arranged setup and preparatory activities for the experiments to ensure that the proceedings' measurements and results are reliable.

2. Materials and Methods (Experiments and Analysis)

A schematic description of the first experimental setup, i.e., a vibrating plate in a mini-anechoic chamber, is shown in Figure 1a and its photo is shown in Figure 1b. A thin square aluminium plate, as shown in Figure 1b, 250 mm × 250 mm × 2 mm, is centrally attached to a shaker (LDS vibrator type V408,10/32UNF) by a screw supporter and excited in a vertical direction. The frequency of the sinusoidal drive signal is defined in the LabVIEW software and fed to the shaker via a dynamic signal acquisition module/card (NI USB4331) and an amplifier (LPA1000). The response from the central point of the upper surface of the plate is taken using an accelerometer (PCB 352C22, sensitivity 10 mV/g). In Experimental Setup 1 (Figure 1a), this signal is recorded using an acquisition card (NI UBS4331). Nodal lines of the distinctive mode shapes are visualized by using poppy grains scattered over the upper surface of the plate and are also recorded by a camera placed above it. The signal from the camera is taken outside the chamber to a computer, which makes it possible to produce videos and photos of the experiments and the patterns of interest. The acoustic response is obtained from a microphone system PCB 378B02 (1/2″ prepolarized free-field condenser microphone with a sensitivity of 50 mV/Pa and 1/2″ ICP preamplifier), placed above the central point of the plate. The signal is then, via the NI USB4331 card, taken to an oscilloscope (Rohde & Schwartz RTB2K-102), which is depicted by a violet arrow in Figure 1a. It should be noted that the careful and thoughtful preparation for the experiment also includes the validation that the responses taken are from the plate and not from the shaker, which is elaborated in the Appendix A. The sinusoidal signal of variable frequency and amplitude has been created in LabView and sent to the shaker, and the resulting signal is also acquired from the acquisition module in the opposite direction, as depicted by the opposite green arrows in Figure 1a. Four characteristic frequencies are used as follows: 289 Hz, 553 Hz, 1430 Hz, and 1900 Hz (this is discussed in Section 3 related to Tables 1 and 2). In all the cases, the amplitude of the signal is set to 14 g.



(**a**) (**b**)

Figure 1. Experimental Setup 1: (**a**) schematic description; (**b**) photo of the equipment used in a mini-anechoic chamber.

Table 1. Photos of the vibration and acoustic responses with the values of the corresponding frequencies.

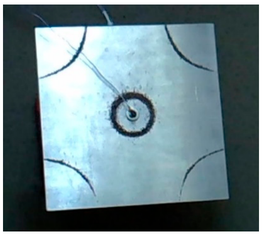
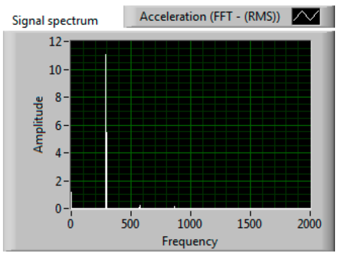
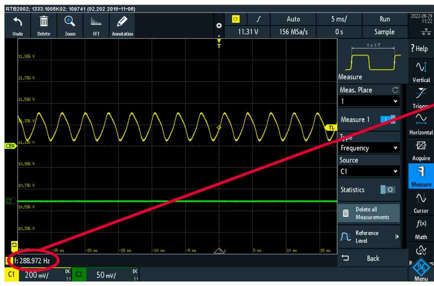
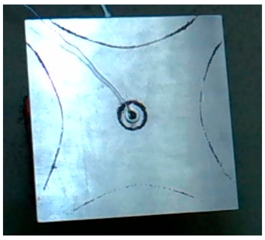
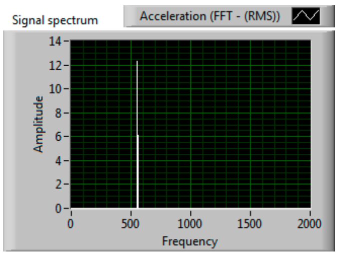
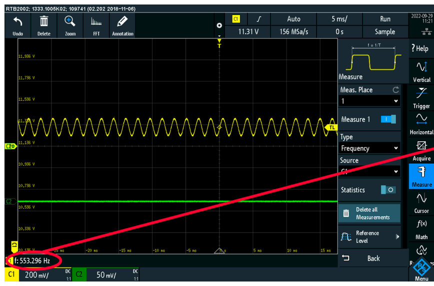
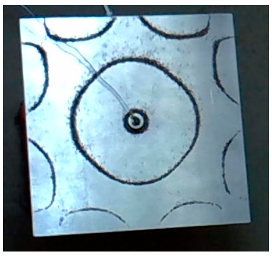
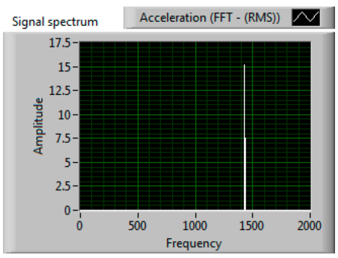
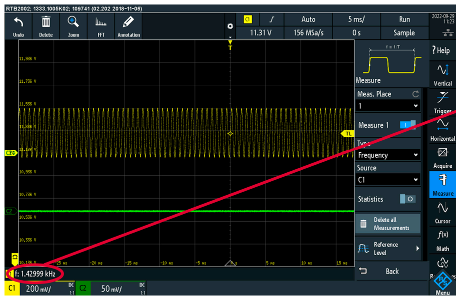
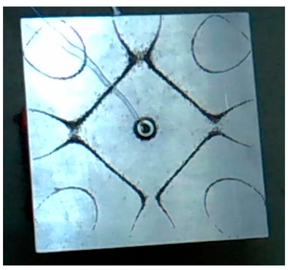
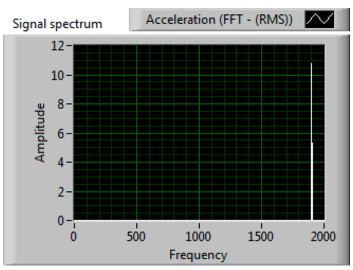
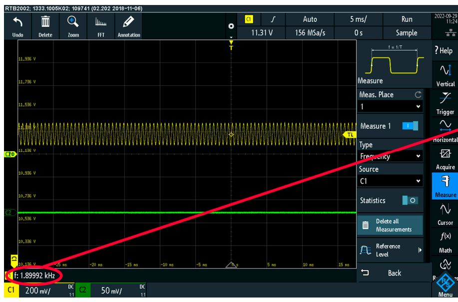
		Accelerometer		Microphone	
Mode	**Nodal Lines on the Plate**	**Response in LABView from the Accelerometer (Signal Spectrum)**	**Frequency f_v**	**Response on the Oscilloscope from the Microphone**	**Frequency f_s**
A			Peak frequency = 289 Hz		Not sinusoidal ≈ 289 Hz (first/lowest
B			Peak frequency = 553 Hz		Sinusoidal ≈ 553 Hz
C			Peak frequency = 1430 Hz		Sinusoidal ≈ 1430 Hz
D			Peak frequency = 1900 Hz		Sinusoidal ≈ 1900 Hz

Table 2. Acoustic responses from Experimental Setup 2.

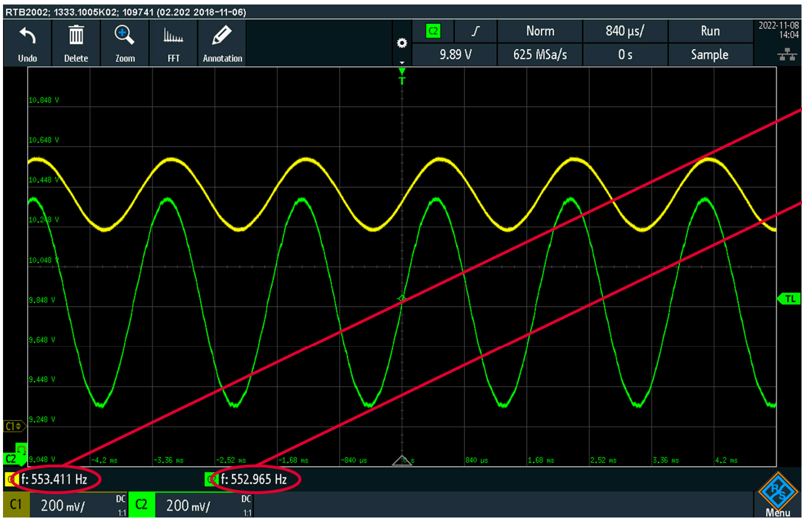
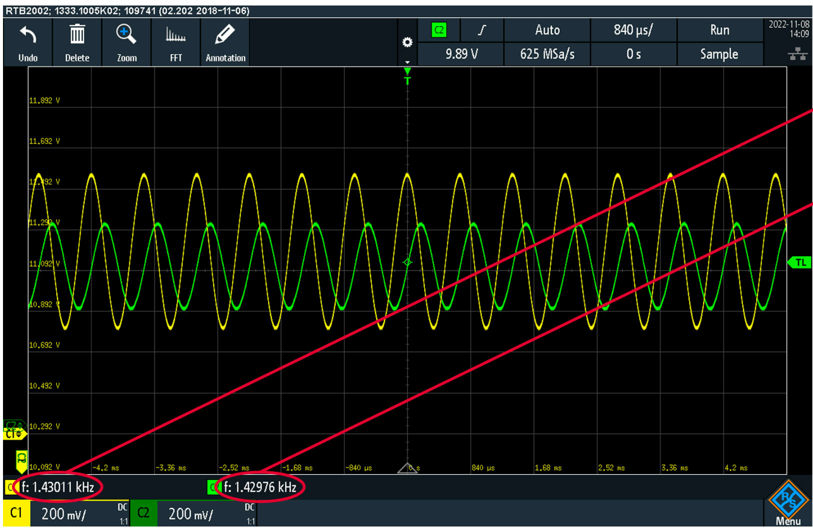
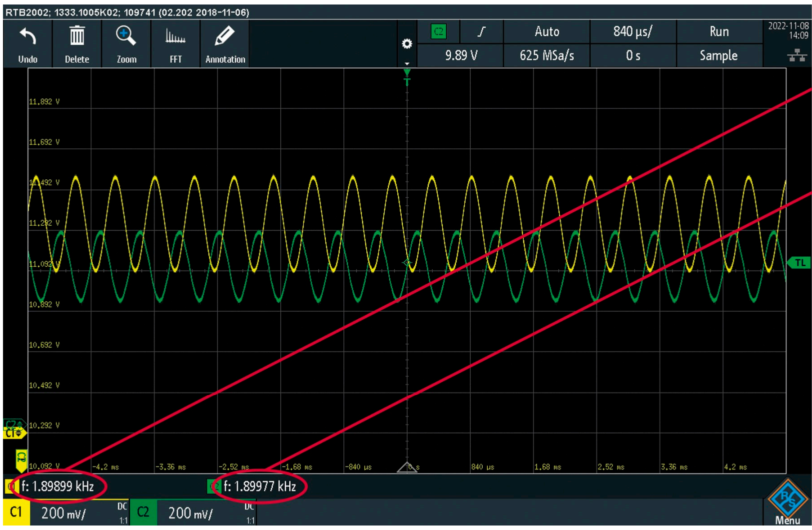
Mode	**Oscilloscope**		
	Response	**Frequency** f_s **(Channel C1)**	**Frequency** f_v **(Channel C2)**
A		≈289 Hz	≈289 Hz
B		≈553 Hz	≈553 Hz
C		≈1430 Hz	≈1430 Hz

Table 2. *Cont.*

Mode	Oscilloscope		
	Response	Frequency f_s (Channel C1)	Frequency f_v (Channel C2)
D		≈1900 Hz	≈1900 Hz

Videos of the pattern formation in all four cases (Videos S1–S4) are provided as Supplementary Material to this paper (please note that some of the nodes are acoustically associated with unpleasant sounds, so it is advised to appropriately decrease the sound volume while listening or to use ear protectors). The existing unpleasant sound in these videos, associated with high frequencies with subjectively disturbing psychophysiological acoustic effects, explains the motivation for the use of an anechoic chamber. Namely, besides getting the direct sound, which is the primary motivation, placing the experimental setup in the chamber and closing its door provides the second motivation as the experimenters are protected from it. The experiments can still be carried out inside the chamber and monitored by using the camera, as in this study.

The experiment in the mini anechoic chamber (Figure 1b) is repeated with a modification of how the vibration is acquired to demonstrate another way of correlating the acquired vibrational and acoustic signals. As shown in Figure 2, Experimental Setup 2 is similar to Experimental Setup 1, with the exception that both the signal from the microphone and the signal from the accelerometer are taken to the two-channel oscilloscope and shown on its screen (Rohde & Schwartz RTB2K-102), as depicted by the double violet arrows in Figure 2. The corresponding results are discussed in Section 3 and included in Table 2.

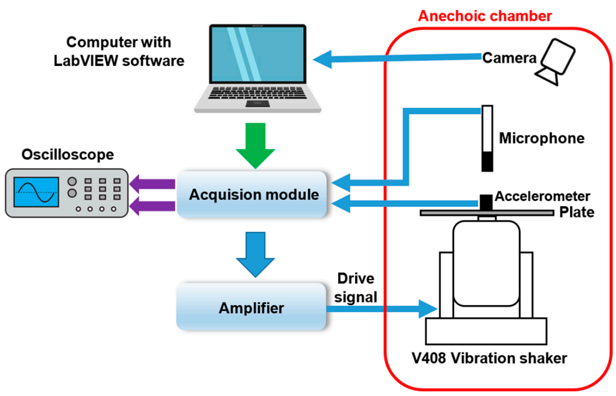


Figure 2. Experimental Setup 2: schematic description.

3. Results

Table 1 contains both the vibrational response and acoustic response acquired for four distinctive mode shapes labelled as Mode A, B, C, and D obtained in Experimental Setup 1 (Figure 1). The second column of Table 1 contains photos of the patterns created on the plate. The third and fourth columns show the vibration response obtained from the accelerometer: the frequency response diagram and the corresponding vibration frequency value f_v. The fifth and sixth columns present the acoustic responses obtained in terms of the acoustic signals' photos from the oscilloscope and the corresponding frequency values f_s. Table 1 shows that only in Mode A, the response recorded was complex (periodic and two-harmonic), whereas in all other cases, it was pure (sinusoidal). In Modes B–D, the ratio of the frequencies f_v/f_s is calculated to be unity, so both the vibration signal from the accelerometer and the acoustic signal from the microphone have the same frequency, which implies that the identification of the mode can be used from either of these signals, i.e., utilizing the vibro-acoustic response from the plate. In Mode A, the same unity value is obtained as the ratio of the excitation frequency and the one corresponding to the lowest value in the response, which is also indicated in Table 1.

The results from Experiment 2 are collected In Table 2 for all four modes A-D, as noted in the first column of this table. The second column of Table 1 contains photos of the patterns created on the plate. The third and fourth columns show the vibration response obtained from the accelerometer: the frequency response diagram and the corresponding vibration frequency value f_v. The fifth and sixth columns present the acoustic responses obtained in terms of the acoustic signals' photos from the oscilloscope and the corresponding frequency values, f_s. Table 1 shows that only in Mode A, the response recorded was complex (periodic and two-harmonic), whereas in all other cases, it was pure (sinusoidal).

They clearly show the same frequency for both the vibration and sound signals acquired and agree with the results obtained in Experimental Setup 1. However, this approach offers the possibility to directly observe the shapes of the signals as well as their phase correlation.

4. Discussion

Chladni plates and patterns have been extensively investigated from a research and educational point of view, but this study, as far as the authors are aware, has taken an original approach, in which vibro-acoustic responses of the Chladni plate were experimentally collected and analysed for the sake of mode identification. To achieve this, a vibrating plate was placed in an anechoic chamber. The aim was to measure just a direct sound from the plate and to protect experimenters from the unpleasant sound associated with certain modal frequencies as they could cause subjectively disturbing psychophysiological effects. The plate was centrally attached to the top of a shaker via a screw, and the shaker was harmonically excited in the vertical direction with a known and controlled frequency, transferring vibrations to the plate. The resulting vibrational modes and nodal lines were identified by using poppy grains spread over the plate, and the photos and videos were taken by a camera placed above the setup, which was inserted among the acoustic wedges on the roof of the chamber. An accelerometer was attached to the center of the plate. The acoustic response was measured using a microphone placed above the central point of the plate. Both the vibrational and acoustic responses were measured in the two experimental arrangements. The first one included taking the signal from the accelerometer to LabView software and the signal from the microphone to the oscilloscope. Their forms and the frequency contents were compared and found to be equivalent. The second one involved taking both signals to a two-channel oscilloscope, in which their features could be compared straightforwardly. Thus, it was shown in both arrangements that one can use either vibrational or acoustic responses as identifiers of the corresponding patterns formed on the plate and the associated modal frequency. The existing symmetry using the exact correspondence between vibrational and acoustic responses can create a strong educational message and useful demonstrations for those interested in physics and vibro-acoustics, in particular. In addition, the existing symmetry as an equivalence in the shape and frequency content of two signals may open some horizons for engineering applications, such as mode identification.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/sym15091748/s1, Video S1: Chladni plate in Mode A; Video S2: Chladni plate in Mode B; Video S3: Chladni plate in Mode C; Video S4: Chladni plate in Mode D.

Author Contributions: Conceptualization, I.K.; methodology, I.K.; software, Z.K.; conducting experiments, Z.K. and I.K.; analysis of the experimental results, I.K. and Z.K.; visualization, I.K. and Z.K. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available in Tables 1 and 2, as well as in Videos S1–S4. The numerical data obtained from Experiment 1 are available upon request from the corresponding author.

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Appendix A

To verify whether the experimental results stem from the plate and not from the shaker itself, an element with the same mass as the plate (0.2785 kg) was built using lead as a concentrated mass, as shown in Figure A1a, and attached to a shaker centrally. The shaker was driven at the frequencies shown in Table 1, and the acoustic response was recorded using the same microphone system placed above the mass (Figure A1b). In Modes A and B, the amplitude of the acoustic pressure recorded was zero, whereas in Modes C and D, it was extremely small and negligible, confirming that the signals acquired in the experiments with the plate really stem from the plate.

(**a**) (**b**)

Figure A1. (**a**) Discrete element from lead with the same mass as the plate; (**b**) element on the shaker in the same experiment as the plate.

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