Experimental, Modal, and Harmonic Response Analysis of a Chladni Plate at Ultrasonic Frequencies

Nitin Khedkar
Symbiosis International University, India
nkkhedkar@gmail.com (corresponding author)

Kiran Wani
Symbiosis International University, India
kiranwani2010@gmail.com

Vijaykumar Jatti
Symbiosis International University, India
vijaykjatti@gmail.com

Vivek Joshi
College of Engineering, Pune, India
vivek.joshi411030@gmail.com

Received: 2 September 2023 | Revised: 14 October 2023 | Accepted: 24 October 2023

ABSTRACT

Mode shapes and natural frequencies of mechanical structures can be determined with the Chladni approach. Visual patterns are generated on the Chladni plate if it is exposed to vibrations. These patterns are known as Chladni patterns/figures. Mechanical vibrators are used to excite the plates at particular frequencies for pattern generation, but based on the making and application, their range is limited up to 10 kHz. Piezoelectric transducers are a special kind of transducers that are capable of generating ultrasonic frequencies and if are attached to a plate, intricate visual patterns can be generated, based on the material properties and the shape of the plate. The current research focuses on experimenting with and simulating Chladni figures in the ultrasonic frequency range. The simulations were performed in ANSYS Workbench as a validation of the experimental work.

Keywords-Chladni plate; ultrasonic frequency; mode shapes; modal analysis; harmonic analysis

I. INTRODUCTION

A scientific instrument known as the Chladni plate is often used for the visualization of sound waves. The patterns generated on these plates are called Chladni figures. Applying the same logic on different materials, different Chladni figures are formed [1, 2]. The Chladni plate is a flat plate, fixed at the center, while being able to vibrate freely when excited externally. If a thin layer of powder or sand is present on the plate, intricate figures are formed as the particles moves in response to the vibrations. The Chladni plate has many applications in the fields of vibration and acoustics. Engineers use it as an instrument to study the behavior of various materials under vibrations and to design materials that could overcome the harmful effects of unwanted vibrations. By studying these patterns of vibrations that are produced on a Chladni plate, researchers can develop new techniques for reduction of noise and vibrations in various types of structures, aircrafts, and automobiles.

Authors in [3] created a setup with the use of mechanical vibrator, which is able to generate sine wave signals. The Chladni patterns can be formed on aluminum plates of two different shapes, i.e. a 16 cm × 16 cm square plate and a 16 cm diameter circular plate. By sweeping the frequency, Chladni figures are obtained up to frequency of 5000 Hz. In addition, simulations were performed in ANSYS Workbench and were compared with the experimental figures. The error in the frequencies with similar patterns was less than 15%. Authors in [4] prepared a setup using a speaker as an excitation device. Modal analysis was performed in ANSYS, and the results were compared, exhibiting an error of 11%. Authors in [5] added stiffeners on the plate and studied their effect on the patterns. Authors in [6] studied and simulated the vibration patterns generated on plates with varying thickness. The frequency of vibration can reach the ultrasonic range and the material would have totally different vibration response. Authors in [7] studied the effect of ultrasonic vibrations on the material. The study of the vibration patterns in time and frequency domains has important applications in industry. One of the widely used applications is machine fault detection. Authors in [8] studied the bearing fault detection using time domain analysis and detected faults in industrial bearing using this method.

The ultrasonic vibrations can be applied in different industrial applications. Authors in [9] used ultrasonic excitation vibrations of 22.3 KHz for transporting a load of 4.0 Kgf. Authors in [10] used ultrasonic frequencies for particle size measurement in a batch reactor to monitor the reaction process. Ultrasonic vibration assisted grinding is also used on hard cutting materials like titanium alloys and nickel based super alloys. Authors in [11] worked on developing an ultrasonic based vibration plate sonotrode for grinding applications. Authors in [12] included modal analysis of airborne ultrasonic rectangular plate power transducer to the numerical and experimental work.

In material science, mechanical properties can be studied with the help of Chladni figures. An example of that is Young's modulus, which can be studied by measuring the natural frequencies of the plate. In the medical field, particularly in imaging with the use of ultrasound, ultrasonic Chladni figures play an important role and are used in the visualization of the behavior of tissues and organs. In ultrasonic cleaning, these figures can be used for the effective optimization of the cleaning process. By identifying the resonance frequencies, more powerful cleaning can be provided.

II. OBJECTIVE OF THE STUDY

Standing waves are formed on the Chladni plate, depending on the boundary conditions and frequency. The figures are generated as the sprinkled powder moves at the nodal points. The figures generated can be captured. These images are difficult to analyze as the patterns generated are complicated and needed to be pre-processed. As the shapes are miscellaneous, some amount of sprinkled powder may occupy cavities present at anti-nodes, so image filtering is recommended. In image processing, converting captured image in to grey-scale and applying canny edge detection is a way to filter out the unwanted particles.

In simulations, Chladni patterns are formed with the use of the modal analysis concept, in which the mode shapes are generated on the plate at the natural frequencies which are based on the material properties and dimensions of the test specimen. But, in case of harmonic analysis, the external excitation is provided, and the mode shapes are formed at the required frequencies. Both analysis techniques are equally important and are used to simulate the behavior of the Chladni plate. With the use of both analysis techniques, Chladni patterns could be formed in simulations and can be validated with the help of the experimentally generated patterns. The error between the simulated and the experimentally generated patterns should be investigated as the generated patterns differ slightly from one another.

III. SIGNIFICANCE OF THE CURRENT STUDY

This study studies the behavior of Chladni patterns in the ultrasonic frequency range. The results obtained can be used for design and optimization in the performance of various materials, which are regularly in contact with ultrasonic vibrations. In addition, two different methods for the analysis of Chladni plate are considered, which could be useful for researchers and professionals to work on the most appropriate method for their specific applications. This study is limited to stainless-steel Chladni plates and frequencies up to 50000 Hz. The experimental setup and simulation conditions used in this study may not be suitable for other applications. The study assumes that the material properties are available. Overall, these studies demonstrate the effectiveness of different techniques and the importance of validating the simulation results with experimental measurements.

IV. MATERIALS AND METHODS

Experimentation is performed on a square 160 mm × 160 mm stainless steel plate with thickness of 0.061 mm. In addition, a hole of 3 mm diameter is drilled at the mid-point of the plate. To create a contact between the vibrator (ultrasonic transducer) and the plate, an adhesive is used on a screw and is placed between the plate and the vibrator.

A. Experimental Analysis

The experimental setup is shown in Figure 1. Based on the requirements for the Chladni plate analysis, the following components are used: A Chladni plate made up of stainless steel, an ultrasonic transducer to provide vibrations to the plate at ultrasonic frequencies in the range of 19600 to 50000 Hz, and a MOSFET type controller (frequency generator) to provide the required excitations at the required frequencies. A stand is used to support the transducer. Also, fine salt, a piece of cloth or sponge, and a camera to take snapshots of the Chladni figures were utilized.

Fig. 1. The experimental setup.

B. Experimental Procedure

The steps to be followed for the experimental analysis of the plate are:

- At first, creating a strong contact between the plate and ultrasonic transducer is a must. To do so, a special screw which is available with a transducer is used. That screw is stick with the plate by using a suitable thin adhesive layer.

The layer of adhesive should be as thin as possible as thick layer tends to damp vibrations.

- Afterwards, the screw must be tightened to the transducer, allowing some clearance, as the point of contact between the transducer and the plate must be the screw. An excess point of contact may increase the excitation area which tends to create errors in the figures.
- After the suitable excitation frequency is selected, vibrations are provided to the plate via the transducer. The fine salt is sprinkled on the plate. The amount of salt to be sprinkled on the plate should be just sufficient to trace the patterns. More amount of salt tends to create dense or thick layers which may trace unwanted areas.
- The excitation is switched off only when the salt gets accumulated at the nodal lines. When taking a photograph of the shape the whole plate must be present in the photograph and suitable exposure of light must be ensured.
- After the photograph is taken, the plate must be cleaned with a piece of paper, sponge, or cloth.

Note: While performing the experimentation, the plate must be perpendicular to the excitation source as a slight misalignment creates errors in the figures.

C. *Experimental Mode Shapes of the Chladni Plate*

Based on the limitations of the controller and ultrasonic transducer, the frequency can only be varied from 19.6 kHz to 50 kHz with intervals ranging from 100 to 500 Hz.

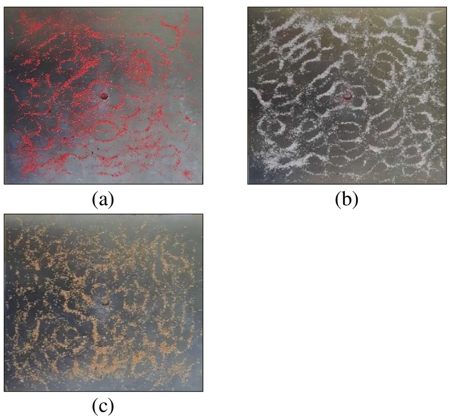

Fig. 2. Mode shapes generated with experimental approach at the same frequency: (a) red crystal powder, (b) fine salt, (c) sand.

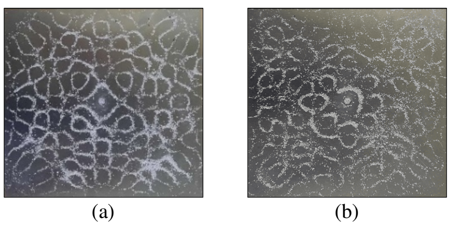

Fig. 3. Mode shapes generated from the experimental approach at (a) 19800 Hz, (b) 26000 Hz.

Figure 2 shows photographs of Chladni figures formed at the same frequency for different sprinkling materials. As the patterns are becoming more and more complex with increasing vibration frequency, the nodal lines are getting thinner and thinner. For tracing the figures, fine salt is used. Some captured images of the generated mode shapes can be seen in Figure 3.

V. NUMERICAL ANALYSIS

A. *Simulation of Mode Shapes on a Square Plate*

For simulation and analysis with the ANSYS software, the first step is to create the model of the plate. For this purpose, ANSYS's Design Modeler is used to create the simple geometry of the plate. The next step is to select the plate's material. The material properties of the plate are shown in Table I.

TABLE I. MATERIAL PROPERTIES OF THE CONSIDERED CHLADNI PLATE

Property	Value
Density	7850 kg m^{-3}
Poisson's ratio	0.3
Young's modulus of elasticity	200 GPa

Boundary Conditions: To simulate the experimentation environment accurately, boundary conditions are provided. Boundary conditions are used to define the constraints which are applicable to the physical model. Here, fixed support is provided to the inner part of the hole and excitation is provided to simulate the vibrations of excitation frequencies. In addition, a material library is available in ANSYS and an artificially created new material is added in ANSYS, by providing the basic information of that material.

Mesh Generation: Meshing plays an important role in the generation of patterns. Complex patterns are formed only if the element size is small. But with the reduction in the element size, computation time increases. These simulations are performed by considering the element size between 3 and 6 mm.

B. *Modal Analysis of a Square Plate*

During the process of modal analysis simulation using ANSYS, the material is assigned to the model of the plate and the value of the number of modes is assigned. The corresponding modal frequencies are calculated, and at those frequencies, the mode shapes are generated. The simulated shapes are as shown in Figure 4.

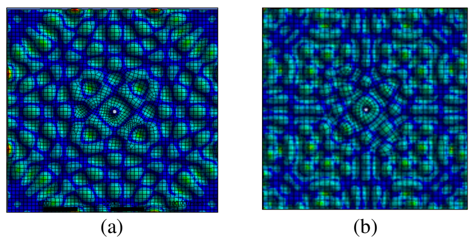

Fig. 4. Mode shapes generated from the modal analysis in ANSYS Workbench. (a) 18944 Hz, (b) 26695 Hz.

C. Harmonic Response Analysis of a Square Plate

In harmonic analysis, again the model is created, the material is selected, but in ANSYS Workbench, instead of selecting modal analysis, harmonic response is selected. Similar to modal analysis, the material is assigned to the geometry, and in the analysis settings, the frequency range in which the mode shapes are to be found is selected. As the experimental and simulated` results may have inherited some amount of error, the number of intervals must be wisely chosen. Unlike in modal analysis, where natural frequency values are calculated based on the geometry, here, external excitation must be provided to get response shapes at the required frequencies. The patterns generated during the harmonic response analysis are shown in Figure 5.

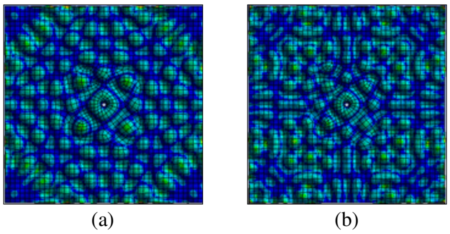

Fig. 5. Mode shapes generated from the harmonic response analysis in ANSYS Workbench. (a) 19020 Hz, (b) 26972 Hz.

VI. RESULTS AND DISCUSSION

A. Experimental Results

Chladni patterns were obtained experimentally on a thin stainless-steel plate at different ultrasonic frequencies.

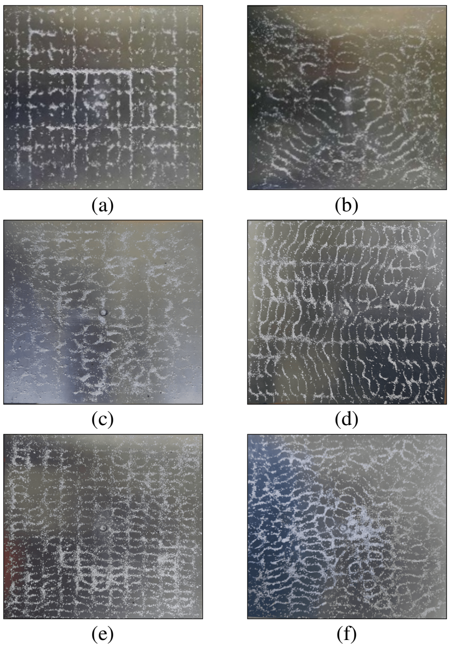

Fig. 6. Experimental mode shapes: (a) 26000 Hz, (b) 27000 Hz, (c) 32000 Hz, (d) 43800 Hz, (e) 46200 Hz, (f) 46700 Hz.

The patterns were generated on sprinkling fine salt that was placed on the plate. The salt's crystals are dynamic at antinodes and are forced to move towards nodal points, where they get stability. This stationary behavior of salt particles results in the generation of complex figures at different modal vibrations. Some of these shapes are shown in Figure 6.

B. Simulation Results

For the simulation of Chladni plates, modal and harmonic analysis were performed in ANSYS Workbench. The results of modal analysis are shown in Figure 7 and the results of the harmonic response are shown in Figure 8. In the simulation of modal analysis, a model of a thin steel plate of defined dimensions is created in the Design Modeler of ANSYS. The material is selected from the material library.

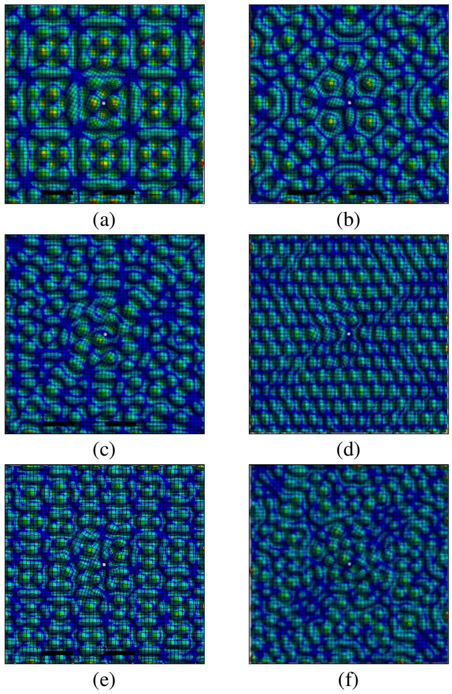

Fig. 7. Mode shapes generated from the modal analysis at other frequencies. (a) 22321 Hz, (b) 26994 Hz, (c) 32994 Hz, (d) 41645 Hz, (e) 45363 Hz, (f) 46944 Hz.

TABLE II. COMPARISON OF EXPERIMENTAL AND SIMULATED RESULTS

Experimental frequency	Modal analysis	Harmonic response analysis	Error with reference to modal % age	Error with reference to harmonic % age
19800	18944	19020	4.5185	4.1009
24000	22321	22483	7.5221	6.7473
26000	26695	26972	2.6035	3.6040
27000	26994	27615	0.2078	2.2270
32000	32294	32105	0.9135	0.3270
43800	41645	44874	5.1750	2.3935
46200	45363	45247	1.8450	0.5198
46700	46944	46940	0.5198	0.5113

In harmonic response analysis, the material is selected and the model is either created or imported. In this analysis, frequency range is needed to be chosen and the number of intervals is selected. One way to get a specific zone is to generated patterns for say 10000 Hz range having intervals of

100 Hz. As the generated patterns are similar to neighboring patterns up to some extent and once the required patterns are achieved, then the respective range is chosen with intervals of 1 Hz.

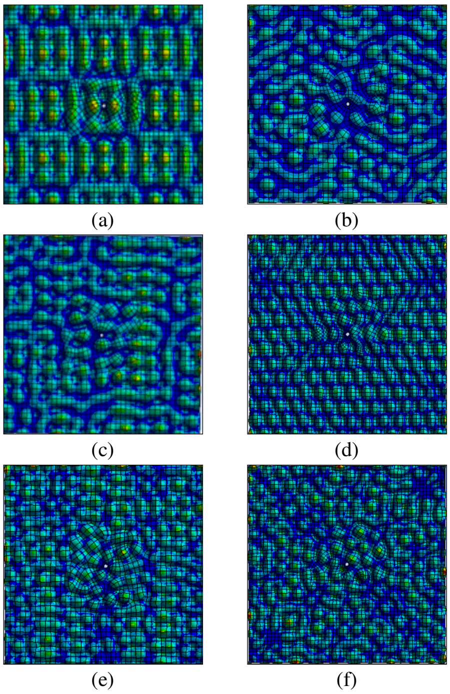

Fig. 8. Mode shapes generated from the harmonic response analysis. (a) 22483 Hz, (b) 27615 Hz, (c) 32105 Hz, (d) 44874 Hz, (e) 45247 Hz, (f) 46940 Hz.

The comparison of the experimental and simulation obtained modal frequencies are compared is shown in Table II.

C. Comparison of Simulation and Experimental Results

From the modal and harmonic response analysis in ANSYS, the simulated results were obtained, and these results were compared with the experimentally obtained results. Since the shapes obtained during experimentation and simulations are very complex, they are very difficult to compare visually. So, they can be processed using image processing for comparison. From Table II, it can be seen that the maximum error between the experimental and the simulation results with reference to modal frequencies is 7.52%. Similarly, the maximum error obtained with reference to the harmonic response is 6.74%.

VII. CONCLUSION

In this study, the analysis of modal frequencies and mode shapes of a square-shaped Chladni plate at ultrasonic frequencies are covered. The study is based on the comparison of experimental and simulated results of the Chladni plate at ultrasonic frequencies. The experimental modal analysis was conducted by locking the plate at the mid-point using an ultrasonic transducer as an excitation device. Numerical harmonic response analysis and modal analysis were performed by providing similar constraints in the ANSYS Workbench. Due to the complexity in the produced figures, good agreement is only found in some results. In some cases, which are not mentioned in the study, the patterns show some common features up to some extent, but 100% similarities cannot be found without the introduction of image processing.

Since in the available literature very little work has been done on the study of modal analysis of plates for the ultrasonic frequency range, this study contributes by exploring this area. For experimentation purposes, an innovative method was adopted, which created unique patterns on the plate at ultrasonic frequencies. This study will help explore the application of ultrasonic vibrations in various industrial applications.

Due to the limitations of the frequency generator and transducer, going above 50000 Hz is unachievable. But in the future, changing plate dimensions and shape, playing with permutations and combinations of frequency, changing the number of transducers, or the power or wattage given to the transducer will bring more complex patterns into the picture. In addition, changes to the boundary conditions and to the material or using the same materials but with different manufacturing processes may result in different patterns. So, it may be possible to identify the manufacturing process without undergoing any other destructive or non-destructive testing.

With increase in the complexity of the patterns, it will become way more difficult to simply compare experimental and simulated images. So, image processing is a must, making tracing or comparing patterns a simpler task.

REFERENCES

[1] M. Sheldrake and R. Sheldrake, "Determinants of Faraday Wave-Patterns in Water Samples Oscillated Vertically at a Range of Frequencies from 50-200 Hz," *WATER*, vol. 9, pp. 1–27, Oct. 2017, https://doi.org/10.14294/WATER.2017.6.

[2] S. L. Garrett, "Membranes, Plates, and Microphones," in *Understanding Acoustics: An Experimentalist's View of Sound and Vibration*, S. L. Garrett, Ed.Springer International Publishing, 2020, pp. 283–330.

[3] A. Kumar, S. Shiva Chary, and K. P. Wani, "Modal Analysis of Chladni Plate Using Cymatics," in *ADMMS International Conference 2020*, 2020, https://doi.org/10.4271/2020-28-0320.

[4] K. Gurukiran and P. K. Samal, "Experimental determination of mode shapes of a plate using speaker as excitation device," *IOP Conference Series: Materials Science and Engineering*, vol. 1189, no. 1, Jul. 2021, Art. no. 012029, https://doi.org/10.1088/1757-899X/1189/1/012029.

[5] S. Gaygol and K. Wani, "Modal analysis of plate to analyze the effect of mass stiffeners using the Chladni plate approach," *Materials Today: Proceedings*, vol. 72, pp. 1314–1321, Jan. 2023, https://doi.org/10.1016/j.matpr.2022.09.305.

[6] V. A. Le and X. T. Nguyen, "The Effect of Cracks on the Free Vibration of a Plate with Parabolic Thickness," *Engineering, Technology & Applied Science Research*, vol. 13, no. 4, pp. 11100–11105, Aug. 2023, https://doi.org/10.48084/etasr.5923.

[7] F. Ahmad, A. Z. Al-Khazaal, N. Ahmad, and I. Alenezi, "Remediation of Sulfidic Wastewater by Aeration in the Presence of Ultrasonic Vibration," *Engineering, Technology & Applied Science Research*, vol. 8, no. 3, pp. 2919–2922, Jun. 2018, https://doi.org/10.48084/etasr.1956.

[8] Y. Bella, A. Oulmane, and M. Mostefai, "Industrial Bearing Fault Detection Using Time-Frequency Analysis," *Engineering, Technology & Applied Science Research*, vol. 8, no. 4, pp. 3294–3299, Aug. 2018, https://doi.org/10.48084/etasr.2135.

[9] T. Ishii, Y. Mizuno, D. Koyama, K. Nakamura, K. Harada, and Y. Uchida, "Plate-shaped non-contact ultrasonic transporter using flexural

vibration," *Ultrasonics*, vol. 54, no. 2, pp. 455–460, Feb. 2014, https://doi.org/10.1016/j.ultras.2013.07.002.

[10] G. Carson, A. J. Mulholland, A. Nordon, M. Tramontana, A. Gachagan, and G. Hayward, "Particle sizing using passive ultrasonic measurement of particle–wall impact vibrations," *Journal of Sound and Vibration*, vol. 317, no. 1, pp. 142–157, Oct. 2008, https://doi.org/10.1016/j.jsv.2008.03.005.

[11] Y. Cao *et al.*, "Development and performance of a novel ultrasonic vibration plate sonotrode for grinding," *Journal of Manufacturing Processes*, vol. 57, pp. 174–186, Sep. 2020, https://doi.org/10.1016/j.jmapro.2020.06.030.

[12] R. R. Andrés, V. M. Acosta, M. Lucas, and E. Riera, "Modal analysis and nonlinear characterization of an airborne power ultrasonic transducer with rectangular plate radiator," *Ultrasonics*, vol. 82, pp. 345–356, Jan. 2018, https://doi.org/10.1016/j.ultras.2017.09.017.