Computational Study of Cymatics with Experimental Analysis

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Abstract: Cymatics is a visual representation of sound and vibrations, on surfaces of plates, diaphragms, and membranes in the forms of auditory-images. The surfaces that are exposed to these vibrations are sprinkled with fine particles that accumulate at nodes, to create visualizations of specific geometry unique to the particular frequency. This paper discusses the designing of an experimental platform, dedicated towards observing the behavior of cymatics, through analysis of such visualizations (Chladni patterns). This is further investigated by performing a numerical modelling using finite element simulation. Two millimeter thickness Aluminum (Al) plates of three shapes consisting of surfaces with equal areas were used for both experimental and finite element analysis (FEA). FEA was performed using ANSYS simulation software and patterns were derived for different vibrational frequencies. The results demonstrated that the 60% of the experimental imagery conforms with the visualization generated by ANSYS software. Additionally, the lowest average frequency differences with respect to the simulation results an average deviation for similar images was found to be 9.2% and 2.8mm for the triangular shape plate, validating that the shape of the plate plays a paramount role in cymatics analysis. An image processing technique was used to determine the deviation between the images created by experimental platform and FEA for all the three shapes. The results demonstrate that Chladni patterns are best represented by a triangular shaped plate.

Keywords: Cymatics, Finite Element Analysis, Chladni Patterns, Vibration, Resonance

1 Introduction

Cymatics is the study of sound and vibration made visible, typically on the surface of plates or liquid. Each frequency of sound causes a particular pattern to be formed on the plate. This study of vibrational wave phenomena is also called 'Cymatics' (Raghu, 2016). Every object or system in this universe acquire an infinite number of resonant frequencies which increase the amplitude of the system. This frequency is equal or close to the natural frequency of the system. Even though the resonance causes a massive vibration, specific regions of the object or system become stationary. When there are particles placed over this vibrating system, they will vibrate until they find those tranquil regions. These regions of standing waves have minimum frequencies called nodal frequency where the particles gather, and form quite complex patterns called Chladni patterns. The basic phenomenon of cymatics is to shows how vibrations interact to create the node shapes for different frequencies. When a membrane vibrates at its natural frequency, it shows specific dynamic behavior. Therefore, contemplating the nature of cymatics assists in determining the behavior and characteristics of invisible acoustic phenomenon.

Behavior of the cymatics refers to the phenomenon of sand particles on a flexural vibrating plate moving and aggregating at the nodal positions of the plate [1, 2]. That demonstrates the effects of the resonance phenomenon over two dimensional objects. Although Chladni effect has applications in the visualization of vibration modes and ultrasonic motor [3], and potential applications in micro and nano manipulations [4], research on its characteristics is deficient. Recent contemporary advancement of computer technologies facilitates the simulation of complex natural occurrences that exist in the world [5] and for solving and validating engineering problems.

The cymatics patterns represent the effects of vibration, with specific force and frequency, over one or many objects. Cymatics can have multiple applications, including cloaking of flexural vibrations in a structured plate that has been investigated in D. Misseroni et al. [5] They have used finite element simulation to validate their model. Cymatics or sound vibrations can come in contact physically through the body and have an effect on our consciousness at the mental, emotional, and spiritual levels. John et al.[6] used cymatics as a sound visualization tool. Cymatics has been used as a sound therapy in spirituality and consciousness [6]. This phenomenon is used in medical industry as a method of healing by exposing sounds to patients and this provides effective relief of stress, injury and chronic pain[7]. More over cymatics is used in the field of education to accelerate the learning process and brain activity to overcome disturbances in the learning process [8] and also as an elegant natural art form.

To identify the behaviour of the cymatics and to create the Chladni patterns, specific resources and techniques are required. Conducting of experiments is limited by the physical properties and accuracy of the experimental equipment[9]. The application of computational technology in this scenario would ease the process of investigating this phenomenon, and would not only save time and resources, but would allow for the creation of conditions which would be difficult to recreate using existing technology [8, 10].

Modal analysis is a process of representing various natural features of a geometry (structure) which may include damping, mass, modes shapes and frequency (Polytech, 2001). Modal analysis is significant in evaluating the mode shapes generated by a component under vibrational excitation. These mode shapes of cymatics visualization can be used to determine the displacement or response of the component under the influence of vibrations in day today applications. Results obtained from the modal analysis will generate a number of resonances, for which the frequency can be determined by measurement. Vibrations may be exceptionally high when a structure vibrates at frequencies higher or closer to the natural frequency of the body [11]. This phenomenon is used to identify the behaviour of the cymatics with reference to the nodal frequencies.

2 Methodology

This section presents the design and implementation of the system to determine the various images according to the frequencies and its significant components. The section introduces the finite element analysis, selection of material and details of the fabricated experimental set up. The schematic diagram (Fig.1) illustrates the overall methodology of the study.

2.1 Finite Element Analysis (FEA)

Finite Element analysis (FEA) is widely used to predict the behavior of engineering designs under given boundary conditions. We can use this analysis for determining the impact of pressure, heat, vibration etc. on a design and for solving problems in mathematical models. Moreover, the FE analysis precisely can be used in solving complicated differential equations with numerical solutions. Therefore, FE model analysis has been used to calculate the natural frequencies of vibrating models [11]. There are many simulation software that are being used for different purposes. Modal analysis using ANSYS is an effective method of determining vibration characteristics [12]. ANSYS enables the harmonic analysis which is used to determine the response under a steady-state harmonic loading at a given frequency.

For this study finite element analysis was carried out for selected plates with two plates with different materials (aluminum and steel) (Table 2) and for different shapes of plates to observe the behavior of the Chladni patterns. Simulation was performed with free and fixed boundary conditions for square, triangular and circular shapes to identify the suitable boundary condition to get the maximum patterns in low frequencies as demonstrated in Table 3.The surface area of each shape was considered as 900 cm^2 and the thickness as 2mm for both aluminum and steel plates.

2.2 Boundary Conditions

Edges free boundary conditions were used for circular, triangular and square plates as shown in Fig.2.

Thin shell type element (shell 281) consists of eight nodes with six degree of freedom at each node (Fig.3) and this was used to model the plates.

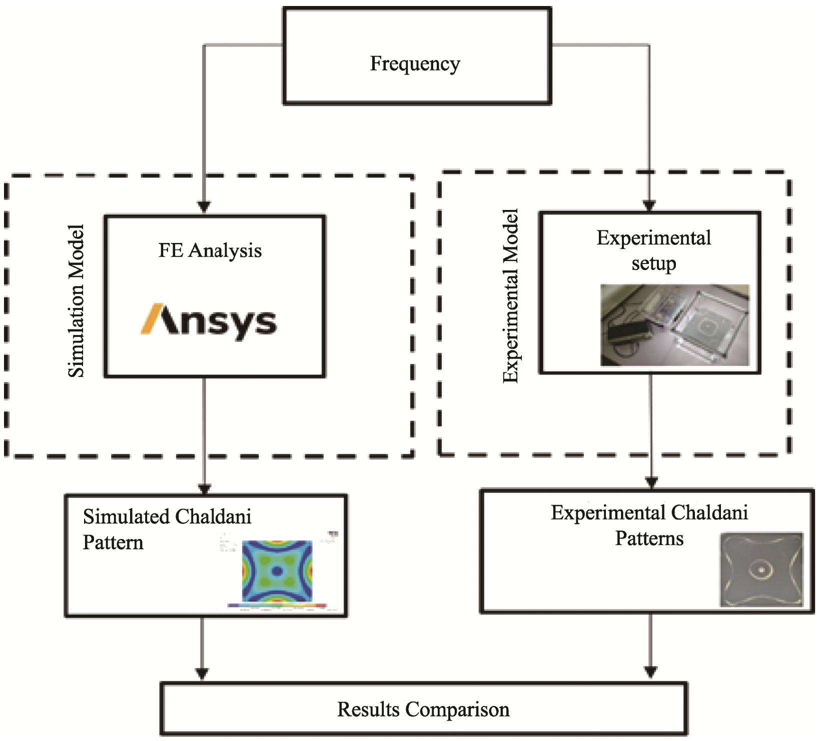


Fig.1 Schematic Diagram of the Overall Methodology

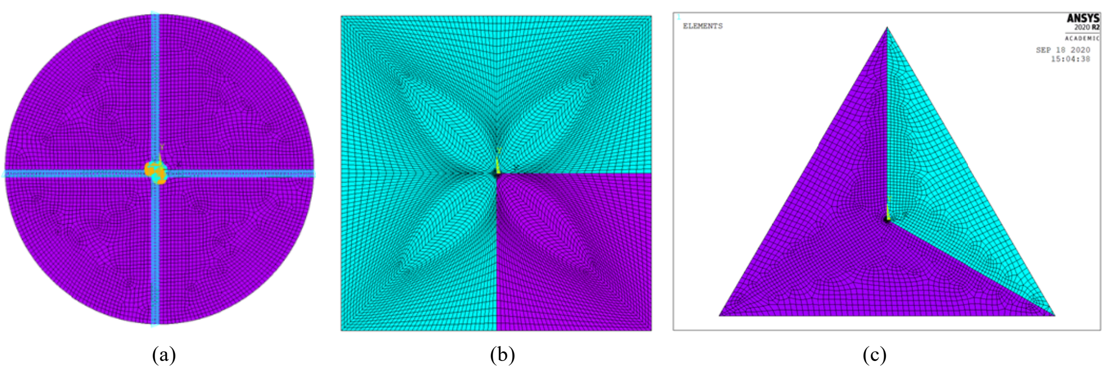


Fig.2 Nodes and Mesh details for Plates (a) Circular (b) Rectangular (c) Triangular Shapes

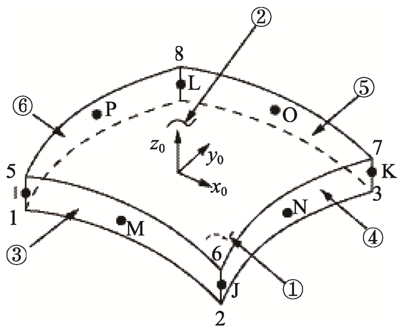


Fig.3 ANSYS Shell Element 281 (Reference Manual 2009)

Thin shell type elements were used in different plate shapes for analysis as presented below in Table 1 and Table 2 shows the material data used for the ANSYS software for the simulation.

Table 1 Plate Simulation Data

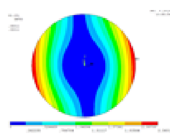
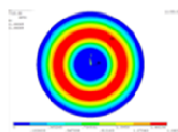
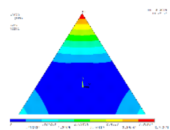
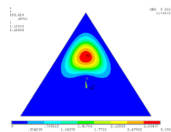
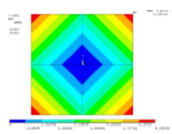
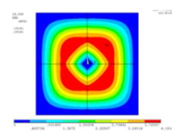
Shape of plate	No. of Nodes	No. of Shell Type Elements
Circular	17786	5853
Triangular	9726	3187
Square	6476	19709

Table 2 Material Data

Parameter	Steel	Aluminum
Modulus of Elasticity (GPa)	200	69
Poisson Ratio	0.3	0.3
Density(kgm^{-3})	800	2700

Initially the finite element analysis was performed under free and fixed boundary conditions to observe the effect of boundary conditions on nodal frequencies for all three shapes and the results are presented in Table 3. Simulated figures showed the nodal displacement perpendicular to the plate. The displacement varies from zero to higher values. Comparison of the results of modal analysis (Table 3) of free and fixed boundary conditions, show that for free boundary condition, pattern created frequency (mode 1) for circular shape was 102.15 Hz, for triangular shape 33.867 Hz and for square shape mode 1 frequency is 37Hz. The mode 1 frequencies for fixed boundary conditions for same shapes are 715Hz, 383Hz and 603Hz as illustrated in Table 2. Therefore mode 1 nodal frequencies for free boundary conditions showed a lesser value than the fixed boundary conditions for all three shapes. Therefore, for both experimental and FEA, free boundary condition was selected.

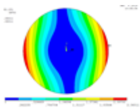
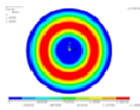
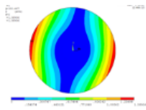
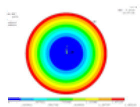
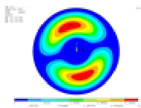
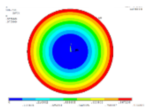
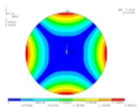
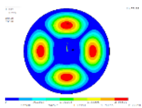
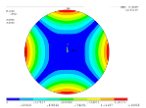
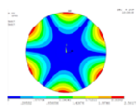
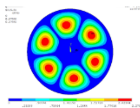
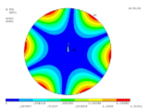
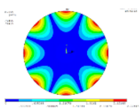
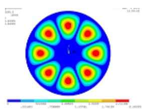
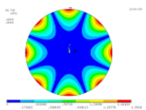
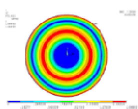
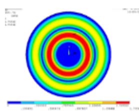
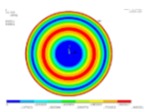
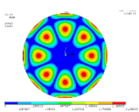
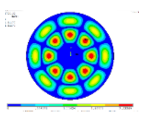
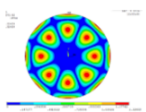
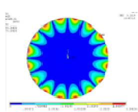
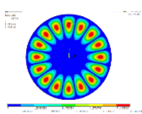
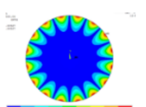
Table 3 ANSYS Simulation in the Case of Free and Fixed Boundary Conditions

Free Boundary Conditions (Mode1) Frequency for Each Shape (Hz)	Fixed Boundary Conditions (Mode 1) Frequency for Each Shape (Hz)
 102.15	 715.86
 33.867	 383
 37	 603

Second analysis was performed to select the material of the plates giving clear cymatics visualization (Chladni patterns) under low frequencies (Table 4).

The mode shapes of the circular plate according to the boundary conditions are shown in Table 4. A critical analysis of the mode shapes from different boundary conditions further depict that the results of the free boundary condition begin at lower frequencies than the fixed boundary condition. Also, when comparing the results of Al and steel plates at free boundary conditions, the Al plate shows the patterns in somewhat lower frequencies than steel plates for each mode. Therefore, for the experimental analysis, Al plates with 2mm thickness were used under free boundary conditions.

Table 4 Comparison between Frequencies of Al and Steel Plates

Mode No.	Free Boundary Condition Al plate Frequency for Each Shape (Hz)	Fixed Boundary Condition Al plate Frequency for Each Shape (Hz)	Free Boundary Condition Steel Plate Frequency for Each Shape (Hz)
1	 102.15	 715.86	 102 102
2	 106.95	 741	 106
3	 127.13	 832	 229
4	 229.37	 1015	 334
5	 391.56	 1295.9	 399
7	 672.62	 1971.7	 673
13	 1364	 2720	 1373
14	 1459.9	 3037.6	 1485

3 Experimental Setup

A prototype was developed to visualize the cymatics behaviour experimentally and the potential of the experimental set up for different shapes was evaluated.

To confirm the validity of the Chladni pattern, a series of tests were conducted for square, circular and triangular shapes of aluminum plates. The thickness and the surface area of the plates were similar to plates used in FE analysis Frequency was generated by the signal generator through an amplifier to the actuator which is chosen as a speaker as shown in Fig.5. Piezo electric and electromagnetic actuators were used to vibrate the plate. The amplifier was slowly adjusted until vibration commenced. The actuator is balanced by a level bed taking the leveling of the vibrating plate into consideration. A lighting system is added to the system for visualizing the cymatic pattern more clearly. The signal generator generates different frequencies and created Chladni patterns and model frequencies were observed and recorded (Fig.4). Generated frequency is initially set to 1 Hz and increased by 0.001 Hz to create most accurate results, and the images were recorded by 13 MP camera. Graded sand with approximately 440μm's of diameter were used as the particles that congregate in response to the resonance pattern.

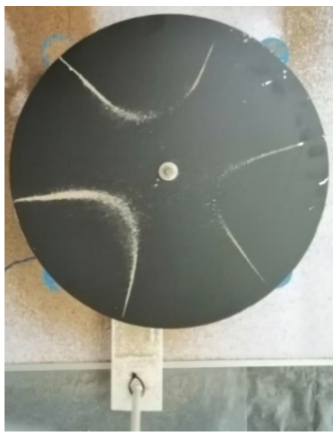


Fig.4 Model Detection

Designed experimental set up mainly consists of a frequency generator, amplifier, actuator, and plate as shown in Fig.5.

The results of the cymatics visualization patterns created from the fabricated experimental set up and the relevant frequencies were recorded as shown in Fig.6, 7 and 8 for all three shapes of aluminum plates.

4 Results and Analysis

The experimental and simulation results are presented in two sections. A prominent resemblance exists between the plots from the experiment and those obtained from the FE analysis for 60% of the images. A comparison of model frequency to operating frequency along with the actual image to the generated FE image is presented below in Tables 9, 10, and 11. Therefore, the percentage of difference of model frequencies were calculated, respect to FEA and the results show that the average percentage of frequency difference with respect to FEA analysis for square shape is 12.5% for triangular shape is 9.2% and for circular shape is 31.3%.

Image processing techniques were used to identify the deviation of the Chladni pattern, created experimentally vs finite element analysis, and the average deviation for similar patterns is also presented in the Tables 9, 10, and 11 respectively.

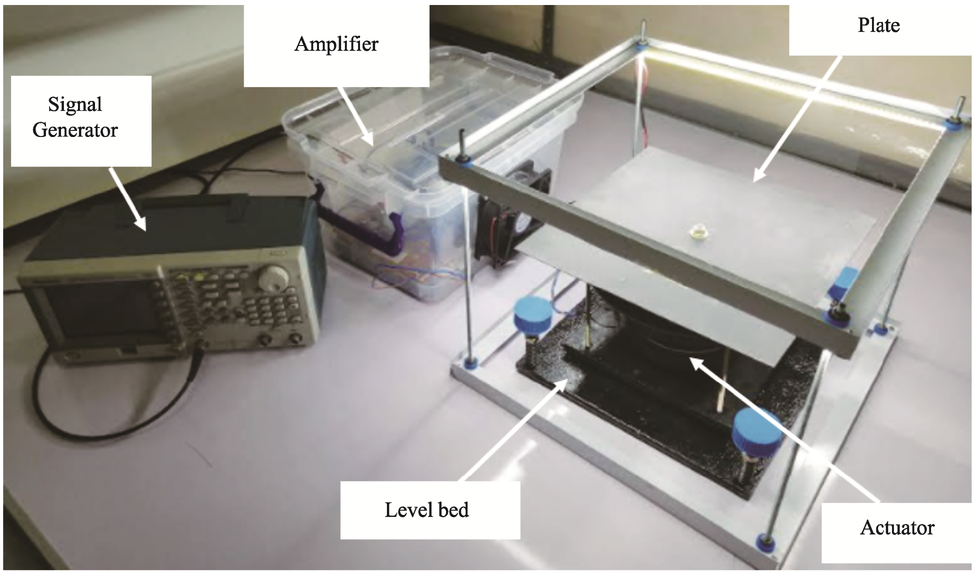


Fig.5 Fabricated Experimental Setup

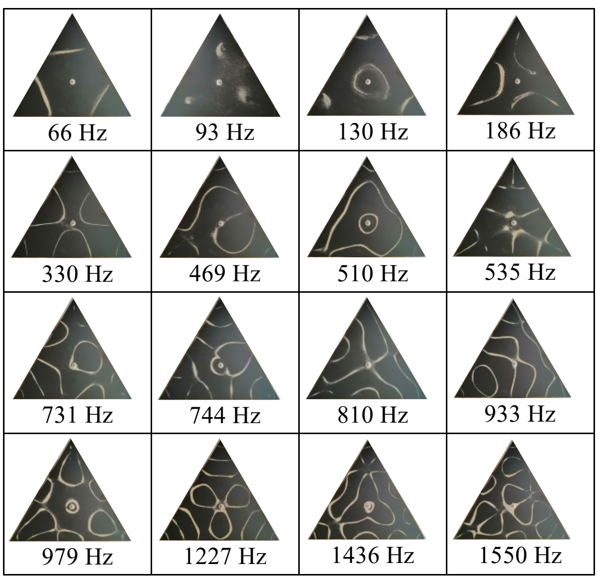


Fig.6 Experimental Results for Triangular Plate

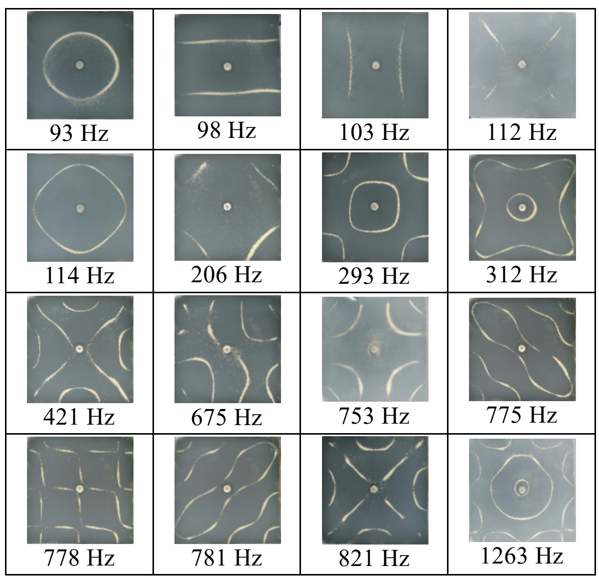


Fig.7 Experimental Results for Square Plate

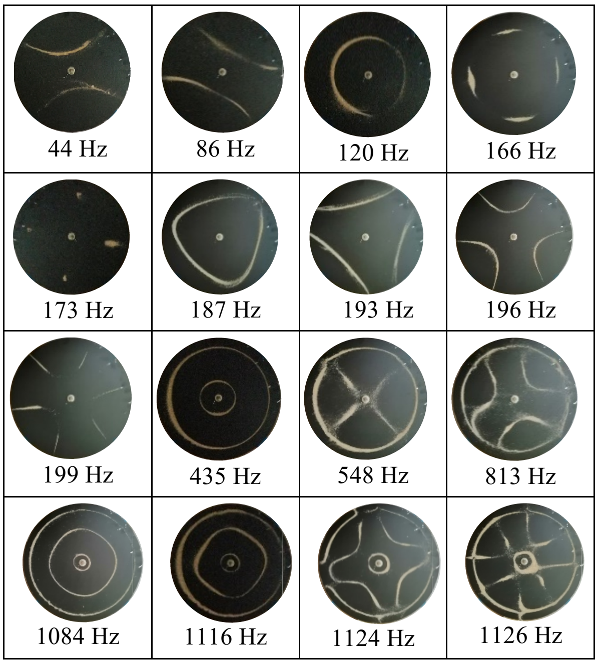
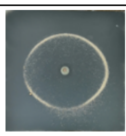
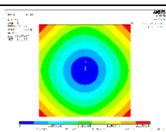
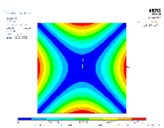
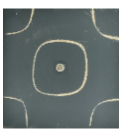
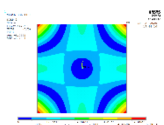
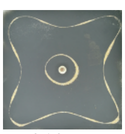
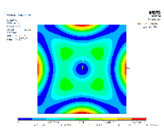
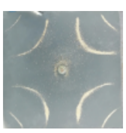
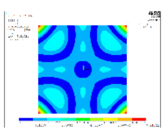
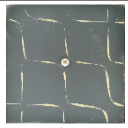
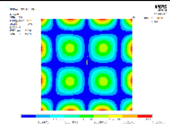
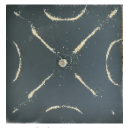
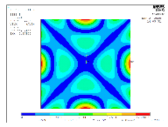
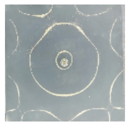
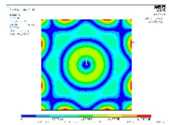
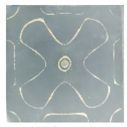
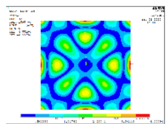
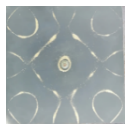
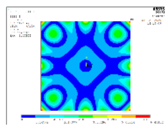
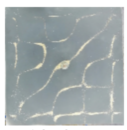
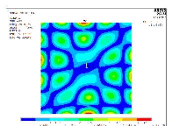
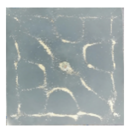
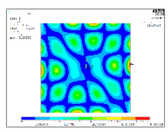


Fig.8 Experimental Results for Circular Plate

Table 9 Comparison of experimental and FE results for square shape

Matched Experimental Patterns	Matched Simulated Patterns	Frequency Diferrence withRespect to FEA (%)	Image Deviation (mm)
 93Hz	 64.029Hz	45	45.3
 112Hz	 106.061Hz	5.7	3.8
 293Hz	 256.049Hz	14	4.2
 312Hz	 495 Hz	37	5.5
 753Hz	 793.802Hz	5	4.1

Continued Table 9

Matched Experimental Patterns	Matched Simulated Patterns	Frequency Diferrence withRespect to FEA (%)	Image Deviation (mm)
 778Hz	 832.393Hz	6.5	4.8
 821Hz	 880.794Hz	6.7	2.3
 1263Hz	 1284.78Hz	1.7	4.1
 1487Hz	 1595.04Hz	6.8	1.8
 1652Hz	 1762.72Hz	6	2.8
 1852Hz	 2018.79Hz	8	6.6
 1862Hz	 2018.79Hz	8	2.8
Average Frequency Difference with Respect to FEA (%)		12.5	
Average Image Deviation (mm)			9.1

Average of frequency difference with respect to the FEA results for rectangular shape plate is 12.5 (%) and average image deviation between experimental results and FEA results is 9.1.

Average difference of frequency with respect to FEA results for rectangular shape plate is 9.2 (%) and average image deviation between experimental results and FEA results is 2.8.

Table 10 Comparison of Experimental and FE Results for Triangular Shape

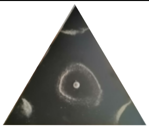
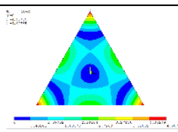
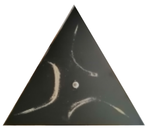
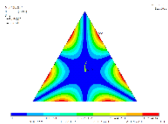
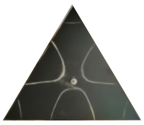
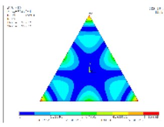
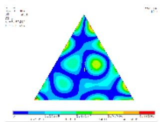
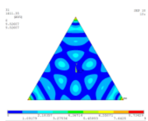
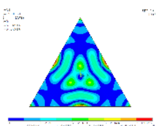
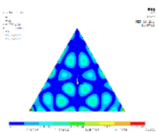
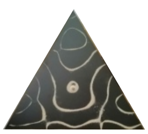
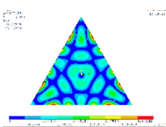
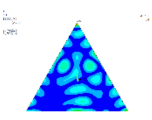
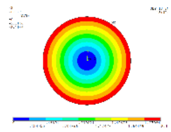
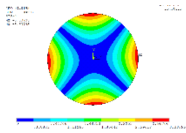
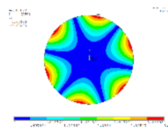
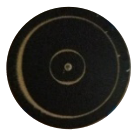
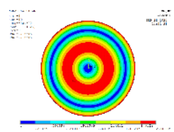
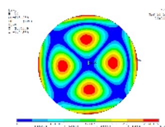
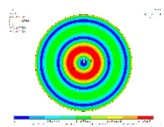
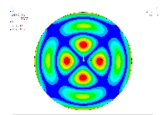
Matched Experimental Pattern	Matched Simulated Pattern	Frequency Difference with Respect to FEA(%)	Image Deviation (mm)
 130Hz	 152.24Hz	14.6	4.96
 186Hz	 213.83Hz	13	12.2
 330Hz	 380.04Hz	13	10.2
 731Hz	 832.98Hz	12	3.5
 1227Hz	 1411.4Hz	13	2.1
 1436Hz	 1598.6Hz	10	5.5
 1550Hz	 1774Hz	12	2.2
 1619Hz	 1807.2Hz	10	8.0
 1650Hz	 1896.7Hz	13	3.9
Average Frequency Difference with Respect to FEA (%)		9.2	
Average Image Deviation (mm)			2.8

Table 11 Comparison of Experimental and FE Results for Circular Shape

Matched Experimental Pattern	Matched Simulated Pattern	Frequency Error (%)	Image Deviation (mm)
 120Hz	 67Hz	79	53.9
 173Hz	 91Hz	90	22.1
 199Hz	 211Hz	5.7	8.0
 435Hz	 381Hz	1.4	11.5
 548Hz	 615Hz	11	2.5
 1184Hz	 1104Hz	7.2	5.4
 1550Hz	 1774Hz	12.6	2.4
Average Frequency Difference with Respect to FEA (%)		29.5	
Average Image Deviation (mm)			15.1

Average difference of frquencies with respect to FEA results for rectangular shape plate is 31.3 (%) and average image deviation between experimental results and FEA results is 15.1.

5 Conclusion

The fabricated prototype produced results which are close to the phenomenon of cymatics and the visualization of Chladni patterns, even when thousands of particles are involved. For this phenomenon of cymatics, modal analysis is significant in evaluating the mode shapes generated by the test platform under vibrational excitation. Results obtained from the modal analysis was generated due to number of resonances and therefore the frequency for each pattern was recorded by measurement for both test and FE analysis. Sand with approximately 440µm diameter were used as the particles for measurement. Experimentally generated modal shapes (images) were compared with the results by FE analysis for square, triangular and circular shapes. Both experimental and FE analysis were performed using 2mm thick aluminum plates with same dimensions. ANSYS software was used for the simulation and the experimental analysis was performed using a fabricated test platform. The results from experimental were on par with simulated results. A total of 56 Chladni patterns were created experimentally and 60% of them were similar to patterns generated by the ANSYS software. Results shows that, the average frequency difference with respect to the finite element analysis was found to be 12.5% for square plates, 9.2% for triangular plates and 31.3% for circular plates. An image processing technique was used to evaluate the deviation between the images created by the test platform and FEA for all three shapes. The results show that the average deviation between the images of experimental and FEA is for square shape 9.1mm, for triangular shape 2.8mm and for circular shape 15.1mm. Therefore, studies of the behaviour of cymatics of various frequencies for different shapes of plates, demonstrated that for the triangular shaped plate, the experimental results are in good agreement with the FEA results for formation of chladani patterns.

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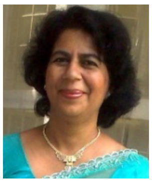

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