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Analysis of Vibrating Plates with Acoustic Holography and Eddy Currents

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Abstract

The aim of this project was to compare various methods of analyzing vibrating plates, including the use of a previously untested eddy current probe. The data collected gave us insight on the various vibrational modes of the plates. They also demonstrated dramatic effects on the vibrational modes as the boundary conditions of the plates were altered. We confirmed the correlation of various measurement techniques, albeit with differing levels of resolution.

Introduction

Understanding the vibrational modes of a body is important for understanding its acoustical and structural characteristics. The simple case of a vibrating plate provides us with a way to test and compare various measurement techniques on a well-researched experiment. The theory behind vibrating bodies has been understood for centuries, but depending on the experimental setup, some examples are too complex to be insightful. The simplified behavior of a vibrating plate or membrane can be approximately described by the wave equation,

$$\nabla^2 u = \frac{1}{v^2}\frac{\partial^2 u}{\partial t^2}.$$

While solving this differential equation is fairly straight forward, the boundary conditions of the plates in this experiment are unclear. Taking direct measurements was a more attractive option.

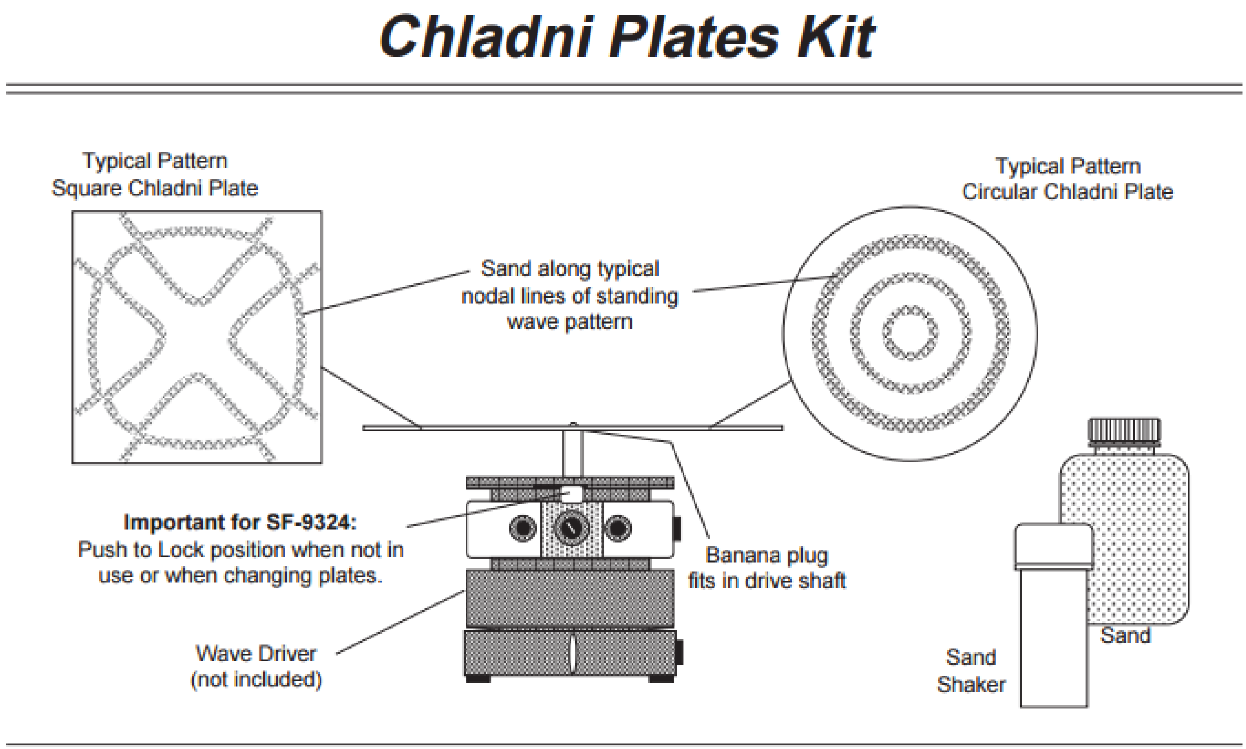
Perhaps the most famous tool for analyzing the vibrations of an object is the use of Chladni patterns, named in honor of the German physicist Ernst Chladni, who invented the technique. Chladni patterns provide a simple and inexpensive method of observing characteristics of a vibrating plate at its resonant frequencies, by placing sand on the plate and allowing it to settle along the nodal areas of the plate. While this technique provides the clearest picture of a plate's vibrational interference patterns to the unaided eye, it does not display information on phase and even fails to show many resonances.

Near-field acoustic holography provides much more data than Chladni patterns, at the cost of ease of use. If one collects data on the pressure and particle velocities at several points over the plate, they can calculate many other acoustical variables, such as particle acceleration, particle displacement, and acoustic impedance. In addition, one can collect information on the phase of vibrational modes, which has proved useful for finding additional resonances in the system.

The last method used to measure characteristics of the vibrating plates was to induce and measure eddy currents in the metallic plates. The eddy current probe was successful and demonstrated that it is at least capable of matching the displacement data collected from the near-field acoustic holography, potentially with an even higher spatial resolution.

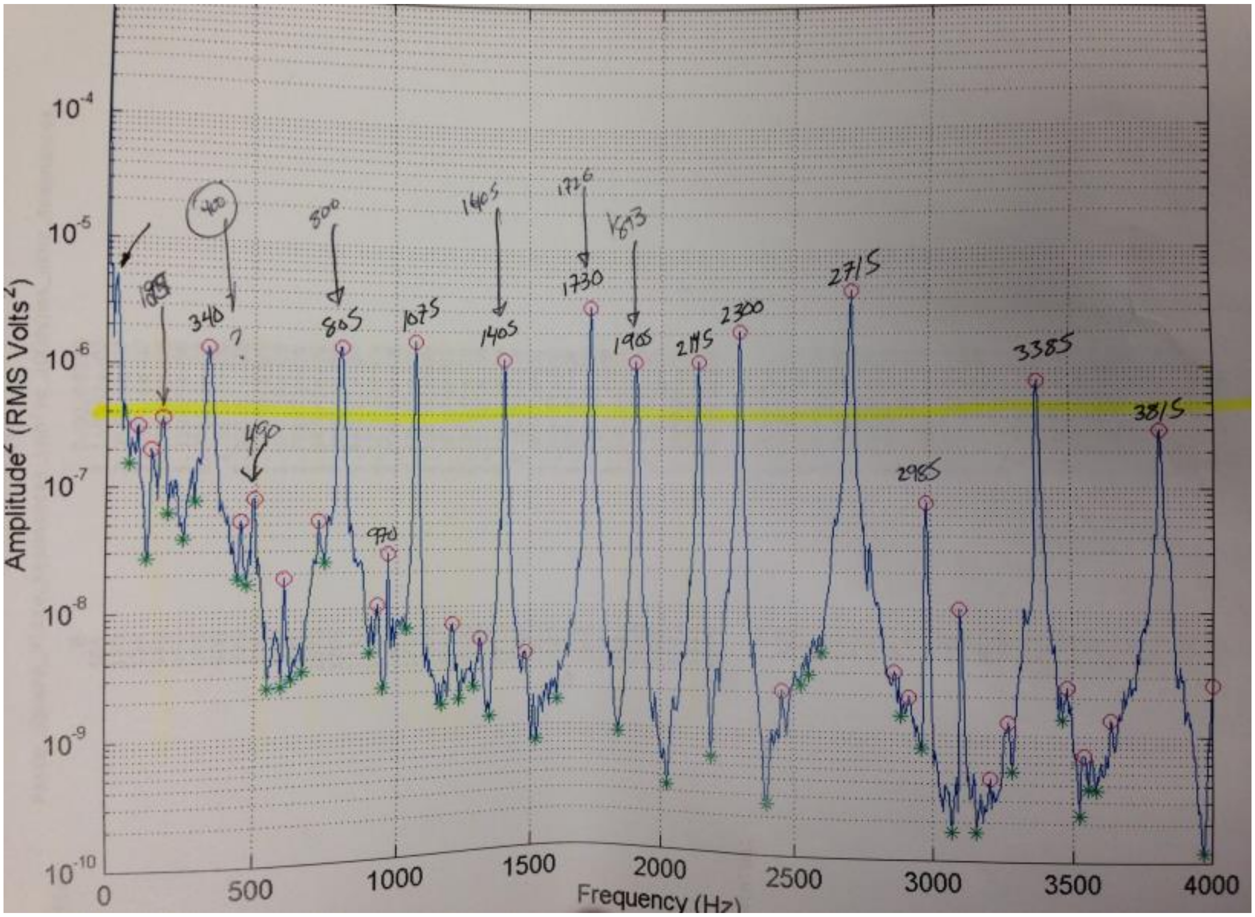
Experiment 1: Chladni Patterns, Setup

For this project we used the PASCO Scientific Mechanical Wave Driver (model no. SF-9324) and Chladni Plates Kit (model no. WA-9607). The mechanical driver was a standard electromagnetic driver, and was essentially a speaker with a post attached to the voice coil. The aluminum plates were fixed to this post. When the driver was supplied with an alternating current, the various modes of the plate were excited. We used a 24 cm × 24 cm square plate, as well as a circular plate with a diameter of 24 cm. The circular plate was attached to the post at its center or to a point slightly off center. The on-center circular plate produced symmetrical vibrational interference patterns, while the off-center plate produced asymmetrical patterns. As the plates were driven at a resonant frequency; sand was sprinkled onto the plates, which settled along nodal lines.



An illustration of the PASCO Mechanical Driver and Chladni Plates used in the experiment. Retrieved from http://www.pasco.com/file_downloads/product_manuals/Chladni-Plates-Kit-Manual-WA-9607.pdf

To find the resonant frequencies of the various plates, we used a Hewlett Packard 3562A spectrum analyzer. With the mechanical driver exciting the plate at a low frequency, the spectrum analyzer discerned the resonant frequencies of the plate. We then used a function generator to run the driver at the various resonant frequencies, which gave us the Chladni patterns for the different plates. Not every resonance detected by the spectrum analyzer had a well-defined Chladni pattern. In order to elucidate the behavior of these resonances, a different measurement technique was required.



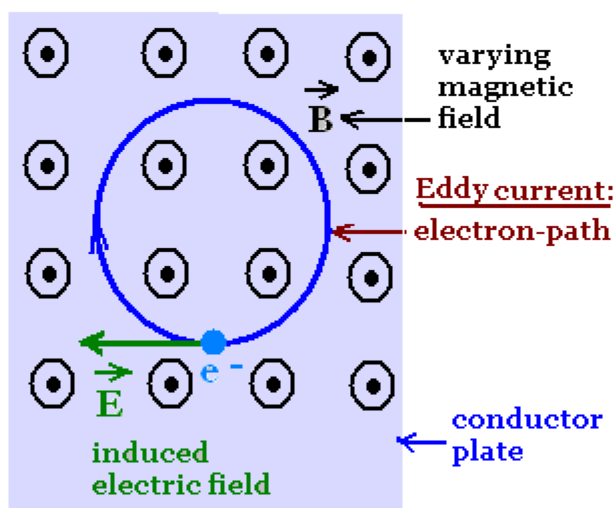
The frequency response plot for the centrally-supported square plate, produced using the spectrum analyzer. The resonant frequencies of the plate are circled and labeled with their values in hertz.

Experiment 2: Near-Field Acoustic Holography, Setup

Using the same mechanical driver and plates from the Chladni pattern experiment, we collected data using near-field acoustic holography. The measurements were taken at the resonances we found using the spectrum analyzer, ranging between 200 to 4,000 Hz. The different plates were scanned using particle velocity and pressure probes, which hovered just millimeters over the vibrating surface. Data was collected at 1 cm intervals across the plates; making the process quite lengthy, covering roughly 500 cm^2 of area. Each scan took about 6 hours to complete, making it difficult to maintain a steady driving frequency over the length of the data acquisition process. As conditions such as humidity and temperature varied during the scan, the resonant frequency varied as well. In order to keep the plates at their resonance frequencies, we made use of SRS-830 Lock-In Amplifiers, a pair of monitoring microphones, as well as some MATLAB code to mode-lock our plates. For more information on how mode-locking was accomplished, one should contact Professor Errede. As this type of scan was not new to his laboratory, MATLAB code had already been developed to interpret the data and calculate many other acoustic quantities. Many scans were performed throughout the semester and we have amassed a large amount of data on the three different plates.

Experiment 3: Eddy Current Probe, Setup

The final means by which measurements were made on the vibrating plates was with a newly designed eddy current probe. The probe used a permanent magnet from an electric guitar pickup. The magnet was wound with approximately 5,000 turns of copper wire, and attached to a probe. The probe was used to scan the plates in the same manner as the previous method. The vibrating plates experienced a changing magnetic flux from a permanent magnet stationed in close proximity to the plates, which induced an electric field in them. This electric field generated what are known as eddy currents- areas in the plate where electrons move in circular orbits. These orbiting electrons produced a changing magnetic flux in the probe's coil, which



An illustration of eddy currents produced by a time-varying magnetic field.
Retrieved from scientificsentence.net

produced an EMF that we measured. We scanned the plates while they were mode-locked to their resonant frequencies.

Because we were not able to successfully run the experiment until close to the end of the semester, we did not collect as much data from the eddy current probe as the near-field acoustic holography. However, the data we did collect agreed with the data from the near-field acoustic holography, making this experiment a success.

Experiment 1: Chladni Patterns, Results

We were only able to find Chladni Patterns for a fraction of the resonances detected by the spectrum analyzer. The patterns for the on-center circular plate all exhibited circular symmetry, the patterns for the square plate exhibited 4-fold rotational symmetry, and the patterns for the off-center circular plate exhibited reflected symmetry across the axis connecting the driver post and the center of the plate. It is worth pointing out how vastly different the behavior was between the on-center and off-center circular plates.

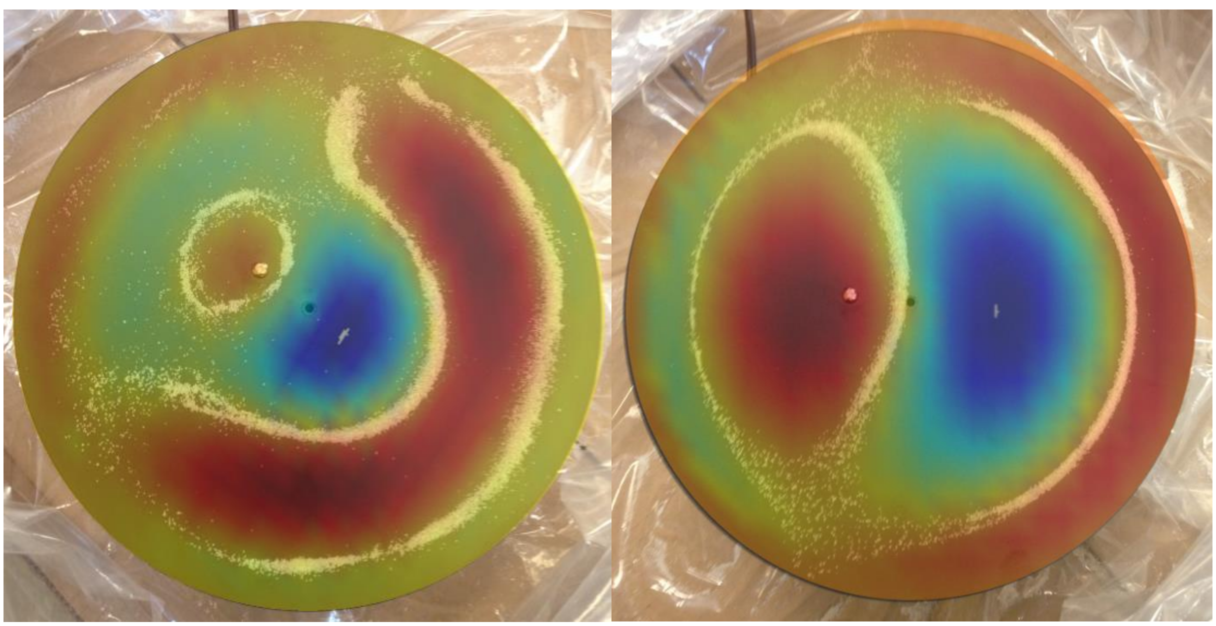
Typical Chladni patterns from a centrally-supported circular plate. Higher frequency resonances contain more circular nodal lines.

Chladni patterns from the non-centrally-supported circular plate. There is no discernable relation between the patterns produced by the various resonances, except that they all exhibit reflected symmetry.

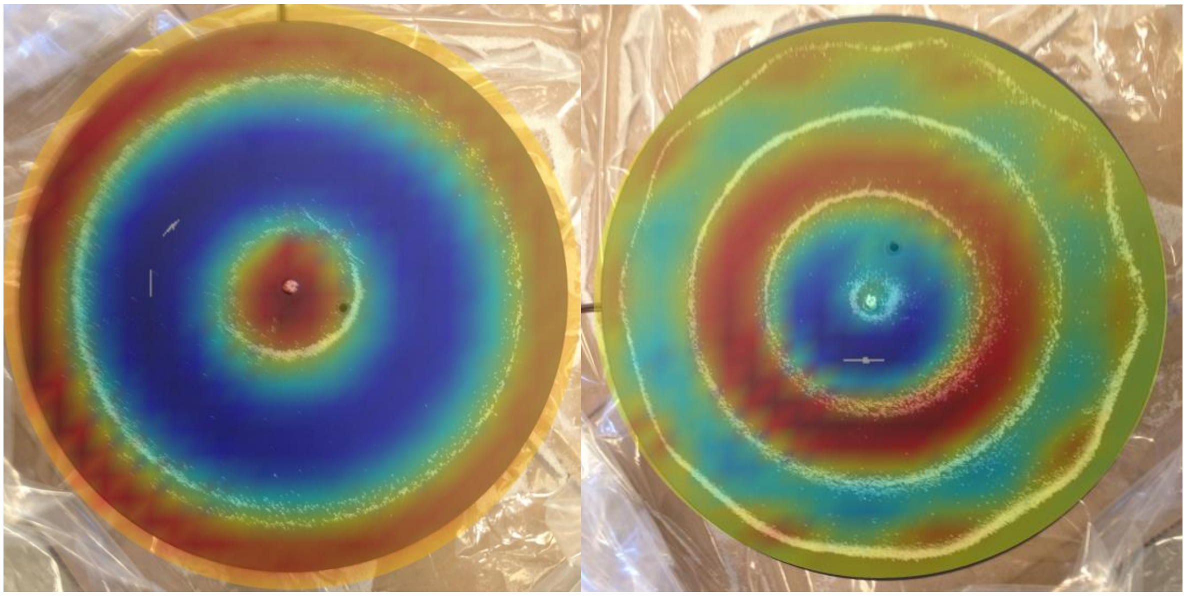
Chladni patterns from the centrally-supported square plate. There is no discernable relation between the patterns produced by the various resonances, except that they all exhibit 4-fold symmetry.

Experiment 2: Near-Field Acoustic Holography, Results

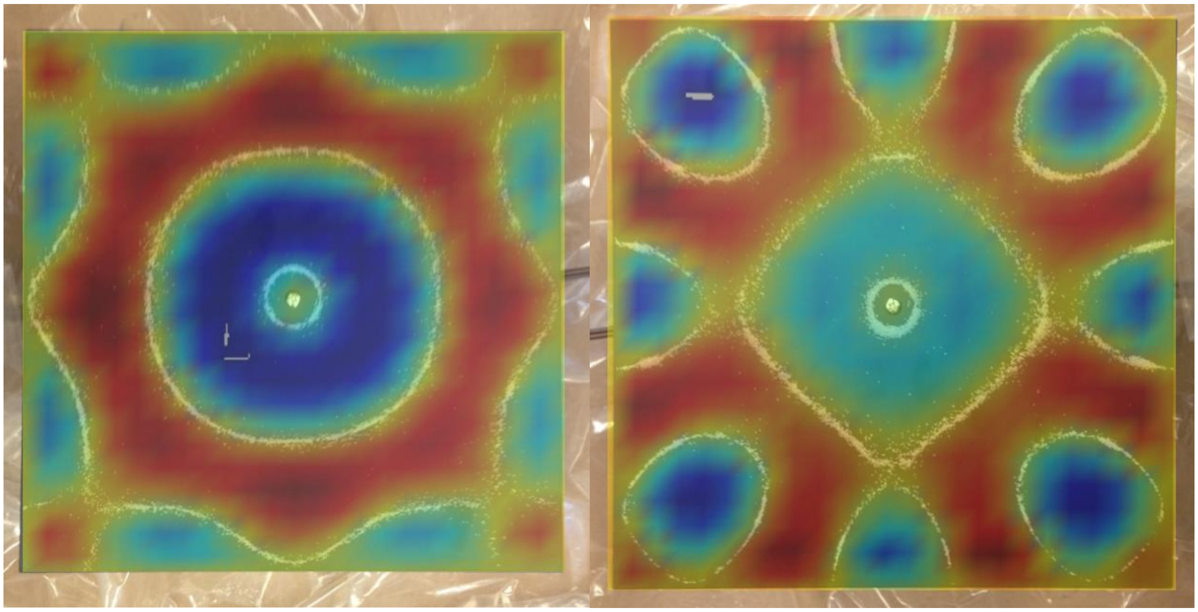
We collected a large amount of data from our near-field acoustic holography scans over the course of the semester. Even though this type of data collection provided us with much more information than the Chladni patterns, one of the interesting findings was how well the two methods reproduce the same results. To illustrate this, we superimposed the displacement data collected from the acoustic holography scans with the images of the corresponding Chladni patterns. The correspondence between the two is quite striking.



Acoustic holography displacement maps for the non-centrally-supported circular plate, superimposed onto their corresponding Chladni patterns.

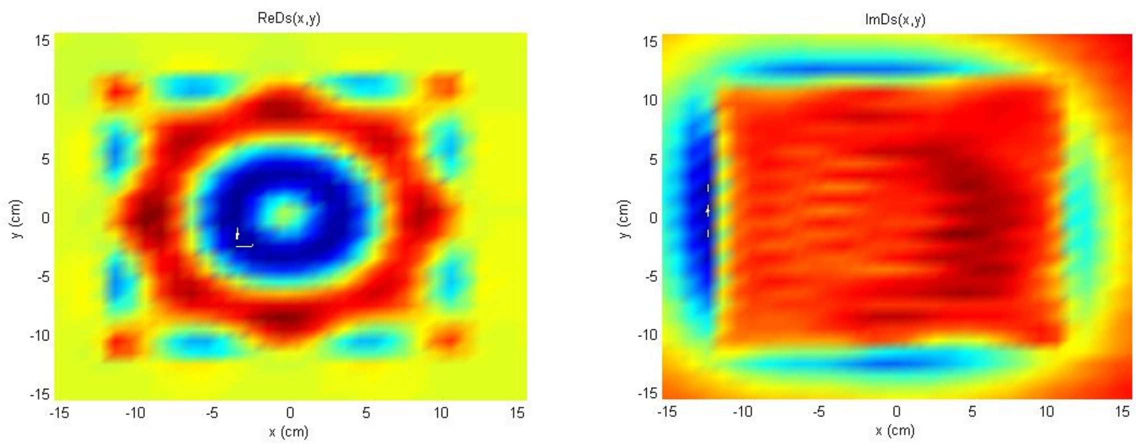


Acoustic holography displacement maps for the centrally-supported circular plate, superimposed onto their corresponding Chladni patterns.

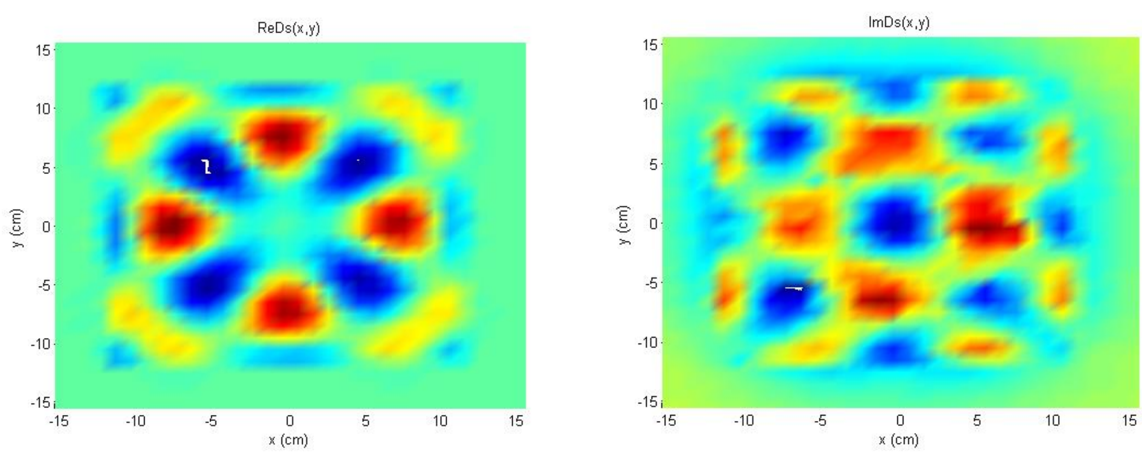


Acoustic holography displacement maps for the centrally-supported square plate, superimposed onto their corresponding Chladni patterns.

Another interesting result we obtained from analyzing the acoustic holography data was the presence of “hidden” resonances. That is, we found some resonances that were in very close proximity to other, more prominent, resonances. The Chladni patterns were unable to resolve these resonances, but they appeared in the imaginary displacement maps. The fact that they appeared in the imaginary displacement implies that they were out of phase with the more prominent vibrational mode.



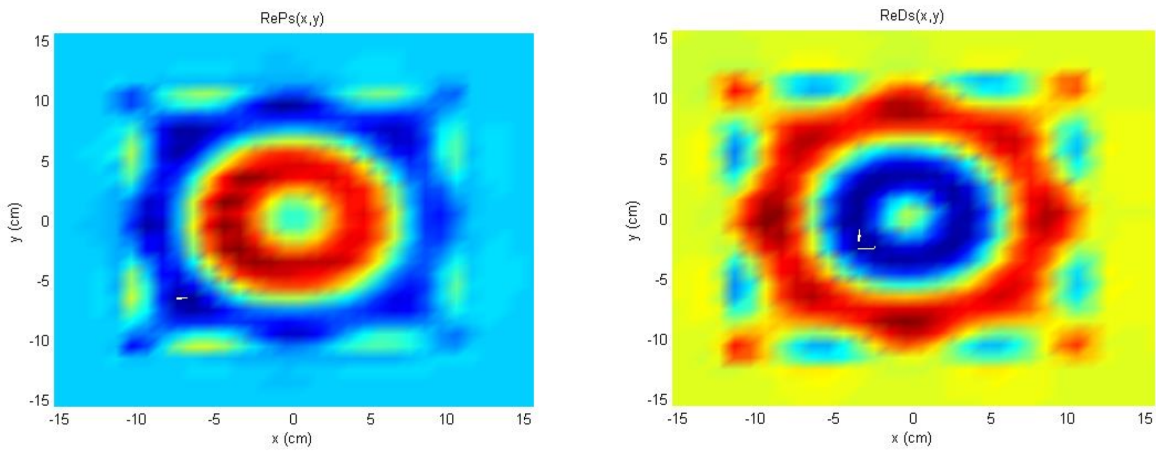
The real and imaginary displacement maps for the centrally-supported square plate, driven at 802 Hz. The two maps do not appear at all similar, indicating there are actually two vibrational modes near 800 Hz out of phase with each other.



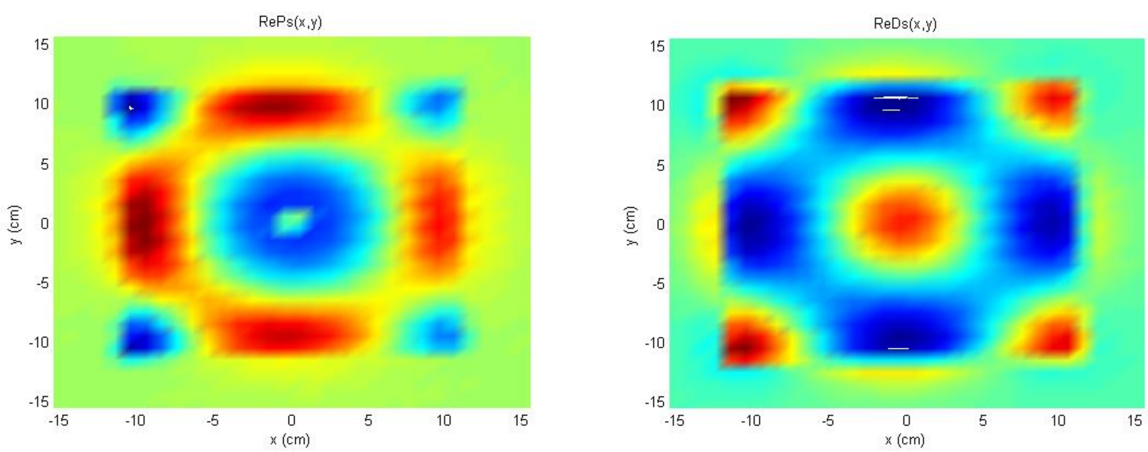
The real and imaginary displacement maps for the centrally-supported square plate, driven at 970 Hz. Once again, the two maps appear distinct, indicating another vibrational mode.

Experiment 3: Eddy Current Probe, Results

As mentioned earlier in this report, the eddy current probe only came into function late in the semester, so only a few scans were run. The little data we acquired agreed with both the Chladni patterns and the near-field acoustic holography results. Given more time, we are confident we could have produced results from varying resonant frequencies that would have matched the results from the previous two methods.



The image on the left is map of the intensity of the measured EMF measured by the eddy current probe. It clearly corresponds to the displacement data obtained from near-field acoustic holography, shown on the right.



Another comparison between the eddy current probe data, left, and the near-field acoustic holography data, right.

Conclusion

Our initial goal was to compare the various techniques for analyzing the vibrational modes of mechanically driven plates. As we showed above, the 3 techniques we used were consistent with one another. The near-field acoustic holography seemed to be the most useful technique, given the amount of acoustical data that we obtained from a single scan. The eddy current probe should not be regarded merely as a novelty, though. There is a possibility that it could produce a higher resolution map than the acoustic holography can, and if we had more time our research would probably head in that direction. It would come at the cost of even longer data taking sessions. However, even if it were possible to produce higher resolution scans, it may not be practical. Lastly, Chladni patterns, while not as useful for serious data taking, are still unmatched in their simplicity and ability to analyze vibrational modes in real time.

Acknowledgements

We would like to thank Professor Errede for his assistance with building our eddy current probe, his assistance in the data taking process, and his guidance on possible directions to take our research.