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A COMPUTATIONAL APPROACH AND EXPERIMENTAL VALIDATION FOR THE ASSESSMENT OF ADDED MASS FOR FUEL PLATES

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ABSTRACT

Current efforts are underway to convert the fuels of high-performance research reactors (HPRRs) from a standard highly enriched uranium (HEU) fuel to a high-density low enriched uranium (LEU) fuel combined in a molybdenum alloy. The conversion process has raised a renewed interest in determining the hydro-mechanical properties of the fuel plate. Of great interest is the excitation frequency and the response frequency of the plate. Accurate determination of these frequencies is difficult and costly to perform experimentally; as such, computational methods are desired to assess the response of the plate. Current state of the art requires the use of strongly coupled computational fluid dynamics (CFD) to computational structural mechanics (CSM) simulations. These simulations require the use of large clusters in order to be performed in a reasonable time frame. Previous work conducted between the Idaho National Lab (INL) and Oregon State University (OSU) under a Nuclear Science User Facilities (NSUF) program showed promise with a new method designed to determine the frequency of a structure. The method used purely computational structural mechanics (CSM) to determine the natural frequencies of a body submersed in a fluid. The method was achieved by treating water as a pseudo-solid instead of as a fluid.

The goals of this study are to (1) determine the change in the fundamental frequency of the plate when submersed in a fluid and (2) asses the ability for the pseudo-solid approach to determine the fundamental of frequency of a plate in channels. For objective (1) a small experiment, frequency identification in a fluid experiment (FIFE), has been created for the purpose of determining the change in frequency of a plate from air to fluid to fluid channels. The experiment uses sound excitation as a driving frequency and the response is measured via strain gauge, complimented with a hydrophone and microphone. Experimental results have been obtained for both air and water. The experimental results are further used to validate the pseudo-solid approach to achieve objective (2). The pseudo-solid approach has shown excellent agreement with theoretical determinations of frequencies of bodies submersed in a fluid. This paper outlines the experimental results of the FIFE as well as the validity of the pseudo-solid method.

KEYWORDS
Fluid-Structure Interaction, Added Mass, Computational Structural Mechanics, Vibration

1. INTRODUCTION

In 2004 the Global Threat Reduction Initiative, (GTRI) was established by the National Nuclear Security Administration (NNSA). Under the GTRI, nuclear fuel from research reactors around the United States is being converted from Highly Enriched Uranium (HEU) to Low Enriched Uranium (LEU). The switch from HEU to LEU is often achieved through a direct replacement of HEU with LEU. Unfortunately, a direct conversion from HEU to LEU results in the reactor producing fewer neutrons. Direct conversion from HEU to LEU may also prevent the reactor from achieving criticality. The lack of neutrons is often overcome by replacing in-core reflector elements with fuel elements. High Performance Research Reactors (HPRRs) such as the Advanced Test Reactor (ATR) at the Idaho National Lab (INL) don't have the luxury of adding more fuel elements. To decrease the enrichment but preserve the neutron economy, the mass fraction of uranium in the fuel is increased. While the issues of the neutron density in the core is solved, the mechanical properties of the new LEU fuel are fundamentally different from the old HEU fuel. The conversion process from LEU to HEU for HPRRs thus requires qualification of the new fuel.

When it comes to qualification of fuel, a primary concern is ensuring the fuel won't undergo unwanted vibrations under normal operating conditions. Conversely, it is important to identify the conditions under which the fuel will experience significant vibrations. An object in a flow will undergo the largest amplitude vibrations when excited at a resonant frequency of an object. For simple geometries, in an air, or highly compressible fluid, e.g. air, determining the resonant frequency of an object is simple. When more complex geometries are used, or a fluid is added, it becomes much more complicated to determine the frequency. To determine the resonant frequency the options are limited, often times requiring gross assumptions about the geometry or expensive computational simulations (or sometimes both).

To improve both time and accuracy, a computational pseudo-fluid approach developed by Howard et. al. in 2014 was used to determine the frequency of a body immersed in a fluid [1]. The method showed excellent agreement with theory and provided an accurate result for a cantilevered beam experiment. Time constraints prevented the method from being further applied to plates with various boundary conditions. In 2014 Britsch et. al. applied the method to knife-edge and sinusoidal plates [2]. The results proved inconclusive due to the unique nature of the boundary conditions. The method is being further investigated for future use in the analysis of fuel plates. To adequately assess the methods ability to characterize the vibrations seen in plates with high aspect ratios, a fundamental study is required to provide sufficient information as to the behavior and potential excitation mechanisms of fuel plates. To this end a bench top experiment referred to as the Frequency Identification within a Fluid Experiment (FIFE) was designed to provide insights and experimental results to aid in the assessment of the computational approach. The work herein provides the results and assessment of a series of experiments conducted to provide sufficient experimental data to assess the pseudo-fluid method developed by Howard.

2. THEORY

The frequency of plates are well characterized in air, as both experiment and theory provided the frequency of a plate under ideal boundary conditions [3]. This is partially true of a plate submerged in a fluid. When a plate is submerged in a fluid, it is subject to an added mass. Typically, added mass is characterized by the equation:

$$m_a = m_p \left(\left(\frac{f}{f_o} \right)^{-2} - 1 \right) \qquad (1)$$

where m_p is the mass of the plate, f_o is frequency in a vacuum, and f is the frequency of the plate submersed in a fluid. The solution for a rigid plate in a fluid was characterized by Patton [4]. For a plate free of a blocking structure, the frequency of a plate is approximated using strip theory which calculates the added mass of the fluid based on the vibrational mode of the plate [3]. Strip theory provides a reasonable approximation for plates without walls. Nuclear fuel plates are often in an array which adds one more challenge to the problem of added mass. If the spacing between plates is sufficiently large, fluid will be pushed along the length of the plate. Strip theory is not truly applicable as it assumes one side of the plate is much longer and fluid only moves parallel to the short edge. While fuel plates do have high aspect ratios, the fluid cannot move parallel to the short edge, and thus must move in the transverse direction. The approaches presented in Blevins and Patton may be used here accounting for the fact the fluid only flows along one edge. For vibrational characteristics of a plate near a channel, a method was presented by Fritz [5]. The method describes the added mass near the wall as,

$$m_a = \frac{\rho_f l^3 w}{12d} \tag{2}$$

using the fluid density (ρ_f), plate length (l), plate width (w), and distance from the wall (d). The method, unfortunately yields a result of 0 at distances far from the wall which is unphysical. To account for the discrepancies between the method by Fritz and Patton, the methods were hybridized to allow for added mass as a function of the gap thickness without providing an unphysical results by Howard and Marcum [6].

3. EXPERIMENT

To examine the various theoretical approaches, provided a potential means for validation of the pseudo-fluid approach and provide additional insights into the behavior of plate vibrations in channels and in a fluid the Frequency Identification in Fluid Experiment (FIFE) was constructed.

3.1 Description

The experiment portion was conducted using the Frequency Identification in Fluid Experiment (FIFE). The FIFE was an experiment designed to test the frequencies of a single plate and plate array. The FIFE was designed to be clamped on the length and free along the width of the plate as shown in Figure 1.

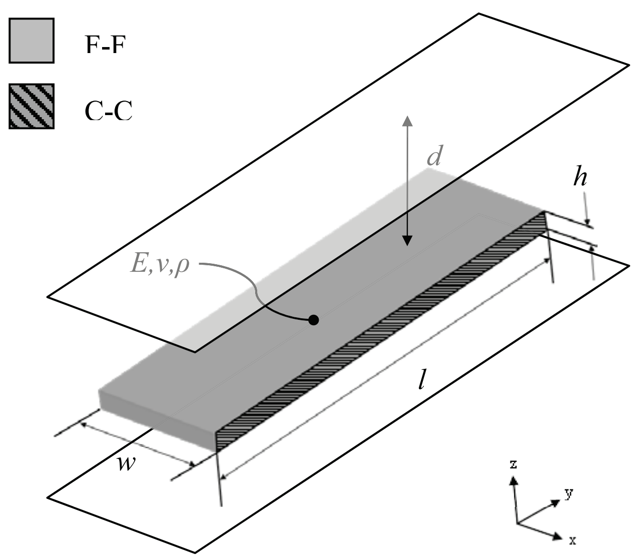

Figure 1. General design and nomenclature.

The switch between a single plate and plate array is achieved by the use of shims which help provide the fixed boundary condition, reduce the effective width of the test plate as well as providing the separation distance (*d*) between the plates. At the top and bottom of the plate array are rigid boundary plates. The shims and plates are connected to t-slot aluminum supports via all thread bolts with clamping being obtained through tightening nuts as much as possible. The supports are then attached to a larger structure to remove wall effects when testing a single plate underwater. The dimensions and properties for the pertinent test components are listed in Table I. Two different configurations were used for testing. A single plate with shims and a six plate array with a single shim between each plate and a boundary plate on top and bottom.

Table I. Geometry of experiment.

Component	Length (*l*) [cm]	Width (*w*) [cm]	Thickness (*a*) [mm]	Material
Test Plate (Effective)	20.32	10.16 (5.08)	127	Aluminum
Boundary Plate	20.32	10.16	635	Stainless Steel
Shim	20.32	2.54	508*	Stainless Steel

Taking the information from the components in Table I, the theoretical values for the frequency drop due to the different models outlined in the theory is presented in Figure 2.

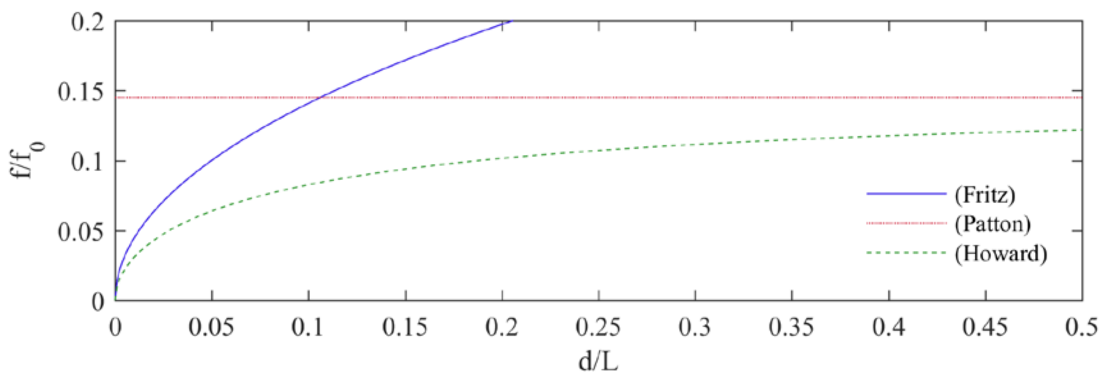

Figure 2. Theoretical approaches to the experimental plate frequency solution.

Figure 2 shows the various trends in the frequency shift of a rigid plate in a channel. For the geometry listed in Table I. A gap with a single shim spacing is anticipated to produce a frequency 8%-5% of the original value based on the method used.

3.2 Conduct

The FIFE utilizes two primary methods for excitation. The first is a pluck test. Plucking was achieved with a plastic rod, pressed on the edge of a plate then released. For the single plate, 3 plucks were taken at the opposite end of the strain gauge for five microphone locations along the plate (15 total). For the plate array, three plucks were taken on each plate at either end (36 total). The tests were repeated in air and in water. To analyze the frequency domain of the test, a Fast Fourier Transform (FFT) was conducted over the range of time a detectible plate response was seen. Since the magnitude of the FFT response is sensitive to both duration of the time collection and pluck magnitude, all responses were normalized to

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* The thickness of the shim acts as the separation distance (*d*) for a plate array.

the maximum peak response. The results were then averaged to show the dominance of certain peaks in a pluck.

The second method of excitation is obtained through a speaker suspended over the test plate. Two speaker tests were conducted with a single plate in air. The first was a mode shape investigation. The mode shape investigation was performed by using a signal generator to apply a known signal. The results from a pluck tests were used to determine the known plate frequencies and each peak within the range of the speaker excitation limits was investigated. Sand was placed on the plate and distributed randomly across the surface. The signal generator was then set to the excitation frequency and then the speaker was turned on. The resulting sand profiles were then recorded.

For the second sound test, the speaker frequency was controlled via a MATLAB sound file. The speaker was run for 10 seconds. During those 10 seconds the speaker changed frequencies every 0.1 seconds stepping up from 100Hz – 10,000 Hz. The test was then repeated by stepping down to look for hysteresis. The range was then cut in half and the most prominent peak from the previous test was placed at 1/5 of the new range. The process was repeated until the smallest change in frequency was less than 1 Hz. This test was conducted for a completely submerged plate, however, no significant strain was observed on the plate from the speaker. For the frequency analysis, a rolling FFT was used. The largest magnitude peak and corresponding frequency were recorded for each window.

In all tests, a single test plate is instrumented with a stain gauge. For the single plate plucks, the microphone was moved along the length of the plate. In the array tests, the microphone was positioned in-line with the instrumented plate.

4. RESULTS

The following section details the results of the aforementioned tests. In general, results of plate response in air were well characterized, however, the water results were more difficult to characterized due to dampening experienced by the plate. The plate array results were also difficult

4.1 Single Plate

For the single plate in air, there was excellent agreement between the microphone and strain based responses of the plate. Perhaps the most significant result is the most prominent peak detected isn’t always the first mode. The fourth mode and fifth mode produce a larger strain for the high aspect ratio plate. The first peak, on average was about 80% of the maximum peak of a given test. The biggest disagreement between the microphone and strain response was the relative magnitudes of the peaks being produced. Figure 2 shows the strain and microphone response for all the tests normalized to the largest peak in the test. The results are then averaged for the instrument and compared to one another.

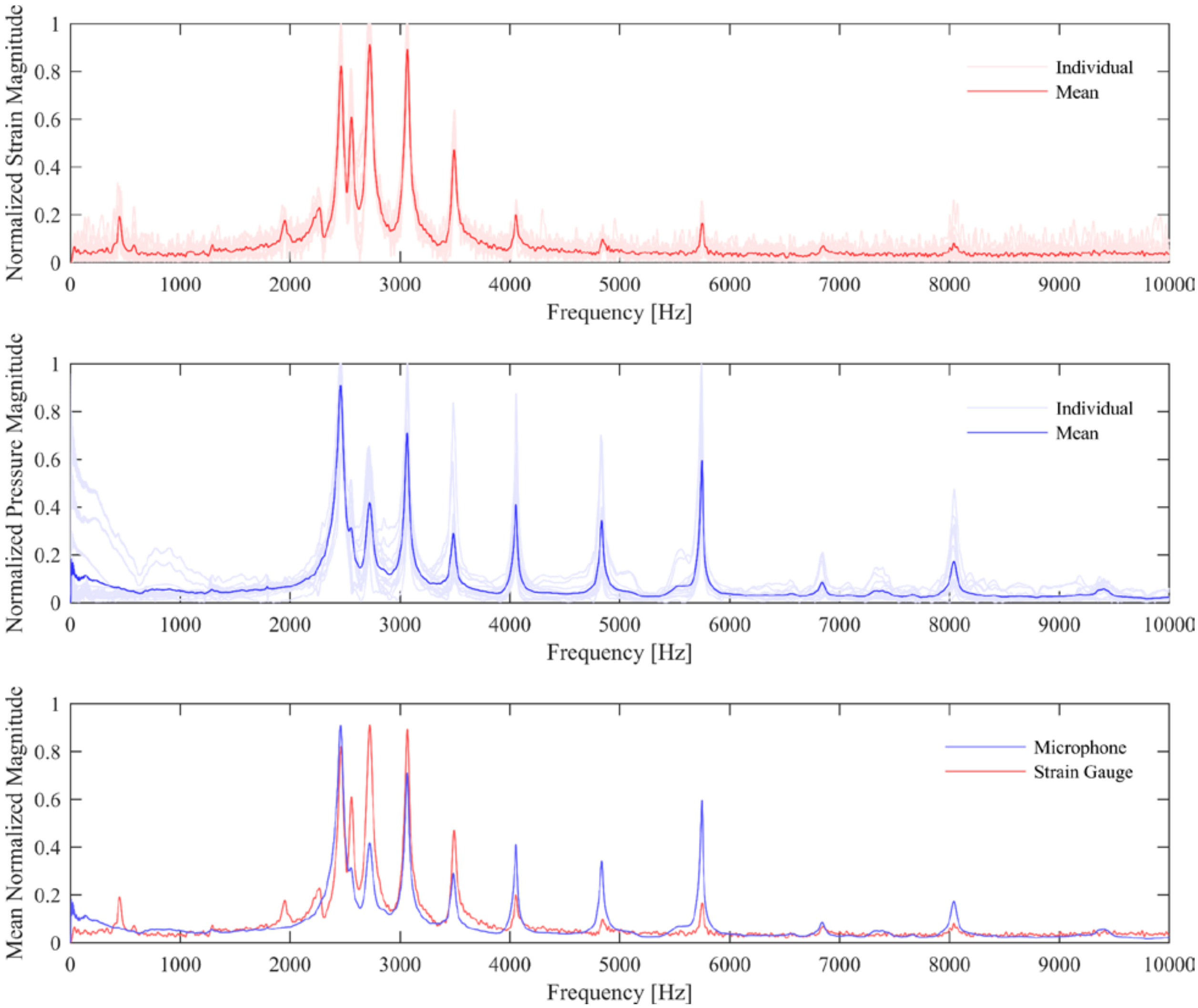

Figure 3. Single plate response to plucks in air.

Figure 3 objectively allows one to define peaks of interests to determine modal shapes of the plate. The second portion of the study was investigating the mode shape response of the plate. The major peaks starting with the first one around 2400 Hz, were examined. Sand was distributed across a plate in a random pattern and then the speaker was tuned to the peak frequencies. Only the first four peaks produced any change in the sand profile as the speaker amplitude diminished above 3000 Hz. The sand profile was averaged symmetrically across the width to account for obstructions in the original image. These profiles are plotted in Figure 4. It is of interest to note, the first peak, while dominant when measured by the microphone is the third most dominant peak for a strain gauge. Figure 4, however shows that the first mode doesn't dominate. In addition, a typical "second" mode is dominated by the primary mode, and only the third mode begins to show. The fourth and fifth modes are the most dominant modes when a plucking excitation frequency is used. Figure 4 demonstrates these mode shapes, and the typical "third" mode is heavily influenced by the primary mode.

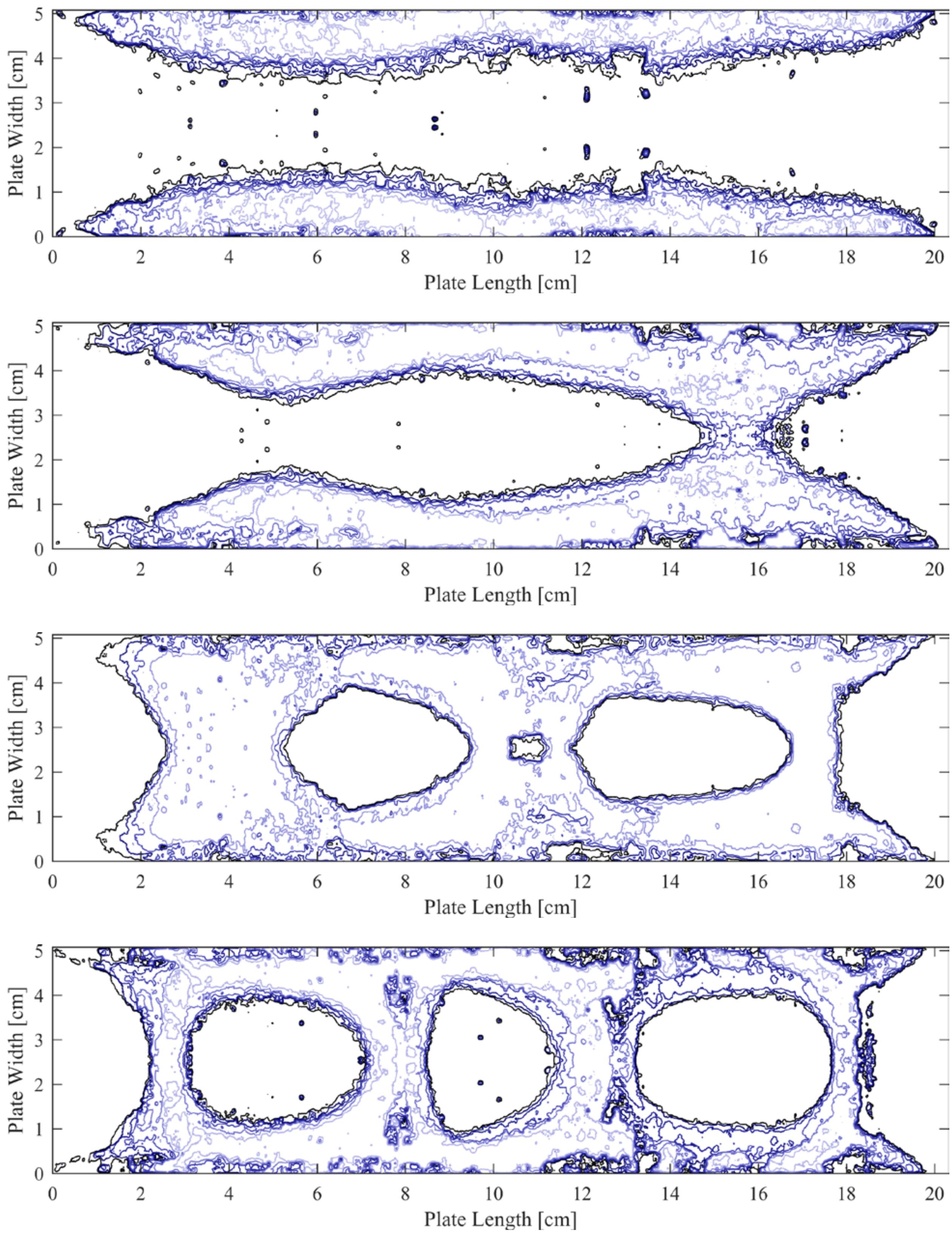

Figure 4. Sand contours of a single plate in air. From top to bottom: 2400 Hz, 2500 Hz, 2700Hz, 3100 Hz excitations frequencies.

With the mode shapes defined, it is also of value to get a complete response of the plate to various excitation frequencies. Figure 5 shows three different response curves. The first in blue is the microphone response. In effect it is proportional of the force of excitation. The second is the strain response of the plate in red and is representative of the displacement of the plate. The third is the strain response per pressure response, showing the deflection per load at a given frequency. The results show all data collected for both ramp up and ramp down in frequencies. The variations in the curve are more an issue of the rolling FFT than a physical variation. At the smallest change in frequency, the line is virtually continuous. Light colors indicate data collected over the larger change of 100 Hz increments increasing in darkness to the smallest change of 0.78 Hz increments.

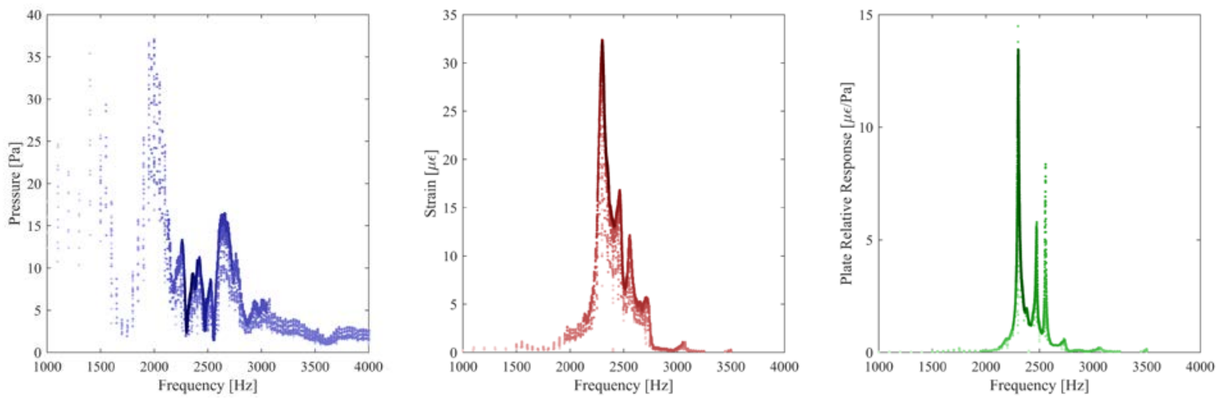

Figure 5. Plate response to an acoustic source in air.

The data in Figure 5 shows a very clear trend in the plate response to varying amplitude of frequency. It is interesting to note that a shift occurred in the corresponding frequencies form the initial pluck tests. The most likely reason for the shift is due to an inadvertent loosening of the boundary conditions during the mode shape tests.

The last single plate test was a comparison of the single plate response in water. For this test a microphone was swapped out with a hydrophone. The results, in the same style as the air pluck data, are presented in Figure 6. Whereas the air test showed great agreement, the water tests showed significantly different levels of agreement. A three peak dominant structure is still seen in the strain data, however is no longer present in the hydrophone data. The largest issue with the water tests is the large amounts of dampening associated with water. This results in a significantly less resolved peak. A large peak is seen around 80 Hz in the hydrophone data. While the origin of the peak is not known, it is likely a response from a wave inside the tank.

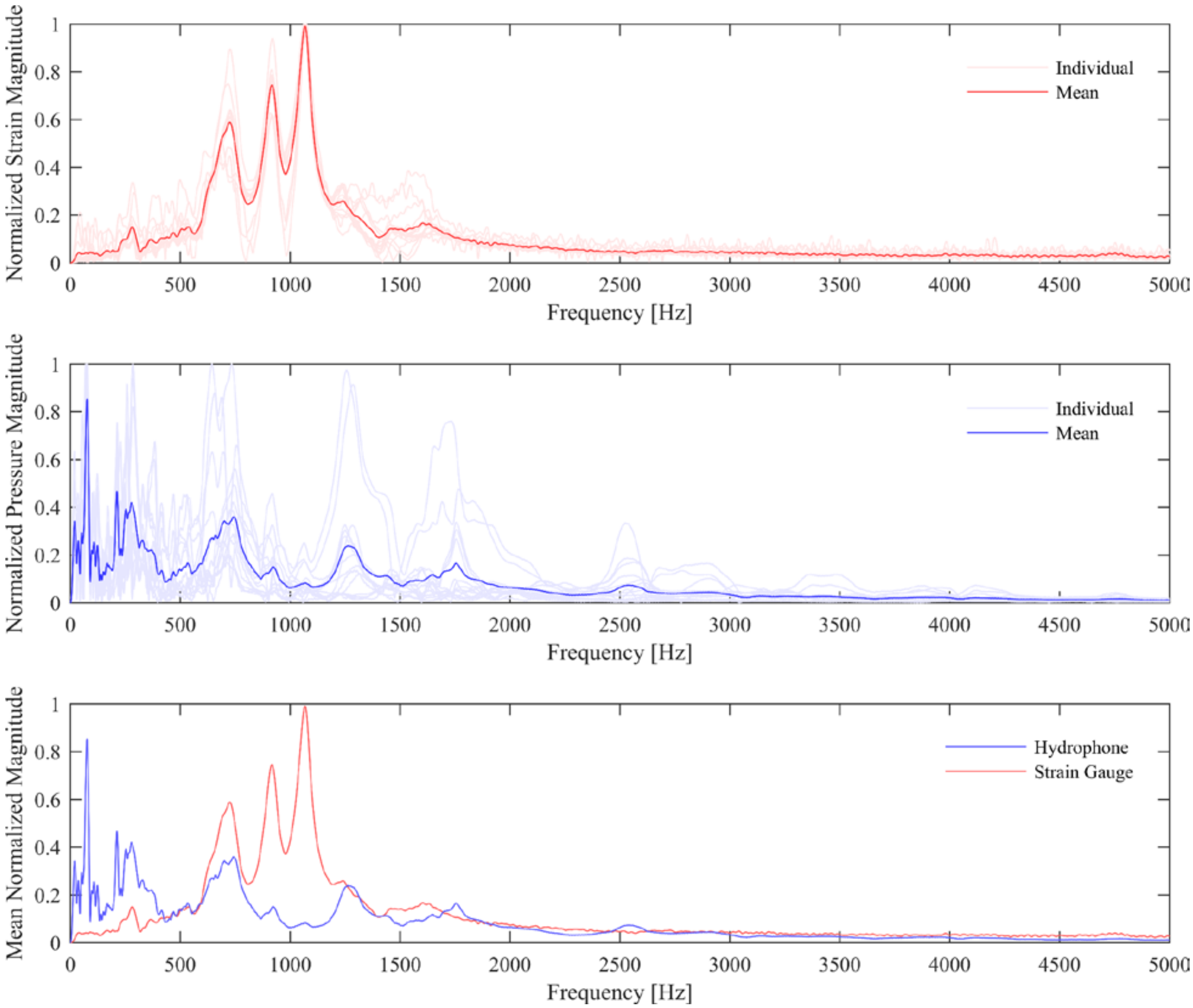

Figure 6. Single plate response to plucks in water.

4.2 Plate array

For each test location, there was a common response, however, it varied from pluck location to pluck location. In general responses for a pluck location were consistent, but not necessary for either end of the plate. Consequently, Figure 7 shows a range of frequencies for each individual plate. It should be noted plate 1 is the top of the plate array, and plate 4 was the instrumented plate. In Figure 7, the frequency of each test is separated by a faint dotted line. The two different ends of the plate results are separated by a dashed line and the plate being plucked is separated by a solid line. In general, strain responses were at a lower frequency than the microphone response. The average profiles were much less coherent than the average profiles for a single plate. Higher frequency peaks weren't seen as much as in the single plate results.

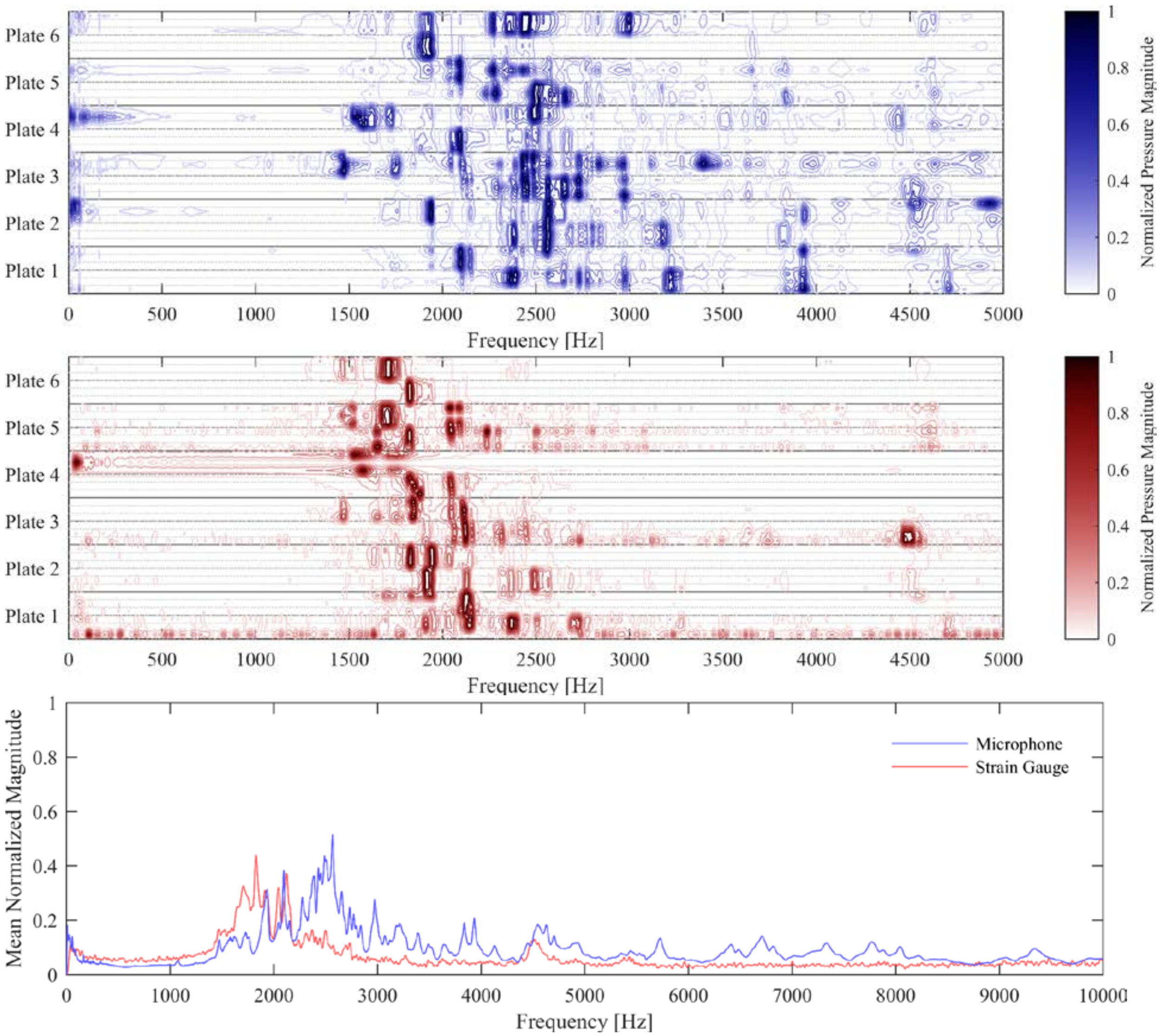

Figure 7. Plate array response in air for pressure (top), strain (middle) and average (bottom).

The overall frequency shift in the strain could be due in part of the addition of channels, however a more likely culprit is the boundary conditions on the plate. Since a single plate is no longer being clamped, it is quite possible strain is distributed through the boundary plates and other plates more resulting in a smaller force, ergo a less rigid boundary condition being applied to the plate. This proved a much lower frequency as the plate shifts from a fixed mode to a pinned mode.

The final test compared the plate array response in water. The results are seen in Figure 8. The hydrophone data showed a definite bias towards plucks from the opposite side. What is somewhat surprising on initial observations is a more prominent peak is seen in both the strain and hydrophone responses. For the hydrophone, the results from the hydrophone are visible only when the side away from the hydrophone is being plucked (bottom for each plate section). Plucks on the same side resulted in too much noise near the microphone to be discerned, thus creating low amplitude peaks. This was not the case for the strain gauge response however and data was seen for all plates.

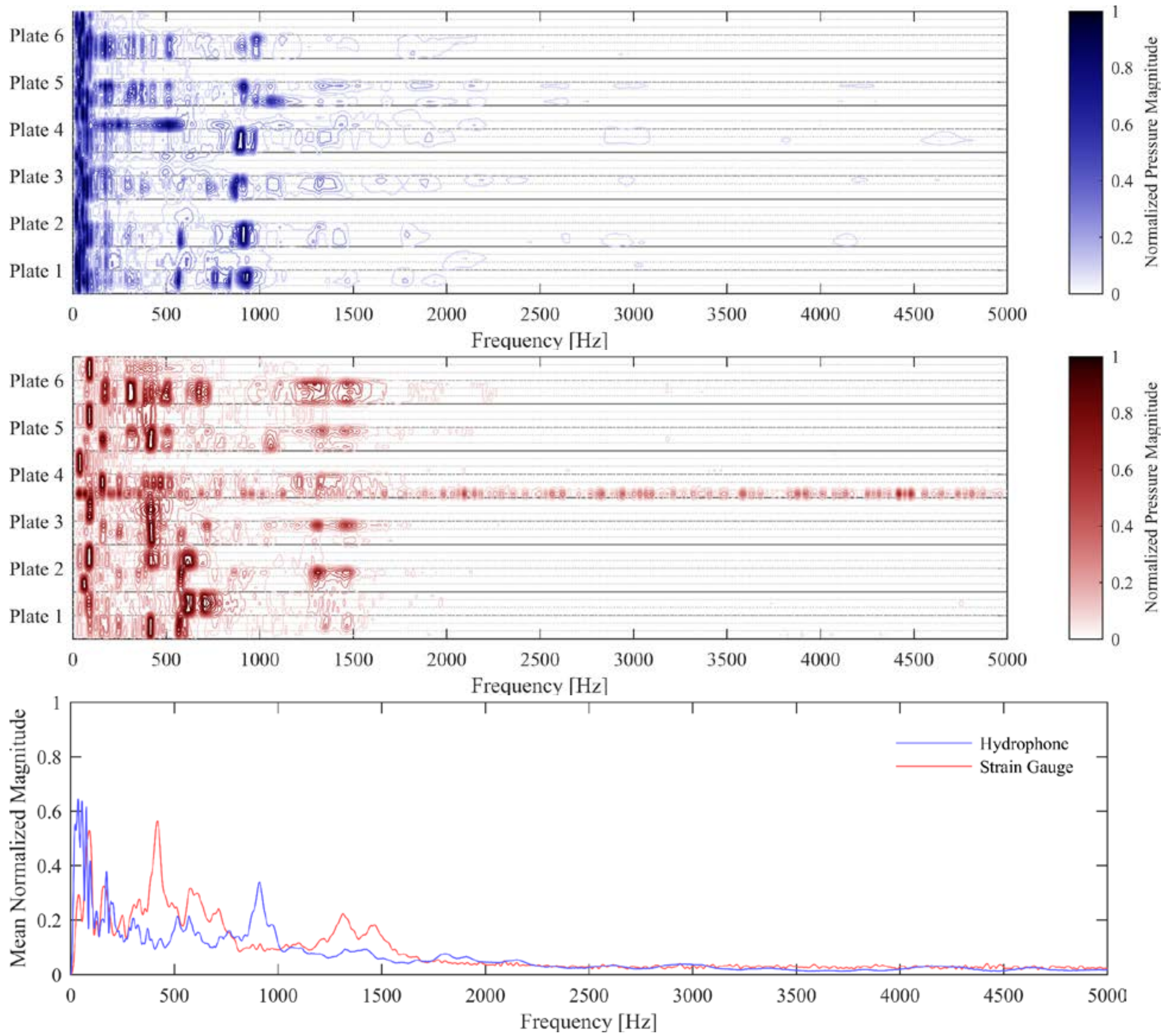

Figure 8. Plate array response in water for pressure (top), strain (middle) and average (bottom).

The final results presented in Table II show the change in frequencies for the various tests. For the single plate in air and water, the value is in between an infinite channel and a free plate, about twice the value expected for a plate in a channel. This is likely due to the fact that the plate was surround by shims and supports, but did not have a top test plate allowing water to move down and around the sides. In general the fluid makes a significant impact on the frequency of the plate. The presence of the channels appear to reduce the frequency substantially when compared to the free plate. It could be possible that the frequencies being observed do not correspond to comparable modes, i.e. a mode dominates on one instrument compared to another.

Table II. Comparison of the change in frequencies.

Frequency Ratio Comparison for Dominant Peak (f_{row}/f_{column})						
Plates	Fluid	Measurement	Strain Measurement			
			Single Plate		Array of Plate	
			In Air	In Water	In Air	In Water
Single Plate	Air	Strain	1	3.389	1.348	5.88
		Pressure	0.999	3.385	1.346	5.87
	Water	Strain	0.295	1	0.398	1.735
		Pressure	0.301	1.022	0.406	1.773
Plate Array	Air	Strain	0.742	2.514	1	4.362
		Pressure	1.042	3.532	1.405	6.129
	Water	Strain	0.170	0.576	0.229	1
		Pressure	0.370	1.253	0.498	2.174

5. CONCLUSIONS

Data was collected for a single plate and an array of plates in both air and water. Mode shapes were investigated as well as the plate response to acoustic excitation. Perhaps the most significant results obtained is the comparison of strain response to mode shape. It is often assumed the longest lasting mode is the primary mode, therefore the mode with the strongest signal. The results from the single plate in air show the dominant mode is also dependent upon the mechanism of excitation, form of measurement and location of measurement. For high aspect ratio plates, excitation on the leading or tailing edge can result in higher order mode frequencies more readily than lower order modes. On top of this, some modes characterized theoretically, may be washed out by lower order modes, e.g. the second order mode was close enough in frequency to the primary mode not to be observed, and especially in geometries were a mode in a specific direction dominates. This means identification of a higher order mode may not be the true mode. While the pluck tests for a plate array hint at the first mode is quite possible the fourth mode is being observed when placed in a fluid. Without well-defined peak structure or verification of mode shape, experimental characterization of changes to frequencies are difficult to ascertain.

The experimental data collected for a plate in air provide excellent data for the assessment of the computational approach, however, more resolved data is need for validation of the approach in water. If successful, the approach may provide more insight into the experimental results as well as the change in frequencies for plates submerged in a fluid. The future goal of the work is to use the experimental data for characterization of the pseudo-fluid approach.

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