On the acoustic radiation from the hammered dulcimer

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ABSTRACT

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The contributions of cavity and structural resonances to the sound radiation from a hammered dulcimer have been investigated. Results indicate that the sound quality of the lowest notes is affected by a relatively weak structural resonance in that frequency range. Additionally, near-field acoustical holography indicates significant sound radiation from front and back sound holes at frequencies of importance, contradicting the commonly held notion that the dulcimer's sound holes serve no acoustical purpose.

Keywords: near-field acoustical holography, hammered dulcimer, scanning laser Doppler vibrometry

ACKNOWLEDGMENTS

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Chapter 1

Introduction

1.1 The hammered dulcimer

The hammered dulcimer is a stringed instrument consisting of a wooden trapezoidal body with metal strings stretched across the frame. Our research dulcimer can be seen in Fig. 1.1. Musicians play the dulcimer by hammering the strings with small hand-held wooden mallets. These mallets

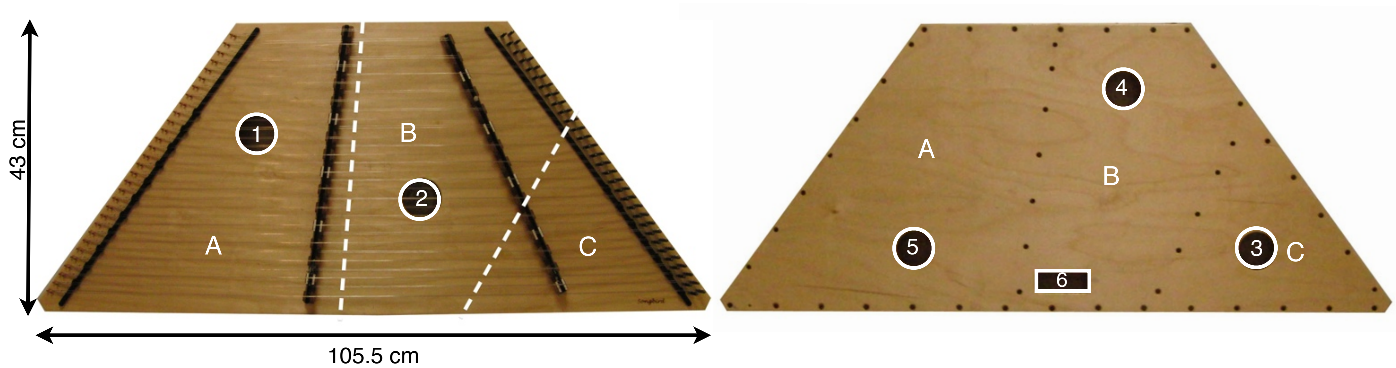


Figure 1.1 A picture of the front and back of our research dulcimer. The dulcimer's 6 sound holes are labeled 1-6. Sound hole 6 also serves as a carrying handle. The white dashed lines on the front, and the lines of wood screws on the back indicate the locations of the two internal braces. Although these braces split the dulcimer cavity into nominally three chambers (A-C), small slits in the bracing material allow airflow between cavities.

will sometimes have felt tips to get a softer tone from the instrument. Dulcimers usually have two or three equally tuned strings for each playable note. Each of these string clusters are called courses. A typical dulcimer can have around 30 courses. Having multiple strings per note makes the dulcimer louder. A typical dulcimer is constructed with two bridges, with around 15 courses going over each. Musicians play the courses on both sides of the left bridge and only on the left side of the right bridge. The left bridge splits the dulcimer into a 3:2 ratio, which effectively makes the strings played on the left side of the left bridge a musical fifth above the same strings played on the right side on the bridge. This can be seen again in Fig. 1.1; the strings that lay across the left bridge can be played on either side of the bridge. A typical dulcimer can span anywhere between 2 1/2 and 5 octaves, depending on the size of the instrument. A common tuning scheme can be seen in Table. 1.1

The hammered dulcimer is truly a global instrument; variations of the dulcimer exist in many countries. China has a variation known as the yangqin, which is said to have originated in Persia. The cimbalom is larger version of the hammered dulcimer which is found in Eastern Europe. In the Middle East they call it the santur. Though these dulcimers go by different names, they all have have the same characteristic design of a trapezoidal body with strings stretched across. Despite its global presence, the hammered dulcimer only became popular in the United States with a recent folk music revival. [1]

Unlike other instruments, such as the violin, the hammered dulcimer does not have a common construction design. There is no "Stradivarius" of the hammered dulcimer. Each builder tends to have their own set of ideals in construction. This makes research on the dulcimer a bit different because we can't account for all these design variations. Yet, this also increases the importance of our research since our research could provide scientific evidence to support certain design changes. Our research could have very real and immediate effects on the hammered dulcimer community.

Despite the numerous construction variations, there are a few common beliefs in the dulcimer

Left bridge, left side	(Hz)	Left bridge, right side	(Hz)	Right bridge, right side	(Hz)
E6	1319	A5	880	D5	587
D6	1175	G5	784	C5	523
C6	1047	F5	698	B4	494
B5	988	E5	659	A4	440
A5	880	D5	587	G4	392
G5	784	C5	523	F4	349
F#5/Gb5	740	B4	494	E4	330
E5	659	A4	440	D4	294
D5	587	G4	392	C4	262
C#5/Db5	554	F#4/Gb4	370	B3	247
B4	494	E4	330	A3	220
A4	440	D4	294	G3	196
G#4/Ab4	415	C#4/Db4	277	F#3/Gb3	185
F#4/Gb4	370	B3	247	E3	165
E4	330	A3	220	D3	147
D#4/Eb4	311	G#3/Ab3	208		

Table 1.1 A table of the notes on our research dulcimer, and the corresponding frequencies. Note that some notes appear in multiple places on the dulcimer. This facilitates playing in different positions and keys. Also note that all the notes on the left side of the left bridge are musical fifths of the corresponding notes on the right side of this bridge. This is due to the bridge breaking the string into a 2:3 ratio.

community. For one, most players and builders mention that the dulcimer has a poor low frequency response. Many players dislike the sound of their dulcimer's lowest strings, saying they sound "tinny" or that they have bad tone. Also, there is a common belief that the sound holes make no acoustical difference and are thereby purely decorative. Because of this, many builders fill the sound holes with decorative rosettes, which can sometimes cover more than 50% of the sound hole. The idea that sound holes are purely decorative seems to stem back to a famous name in the dulcimer community, Sam Rizzeta. He stated, "Soundholes are unnecessary because the space at the frame rails provides for air pressure equalization between the inside and outside of the sound box. Holes can be added for decoration in any design you choose, but the openings should be kept small to prevent weak spots and warping [2]." The idea that the sound holes are unimportant is repeated by D. R. Peterson in Thomas D. Rossing's books, *The Science of Stringed Instruments* and *The Physics of Musical Instruments* [3] [4]. This idea is also repeated in BYU's own descriptive acoustics text book, *Music Speech Audio* [5]. Right off the bat, this claim seemed suspect, because we know that f-holes and sound holes are vital to the radiation of other instruments such as the guitar and violin [6] [7]. Furthermore, in the same *The Science of Stringed Instruments*, A. Peekna describes research where changing the number and location of sound holes improved the sound of Psaltries. Peekna also describes tuning the lower resonances of carved Baltic psalteries by adjusting the areas of the sound holes [8] [9]. Investigating the claim that sound holes are unimportant in hammered dulcimers is one of the key motivators for this research.

Since it would be impractical to acquire and test hundreds of dulcimers, we use a common sized dulcimer and hope to make generalized observations that will hold for most dulcimer types. Our dulcimer is a *Songbird Pheobe*, constructed by Chris Foss, owner of Songbird Dulcimers. It is a 16/15 dulcimer, which means there are 16 courses of strings over the left bridge and 15 over the right. Each course consists of two steel strings. The dulcimer has two structural supports running through the main air cavity of the dulcimer. This dulcimer was specially made with the back plate attached by wood screws instead of glue so that it could be detached if needed. This is also convenient because you can see the screws on the back of the dulcimer and thereby see where these supports cut across the dulcimer. There are two sound holes on the front and three on the back, with a carrying handle on the back that also acts like a sound hole. See Fig. 1.1. The wood used in making this dulcimer is baltic birch.

Unlike other instruments, such as the violin and piano, very little research has been conducted on the hammered dulcimer. Our research focuses on the acoustical radiation of the hammered dulcimer. We want to find the main mechanisms involved in the dulcimer's spectral response. We expect to find that a large part of the radiation is due to the modal response of the body of the dulcimer, but we are also interested to see if the sound holes do in fact play a role in helping the dulcimer radiate. Knowing more about the radiation of the dulcimer can help us know much more about how the sound is being produced. If we can correctly identify the main contributors to the overall sound of the dulcimer, it will be easier to modify these contributors to better optimize the dulcimer. Furthermore, knowing more about the sound coming out of the dulcimer could help the dulcimer community to know where to place microphones to pick up the best range of the dulcimer. Our overall goal is to find the characteristic spectrum of the dulcimer and be able to correctly identify the sounce of the frequency peaks.

1.2 Previous research

Little published research on the hammered dulcimer exists. This is in contrast to the violin, which has multiple books on it's research. The absence of the hammered dulcimer in Western classical music is probably responsible for this lack of interest in the dulcimer. There are some notable exceptions, which we will discuss here. David R. Peterson has done more research on the dulcimer than probably anyone else. He has presented at the Acoustical Society of America's bi-annual conference many times. The abstracts from these presentation can be found on the Acoustical Society of America's website [10]. He wrote a fairly comprehensive chapter on the hammered dulcimer in Thomas D. Rossing's book *The Science of String Instruments* [3]. He also wrote a smaller section in a related earlier book, *The Physics of Musical Instruments* [11]. Both these books are effective overviews of the acoustics of hammered dulcimers, but being as they are reviews in nature, they lack experimental evidence to support many their claims. Peterson also published an article investigating the hammer/string interactions of the dulcimer [12], but since this has no overlap with our research question, we will not discuss it any further here.

1.3 Overview of thesis

Chapter 2 consists of explanations of all the different measurement techniques we used. First, the spectrums from individual notes were measured. Second, we used a swept sine analysis to find the characteristic spectrum of the body of the dulcimer. Next, we used a scanning laser doppler vibrometer to see the modal response of the dulcimer. Lastly, we used near-field acoustical holography to both confirm the scanning laser results and to see if the sound holes had any major acoustical effect.

Chapter 3 begins with using Helmholtz-like resonances to predict where resonance peaks should occur. Chapter three continues by comparing all of the results from the different analyses, comparing the different results looking for patterns. Next, there is the section explaining the conclusions we came to as a result of our analysis. Lastly, possible future research is outlined.

Chapter 2

Methods

2.1 Single note Fourier analysis

We begin our measurements with a relatively simple analysis. We measure the response of each note with microphones and accelerometers. This gives us a simple idea of what the response of the dulcimer should look like. These measurements are also useful because they provide a solid reference for the rest of our analysis techniques. If a more complicated analysis technique does not match the results of these single note measurements, we have reason to question those results.

The single note measurements are relatively simple. We place the dulcimer on a stand in a hemi-anechoic chamber and attached accelerometers to the front and back. We then set up two microphones, one inside the sound hole in the back, and the other near the top plate. Then, we strike each note one at a time, recording 10 second samples for each. Because we're simply striking the dulcimer strings with the hammers, there are obvious variations in striking location and strength. Because of this, we should not compare overall sound pressure levels from measurement to measurement, and instead focus on relative amplitudes of harmonics. A detailed approach to making a reproducible hammer striking mechanism can be found in Alexander and Herbert's paper [13]. This paper explains how the seemingly simple idea of getting reproducible hammer strikes can actually be a relatively complicated process. Because of this complication, we stick to striking the dulcimer by hand. We then conduct Fourier transforms on each of these samples, and the overall frequency response is plotted along with a waterfall plot. A sample of some of the more interesting notes is shown in Fig. 2.1. As one might expect, the higher notes decay a lot faster than the lower notes. The response from each note can be seen in Appendix A.

We notice some interesting trends while looking at the responses from all the different notes. One of the most apparent patterns we observe is lower frequency notes have significantly lower fundamentals. See Fig. 2.1. The poor response of lower notes is a common complaint among many dulcimer players. These measurements confirm that complaint. We also notice that there are certain frequencies at which the dulcimer has clear resonances. The first of these peaks we approximate to be around 270Hz. Using further analysis techniques, we search for the source of these resonance peaks.

2.2 Structural response - swept sine analysis

We conducted a swept sine analysis to understand the spectrum of the dulcimer's radiated sound. This gave us a much clearer picture of where the resonance peaks are. To make a swept sine analysis, we stuck a shaker to one of the bridges of the dulcimer using bee's wax and drove the shaker using an HP analyzer. We placed two microphones in the diffuse field to measure the response from the dulcimer. We also damped the strings on the dulcimer so that we could see only the response of the dulcimer body without confusing them with the peaks from each of the notes. The HP analyzer swept the shaker's input signal through a whole range of frequencies while simultaneously measuring the response from microphones. When the HP analyzer is driving the shaker at a resonance peak, the response measured by the microphones is higher. We then plotted

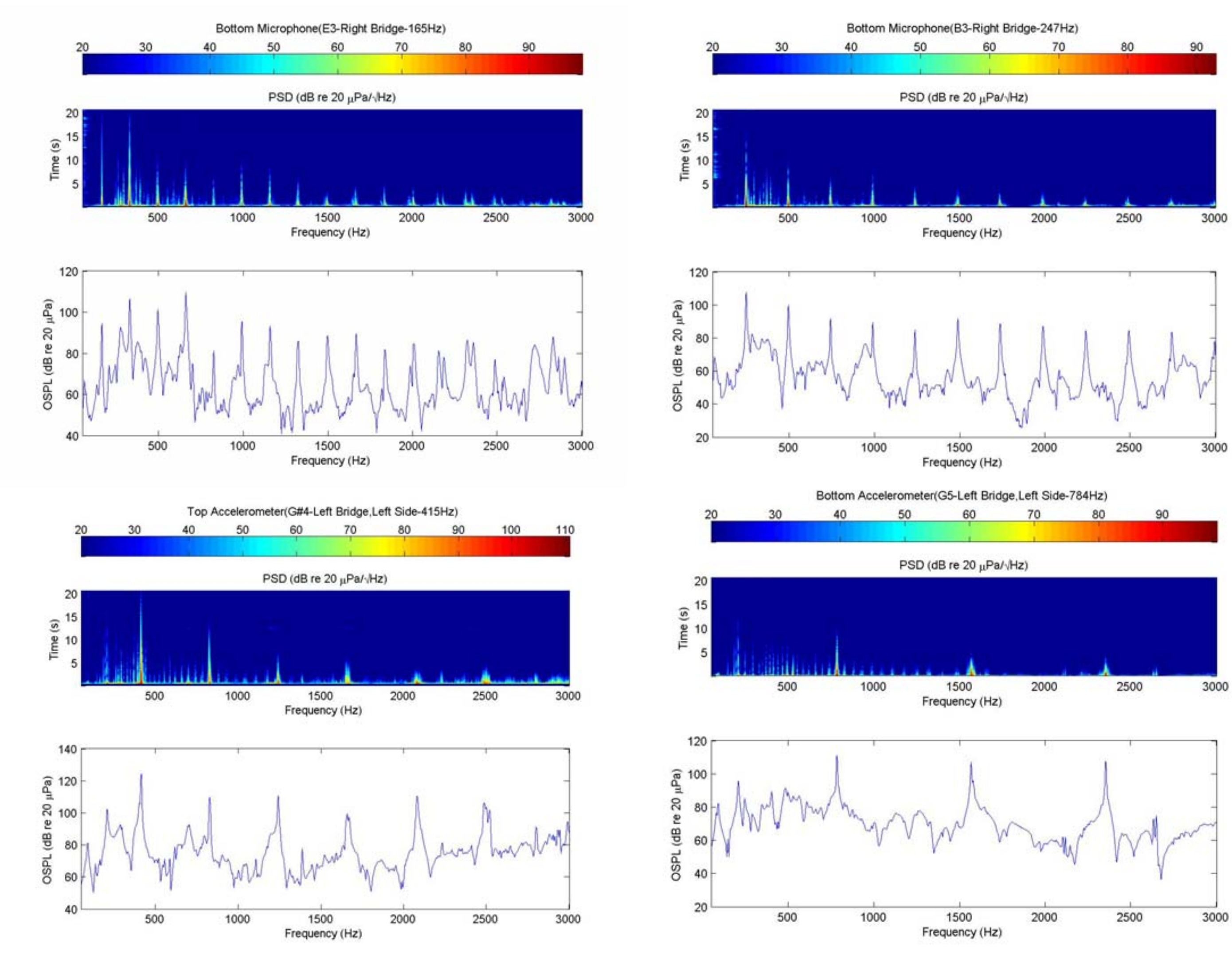


Figure 2.1 Some plots of individual note responses from the dulcimer.

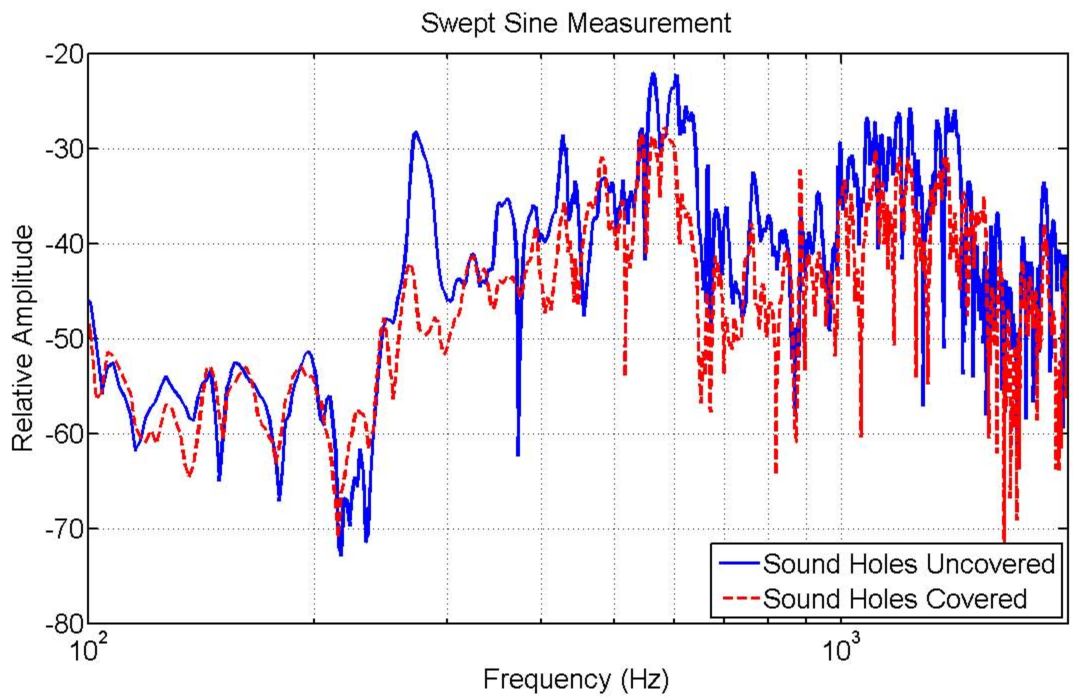


Figure 2.2 Spectrum from swept sine analysis. The spectrum from the sound holes uncovered (blue) is shown along with the spectrum with the sound holes covered (red dashed).

the relative response as a function of frequency. The results are shown in Fig. 2.2.

The swept sine analysis shows us clearly the poor low-frequency response common among dulcimers. We see that the response doesn't really pick up until after around 240Hz. The response below 240Hz seems to be about 15dB less than the average response over 240Hz. Also, we observe specific resonance frequencies . There is a particularly large peak at 270Hz, which we will investigate later in the paper. Now that we have a clearer picture of the dulcimer's spectral response, we can better look for what's causing these resonances.

To investigate the role of the sound holes, we repeated the swept sine analysis, but this time with large foam cutouts inserted into each of the sound holes. Ideally, these inserts should stop sound from radiating from the sound holes without interfering with the structural modes. The results of this variation can also be seen in Fig. 2.2.

As we see, there is a significant drop in many of the largest resonance peaks including the large

270Hz peak, suggesting that the sound holes do in fact have a significant impact in the overall sound from the dulcimer.

2.3 Scanning laser Doppler vibrometry

To understand better the modal response of the body of the dulcimer we use a Scanning Laser Doppler Vibrometer (SLDV). To excite the Dulcimer, we apply the shaker to the bridge of the dulcimer. While continuously shaking dulcimer, we scan both the front and back plates of the dulcimer. This is done both with white noise and single frequencies.

The SLDV gives us some very clear videos showing how the body of the dulcimer is vibrating. Some examples of these videos can be seen in Fig. 2.3. In this snapshot we see a clear modal line going across the diagonal of dulcimer. It is clear that the front and back here are well coupled, confirming the results that T. D. Rossing found in 1995 [11].

Both driving techniques resulted in clear modal patterns at certain frequencies. Though almost any frequency would give a clear modal pattern, only certain frequencies give reasonable vibration amplitudes. Comparing these results with the swept sine analysis, we find that many of the peaks in the response of the dulcimer come as a result of the vibrational modes of the body of the dulcimer. What is particularly interesting is that the dulcimer had relatively high vibrational responses at some of the lower frequencies, yet this does not prevent the dulcimer from having its characteristic poor low-frequency response. One would expect that the modal strength of the body of the dulcimer would directly relate to the relative strengths of the overall acoustic response of the dulcimer, but this is not the case. This suggests that there are more factors in the radiation of the dulcimer to account for than just the structural modes. In our next analysis, we attempt to investigate possible other factors.

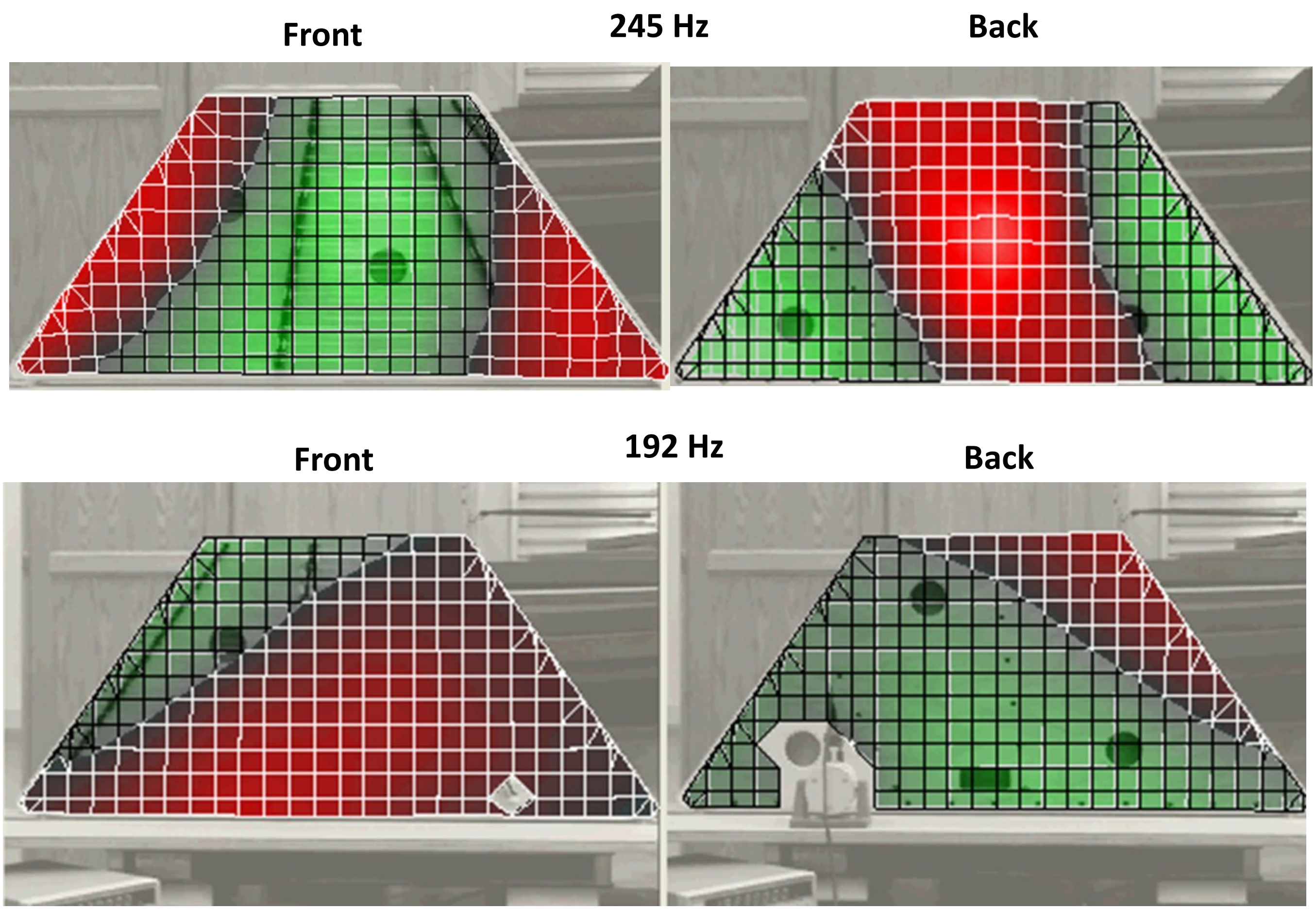


Figure 2.3 An image of a particular structural mode found with the Scanning Laser Doppler Vibrometer.

2.4 Near-field acoustical holography

One of the principal motivations for this study was to characterize the radiation from the soundboard and back relative to the sound holes. The swept sine results shows clear resonance peaks, but cannot tell us the source of these resonances, whether they radiate from the structure of the dulcimer, or from the sound holes. To simultaneously study the structural and sound hole contributions, planar Fourier Near-field acoustical holography is a convenient choice, as a projections of the pressure or velocity fields to the surface of the instrument effectively separates these contributions. Near-field acoustical holography works much like an optical hologram. In an optical hologram, you can see 3D objects though the actual surface is only 2D. Similarly, with NAH, you measure a 2D plane, and as long as you have the phase information, you can find 3D information.

To implement the NAH technique, the dulcimer was placed on a small stand in the anechoic chamber at Brigham Young University and the bass bridge was driven using a shaker driven by Gaussian white noise. The rectangular measurement aperture was 1 m x 2 m, located 2 cm from the back plate and 4 cm from the soundboard (to account for the depth of the bridges). A measurement spacing of 2 cm in each dimension was used, resulting in a 51 x 101 point measurement grid. A custom LabVIEW-controlled three-dimensional positioning system installed in the chamber was used to carry out the measurements, which were performed using Type-1 12.7 mm microphones. A stationary reference microphone was also used to provide phase-coherent measurements necessary to extract complex pressures and perform the NAH processing.

NAH processing was implemented. The results of propagating the measured data to the dulcimer soundboard and back plates are shown in Fig. 3. The upper 15dBre20μPa are shown superimposed transparently over the dulcimer figure. Four frequencies in particular were chosen to give a general idea of the radiation of the dulcimer at different ranges. For example, structural modes are the greatest contributors to the radiation below 260 Hz, so 189 Hz (Fig. 2.4a) was chosen because it shows a clean structural response on the front and back of the dulcimer.

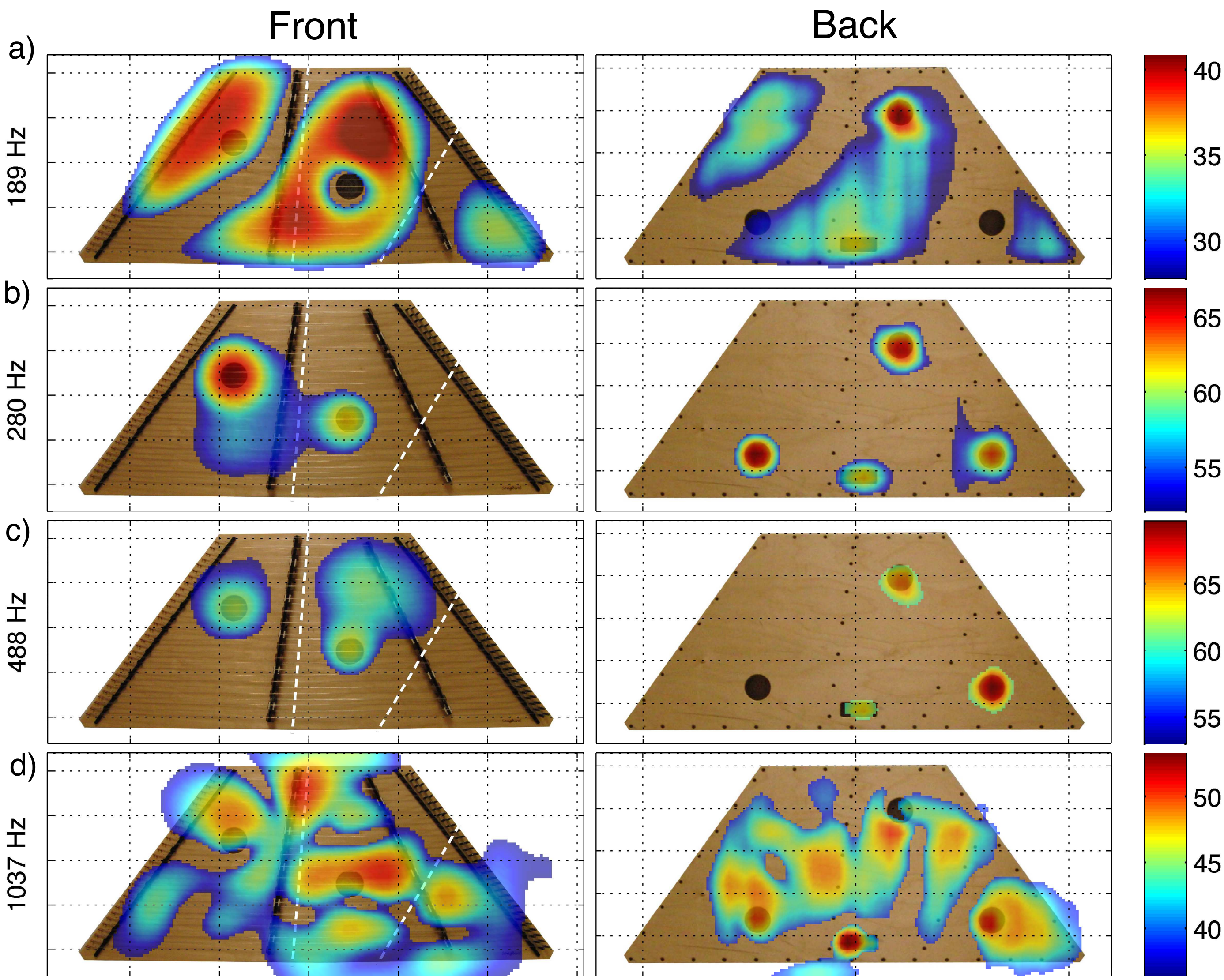


Figure 2.4 The front and back of the dulcimer are shown, with the pressure levels (dBre20μPa) plotted on top. The back is mirrored so that you can easily see relations of cavities. At 189 Hz, we see a clear structural mode. An almost mirror-image structural mode appears at the slightly higher frequency of 220 Hz (not shown). At 270 Hz, we see that most of the radiation is coming from the sound holes. As frequency increases, sound holes continue to be the dominant resonators, as we see in 488Hz. At much higher frequencies, structural modes again become dominate (1037 Hz).

With these NAH results, we can further investigate what causes the response to increase after 260 Hz. There appears to be clear structural responses below this frequency, such as the one seen in Fig. 2.4a. Despite being one of the cleanest structural modes, the dulcimer radiates poorly at 189 Hz compared to the frequencies above 260 Hz. More structural modes below 260 Hz can aslo be seen in Appendix B.1 and B.2. What changes around 260 Hz is that the sound holes become the primary radiators. At 270 Hz, we see that the main radiation, front and back, is coming from the sound holes (Fig. 2.4b). The fact that the sound holes are the primary radiators at 260 Hz is confirmed in Fig. 2.4a, where the resonance peak around 270 Hz is almost completely eliminated when the sound holes are covered. The sound holes continue to play significant roles in the radiation of the front and back of the dulcimer for frequencies above 270 Hz, as can be seen in Fig. 2.4c. The radiation of the dulcimer seems to come from a both the vibrating body and the sound holes. More frequencies where sound holes and the structure are both contributing to the radiation can be seen in Appendix B.3, B.4, B.5, and B.6. At frequencies higher than about 900 Hz, structural modes again become the primary radiators, though sound holes can still be seen to make significant contributions (Fig. 2.4d).

The pressure maps found through doing NAH give some very useful insight into the sound radiation of the hammered dulcimer. The most apparent result was that of the role of the sound holes. It was clear with the majority of the frequencies that the sound holes played a key role in radiating sound power from the dulcimer. In fact, at some frequencies, the sound holes were the only parts that showed significant pressures. Also, the same modal shapes found using the SLDV were confirmed with the NAH. Comparing these results with those of the swept sine, we can much better explain the origin of the resonance peaks found. We again saw modal shapes for the lower frequencies, just like we saw with the SLDV, but frequencies where the response starts to pick up is where significant sound hole radiation is first seen. This goes to suggest that the sound holes are vital in the sound radiation of the dulcimer. A significant increase in sound hole pressure was found around 270Hz, which is precisely where we see a peak in the response of the dulcimer from the swept sine measurement.

Fig. 2.4 showed the magnitude of the pressure on the dulcimer surface, represented in decibels. However, further insight can be gained by examining the relative phase across the instrument. Fig. 2.5 depicts the phase response for the same frequencies.

There are a few more useful insights we can gain through Fig. 2.5. At 189 Hz, a bending mode with a strongly coupled front and back is seen, again confirming T. D. Rossing's earlier research into the coupling of dulcimer's sound boards and back plates [11]. At 280 Hz, we can see that the sound holes in cavity B are resonating in phase with each other, and the sound holes in cavity A are also almost in phase with each other. Sound holes being in phase both front and back suggest a breathing mode within a cavity. Similar cavity coupling is seen at 488 Hz. The phase info gets much more hectic in higher order structural modes, such as at 1037 Hz. These more chaotic structures are a result of higher order structural modes. More of these chaotic structural modes can be seen in Appendix B.7 and B.8.

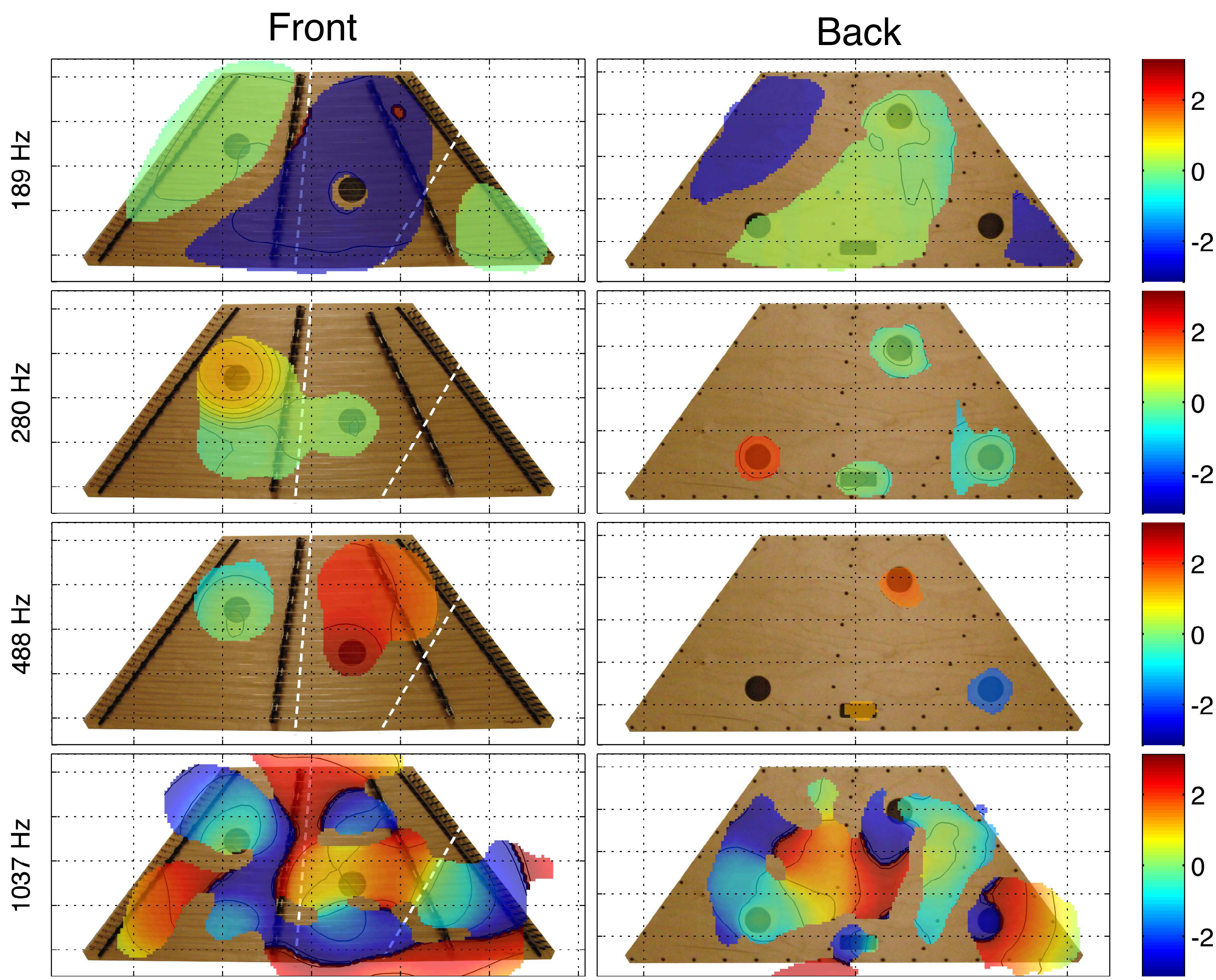


Figure 2.5 The same modes as Fig. 2.4 are shown, but now with the phase relations of the modes.

Chapter 3

Analysis and Conclusions

3.1 Helmholtz Analysis

We notice from our experiments that there are clearly more than just structural resonances which contribute to the overall spectrum of the dulcimer. We suggest that the other non-structural resonances come from Helmholtz-like air cavity resonances. An example of a Helmholtz resonator is an old Coke bottle, which resonates at a certain frequency when air is blown over the top. In this case, the air-cavities and the sound holes are the source of the Helmholtz resonances. These resonances depend on the volume of the cavity and the size and depth of the sound holes. The formula to find the frequency of a Helmholtz resonator is

$$f = \frac{c}{2\pi}\sqrt{\frac{S}{L'\,V}} \tag{3.1}$$

where c is the speed of sound, S is the surface area of the opening, and V is the volume of the cavity. L' is the effective depth of the opening, which in our case is baffled on both sides, so it can be found by adding the original depth L to 1.7 times the radius, r, of the opening, or $L' = L + 1.7r$.

In the dulcimer, we have three separate cavities, which are acoustically connected through small holes in the wood structural bracing that separate the cavities. Instead of developing a full equivalent circuit model for the dulcimer, we will simply consider look at the resonances from separate cavities, and of all the cavities connected, and we will avoid a much more complicated equivalent circuit model. To account for multiple opening in the one cavity, the Helmholtz equation can be extended to be

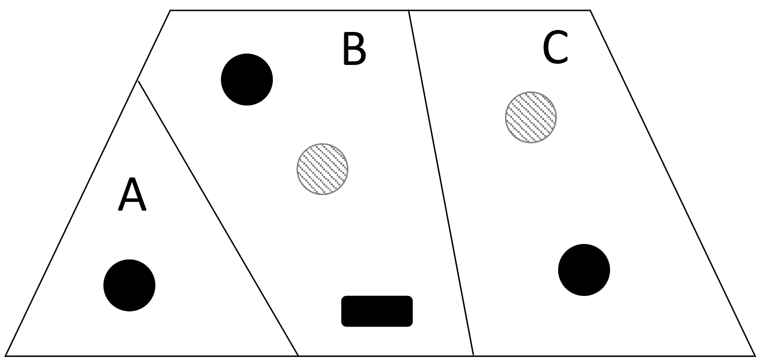
$$f = \frac{c}{2\pi}\sqrt{\frac{(\sum S_i)^2}{V \sum L_i' S_i}} \tag{3.2}$$

We separate the dulcimer into its three cavities, which we will call A, B, and C. See Fig 3.1. As you can see, the frequencies range from 218Hz to 315Hz.

3.2 Analysis

Through these multiple analysis techniques, we now have a much better picture of what causes the the different resonance peaks in the hammered dulcimer. The single note analysis hints towards there being certain resonance peaks in the dulcimer response. Certain frequencies are emphasized, while others are attenuated. The dulcimer also has trouble with radiating the fundamental frequency of its lower notes. This results in the lower notes' non-ideal tone. To investigate further the radiated spectrum of the hammered dulcimer, more sophisticated results were used, such as the SLDV and the NAH.

The characteristic poor low-frequency response of the dulcimer was seen clearly through the single note measurements, as well as the swept sine analysis. The swept sine analysis shows us that the dulcimer begins radiating much more efficiently at around 250Hz. What is particularly interesting is that the SLDV shows that there are some clear structural modes of the dulcimer even below 250Hz. Some of the most fundamental modes are seen in this region. So, the question arises, if the body of the dulcimer has good modal response below 250Hz, why isn't there better sound radiation? To investigate this was the main motivation behind turning to near-field acoustical holography. The NAH scans show us a bit of a fuller picture. For frequencies below 250Hz. the



Cavities	Frequency (Hz)
A	262
B	315
C	218
A and B	299
A and C	230
B and C	264
A, B, and C	260

Figure 3.1 The dulcimer is divided into three sections (A, B, and C) by the structural supports running through the body. The filled in black circles and rectangles represent sound holes on the back, and the shaded circles represent sound holes on the front. The supports or shown as lines running through the dulcimer. On the right, we see the results of eq. 3.2 using all possible combinations of the cavities.

NAH reflects the SLDV results in that we see some clear structural modes. What is interesting is that right around 250Hz, we begin seeing the first sound radiation from the sound holes. This goes to suggest that the better response at these higher frequencies is due to the radiation from the sound holes. Furthermore, the Helmholtz analysis also estimates that the resonance frequencies of the air cavities to be somewhere around this 200-300Hz range.

3.3 Conclusions

Our research has clearly shown that the sound holes do make an acoustical difference in the hammered dulcimer. The NAH shows us that there is a high amount of sound radiation coming from the dulcimer's sound holes. Furthermore, doing swept sine analysis with the holes covered reduced the amplitude of some of the resonance peaks by around 15dB, further suggesting that the sound holes are key in radiating sound. The air cavities and the sound holes may work together to produce Helmholtz-like resonances within the dulcimer. Overall, its clear that the sound holes do in fact have acoustical significance, i.e. are not purely decorative. Furthermore, it the radiation from the sound holes seems to be a major factor in allowing the dulcimer to radiate at lower frequencies. It is very possible that we could use the sound holes to increase the radiation at lower frequencies, and help to fix the poor low-frequency of the dulcimer [9].

Though the data clearly shows some frequencies depend on the sound holes to radiate, there is still a lot of radiation from the dulcimer's structural modes. Clear modal patterns can be seen in both the NAH and SLDV results. We note especially that some of the more basic modal patterns have more trouble radiating than some of the higher frequencies.

Overall, we've shown that the hammered dulcimer's sound radiation comes primarily from two factors: front and back plate modal vibrations and Helmholtz-like resonances from the air cavity and sound holes. Both contribute to the overall sound of the dulcimer, and both are important in

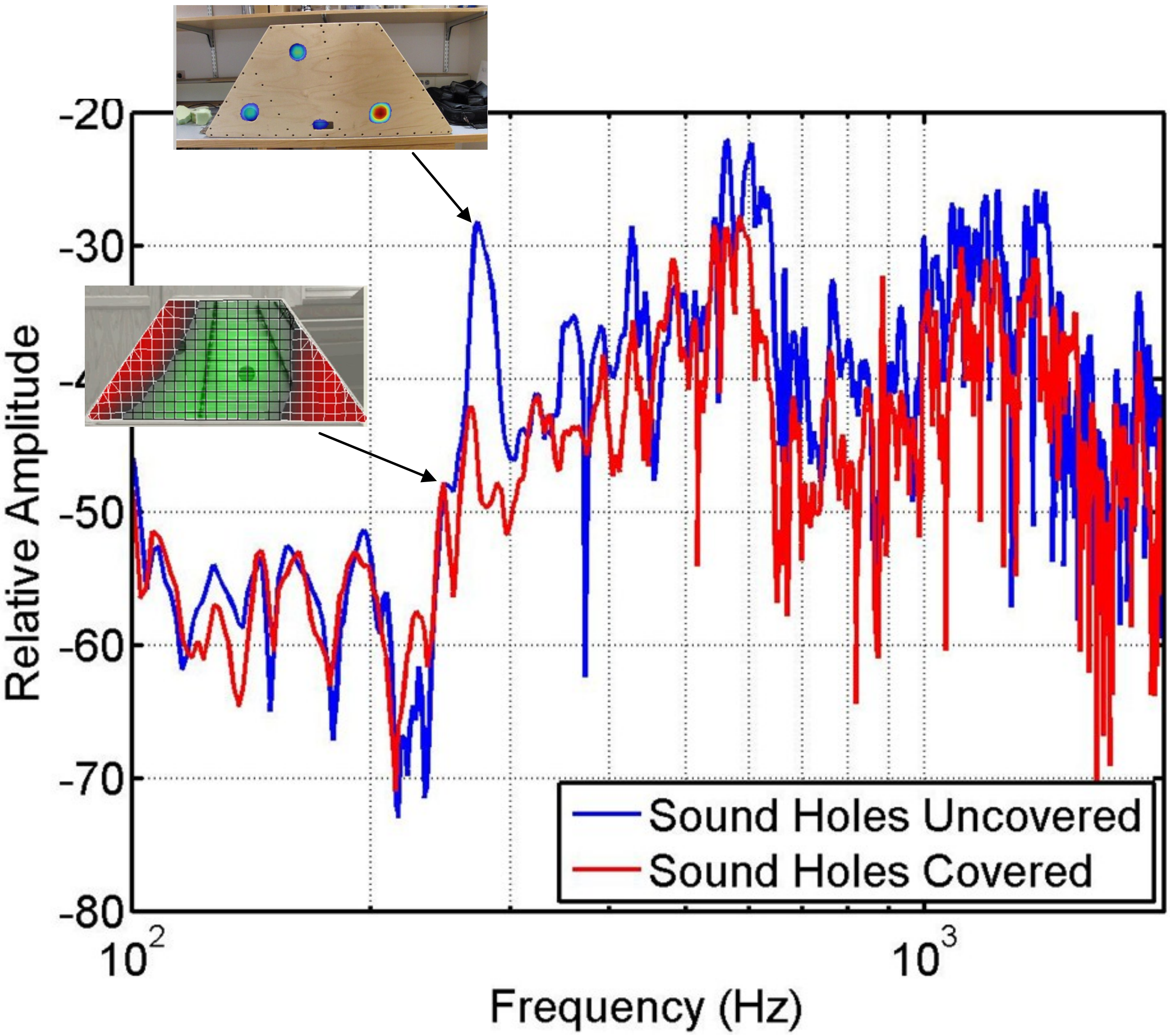


Figure 3.2 The Spectral response of the Hammered Dulcimer, from Swept Sine Analysis, with labels showing the source of radiation for peaks around 270 Hz. We clearly see that without the sound holes, the dulcimer radiates around 265 Hz with a clear structural mode. A much more powerful mode exists at 270 Hz which comes almost purely from the sound holes.

defining the dulcimer's characteristic spectrum.

3.4 Future research

There is still much research that can be done on the hammered dulcimer. First off, all the research conducted in this thesis was conducted on a single dulcimer. As we previously mentioned, there are countless variations of the hammered dulcimer, so one obvious direction future research could take is to repeat the same analysis on different dulcimers. In particular, it would be great to see the same analysis conducted on the more expensive, higher end dulcimers. Also, there is a common variation called "floating top" dulcimers, where the top plate isn't attached to the rest of the dulcimer, and the tension from the strings is what keeps it all together. It would be particularly interesting to look at this type of dulcimer to see if the front and back plates are still strongly coupled.

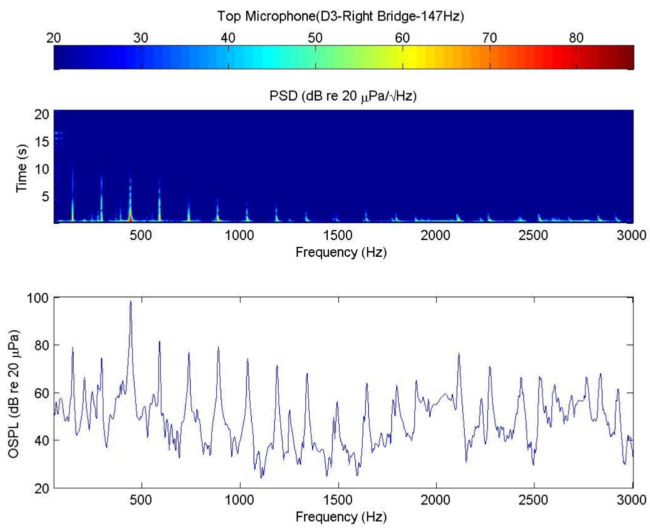
Beyond the analysis conducted here, there are many other methods that could be used to investigate the hammered dulcimer. For example, more extensive research could be conducted with the SLDV, investigating in detail the optimal modal patterns of the dulcimer. Also, different materials could be tested to try to find an optimal sound board that is structurally sound and has good tone. Also, changing the bracing type and pattern of the dulcimer would surely change the modal response of the body, and these changes could be investigated.

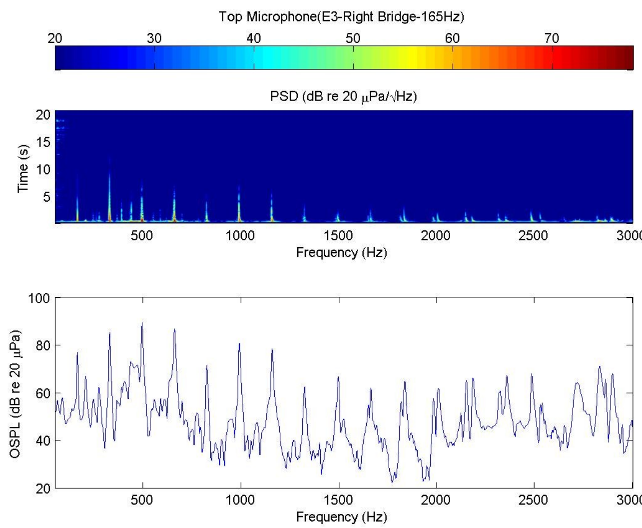
We've shown that there are some clear Helmholtz-like resonances occurring in the dulcimer, but our analysis was a simple first approximation. A much more extensive equivalent circuit model could be used to model the dulcimer. With an equivalent circuit model, it would be fairly simple to experiment with different parameters. It is even plausible to use this model to design a dulcimer with sound holes in optimal locations as to increase the low-frequency response [8] [9].

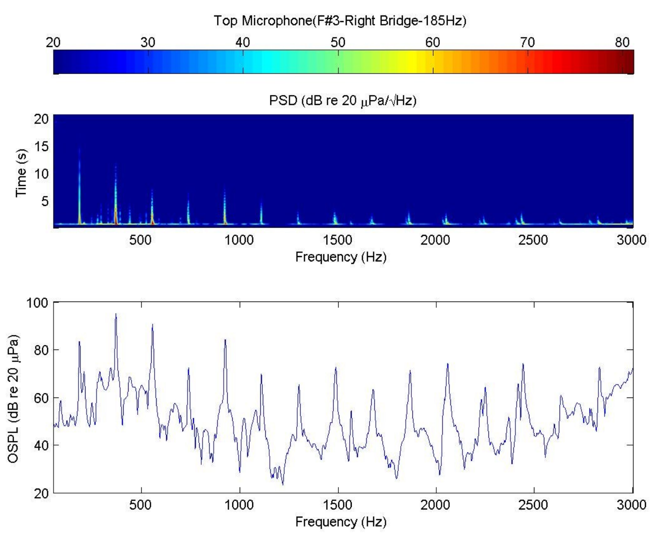
Near field acoustical holography is a relatively new approach to instrumental acoustics, and as such, the methods used in this paper could be applied to many more instruments. A very interesting project would be to do NAH scans on multiple instruments, seeing as NAH can show us not only how plates are vibrating, but also activity in sound holes and other parts of instruments.

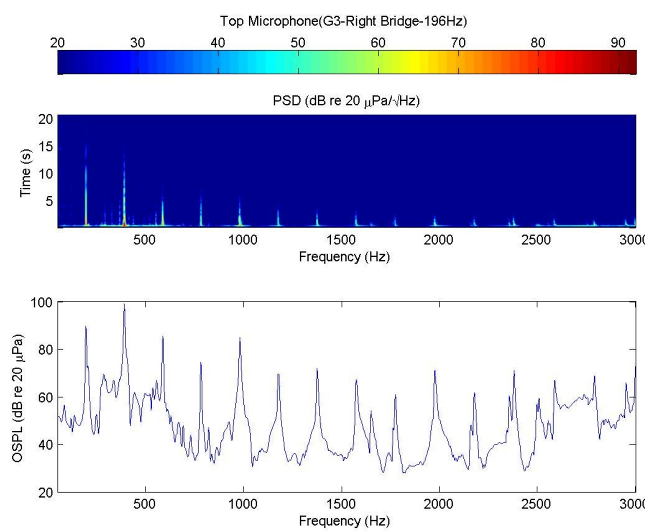
Appendix A

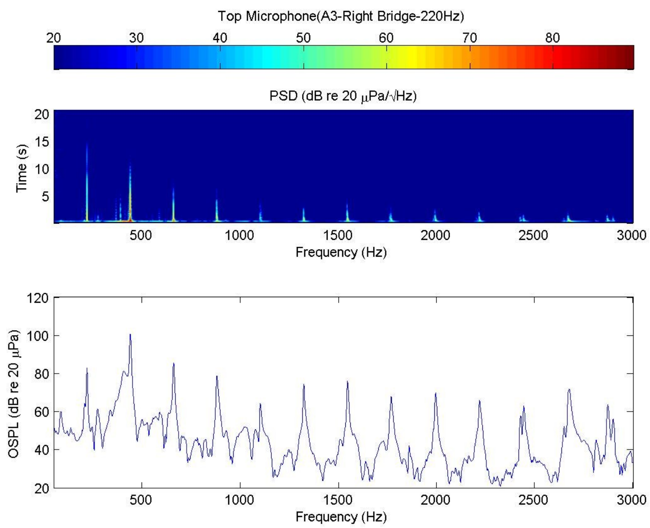
Spectrums From Single Note Measurements

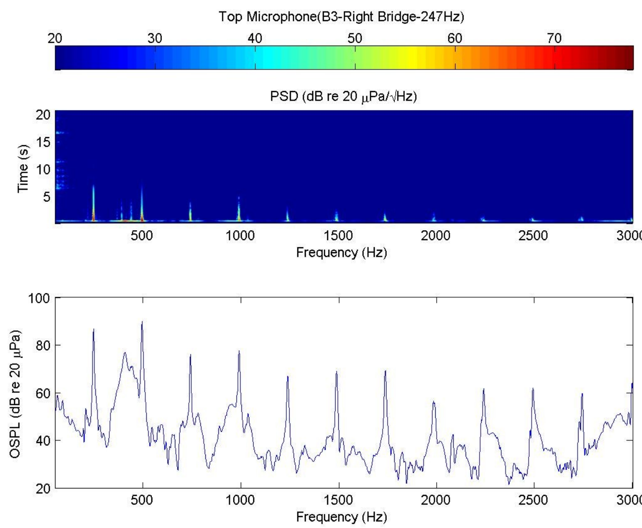

Top Microphone(D3-Right Bridge-147Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

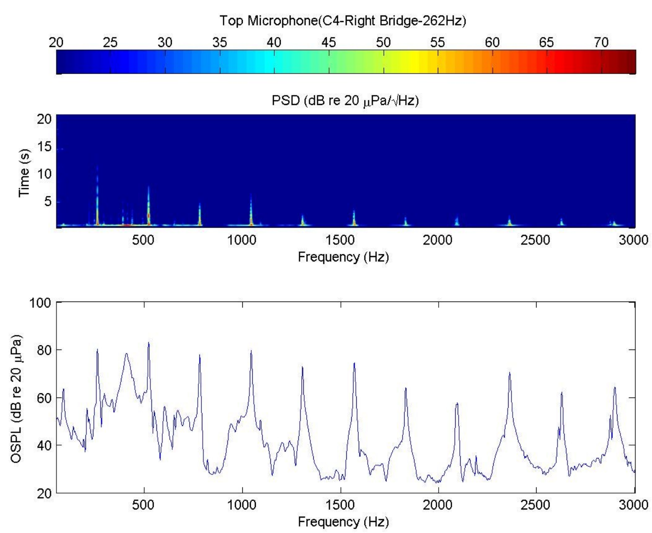

Top Microphone(E3-Right Bridge-165Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

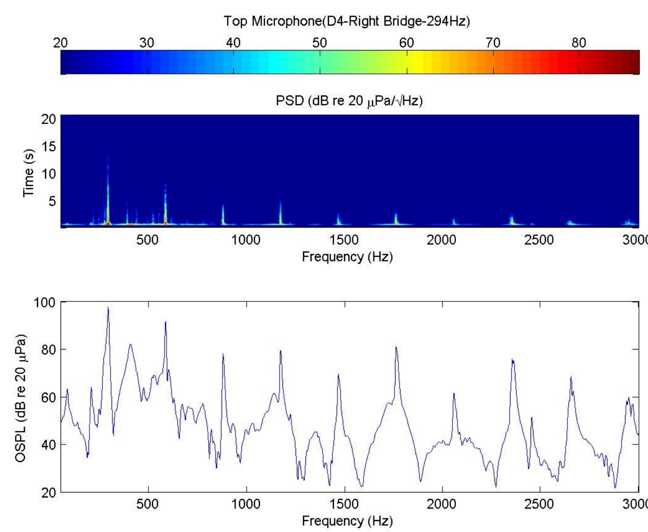

Top Microphone(F#3-Right Bridge-185Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

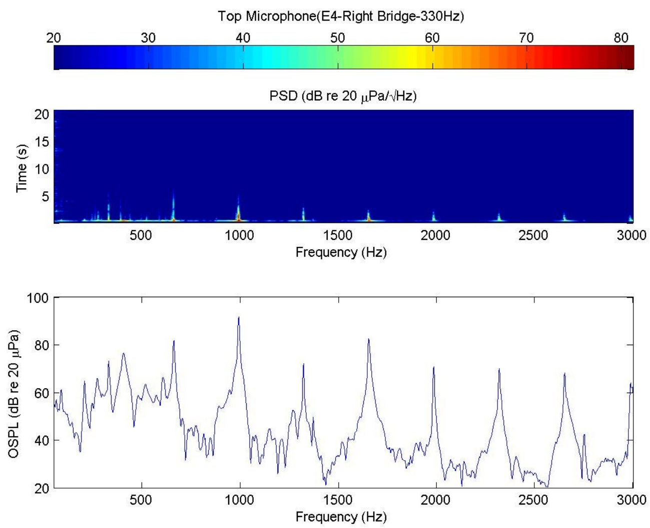

Top Microphone(G3-Right Bridge-196Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(A3-Right Bridge-220Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(B3-Right Bridge-247Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(C4-Right Bridge-262Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(D4-Right Bridge-294Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(E4-Right Bridge-330Hz)
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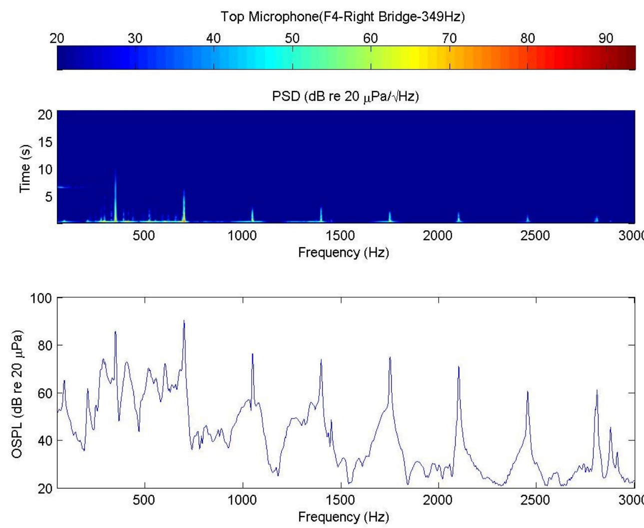
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(F4-Right Bridge-349Hz)
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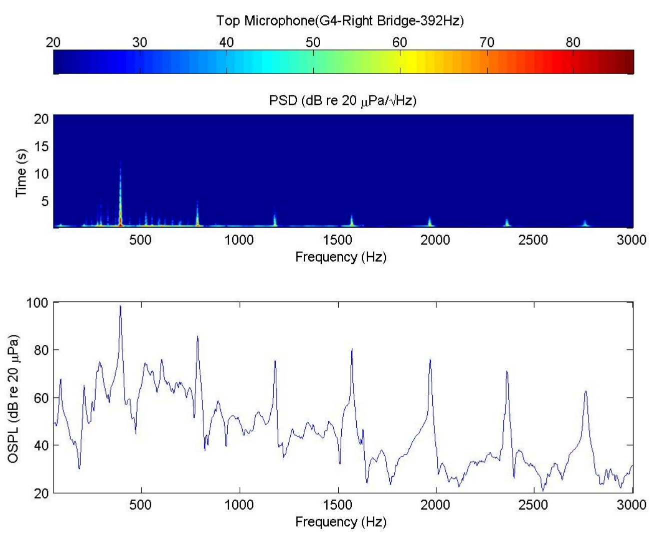
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(G4-Right Bridge-392Hz)
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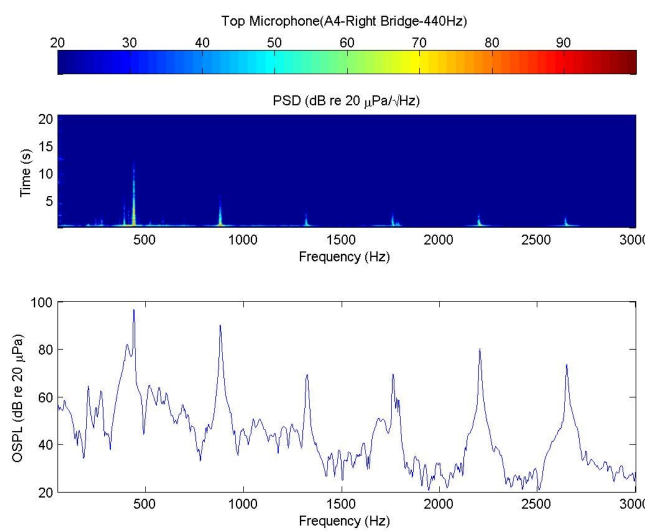
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(A4-Right Bridge-440Hz)
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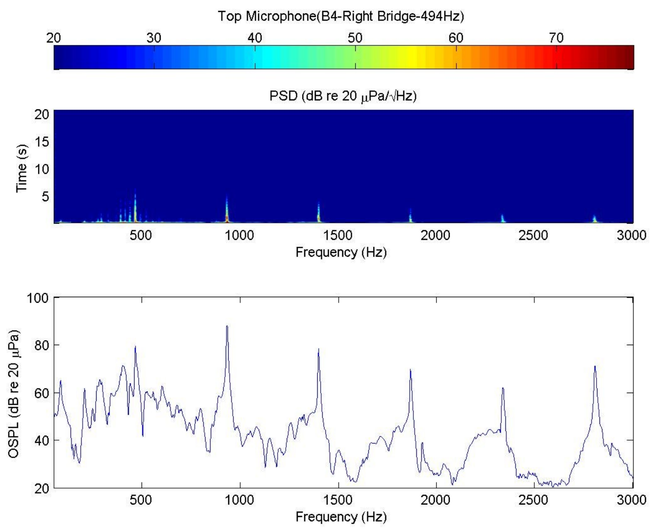
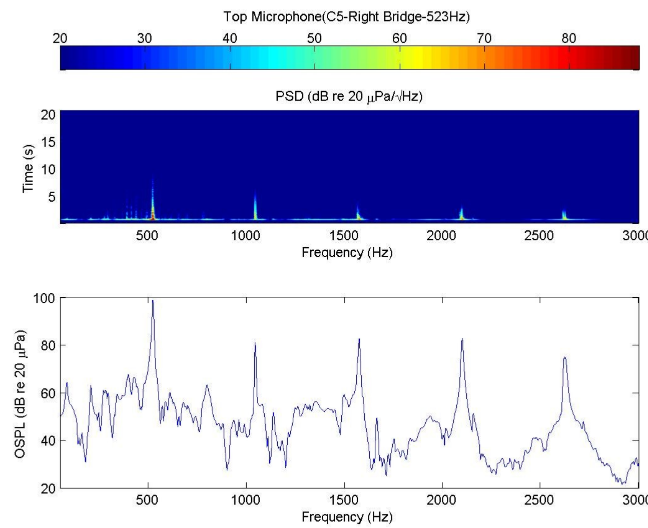
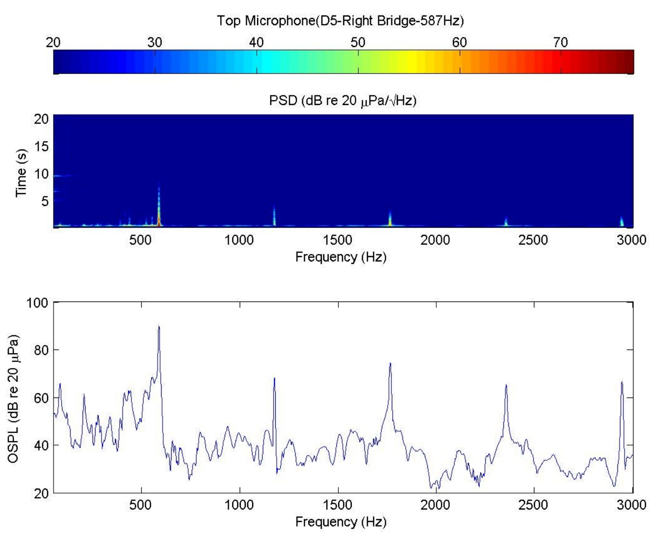
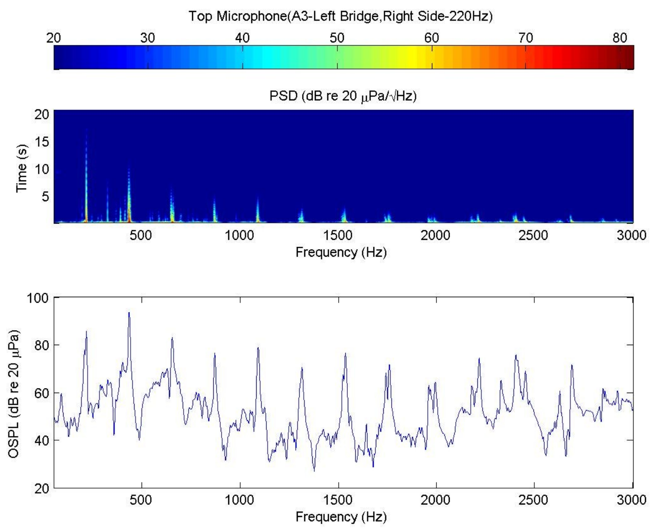
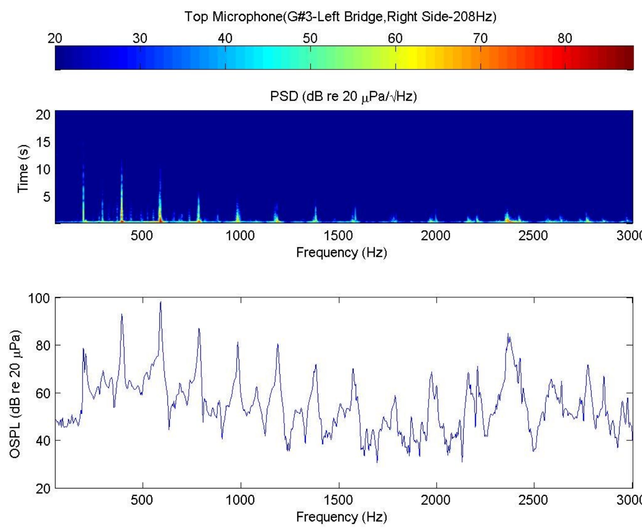
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

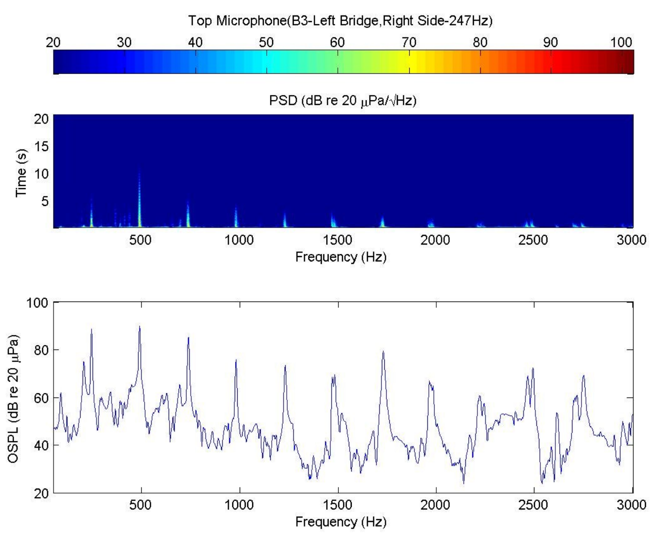

Top Microphone(B4-Right Bridge-494Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

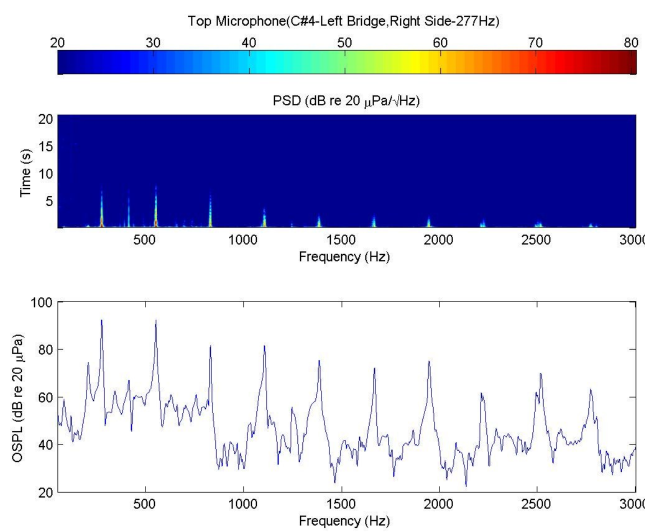

Top Microphone(C5-Right Bridge-523Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

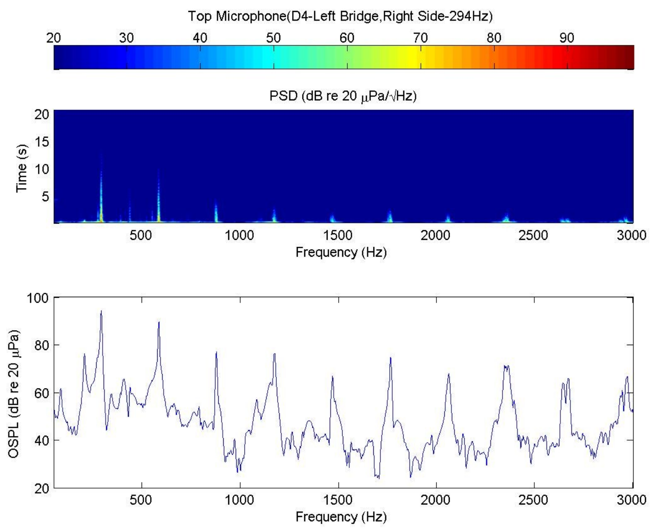

Top Microphone(D5-Right Bridge-587Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

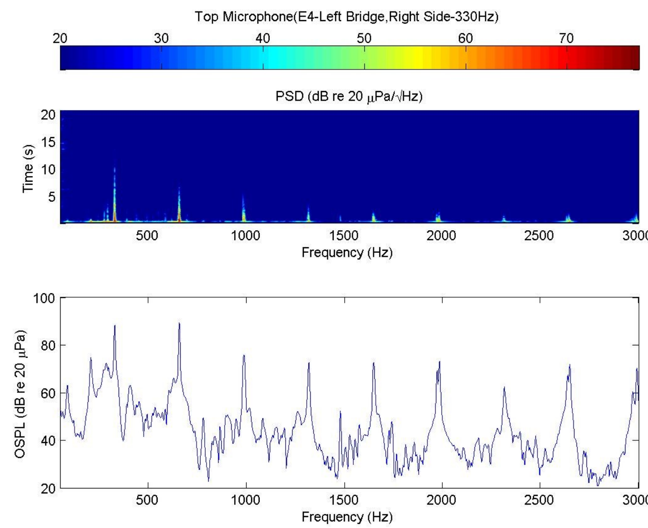

Top Microphone(A3-Left Bridge,Right Side-220Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

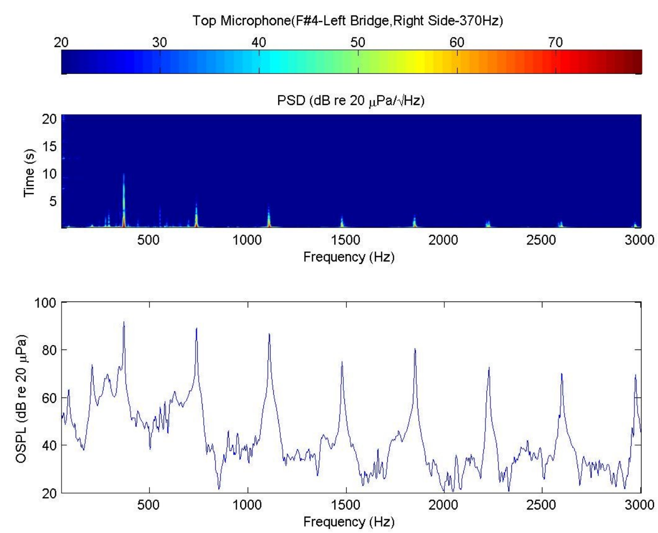

Top Microphone(G#3-Left Bridge,Right Side-208Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

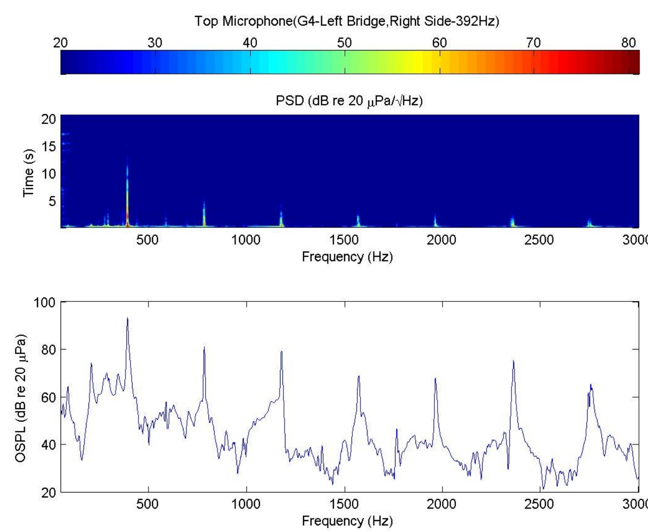

Top Microphone(B3-Left Bridge,Right Side-247Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

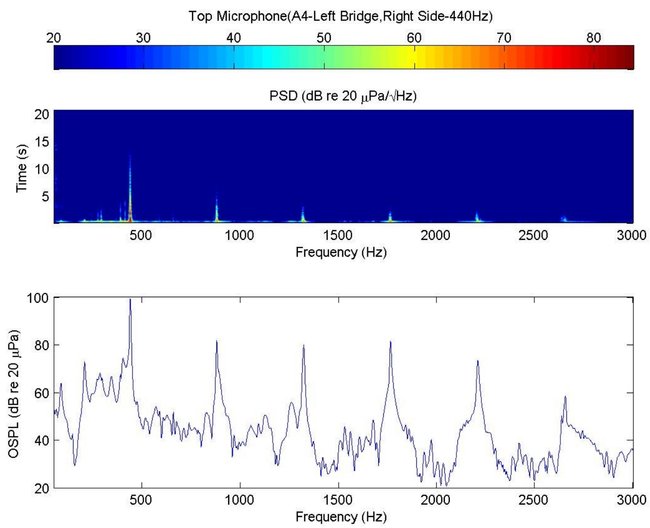

Top Microphone(C#4-Left Bridge,Right Side-277Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

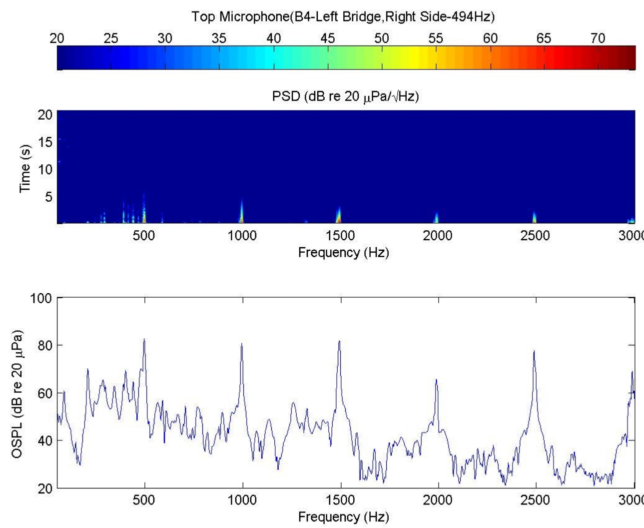

Top Microphone(D4-Left Bridge,Right Side-294Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

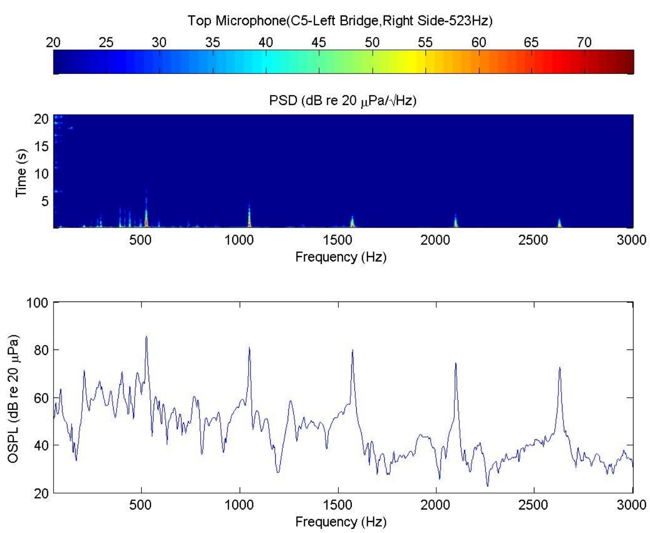

Top Microphone(E4-Left Bridge,Right Side-330Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

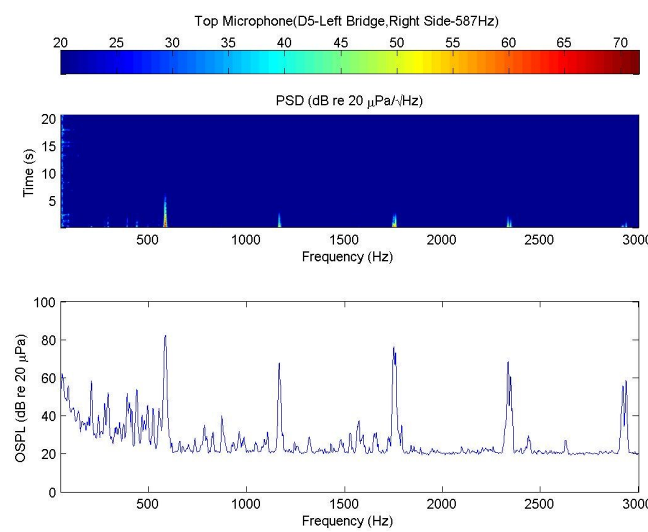

Top Microphone(F#4-Left Bridge,Right Side-370Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

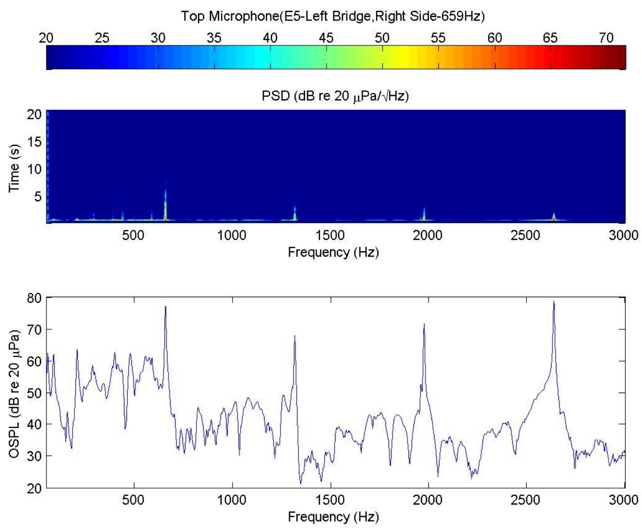

Top Microphone(G4-Left Bridge,Right Side-392Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

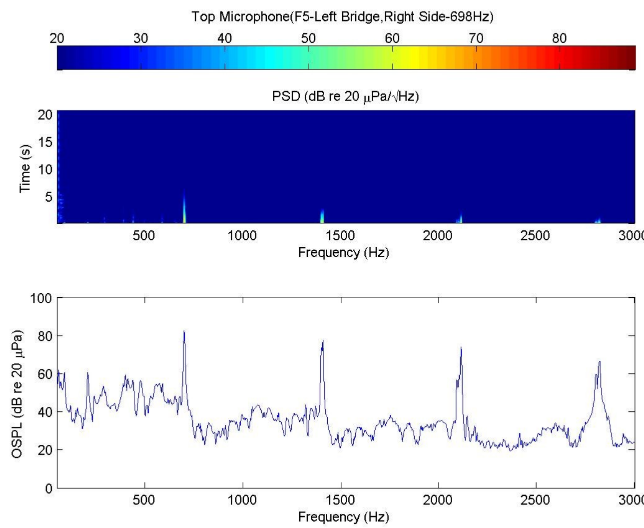

Top Microphone(A4-Left Bridge,Right Side-440Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

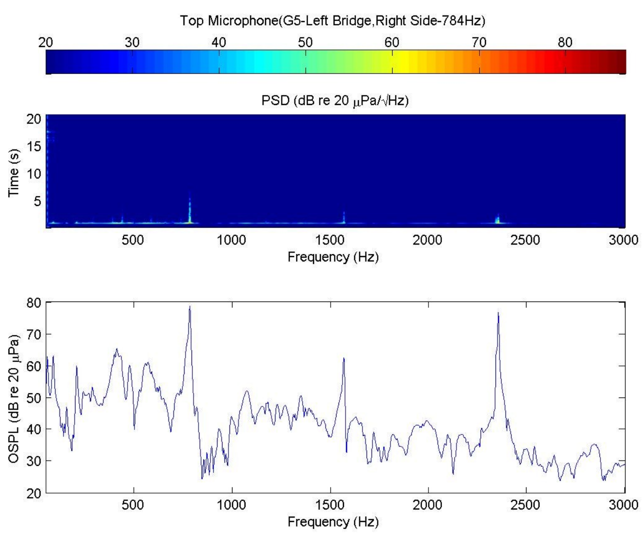

Top Microphone(B4-Left Bridge,Right Side-494Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

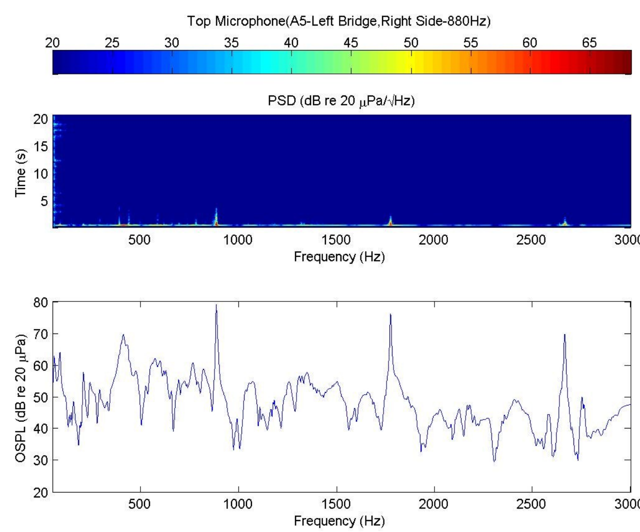

Top Microphone(C5-Left Bridge,Right Side-523Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

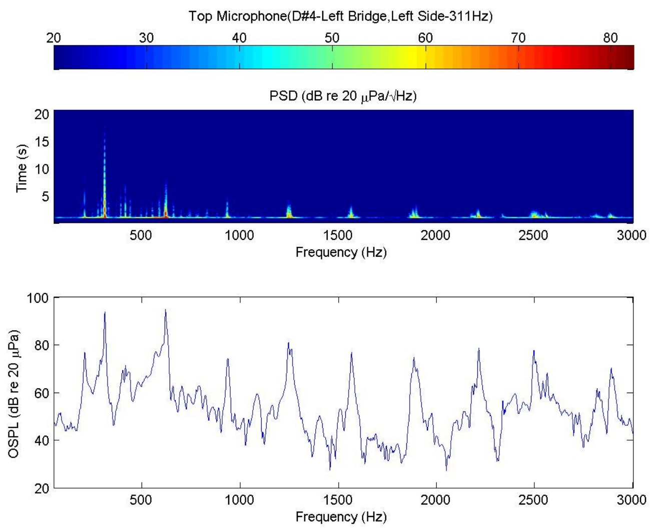

Top Microphone(D5-Left Bridge,Right Side-587Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(E5-Left Bridge,Right Side-659Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(F5-Left Bridge,Right Side-698Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(G5-Left Bridge,Right Side-784Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(A5-Left Bridge,Right Side-880Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)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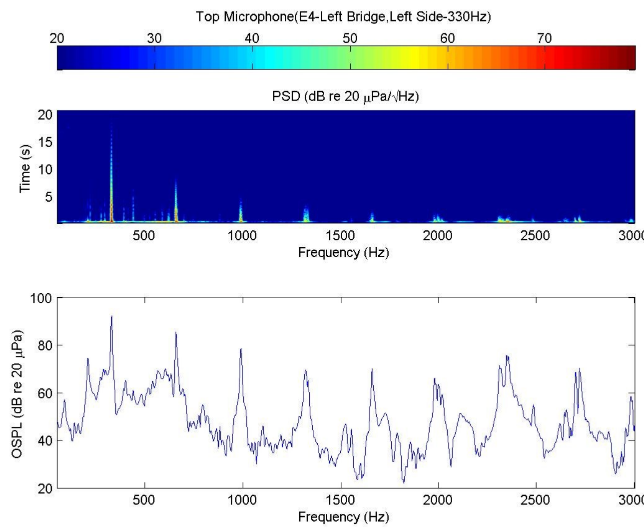
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(E4-Left Bridge,Left Side-330Hz)
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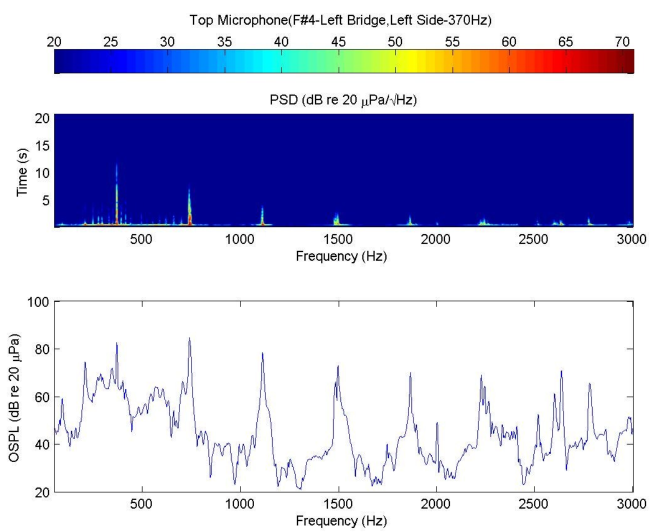
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(F#4-Left Bridge,Left Side-370Hz)
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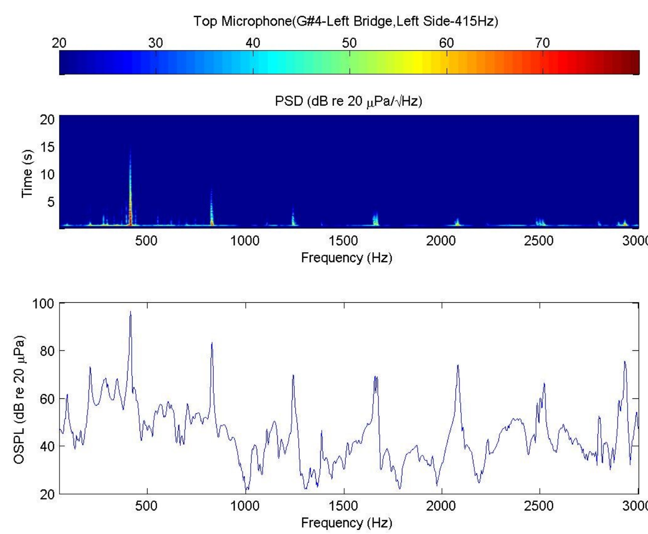
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(G#4-Left Bridge,Left Side-415Hz)
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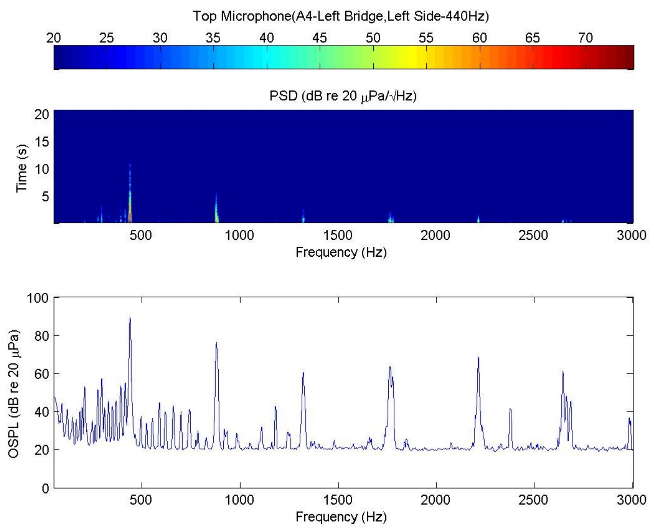
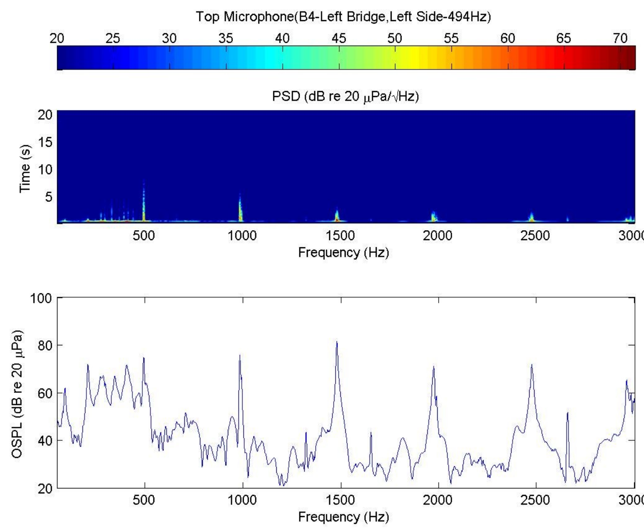
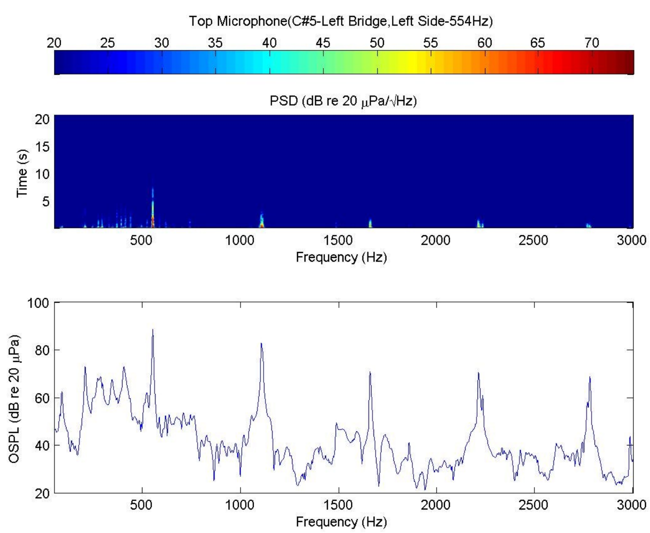
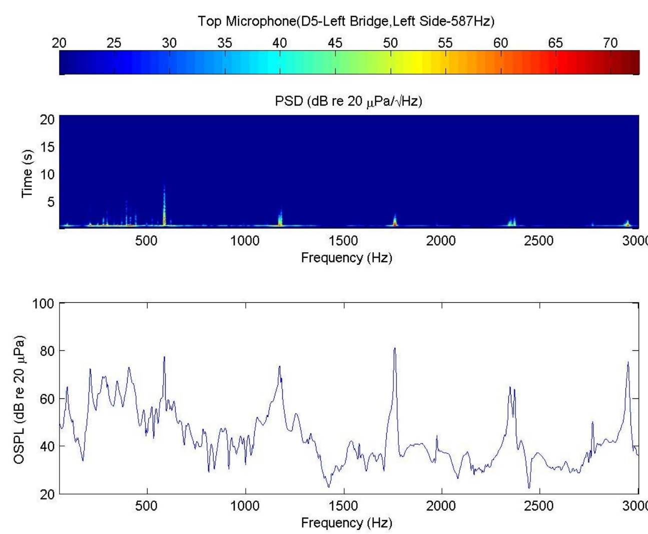
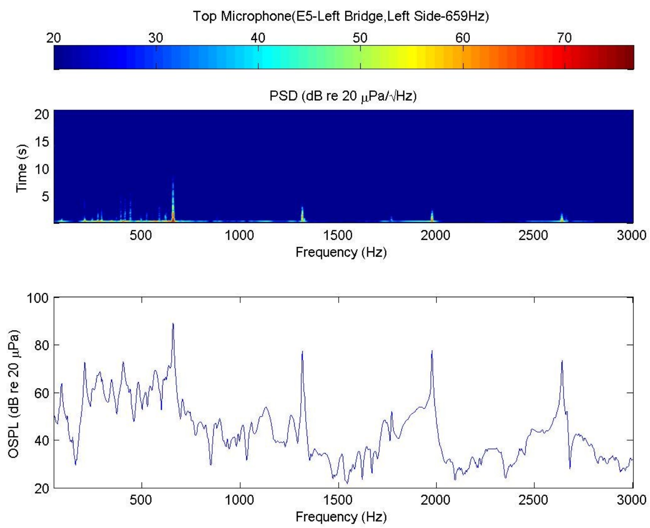
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

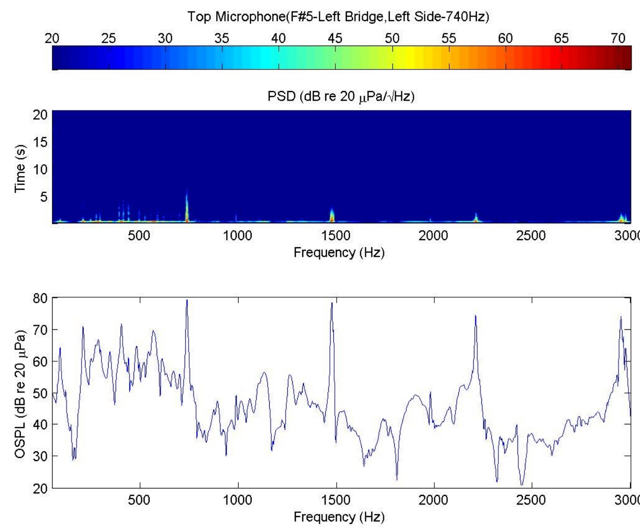

Top Microphone(A4-Left Bridge,Left Side-440Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

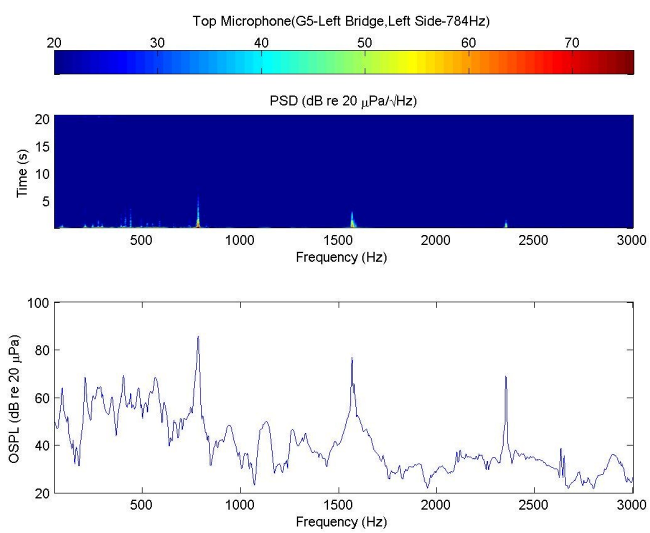

Top Microphone(B4-Left Bridge,Left Side-494Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

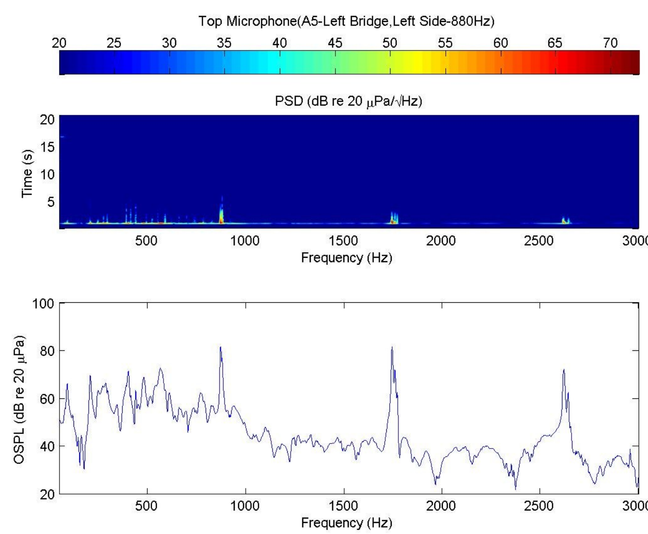

Top Microphone(C#5-Left Bridge,Left Side-554Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

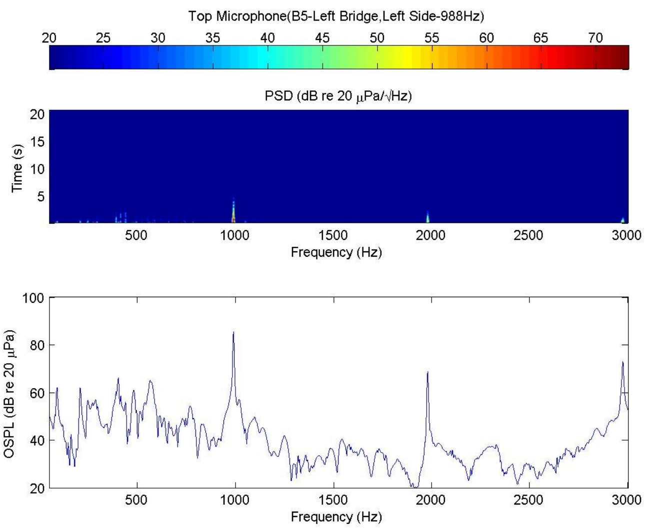

Top Microphone(D5-Left Bridge,Left Side-587Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

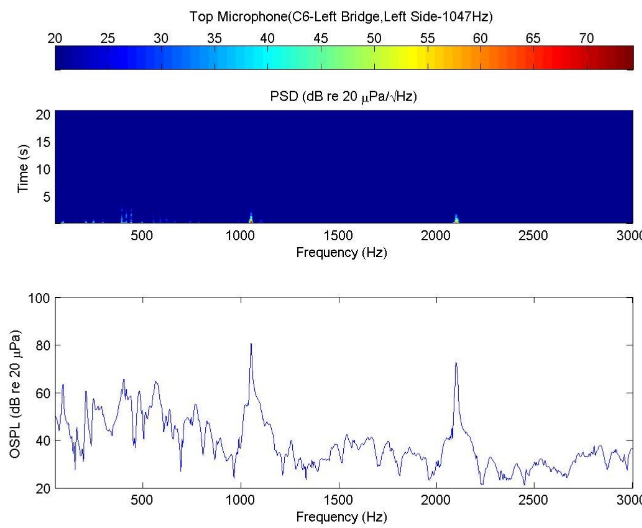

Top Microphone(E5-Left Bridge,Left Side-659Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

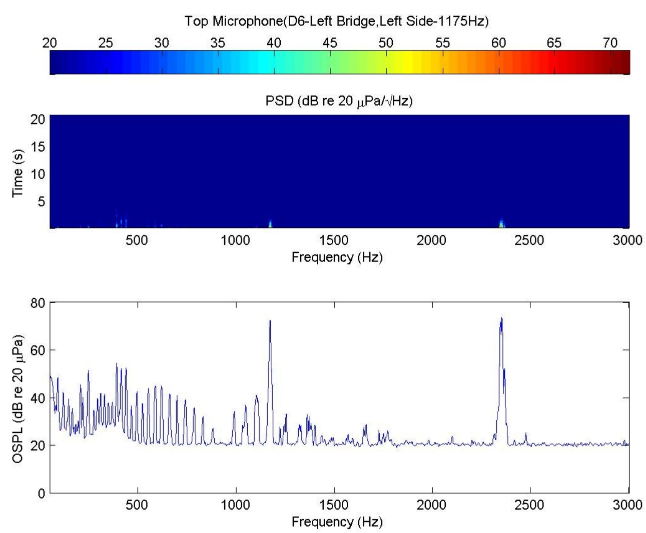

Top Microphone(F#5-Left Bridge,Left Side-740Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

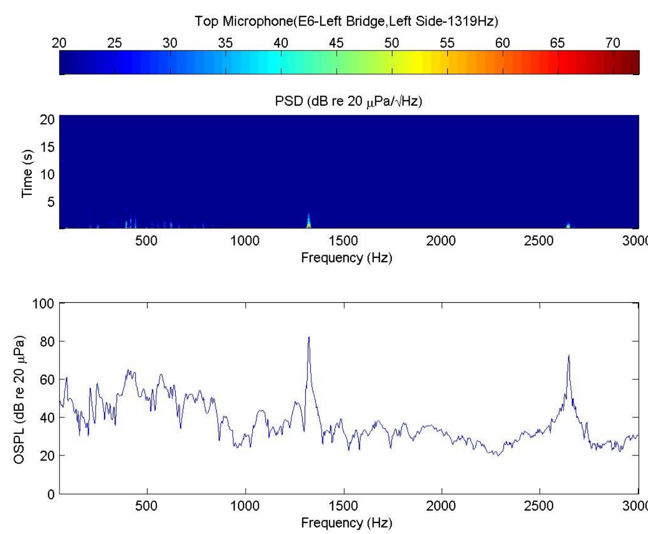

Top Microphone(G5-Left Bridge,Left Side-784Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

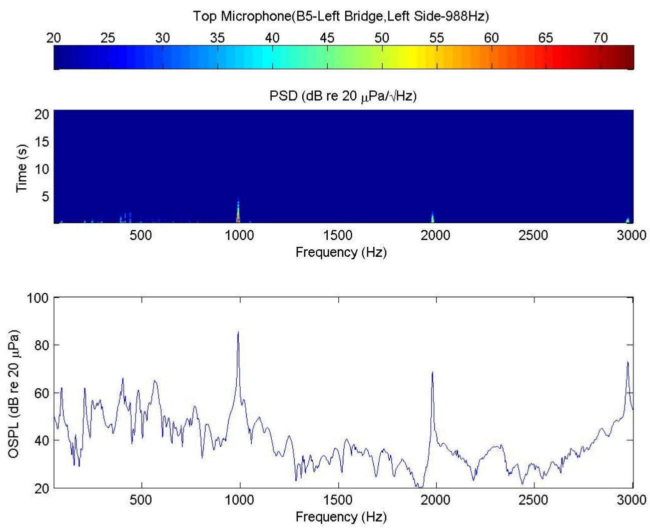

Top Microphone(A5-Left Bridge,Left Side-880Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

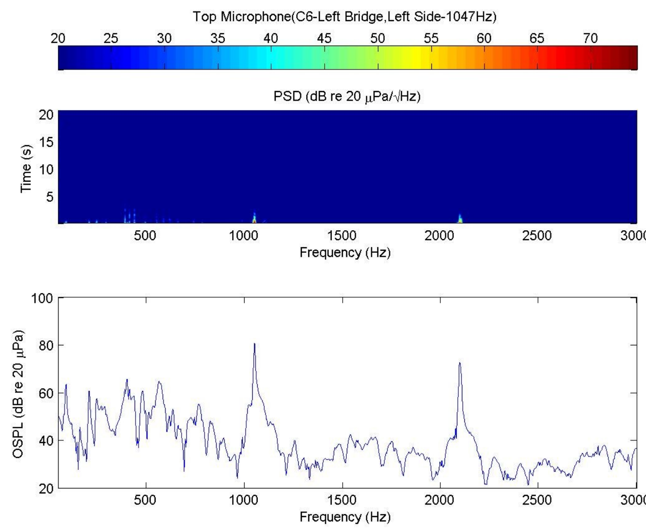

Top Microphone(B5-Left Bridge,Left Side-988Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

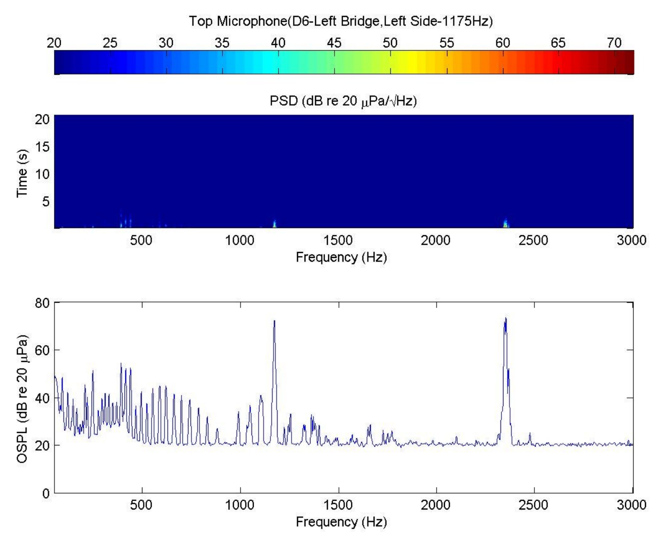

Top Microphone(C6-Left Bridge,Left Side-1047Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

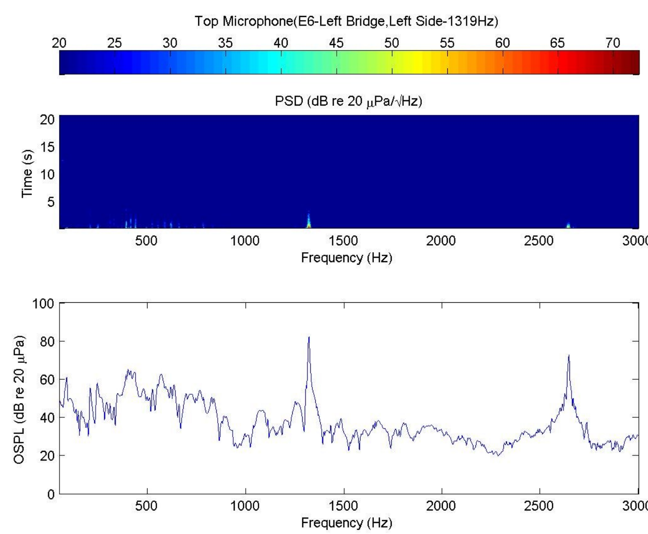

Top Microphone(D6-Left Bridge,Left Side-1175Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(E6-Left Bridge,Left Side-1319Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(B5-Left Bridge,Left Side-988Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(C6-Left Bridge,Left Side-1047Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(D6-Left Bridge,Left Side-1175Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)


Top Microphone(E6-Left Bridge,Left Side-1319Hz)
PSD (dB re 20 μPa/√Hz)
Time (s)
Frequency (Hz)
OSPL (dB re 20 μPa)
Frequency (Hz)

Appendix B

Near-Field Acoustical Holography Results

The following magnitude figures are in dBre20μPa.

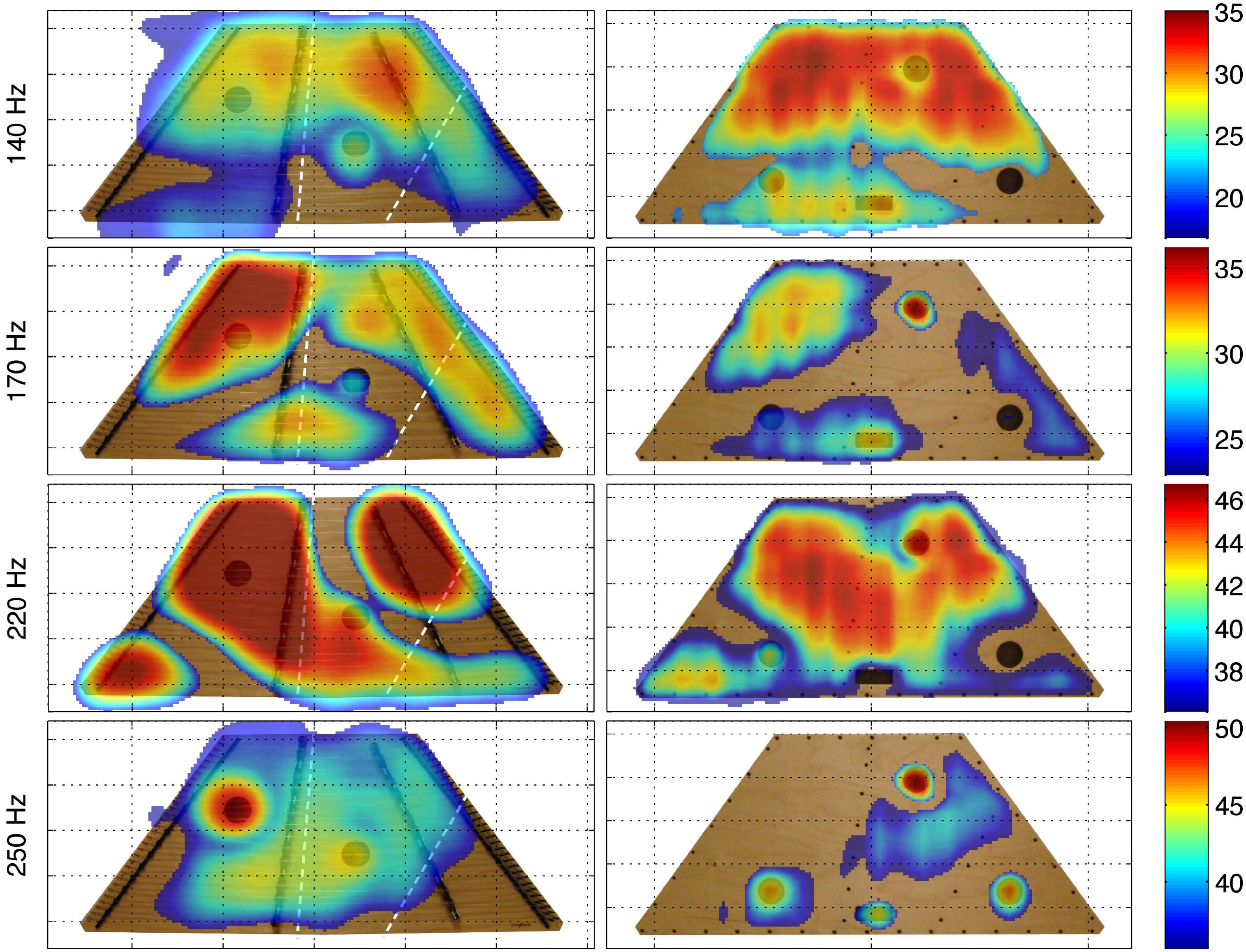


Figure B.1 Reconstructed pressure planes from NAH. These frequencies show structural modes below 270 Hz

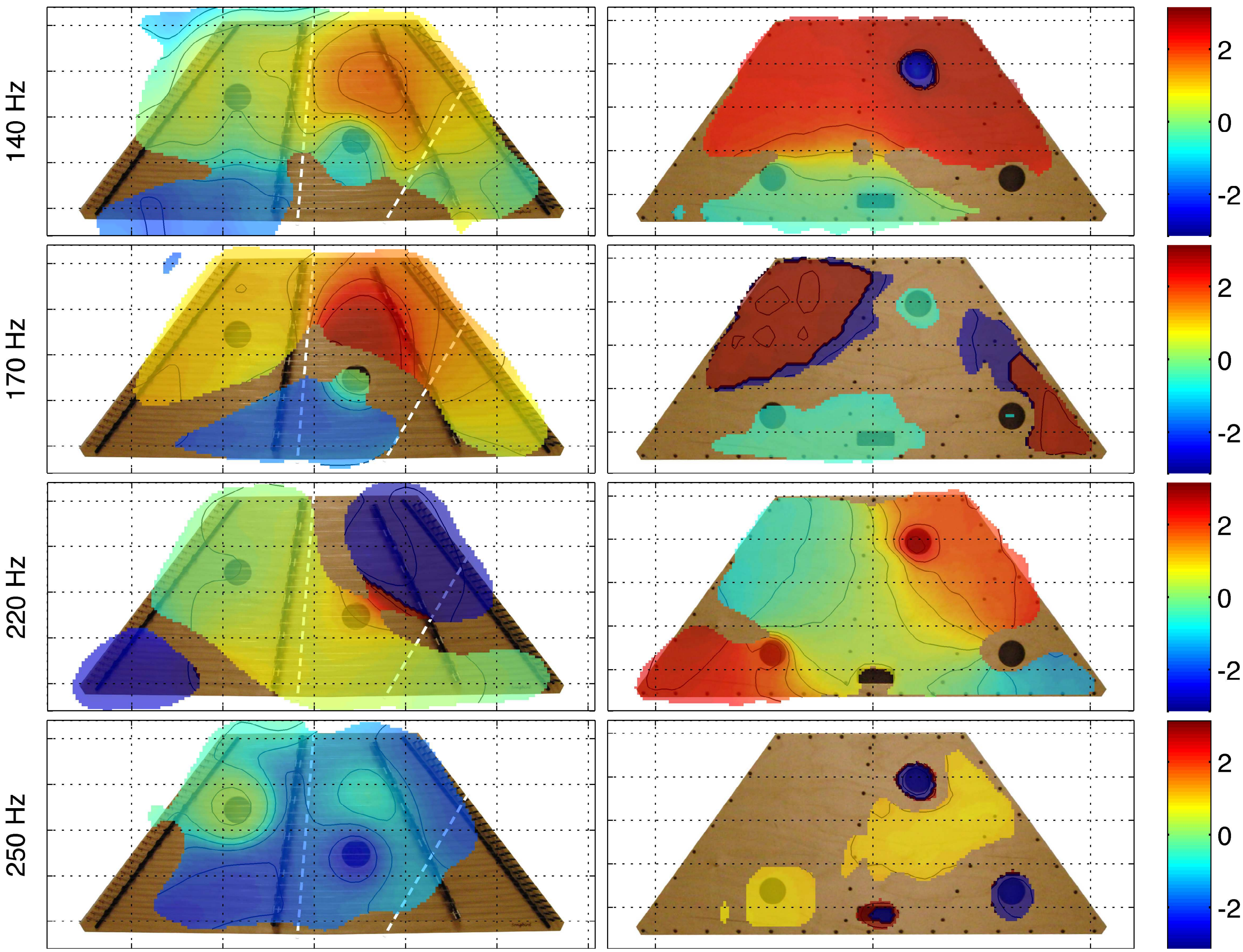


Figure B.2 The phase relationships of the same four frequencies as B.1.

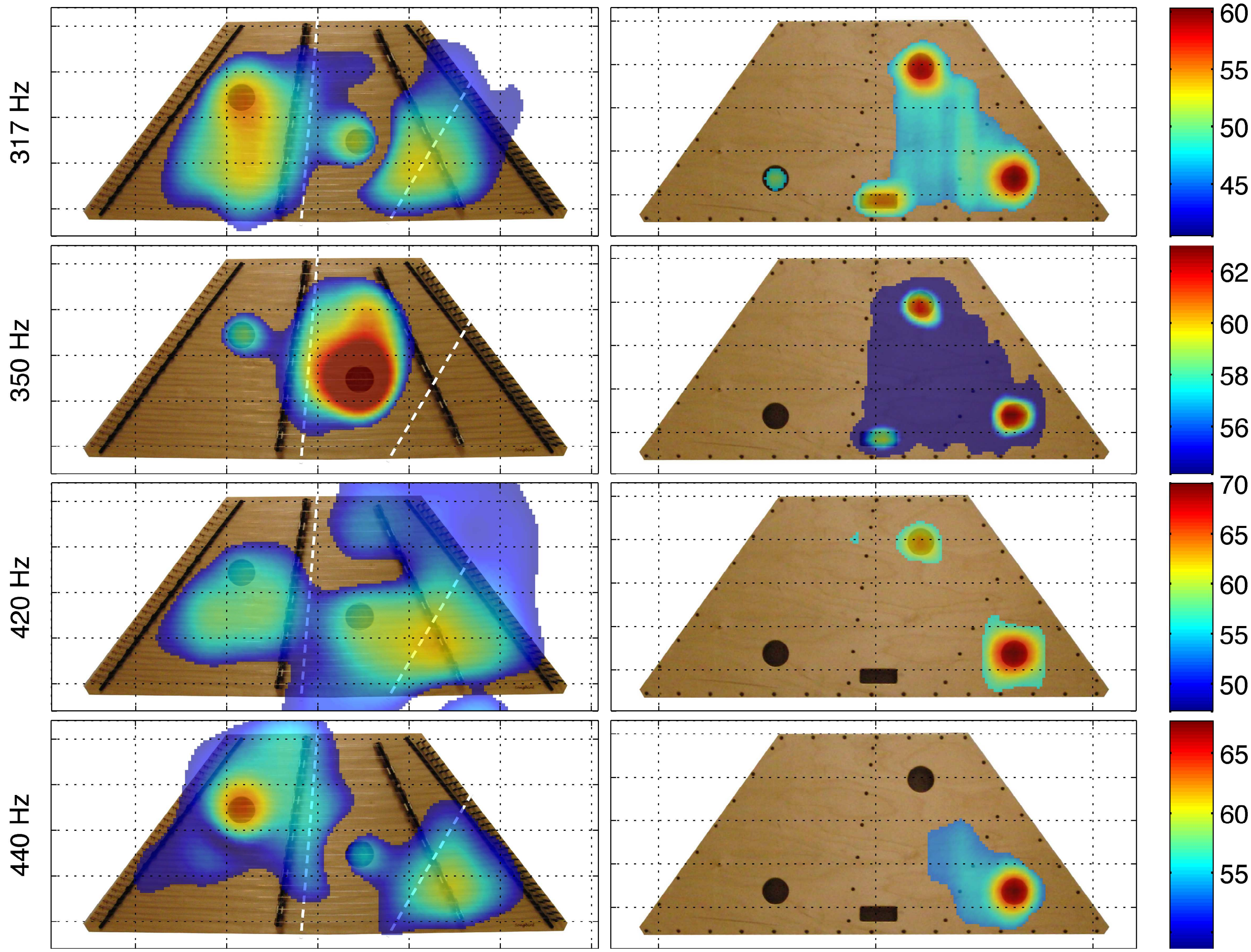


Figure B.3 Four frequencies showing mixed sound hole radiation and structural radiation

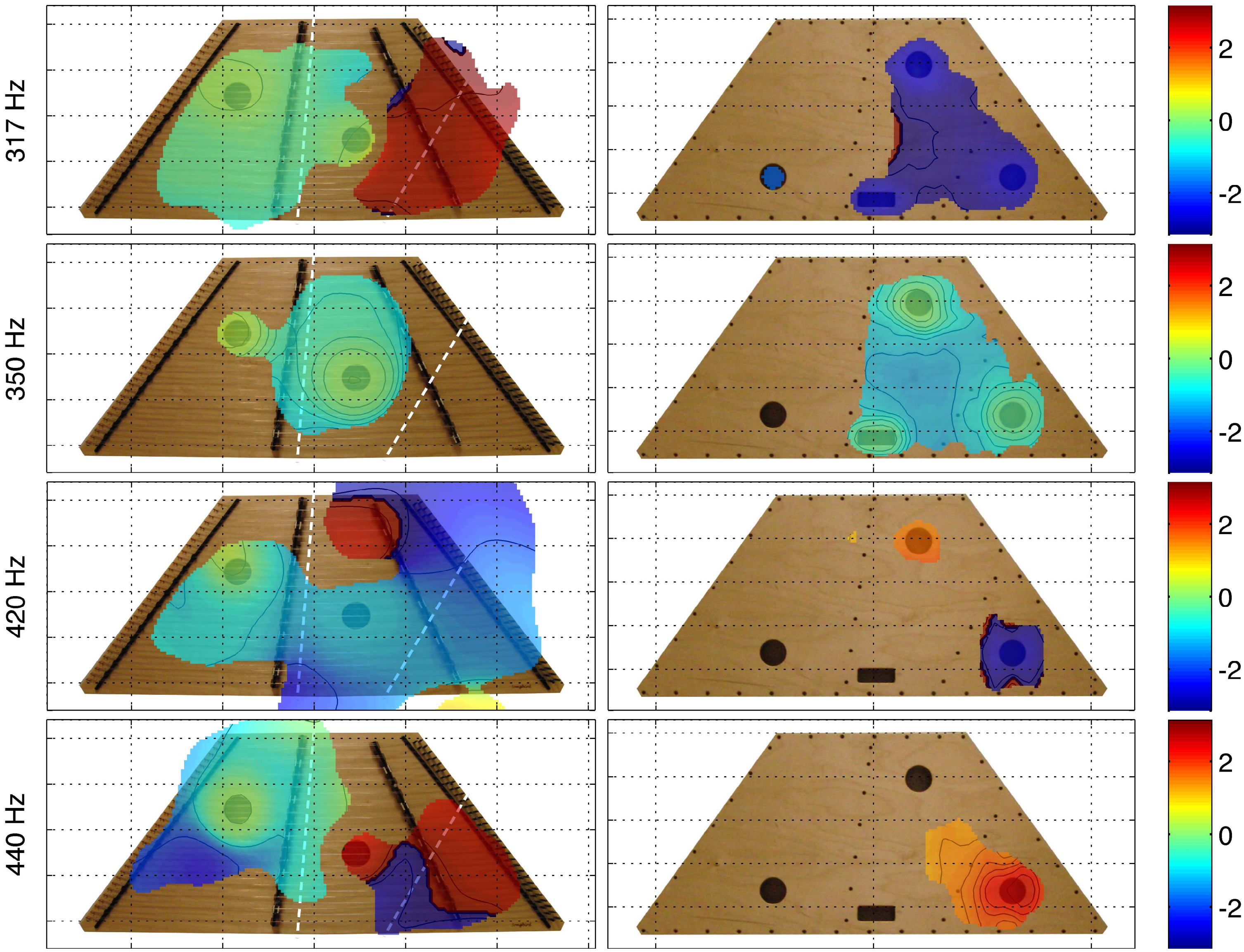


Figure B.4 The phase relationships of the same four frequencies as B.3.

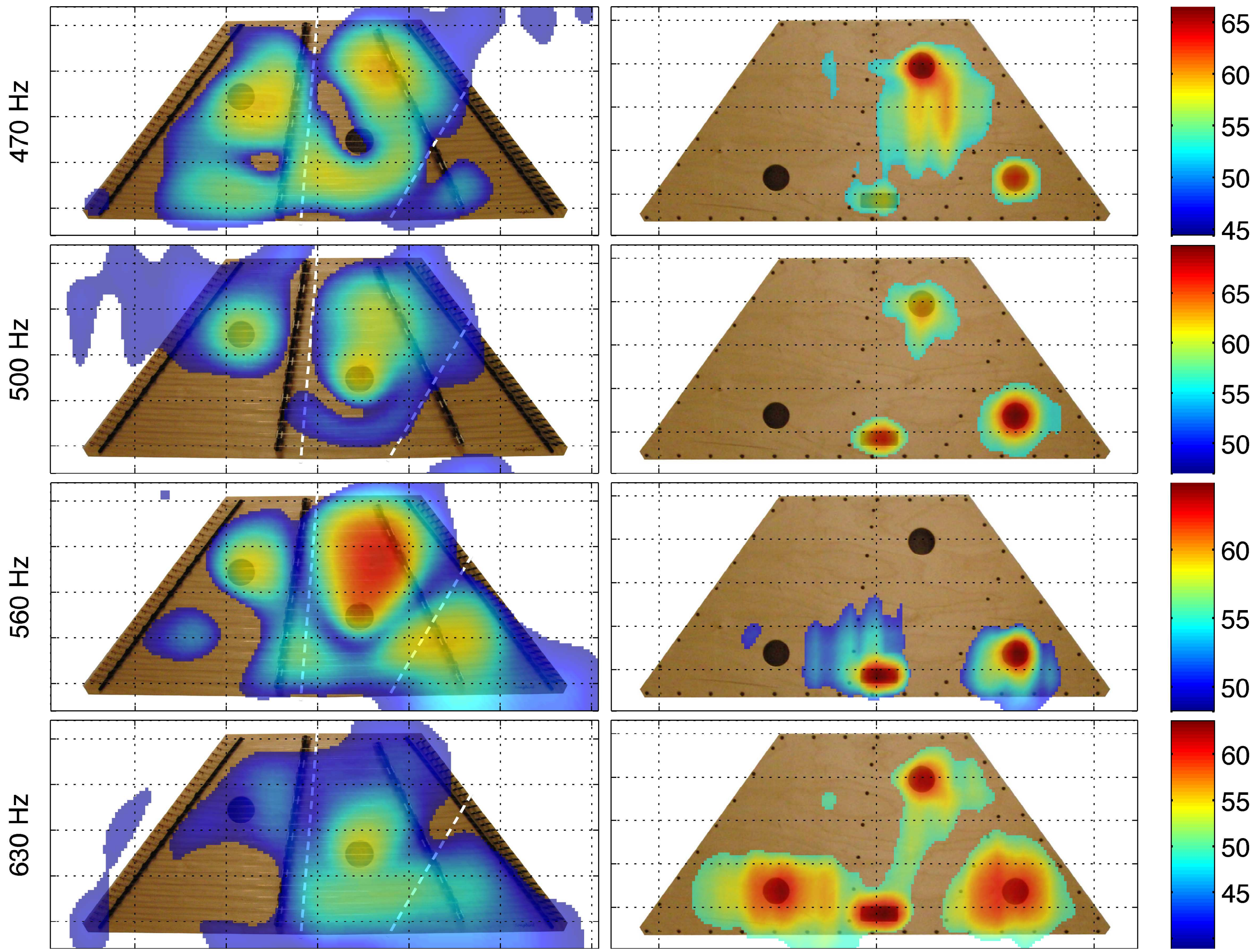


Figure B.5 Four more frequencies showing mixed sound hole radiation and structural radiation

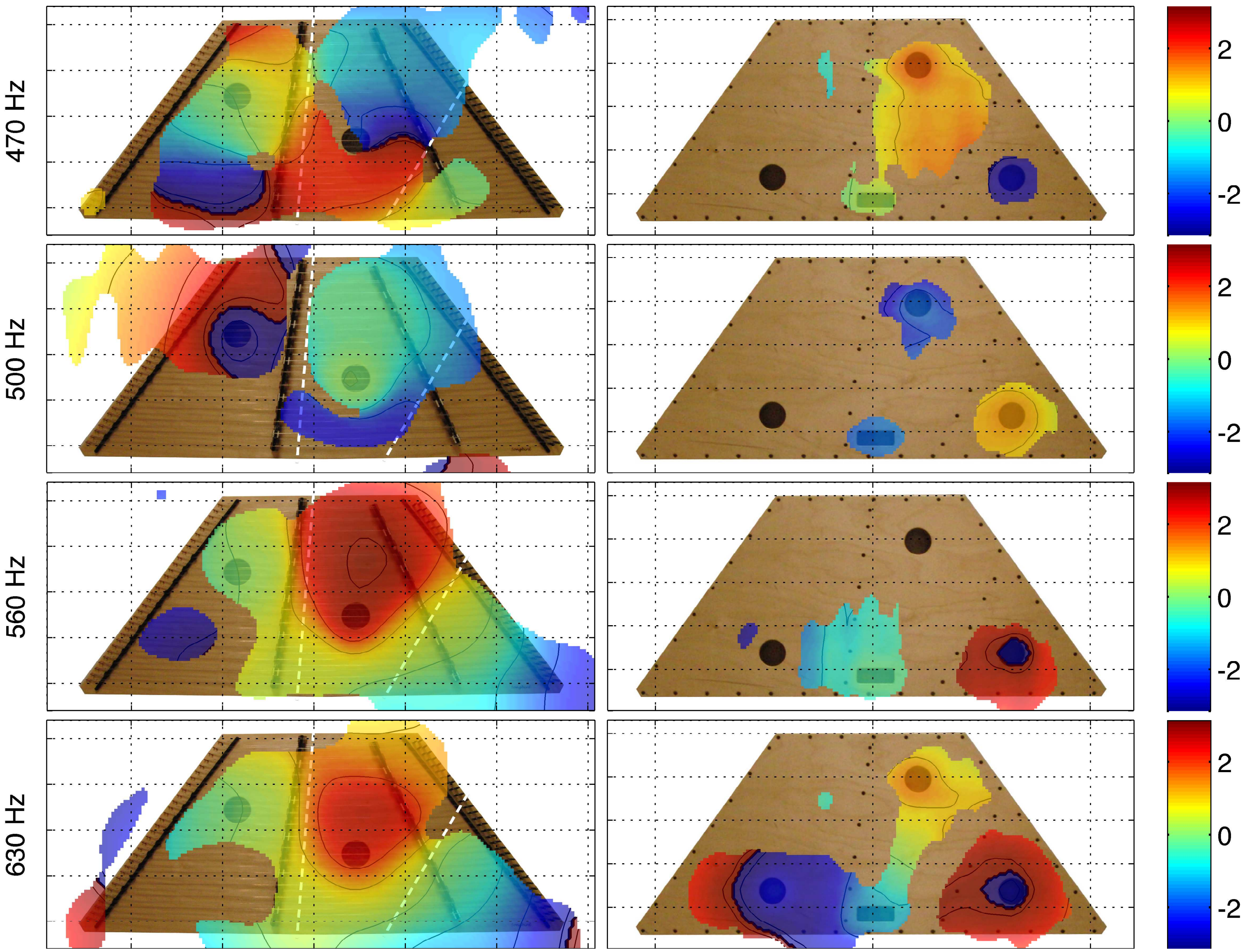


Figure B.6 The phase relationships of the same four frequencies as B.5.

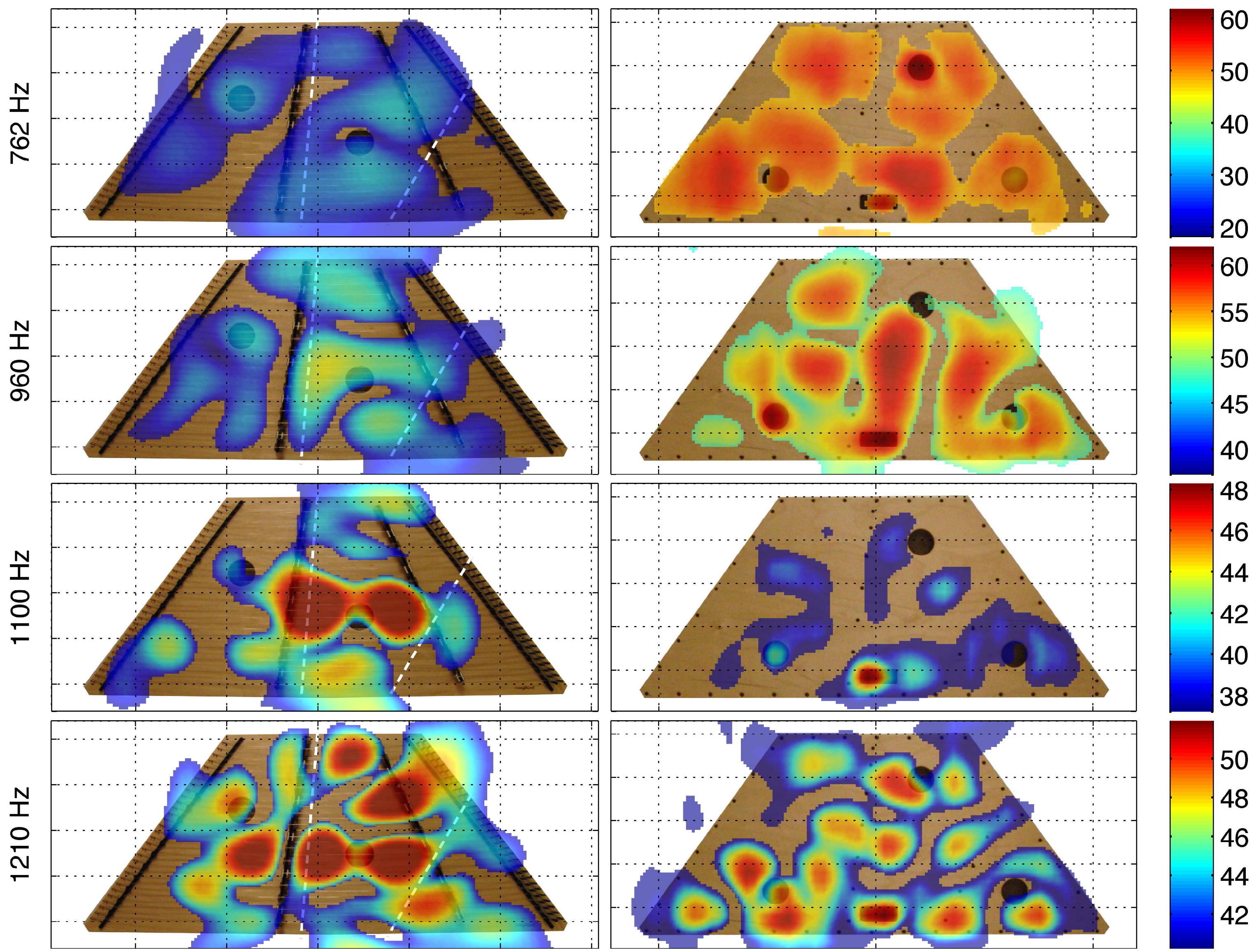


Figure B.7 Four more frequencies showing complicated structural modes which are dominate in higher frequencies.

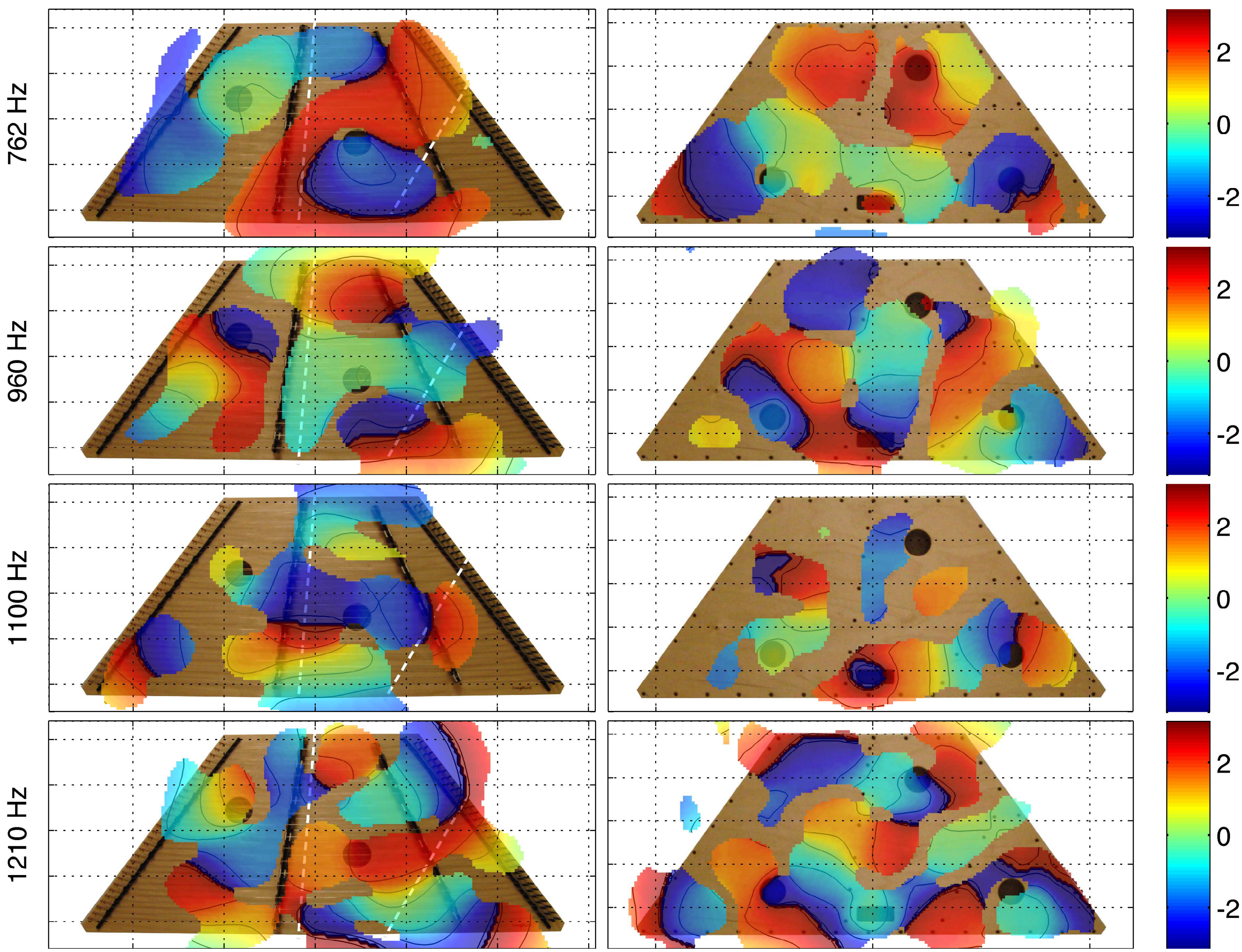


Figure B.8 The phase relationships of the same four frequencies as B.7.

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