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4aMUb5.   Modal response and sound radiation from a hammered dulcimer

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  The sound radiation of the hammered dulcimer has been investigated. The dulcimer studied is a 16/15 fixed-top instrument of typical size with Baltic birch (laminated plywood) soundboard and back. To determine the instrument body resonances, the dulcimer was driven at the treble and bass bridges with a shaker. Accelerometers were used to obtain the resonance frequencies of the soundboard and back, and a microphone was placed inside the instrument to obtain the cavity resonances. The individual resonance peaks found were further investigated using near-field acoustical holography. Preliminary results show that there is little modal response of the instrument at the fundamental frequencies of the lowest notes of the dulcimer. In addition, the vibration coupling to the back plate through the internal bracing causes it to serve as a second soundboard. Lastly, the holography results indicate significant radiation from the sound holes at some frequencies, which may contradict the commonly held notion that the dulcimer sound holes are largely decorative.

1. Introduction

The hammered dulcimer is a stringed instrument of the zither family, typically consisting of a wooden trapezoidal body with metal strings stretched across the frame[10]. Like its close cousins in other cultures (e.g., the santur, yanquin, cimbalom, and hackbrett), the bridges can be used to divide the strings into different ratio lengths corresponding to musical intervals. In the hammered dulcimer, the left or treble bridge typically splits the strings with a 2:3 ratio, which makes a musical fifth. A typical dulcimer can span anywhere between 2 1/2 and 5 octaves, depending on the size of the instrument. For example, the dulcimer used in our research, shown in Fig. 1, is a 16/15 (meaning it has 16 courses of strings of the treble bridge and 15 across the bass) Songbird Phoebe built specially for our project by Christopher Foss of Muscatine, Iowa. The dulcimer is made of Baltic birch and has two strings per course. It has six sound holes: two on front and four on back, one of which serves as a carrying handle for the dulcimer. There are also two slits along the bottom of the dulcimer and one on top that allow the front and back plates to vibrate more freely. These also serve as additional sound holes. The dulcimer is constructed with wood screws in place of wood glue, which allows the back plate to be easily removed.
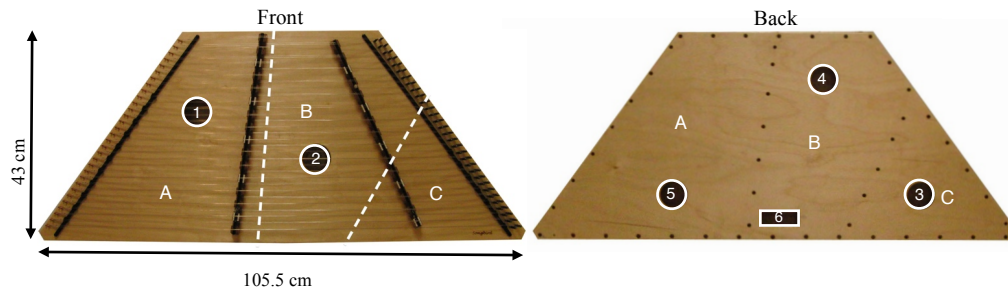
Figure 1: A picture of the front and back of our research dulcimer. The dulcimer's 6 sound holes are labeled 1-6. Sound hole #6 also serves as a carrying handle. The white dashed lines on the front, and the lines of wood screws on the back indicate the locations of the two internal braces. Although these braces split the dulcimer cavity into three chambers (A-C), small slits in the bracing material allow airflow between cavities.

From our inspection of instruments by several luthiers, dulcimer construction can vary greatly, as there is no "Stradivarius" of the dulcimer community to mimic. However, two aspects of dulcimer construction seem common. First, most players and builders agree that the dulcimer has a poor low frequency response; many players say their lowest strings sound "tinny" or that they have bad tone. Second, most within the dulcimer community feel that the sound holes make no acoustical difference and are thereby purely cosmetic. Because of this, many luthiers partially fill the sound holes with decorative rosettes or neglect to include them entirely. The idea that sound holes are purely decorative stems from Sam Rizzeta, who is regarded as the "father" of the modern dulcimer. He stated that sound holes "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] This idea seems to have been repeated without question in other works[3,10].

The idea that holes in the soundboard and/or back of the instrument are acoustically insignificant seems suspect to us at the outset, considering the importance of sound holes in other well-studied instruments such as the guitar or violin[6,7,9]. Consequently, investigation of this claim is one of the key motivators for this research, as it could impact future dulcimer design.

To investigate the radiation of the dulcimer, we use two analysis techniques. First, the characteristic spectrum of the hammered dulcimer is found through a swept-sine analysis to examine the overall spectral response of the instrument and to identify resonances. To characterize the causes of these resonances peaks, near-field acoustical holography (NAH) on the front and back of the dulcimer is employed. The results show that the low-frequency structural modes are relatively inefficient radiators and that the sound holes contribute significantly to the overall radiation.

2. Instrument Response Measurements

As mentioned previously, a swept-sine analysis was used to find the spectral response of the dulcimer. A shaker was used to transversely excite the upper part of the right (bass) bridge between 50 and 3050 Hz using ~2 Hz increments while measurements were made using two type-1 microphones in a large, hard-walled room with low ambient background noise. The microphones were located about 1m in front and behind the dulcimer. The swept-sine analysis was also repeated with the sound holes plugged with lightweight foam, which should eliminate most radiation from these holes. The response of the dulcimer with the sound holes covered and uncovered is seen in Fig. 2a. We clearly see that the radiation increases significantly after 250 Hz, peaking at 280 Hz when the sound holes are uncovered. Without the sound holes, some frequency peaks drop significantly, namely the large peak at 280 Hz. This suggests that the high radiation at these peaks comes as a result of the sound holes.

As a basic check that the shaker excitation of the bridge provided a reasonable guess, recordings of all the individual notes being struck were made and analyzed. The response was measured for 10 seconds after the string was hammered. The block of time from .5 to 2 seconds was then analyzed through a Fourier transform, assuming the signal was fairly stationary through this time because of the long decay of the notes. Examples of these spectra can be seen in Fig. 2b and Fig. 2c.
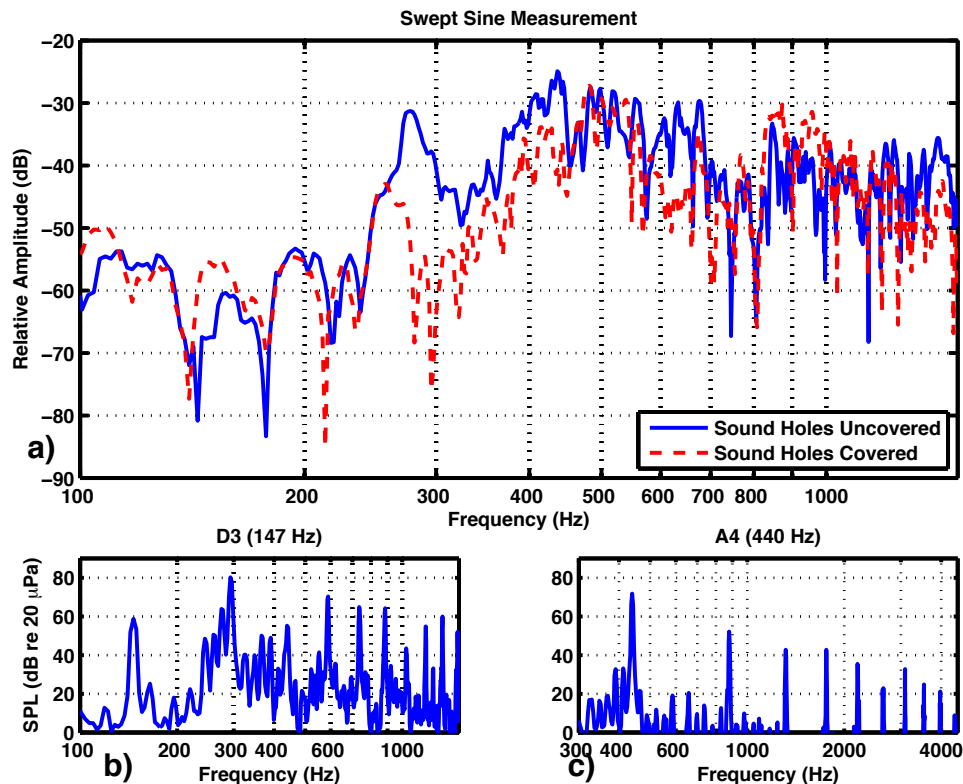
Figure 2: The spectral response of the dulcimer from the swept-sine analysis is shown (a). 12.7 mm microphones are placed in the diffuse field while the shaker drives the right bridge of the dulcimer, increasing the frequency by equal increments. The spectrum is shown both normally and with the sound holes filled with light foam wedges. We also show the spectrum of a struck low note (b) vs. a struck high note (c).

From the spectrum found through the swept-sine analysis (Fig. 2a), the dulcimer's poor low frequency response can easily be seen; it's clear that the dulcimer does not radiate well below 260 Hz. The sound pressure level before this frequency is on average 20 dB lower than the radiation at higher frequencies. The lowest note of the dulcimer is a D3, whose fundamental frequency is 147 Hz and whose second harmonic is 294 Hz. This puts the fundamental frequency of this note in the range with poor response and its second harmonic at the first strong resonance. Fig. 2b, as predicted, shows the fundamental to be 20 dB lower than the second harmonic. The

dulcimer's higher notes, with fundamentals above 260 Hz, respond more normally, with strong fundamentals and successively decreasing partials, as seen in Fig. 2c.

3. 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 show clear resonance peaks, but they cannot tell us whether these peaks radiate from the structure of the dulcimer or from the sound holes. Planar Fourier Near-field acoustical holography (NAH) is a convenient choice of analysis techniques, as a projection of a pressure field to the surface of the instrument effectively separates the sound hole and structural contributions of the radiation. To implement NAH, the dulcimer was placed on a small stand in the anechoic chamber at Brigham Young University, and a shaker was used was used to drive the bass bridge with 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 15 dBre20μPa 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. 3a) was chosen because it shows a clean structural response on the front and back of the dulcimer.
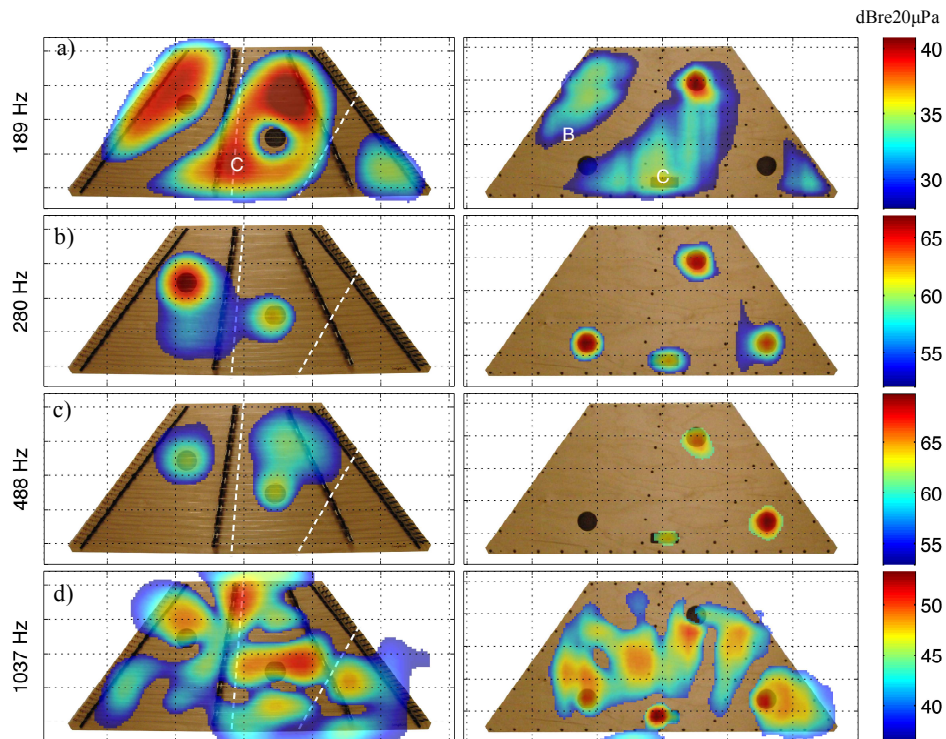
Fig. 3: The front and back of the dulcimer are shown, with the pressure levels (dBre20μPa) plotted on top. The back is mirrored so that relations of cavities can easily be seen. At 189 Hz, a clear structural mode is seen. An almost mirror-image structural mode appears at the slightly higher frequency 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 seen at 488 Hz. At much higher frequencies, structural modes again become dominant (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. 3a. Despite being one of the cleanest structural modes, the dulcimer radiates poorly at 189 Hz compared to the frequencies above 260 Hz. 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. 3b). The fact that the sound holes are the primary radiators at 260 Hz is confirmed in Fig. 2a, 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. 3c. 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. 3d).

Fig. 3 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. 4 depicts the phase response for the same frequencies.
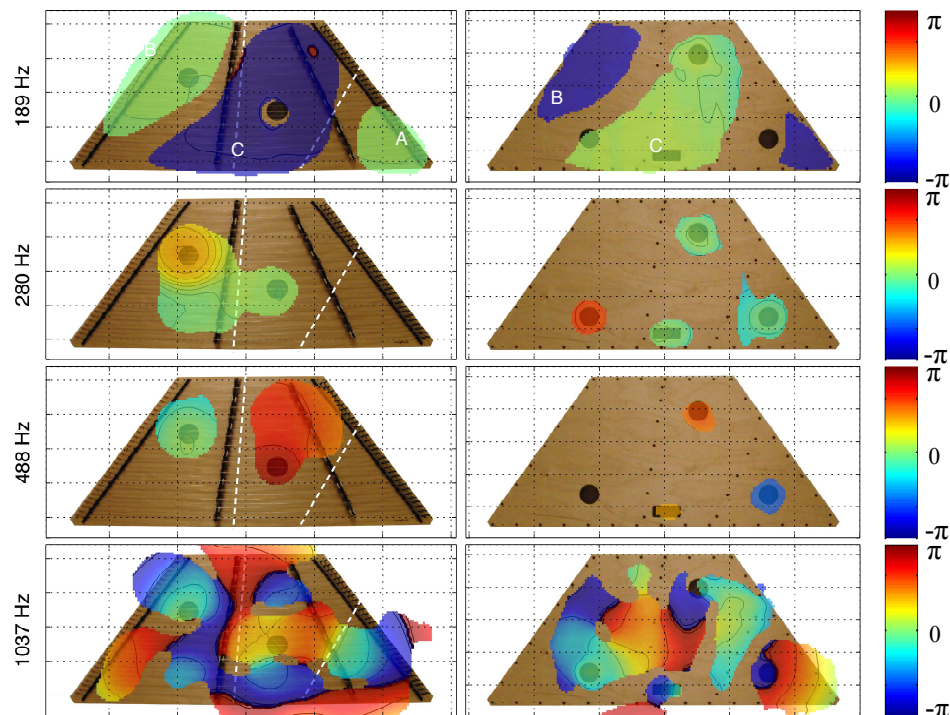

Fig. 4 The same modes as Fig. 3 are shown, but now with the phase relations of the modes.

There are a few useful insights we can gain through Fig. (4). At 189 Hz, a bending mode with a strongly coupled front and back is seen, confirming T. D. Rossing's earlier research into the coupling of dulcimer's sound boards and back plates[5]. 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.

Overall, what we learn from both the swept-sine and NAH analysis is that the structural vibrations and sound holes both contribute to the overall radiation of the dulcimer.

4. Further Analysis

We have shown that the sound holes in the dulcimer do play a significant role in the sound radiation. We now look to investigate the cause of this radiation. One explanation is that the sound holes radiate at least in part

from Helmholtz-like air cavity resonances. Since we have multiple sound holes per cavity, the normal Helmholtz equation has to be extended to

$$f = \frac{c}{2\pi}\sqrt{\frac{(\sum S_i)^2}{V\sum L_i' S_i}} \qquad \text{Eq.1}$$

where c is the speed of sound and V is the volume of the cavity. S_i is the surface area of the different openings, where *i* denotes the number of the sound holes, as labeled in Fig. (1). L_i' represents the effective depths of the openings, which in our case are baffled on both sides, so they can be found through the equation $L' = L + 1.7r$. The results of applying this equation to our dulcimer can be seen in the Table 1.

Table 1: The Helmholtz resonances are calculated using different internal cavities of the dulcimer with their corresponding sound holes. Refer to Fig. 1 to see the how the internal structural supports split the dulcimer into 3 sections, which we label A, B, and C.

Cavities	A	B	C
Resonance Frequency (Hz)	218	315	262

These results correspond fairly well with what we already found in the spectrum and the NAH results. We can look at the response at 270 Hz in Fig. 3, and we see that all the sound holes are very active at this frequency, though the sound holes in cavity A are not in sync, suggesting that the cavities aren't acting entirely as simple Helmholtz resonators.

In conclusion, we have shown that the radiation of this hammered dulcimer comes from a mix of vibrating front and back plates, and sound holes. There is no significant sound hole activity until around 260 Hz, and we also observe that the dulcimer has a weak response at frequencies lower than this. This causes the bass notes to have poor fundamental frequency response, and affect the overall timbre of these strings. Overall, it is clear that the sound holes do play a significant role in the hammered dulcimer.

Future work could involve relocating the size and position of these sound holes to "tune" the dulcimer so that it has a more even response over all its notes[10]. For example, we could increase the volume of the air cavity of the dulcimer, which, according to Eq. 1 would cause the resonance frequencies to drop. If the sound holes were adjusted to where they resonated around 140 Hz, it could greatly help the lowest notes radiate better and thus improve the overall sound of the dulcimer. Future study could also involve studying the effect filling the sound holes with decorative rosettes has on the radiation. Similar research could also be conducted on other construction variations, such as in "floating top" dulcimers. Lastly, using NAH to study the acoustical radiation of instruments is still relatively new, so these techniques could be used to study various other instruments.

Acknowledgments

References and links

[1] P. M. Gifford, *The Hammered Dulcimer, a History,* (The Scarecrow Press Inc., Maryland, 2001).

[2] S. Rizzeta, "Making a Hammered Dulcimer," Encyclopedia Smithonian, History and Culture (1997). http://www.si.edu/Encyclopedia_SI/nmah/hdhist.htm (Last viewed 07/17/2012).

[3] D. Peterson. Hammered Dulcimer. In T. Rossing and N. Fletcher, editors, *The Science of Stringed Instruments* (Springer, New York, 2010), pp. 371-292

[4] N. Fletcher and T. Rossing, *The Physics of Musical Instruments* (Springer-Verlag, New York, 1991).

[5] T. Rossing, "Modes and Vibration in Hammered Dulcimers," Proceedings of the International Symposium on Musical Acoustics (1995).

[6] L. M. Wang and C. B. Burroughs, "Acoustic radiation from bowed violins," J. Acoust. Soc. Am. **110**, 543-555 (2001).

[7] G. Bissinger, E. G. Williams, and N. Valdivia, "Violin *f*-hole contribution to far-field radiation via patch near-field acoustical holography," J. Acoust. Soc. Am. 121, 3899-3906 (2007).

[8] J. Meyer, "Quality aspects of the guitar tone," in *Function, Construction and Quality of the Guitar*," edited by E.V. Jansson (Royal Swedish Academy of Music, Stockholm, 1983), pp. 27-50

[9] E.V. Jansson, "Acoustics for the Guitar Maker", in *Function, Construction and Quality of the Guitar*," edited by E.V. Jansson (Royal Swedish Academy of Music, Stockholm, 1983), pp. 51-75

[10] A. Peekna and T. Rossing. Psalteries and Zithers. In T. Rossing and N. Fletcher, editors, *The Science of Stringed Instruments* (Springer, New York, 2010), pp. 111-114