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Non-contact Modal Excitation of a Classical Guitar using Ultrasound Radiation Force

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Previous studies have demonstrated that it is possible to use the ultrasound radiation force in air for modal excitation of objects ranging in size from microcantilevers that are a few hundred microns in length to hard drive suspensions and other cantilevers a few cm long. The current study demonstrates that the ultrasound radiation force excitation technique can also be used for modal excitation of significantly larger objects, in this case an acoustic guitar. It was demonstrated that the non-contact combination of ultrasound radiation force excitation and a scanning vibrometer allowed measurements of both the frequency response and operating deflection shapes of a Cordoba 45R classical guitar in the range from 70 Hz to 800 Hz. The resonance frequencies and deflection shapes are similar to those measured using a conventional mechanical shaker. By using a pair of ultrasound transducers and adjusting their relative phase difference, it was possible to selectively enhance or suppress different resonances. This is a substantial extension over previous studies because the guitar is several orders of magnitude larger than devices used previously.

I. Introduction:

The goal of modal analysis is to measure frequency response and mode shapes.[1] Originally this required the use of mechanical sensors, such as accelerometers, to measure vibration. In recent years, it has become possible to do non-contact measurement of vibration using optical methods such as laser Doppler vibrometry;[2] by eliminating the contact between the physical transducer and surface, it minimizes the mass loading. For example, several previous studies have measured vibrational modes of guitars using laser vibrometry[3] or holographic methods.[4] For these experiments, and many other applications in modal testing, excitation required physical contact with a transducer such as a mechanical shaker or impact hammer. For some applications it would be desirable to have a localized, non-contact method for exciting vibration. By combining non-contact excitation with laser vibrometry, it would allow fully non-contact modal testing.

Previous studies have demonstrated that the ultrasound radiation force can be used as a non-contact method of exciting structures in air and water.[5,6,7,8] The ultrasound radiation force is caused by the interaction of two frequencies in the ultrasound range that produce audio-range excitation at the difference frequency. In particular, many different structures have been studied in air using ultrasound radiation force excitation, including an organ reed,[9] hard drive suspension,[10] and microcantilevers.[8,11] In addition to being non-contact, there are several other advantages to ultrasound radiation force excitation. Since the ultrasound is incident directly on the surface, it is less likely to excite fixture modes than using mechanical base excitation. Another advantage is that it is possible to excite vibration over a wide range of frequencies – the ultrasound transducers used in the current experiment have been used for objects with frequencies ranging from less than 100 Hz to over 200 kHz. Ultrasound radiation force excitation has another important advantage relative to acoustic excitation using a conventional speaker since the radiation force can be highly localized; the focal spot of the transducers used for this experiment is less than 2mm in diameter. Also, by using the phase shift between two transducers, it is possible to use normal mode tuning to selectively enhance or suppress nearly overlapping modes.[8,12,13]

In the previous studies, the devices that were investigated ranged in size from microcantilevers that are a few hundred microns in length, to organ reeds and hard drive suspensions that are a few cm in length. In the current study, it is demonstrated that this same technique can be used to excite the face of a classical guitar. It is quite remarkable that the same ultrasound transducers have been used for non-contact excitation of a guitar that is over three orders of magnitude larger than a microcantilever, with a three order of magnitude difference in resonance frequency.

II. Theory:

In the current experiment, the goal is to use the acoustical radiation force due to a pair of frequencies in the ultrasound range to excite audio-range resonances of the face of an acoustic guitar. The acoustical radiation force on an object is proportional to the square of the velocity potential.[14,15] If the object is ensonified with a pair of ultrasound frequencies, f_a and f_b, each of amplitude A, the result is a velocity potential

$$\emptyset(t)=A\cos[2\pi f_a t-\varphi/2]+A\cos[2\pi f_b t+\varphi/2]. \qquad (1)$$

In this case, the square of Eq. 1 results in a radiation force[5,6,9] that has a time-independent component, as well as dynamic components at the difference frequency $\Delta f=f_b-f_a$ and high frequency components at $2f_a$, $2f_b$, and f_b+f_a. For f_a and f_b at ultrasound frequencies, in the current experiment in the vicinity of 500 kHz, the high frequency components will be in excess of 1MHz which are orders of magnitude higher in frequency than the acoustic resonance frequencies of a guitar. In contrast, by appropriately selecting the two ultrasound frequencies to be relatively close together, it is possible to have an acoustic radiation force, at the difference frequency, in the range of a few hundred Hz. Therefore, the ultrasound radiation force can be used as a non-contact method of performing audio-range excitation of objects.

It is helpful to write these frequencies in the form $f_a=f_c-f_m/2$ and $f_b=f_c+f_m/2$, in other words, a dual-sideband suppressed carrier (DSB-SC) waveform symmetric about the central frequency f_c. The component of interest for the current experiment is the radiation force component $\boldsymbol{F}(t)$ at the difference frequency (alternately named the modulation frequency) between the sidebands, $f_m=(f_b-f_a)$,

$$\boldsymbol{F}(t)=\boldsymbol{F}_0\cos[2\pi f_m t+\varphi]. \quad (2)$$

The magnitude $\boldsymbol{F}_0$ of this radiation force depends on a number of factors including the magnitude of the intensity of the ultrasound incident on the surface, as well as specific characteristics of the surface.[15] Notice that this driving force is independent of the carrier frequency and depends only on the modulation frequency. Of interest to some readers, in Appendix I, there is a brief discussion of the relationship between ultrasound radiation force excitation and the use of ultrasound to create directional sound fields. Both techniques use a DSB-SC ultrasound waveform with the desired frequencies encoded as the difference frequency between the sidebands.

In the course of the current experiment, the modulation frequency f_m was stepped through a range of frequencies, and the response was measured at each frequency. If the radiation force at frequency f_m corresponded to one of the resonance frequencies of the guitar, it induced a larger amplitude vibration that was detected using the laser Doppler vibrometer. The phase of this radiation force was changed by adjusting the phase constant φ of the ultrasound waveforms.

In the current experiment, the transducers were oriented normal to the face of the guitar; in this orientation, there was the potential for the formation of standing waves. Standing waves were problematic because constructive/destructive interference would cause substantial variations in the amplitude of vibration resulting from the radiation force. In particular, if a constant carrier frequency of about 550 kHz was used, temperature changes of 1.3°C (which can result from currents from the air handling system), or changes in the distance between the transducer and guitar of about 150μm would result in the change from constructive to destructive interference.[16] To eliminate these standing waves, the carrier frequency was varied in packets of 10 cycles. In this technique, a carrier frequency was randomly selected in a 20 kHz wide region, such as 535 kHz to 555 kHz, and held constant for 10 cycles of the carrier; after this 10-cycle packet, a new carrier frequency was randomly selected. Because successive packets did not systematically interfere constructively or destructively, it mitigated the problems encountered when standing waves developed. Further details on the consequences of standing waves for ultrasound radiation force excitation, and the algorithm used to suppress these standing waves are available in Ref. 16.

Normal mode tuning using multiple shakers is a well-established technique for selective excitation of different modes of structures;[17] the current experiment demonstrated that the use of two ultrasound transducers allowed non-contact selective excitation of the modes of a guitar. To perform non-contact normal mode tuning, a pair of ultrasound transducers was focused at two locations symmetric around the centerline on the face of the guitar. These transducers were separately driven by the DSB-SC waveform described by Eq. 1. Both transducers simultaneously generated the same modulation frequency, f_m, even though the central carrier frequency was different for the two transducers. Therefore, both transducers caused a radiation force excitation $\boldsymbol{F}(t)$ at the same frequency. To enable selective excitation using normal mode tuning, the program used to generate waveforms allowed a phase difference φ to be introduced between the pair of transducers. When the two transducers were driven with the modulation signals in phase, the resulting radiation force from both transducers was in phase; this tended to enhance vibrational modes that were symmetric relative to the centerline, while suppressing modes that were antisymmetric. In contrast, when there was a phase difference near 180° between the radiation forces from the transducers, they tended to reinforce modes that were antisymmetric while suppressing symmetric modes. Thus, by merely changing the phase difference of the between the two transducers, it was possible to selectively enhance or suppress different vibrational modes in much the same way as normal mode tuning can be done by varying the amplitude or phase of multiple shakers.[17]

III. Experiment Setup:

As shown in Fig. 1, a Cordoba 45R classical guitar[18] was hung from a support by the bottom of the headstock. A piece of felt was placed behind the strings to dampen string vibrations. A pair of MicroAcoustic Instruments[19] ultrasound transducers were normally incident on either side of the centerline of the guitar. These transducers have a focal length of 70 mm, and a 2 mm diameter focal spot. To facilitate alignment and focusing, each transducer has a pair of diode lasers that converge at the ultrasound focus point. The ultrasound transducer on the left of Fig. 1, labeled Ch1, had a central frequency of 523 kHz, so the random carrier frequency packets were selected between 513 and 533 kHz; the transducer on the right, labeled Ch2, had carrier frequencies chosen between 535 and 555 kHz. Both transducers had bandwidths of over 300 kHz.

To generate the waveforms that were used for ultrasound excitation, a 60 MSample/second 4-channel Strategic Test DAC board (UF2e-6022) was used. A Visual C++ program generated a DSB-SC waveform using Eq. 1 with a fixed modulation frequency f_m, and a randomly varying carrier frequency packets as described in Ref. 16. A reference signal, consisting of only the sinusoidal modulation signal, f_m, was also generated. The waveforms used to drive the 50Ω ultrasound transducers were amplified using 40W ENI240L and 100W ENI210L RF amplifiers to about 70 Volts RMS.

For comparison with conventional excitation, with the ultrasound transducers removed, a Bruel & Kjaer 4810 mechanical shaker was placed in contact with the face of the guitar. A small amount of wax was placed on the end of the stinger where it contacted the guitar. The same point of contact was used for the mechanical shaker as the location of the ultrasound excitation focus points of transducer Ch1 and Ch2. The shaker was driven by a 0.1V amplitude pseudo-random sinusoidal waveform using the built-in function generator in the Polytec vibrometer controller.

To measure the vibration of the guitar, a Polytec PSV-400 scanning vibrometer[2] was directed at the face of the guitar. The Polytec scanning vibrometer software (version 8.712) was used to define a grid of scan points on the face of the guitar. The laser for the scanning vibrometer measurement point was directed at different locations on the guitar, and the Doppler shift of the reflected light was used to determine the amplitude and phase of the velocity of each scan point. The vibrometer was set to the 1mm/s/V scale with a low-pass filter of 100 kHz to filter out the vibration at high frequencies near the carrier frequency of 550 kHz and the high-frequency radiation force components near 1 MHz.

For previous experiments with organ reeds,[9] microcantilevers,[20] or hard drive suspensions,[10] the vibrometer response was large enough that the analog signal from the Polytec vibrometer was sampled directly by an analog to digital converter. However, since the vibration of the guitar face was relatively small, the signal from the vibrometer was on the order of a few mV, and was difficult to resolve from noise. To isolate the component at the modulation frequency, a lock-in amplifier was used. The analog output from the vibrometer was first directed through a Stanford Research SR650 Dual Filter; the high-pass filter was set to 20 Hz to block DC and very low frequencies, and the low-pass filter was set to 5 kHz to eliminate high-frequency components. The output from the filter was directed to the input of a 100 kHz Stanford Research SR830 lock-in amplifier. The reference signal for the lock-in amplifier was the sinusoidal waveform, at frequency f_m, generated by the Strategic Test DAC. The time constant on the lock-in amplifier was set to 300 ms.

IV. Results

a. Mechanical Shaker Excitation for Frequency Response and Deflection Shapes of Guitar

As a reference for the ultrasound excitation studies, the guitar was excited by using a conventional mechanical shaker located at locations Ch1 or Ch2 in Fig 1. The response of a single point on the front of the guitar was measured using the vibrometer. The frequency response between 70 Hz and 800 Hz is shown in Figure 2a.

The operating deflection shapes[22,1] for these resonances were also determined. For resonance frequencies in Figure 2, the operating deflection shape was measured using the

FastScan feature in the Polytec software. This measured the amplitude and phase of the vibrometer output signal when the excitation signal was a 0.2V sine wave directed into the Bruel & Kjaer shaker. The measured resonance frequencies and deflection shapes for this classical guitar were in qualitative agreement with previous studies of vibration of acoustic guitars.[23,4,21] Animation of these deflection shapes can be viewed online.[24]

b. Ultrasound Excitation for measuring Frequency Response of Guitar

The goal of the current study was to demonstrate that these same results could be obtained using non-contact ultrasound radiation force excitation as an alternative to a mechanical shaker. To produce the frequency response curve of Figure 2b, a program, written in Sax Basic was used. The program stepped the modulation frequencies from f_m=70 Hz to 800 Hz. For each frequency, the program caused the Strategic Test DAC board to generate the reference sine wave and the DSB-SC waveform for transducer Ch1 or Ch2 separately. The program waited for a five second settling time, and then took 20 samples of the real and imaginary parts of the output of the lock-in at each modulation frequency. These were accumulated in the complex plane, and were used to calculate the magnitude and phase, along with uncertainties, for the response at each frequency. The plot in Figure 2b shows this average magnitude, with uncertainties, for each frequency.

In comparing Figure 2a, where vibrations were excited using a mechanical shaker, and Figure 2b which used the non-contact ultrasound radiation force excitation, there were a number of similarities and differences. One readily apparent difference was the magnitude of the velocity generated using the two techniques. Since the mechanical shaker was physically connected to the guitar, even with only a 0.1Vpp excitation, it imparted a much larger force than produced using ultrasound radiation force excitation. However, as is clear from the figure, by using a lock-in amplifier to extract these signals, it was possible to obtain a very clear frequency response curve of the guitar. Also, apparent from this figure, the resonance frequencies obtained for both techniques were nearly identical; this is in agreement with other studies that demonstrated that ultrasound radiation force excitation produced similar resonance frequencies as mechanical base excitation.[9,20,11]

Figure 2c showed an important capability of ultrasound excitation, namely that it could be used for selective excitation using normal mode tuning. In this case, the waveforms generated using Eq. 1 for Ch1 and Ch2 had a phase difference of either $\varphi=0^\circ$ (plot symbol ▼) or $\varphi=180^\circ$ (plot symbol ▲) between the modulation signal sent to the two transducers. Of particular interest were the regions near 220 Hz and 660 Hz. In these regions, there were significant changes depending on the phase difference between the transducers.

Figure 3 is a high-resolution scan of the frequency response between 180 and 260 Hz, and Figure 4 between 620 and 730 Hz, excited by the mechanical shaker (Fig. 3a and 4a), transducers separately (Fig. 3b and 4b.). When the mechanical shaker or ultrasound transducers were driven individually, there was significant overlap of the resonances that would make it somewhat difficult to resolve separately. In particular, in Fig. 4a and 4b, there appeared to be at least two peaks in the region from about 650 to 660 Hz, another pair between about 675 and 690 Hz, and another peak near about 704 Hz.

Selective excitation was observed when the two ultrasound transducers were combined with the modulation signals in phase (plot symbol ▼ in Fig. 3c and 4c) or out of phase (plot symbol ▲ in Fig. 3c and 4c). In Fig. 3c, when the modulation phase difference between the transducers was 0° (▼) they reinforced the resonance near 203 Hz, but suppressed the resonance near 232 Hz. In contrast, when the modulation phase difference between the transducers was 180° (▲), the resonance at 232 Hz was enhanced while the resonance near 203 Hz was suppressed. For Fig. 4c, the situation was somewhat more complicated because of the multiplicity of modes. The modes in the region near 655 Hz were enhanced when the phase difference was near 0° while the modes near 685 Hz were suppressed; when the phase difference was 180°, the converse was true showing significant suppression of the modes near 655 Hz and enhancement of the modes near 685 Hz.

These measurements were consistent with deflection shapes near 203 Hz and 655 Hz that were symmetric around the midline of the guitar, whereas the deflection shapes near 232 Hz and 685 Hz were antisymmetric. Therefore, by changing the modulation phase, it was possible to selectively enhance either the symmetric or antisymmetric deflection shapes while suppressing the other. In future studies, it may be possible to use additional ultrasound transducers or further refinements of the position/amplitude/phase of the transducers to further isolate modes, such as separating whether there are separate modes at 648 Hz and 658 Hz.

Figure 5 demonstrated the phase dependence for this selective excitation more clearly.[8] In this case, the modulation frequency was set to either 205 Hz (■) or 232 Hz (●), and the phase difference between the transducers was varied. Since the 205 Hz deflection shape was symmetric, the amplitude was maximal when the phase difference between the transducers was near 0° and 360° when both transducers were driving in phase. In contrast, the antisymmetric mode at 232 Hz was maximized when the phase difference between the transducers was near 180°. While normal mode tuning has been used with multiple shakers, there are few other non-contact excitation methods that have this capability to selectively enhance or suppress vibrational modes, particularly when this can be accomplished by merely adjusting a phase difference.[16]

c. Ultrasound Excitation to obtain Deflection Shapes of Guitar

In addition to obtaining frequency response curves, another important goal of this study was to demonstrate that operating deflection shapes could be obtained for an object as large as the face of the guitar using the fully non-contact combination of ultrasound excitation and a scanning vibrometer. Because of the symmetry properties discussed above, to excite the deflection shapes at 203 Hz and 655 Hz, the two transducers were driven together in phase, whereas to excite the 232 Hz and 685 Hz deflection shapes, the transducers were driven with a 180° phase difference. To obtain an operating deflection shape with the scanning vibrometer, it was necessary to measure both the amplitude and phase of the response at each scan point on the face of the guitar. A program was written in Sax Basic in which the vibrometer measurement beam was moved to each scan point, the amplitude and phase of the vibrometer signal were measured using the lock-in amplifier multiple times and averaged in the complex plane. The results were stored in a file that was compatible with the Polytec scanning vibrometer display software.

Figure 6 shows the operating deflection shapes at 203 and 232 Hz, and Fig. 7 shows the deflection shapes for 655 and 685 Hz measured using this ultrasound excitation technique. As expected, the 203 Hz and 655 Hz deflection shapes were symmetric around the midline of the guitar, while the 232 Hz and 685 Hz deflection shapes were antisymmetric. With the exception of the magnitude, these deflection shapes are similar to deflection shapes measured using a mechanical shaker for excitation. Animation of deflection shapes using both ultrasound excitation and the mechanical shaker can be found online.[24]

V. Conclusions

The results of this study demonstrate that the ultrasound radiation force can be used as a non-contact excitation method for frequency response and deflection shape measurements for an acoustic guitar. By using both the ultrasound excitation and Polytec vibrometer, it is possible to perform completely non-contact modal analysis.

It has now been demonstrated that the ultrasound radiation force can be used for non-contact excitation of objects ranging in size from atomic force microscope microcantilevers and other MEMS devices 300μm in length, to hard drive suspensions and centimeter-scale cantilevers, to an object as large as an acoustic guitar. The exact same ultrasound transducers were used for non-contact excitation of all of these objects, ranging from less than 100 Hz for the guitar, to over 200 kHz for MEMS microcantilevers.

A major focus of future study will be quantification of the radiation force excitation method, including more direct comparisons such as Modal Assurance Criteria between mechanical shaker and ultrasound excitation. More importantly, it is desired to develop protocols for directly measuring/modeling the radiation force applied on an object. Unlike excitation with a mechanical shaker, it is not possible to directly measure the applied force simultaneously with a force transducer. There have been no studies to date that correlated the radiation force on an object in air directly with a corresponding mechanical force from a shaker and the resulting amplitude of vibration.

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Appendix I: Relationship between Radiation Force Excitation and Production of Focused Sound from Ultrasound

Several companies[25,26,27] have developed commercial speaker systems based on the parametric array principle[28] of producing focused sound from an ultrasound source. Since both radiation force excitation and parametric array speakers are based on production of a DSB-SC ultrasound signal, it may be helpful to briefly discuss how these are related. In both cases, the signal of importance is the difference frequency between the sidebands of two ultrasound frequencies. In the situation of radiation force excitation, the original paper by Westervelt,[14] and later theory[15] and experimental[5,9] papers described how the interaction of acoustic waves with a surface can demodulate the waveform and produce the radiation force excitation at the difference frequency. Westervelt's later paper on Parametric Acoustic Arrays[28] described how the non-linearity of the medium itself, air or water, can demodulate the waveform and produce a sound wave that follows the spatial distribution of the original ultrasound waveform. This parametric array effect allows the formation of fairly directional "beam" of sound in air or water. More details about the history of the development of parametric array speaker systems can be found in Ref. 29.

Because the distance between the transducer and surface was relatively small (70 mm), the primary source of excitation is the radiation force excitation (demodulation on the surface of the object), not the parametric array effect (demodulation due to the air between the transducer and surface). Reference 16 details a series of experiments that demonstrated standing wave effects due to constructive/destructive interference of the ultrasound carrier waveform. For example, as the transducer was moved, the distance between maximum and minimum radiation force of 164±7μm was consistent with the distance between maxima and minima for a 550 kHz carrier frequency, but was not consistent with a ~250 Hz sound wave produced from the parametric array effect. This, and other measurements, demonstrated that radiation force excitation was the dominant mechanism for the current experimental setup. Future studies include investigation of the magnitude of the amount of any parametric array sound that is produced between the transducer and surface, and the amount of excitation that this could produce.

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Figures

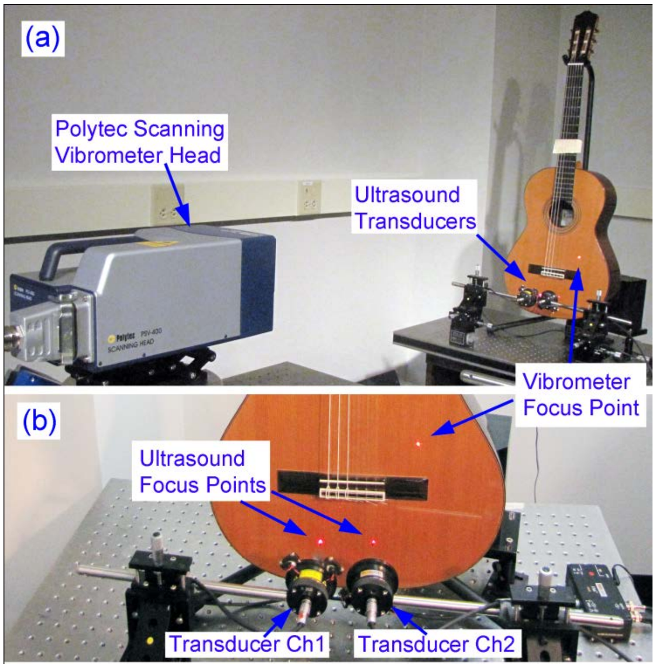

Figure 1: Apparatus used for comparing mechanical and ultrasound excitation of classical guitar. (a) shows the scanning vibrometer head and guitar, (b) is a close up of the lower bout of the guitar showing the location of the ultrasound transducers. A pair of laser diodes on the ultrasound transducers converged at the location of the ultrasound focal spot.

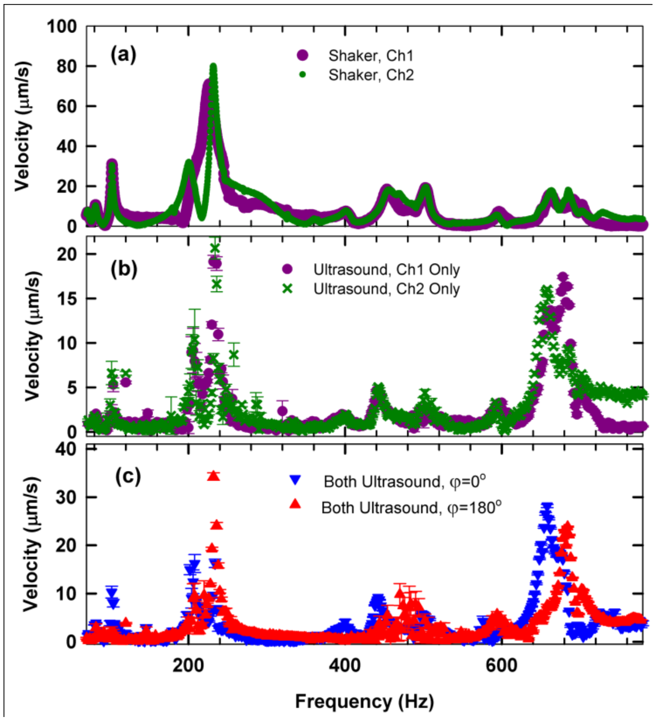

Figure 2: Frequency response curve for Cordoba 45R classical guitar measured at a single location using the laser Doppler vibrometer; the same measurement location was used for both excitation methods. (a) Mechanical excitation using a Bruel & Kjaer shaker at same location as focus point for Ch1 and Ch2, (b) Noncontact excitation of face using ultrasound radiation force excitation from the two transducers separately, (c) Selective excitation when the transducers were driven with the modulation frequency in phase (▼), or 180° out of phase (▲).

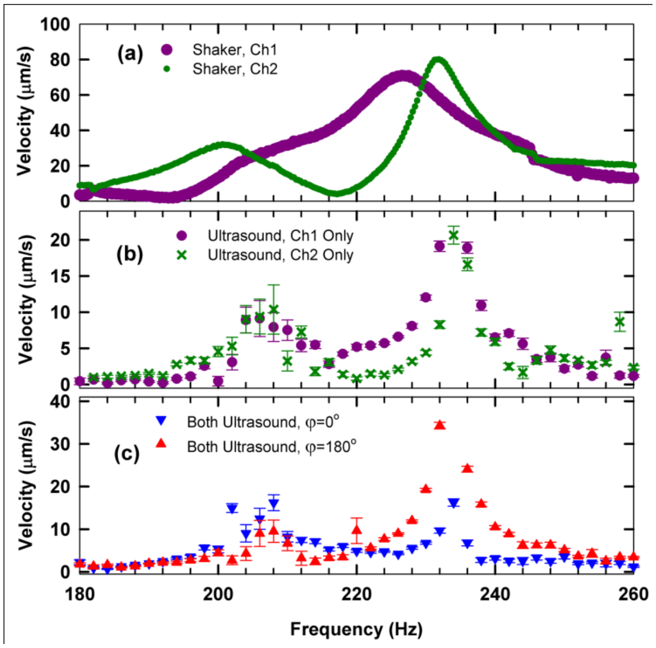

Figure 3: Detail of the region between 180 Hz and 260 Hz showing nearly overlapping resonances. (a) Mechanical excitation using a Bruel & Kjaer shaker, (b) Noncontact excitation of face using ultrasound radiation force excitation from the two transducers separately. (c) Isolation of these resonances was possible using a phase-shifted pair of transducers. When the transducers were driven with the modulation frequency in phase (▼), there was enhancement of the symmetric lower resonance near 203 Hz relative to the antisymmetric resonance at 232 Hz. Conversely, when the transducers were 180° out of phase (▲), the antisymmetric 232 Hz resonance was enhanced relative to the 203 Hz resonance.

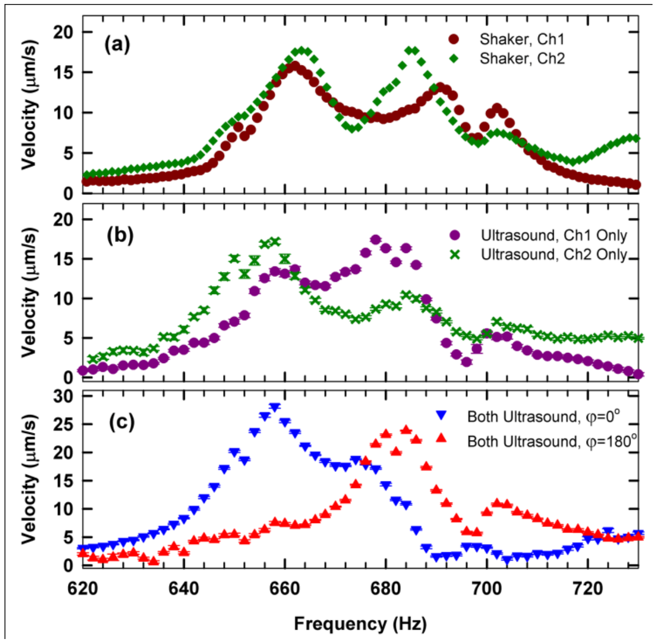

Figure 4: Detail of the region between 620 Hz and 730 Hz. (a) Mechanical excitation using Bruel & Kjaer shaker showing strong overlap of multiple resonances, (b) Noncontact excitation of the guitar face using ultrasound radiation force excitation from the two transducers separately. (c) Demonstration on non-contact normal mode tuning: The region near 655 Hz was enhanced when the transducers were driven in phase (▼), whereas the region near 685 Hz was enhanced when the transducers were 180° out of phase (▲).

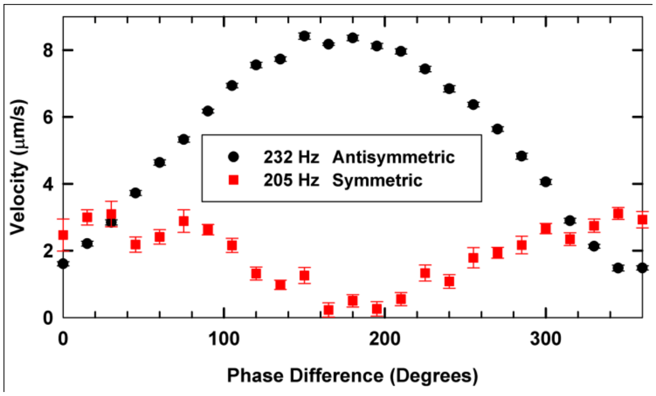

Figure 5: Response of the guitar at 205 Hz and 232 Hz as a function of the phase difference between the ultrasound transducers. The antisymmetric 232 Hz resonance reaches a maximum when the phase between the transducers differs by nearly 180°. At 205 Hz, the maximum amplitude occurs when the transducers are nearly in phase near 0° or 360°. From Ref. 8.

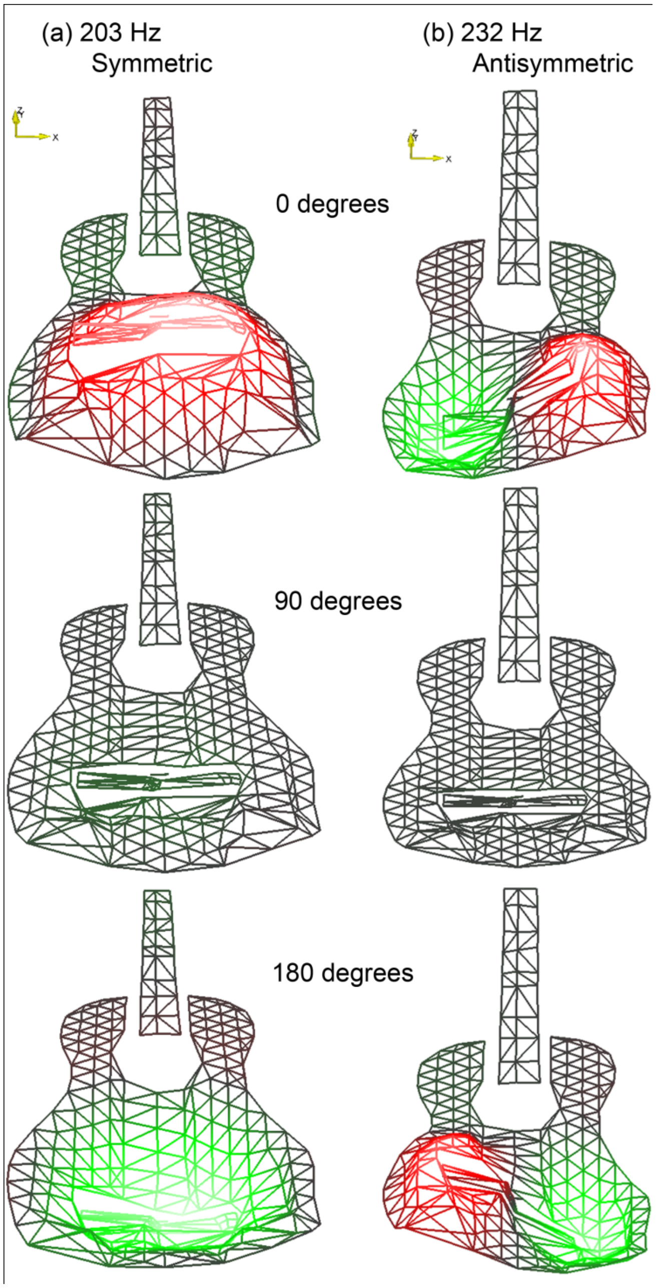

Figure 6: Demonstration of noncontact modal excitation using ultrasound radiation force. Operating deflection shapes of the (a) 203 Hz and (b) 232 Hz resonances measured using a scanning vibrometer, with excitation due to a pair of focused ultrasound transducers. The three images for each resonance are the deflection shape at different phases of a cycle. The symmetric nature, relative to the midline of the guitar, of the 203 Hz resonance and antisymmetric nature of the 232 Hz resonance are evident from these deflection shapes.

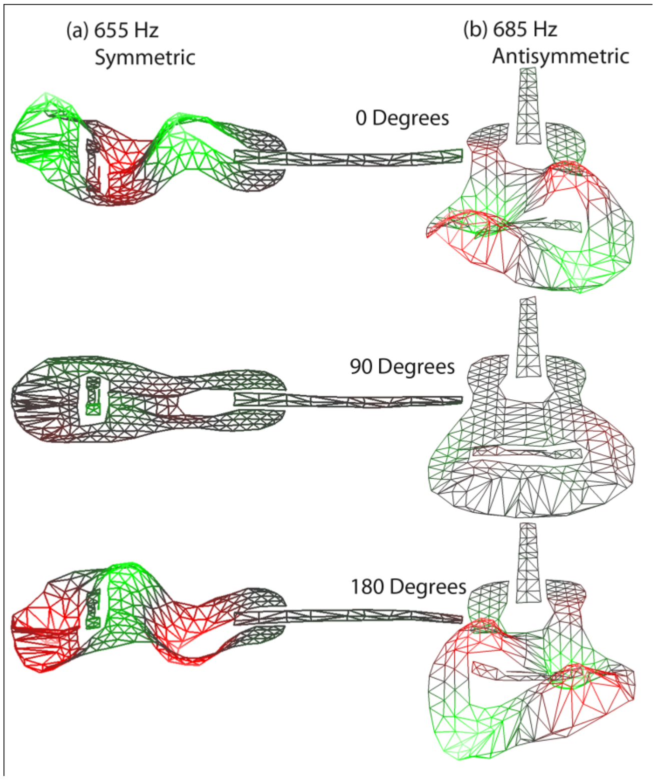

Figure 7: Operating deflection shapes of nearly overlapping resonances measured using noncontact ultrasound radiation force excitation and a scanning vibrometer. As is evidenced from these (a) the 655 Hz deflection shape is symmetric relative to the midline of the guitar, and (b) the 685 Hz deflection shape is antisymmetric relative to the midline.