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Selective excitation using phase shifted ultrasound radiation force from focused transducers in air

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***Abstract*—In recent years, it has been demonstrated that the ultrasound radiation force can be used as a noncontact technique for modal excitation. A novel capability of this method is the ability to perform selective excitation. A phase shift is imparted between the modulation signals emitted from a pair of ultrasound transducers focused at different positions on an object. When there is no phase difference between the radiation force produced by the transducer pair, they push in unison on the object, which induces symmetric or transverse eigenstates. When there is a 180° phase shift between the radiation force from the transducers, they will excite antisymmetric or torsional eigenstates. We describe the first demonstrations of this selective excitation using high-frequency focused ultrasound transducers.**

***Index Terms*—Modal Analysis, Microcantilever, NDE, Radiation Force**

I. INTRODUCTION

ONE of the important tasks in structural dynamics is modal analysis, which is the study of vibrational modes of structures. To perform modal analysis requires an excitation source as well as a method for detecting vibration. In the past, both of these tasks were performed using mechanical transducers, such as a mechanical shaker for modal excitation and an accelerometer to detect vibration. In recent years, the introduction of laser Doppler vibrometers [1] has allowed non-contact measurements of vibration. However, in most cases, it was not possible to perform fully non-contact modal testing because there were few methods to perform non-contact excitation.

A promising technique for non-contact modal excitation is the use of the ultrasound radiation force.[2] In this technique, a pair of ultrasound frequencies are incident on the object under study. The excitation is caused by the non-linear interaction at the surface that causes a radiation force at the difference frequency between the two ultrasound frequencies. This ultrasound radiation force excitation method has a number of unique advantages relative to conventional excitation sources. One of the primary advantages is the non-contact nature of the excitation; this removes limitations such as the requirement for physically attaching a shaker and the resulting mass load. Another advantage is the wide bandwidth available for excitation – the transducers used for the current experiment have been used for excitation of structures at frequencies below 100 Hz to in excess of 200 kHz. As will be detailed in this paper, the ultrasound radiation force technique also allows selective excitation by using the phase shift in the modulation frequency between two transducers. This offers capabilities that are generally not possible using conventional mechanical excitation or non-contact excitation techniques.

Previous studies of selective excitation using ultrasound radiation force have used a 40 kHz diverging pair of ultrasound transducers.[3] The difficulty with these transducers is that the long wavelength and diverging output meant that it was difficult to spatially isolate the output of the two ultrasound transducers. Since the radiation force was overlapping on the object of study, it makes it more difficult to perform selective excitation. The current experiment used a pair of focused transducers in air with a central frequency of about 500 kHz and a 2.5 mm diameter focus. This transducer pair, along with a scanning laser Doppler vibrometer, allowed non-contact excitation and measurements of structures ranging in size from a pair of coupled microcantilevers to as large as a guitar.

II. THEORY

A. Ultrasound Radiation Force Excitation

Previous papers have described in detail the mechanism for ultrasound stimulated excitation.[4,5] If an object is ensonified with a pair of ultrasound frequencies, f_a and f_b, the radiation force that results in a vibration of the object at the difference frequency $\Delta f=f_b-f_a$. In the measurements described below, both frequency components were emitted from a single transducer. Each ultrasound transducer was driven with a dual sideband, suppressed carrier (DSB-SC) waveform consisting of the sum of a pair of sine waves with frequencies of $f_a=f_c-f_m/2$ and $f_b=f_c+f_m/2$ that were symmetric about the central frequency f_c. The velocity potential emitted by the transducer can be written as

$$\emptyset(t)=A\cos[2\pi(f_c-f_m/2)t-\varphi/2]+A\cos[2\pi(f_c+f_m/2)t+\varphi/2] \qquad (1)$$

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where φ is a phase constant. Since the acoustical radiation force goes as the square of this velocity potential, the result is a sinusoidal radiation force that contains both the sum and difference of the two frequencies. 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) $f_m=(f_b-f_a)$,

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

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. Notice that this driving force is independent of the carrier frequency and depends only on the modulation frequency. The phase of this radiation force can be changed by adjusting the phase constant φ.

In the course of the 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 corresponds to one of the resonance frequencies of the object of study, it will induce a larger amplitude vibration that will be detected using the laser Doppler vibrometer.

B. *Selective Excitation Using Phase Shifted Transducer Pair*

To perform selective excitation, a pair of ultrasound transducers was focused at two different locations on the structure under test. These transducers were separately driven by DSB-SC waveform produced by a high-speed DAC card using calculations of Eq. 1. Both transducers would simultaneously generate the same modulation frequency, f_m, even if 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. The software allowed a phase difference φ to be introduced between the pair of transducers, which allowed non-contact selective excitation. When the two transducers were driven in phase, the resulting radiation force from both transducers was in phase; this tends to enhance the excitation of vibrational modes that are symmetric relative to the two focus points while suppressing modes that are antisymmetric. In contrast, when there was a phase difference near 180° between 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.

III. EXPERIMENTAL SETUP

In the current experiment, a pair of Microacoustics[6] ultrasound transducers were used in air. These transducers have a focal length of 70 mm, and a 2.5 mm focal spot.

To generate the waveforms that were used for excitation, a 60 MSample/second Strategic Test DAC card[7] was used. A Visual C++ program generated a DSB-SC waveform with a carrier frequency near 500 kHz using Eq 1. The resulting waveforms were amplified using ENI-240L and ENI-2100 amplifiers to obtain signals with amplitudes of about 70Vrms into the 50Ω impedance transducers.

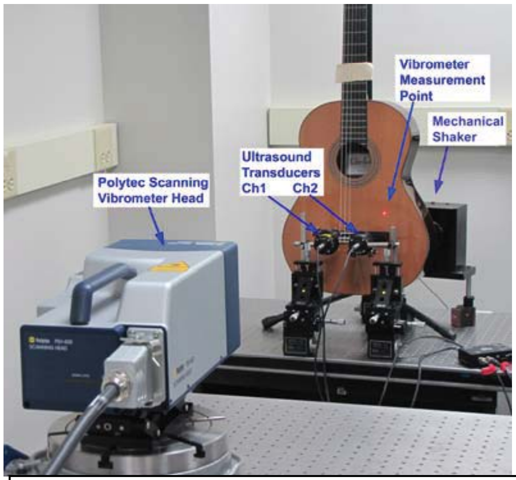

Figure 1: Apparatus used for ultrasound excitation of classical guitar showing Polytec PSV-400 vibrometer, and two ultrasound transducers Ch1 and Ch2 focused at opposite sides of the bridge of the guitar.

Several different structures have been studied using a pair of phase-shifted ultrasound excitation, including a simple brass cantilever,[3] and hard drive suspension.[8] The current study focuses on devices that are significantly larger and smaller than previous studies. In particular, the two devices studied were a Cordoba 45R classical guitar[9] that has resonance frequencies in the neighborhood of a few hundred Hz, and a microcantilever array[10] that has a pair of eigenstates in the neighborhood of 25 kHz.

A. *Ultrasound excitation of guitar*

As shown in Fig. 1, a classical guitar was hung from the top of the neck. A piece of felt was used to damp string vibrations. The pair of ultrasound transducers was focused on either side of the bridge. For comparison with conventional excitation, a Bruel-Kjaer 4810 mechanical shaker was placed in contact with the back of the guitar.

To measure the vibration of the face of the guitar, a Polytec PSV-400 scanning vibrometer[11] was used. Because of the small amplitude of deflection, to extract the vibration signal from the noise, a Stanford Research System SR830 Lock-In amplifier was used to measure the vibrometer output voltage at the difference frequency relative to a sinusoidal reference frequency. Further details can be found in Ref. 12.

B. *Ultrasound excitation of microcantilever array*

The experimental apparatus used to study the microcantilever array is shown in Figure 2.[13] The array, shown in Figure 2b, was a coupled pair of 500µm x 100µm x 10µm Nickel cantilevers separated by 250µm. This structure was used in earlier studies to detect added masses via disorder induced mode localization.[10] The cantilever array was mounted on a Silicon substrate that was 3mm wide by 5mm in length. This substrate was attached to an aluminum plate using double-sided adhesive tape. The pair of ultrasound transducers was mounted at an angle, and their focal point was focused

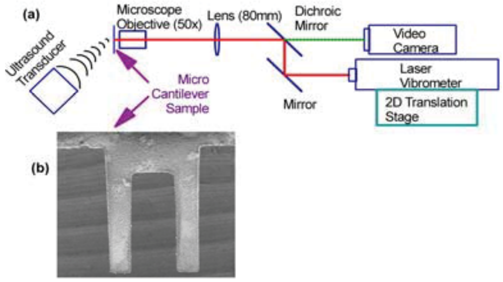

Figure 2: Apparatus used for ultrasound excitation of microcantilever array. The single point vibrometer was focused onto the 500µm length microcantilever array of Figure 2b. The ultrasound transducers were mounted at an angle about 45° relative to the cantilever.

near the left and right edges of the substrate.

For the microcantilever sample, cantilever vibration was determined using a Polytec OFV-3001 laser Doppler vibrometer with OFV-502 measurement head mounted on a two-dimensional translation stage. Using the optical components in Fig. 2a, the vibrometer measurement point was focused to a diameter of roughly 10 µm. The analog output of the laser Doppler vibrometer was sampled at 1 MHz with the NI-USB-6251 ADC.[14] An FFT was performed on the data set; for each modulation frequency f_m, the amplitude and phase was extracted from the FFT data set. Operational deflection shapes were determined by animating the amplitude and phase measured at many points on the surface.

IV. RESULTS

A. Ultrasound excitation of guitar

Fig. 3 shows the results for measurements of the acoustic guitar; the region shown has the two lowest resonance frequencies of the face of this guitar. Fig. 3a shows the response obtained by the vibrometer using a mechanical shaker. Two resonances are clearly seen at about 203 Hz and 232 Hz. As shown in Fig. 3d, these resonances have deflection shapes that are symmetric and antisymmetric about the midline of the guitar. Fig. 3b shows the corresponding response curves when the ultrasound transducers Ch1 and Ch2 were used to excite the guitar separately. It is clear that the resonance frequencies determined using the ultrasound radiation force are nearly identical to the frequencies obtained using a conventional mechanical shaker.

Fig. 3c illustrates the novel capabilities of using a pair of ultrasound transducers for selective excitation. When the transducers were driven with no phase difference (▼), the symmetric resonance near 203 Hz was enhanced, while the antisymmetric resonance near 232 Hz was suppressed. In contrast, when the transducers were driven with a 180° difference in modulation phase (▲) the 232 Hz antisymmetric resonance was enhanced while suppressing 203 Hz resonance.

The result of varying the phase difference can also be seen in Fig. 4. This shows the result when the modulation frequency was kept at either 205 Hz (■) or 232 Hz (●) while varying the phase. As expected for a symmetric mode, the 205 Hz response is maximized when the two transducers were driven in phase, near 0° or 360°, and is minimized near 180°.

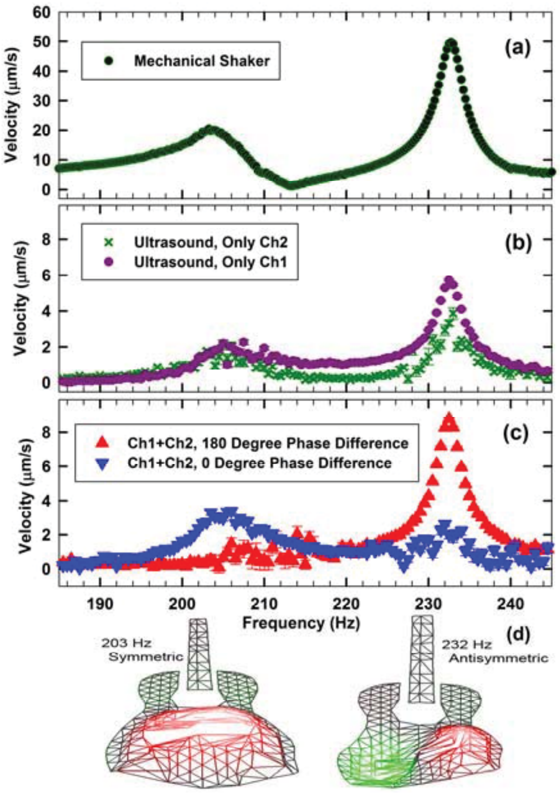

Figure 3: Resonance frequencies of a Cordoba 45R classical guitar. (a) Resonances determined using mechanical shaker, (b) Resonances using ultrasound transducers Ch1 and Ch2 separately. (c) demonstrates selective excitation: enhancement of 203 Hz mode when transducers driven in phase, and enhancement of 232 antisymmetric mode when driven near180° phase difference. (d) deflection shapes for 203 Hz symmetric and 232 Hz antisymmetric modes.

The opposite response was obtained for the antisymmetric 232 Hz mode, where the maximum response is observed near 180° with minimum near 0°. These results show the effectiveness of using the phase difference between the transducers to effectively enhance or suppress one of the resonances.

Fig. 3d shows images of the maximum displacement measured for these deflection shapes. These deflection shapes were determined by driving the two transducers either in phase (for 203 Hz) or at 180° (for 232 Hz) and measuring the

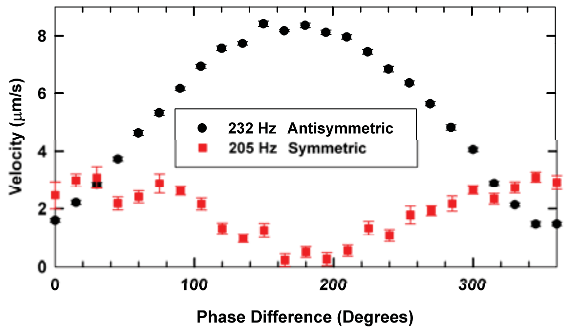

Figure 4: Response of 205 Hz and 232 Hz modes as a function of the phase difference between the ultrasound transducers.

amplitude and phase response at many scan points on the surface. Animation of these deflection shapes can be viewed online.[15]

B. *Ultrasound excitation of microcantilever array*

At the other extreme in terms of size, Figure 5 shows results obtained using the same pair of transducers to excite a microcantilever array that was only 500μm long. This array has two eigenstates near 25kHz. The lower eigenstates at about 24.35 kHz is a symmetric state where the two cantilevers move in phase. The upper eigenstate at 25.49 kHz is antisymmetric, where the two cantilevers move out of phase with each other. The frequency response curve of Fig. 5a, measured using one ultrasound transducer, is nearly identical to that obtained using a more conventional piezo shaker excitation. [10]

Fig. 5b shows results that are qualitatively similar to Figure 3c. The symmetric state at 24.35 kHz (●) shows a maximum at phase angles near 0° and a minimum near 180°. The maximum and minimum for the antisymmetric state at 25.49 kHz (▼) are shifted from their expected positions near 180° and 0° respectively. It is believed that this is caused by a partial overlap of the two ultrasound focus spots; if they completely overlapped, when the phase difference was 180°, the radiation force from both transducers would completely cancel leading to a minimum, even for an antisymmetric deflection shape. This effect was observed experimentally - when the ultrasound focus spots completely overlapped, the curve for both the 24.35 kHz and 25.49 kHz peaks followed nearly identical curves which peaked near 0° with a minimum near 180°.

V. CONCLUSIONS

The results of this study indicate that the ultrasound radiation force can be used for selective excitation of objects as large as a guitar or as small as a microcantilever array; in these samples, the resonance frequencies varied by several orders of magnitude. This complements previous studies that showed this method worked for objects with sizes on the order of a few cm in length.

The results obtained, particularly for the microcantilever array have prompted further experimentation to better understand the relative effect of the two competing effects for partially overlapping ultrasound focus points, as well as what effect the fixturing of the substrate to the support plays.

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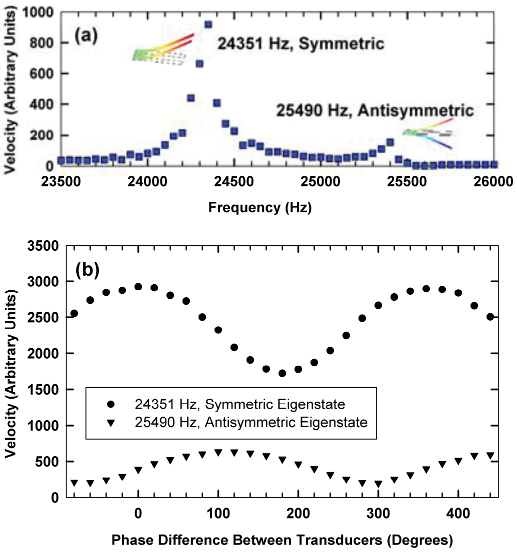

Figure 5: (a) Frequency response of microcantilever array excited using ultrasound radiation force showing symmetric peak (where cantilevers move in phase) near 24.35 kHz and antisymmetric peak (where cantilevers move out of phase) near 25.49 kHz. (b) dependence of microcantilever response with variation in phase difference between transducers showing selective excitation.

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