Noncontact modal analysis of a pipe organ reed using airborne ultrasound stimulated vibrometry

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The goal of this study was to excite and measure, in a noncontact manner, the vibrational modes of the reed from a reed organ pipe. To perform ultrasound stimulated excitation, the audio-range difference frequency between a pair of ultrasound beams produced a radiation force that induced vibrations. The resulting vibrational deflection shapes were measured with a scanning laser vibrometer. The resonances of any relatively small object can be studied in air using this technique. For a 36 mm × 6 mm brass reed, displacements and velocities in excess of 5 μm and 4 mm/s could be imparted at the fundamental frequency of 145 Hz. Using the same ultrasound transducer, excitation across the entire range of audio frequencies was obtained. Since the beam was focused on the reed, ultrasound stimulated excitation eliminated background effects observed during mechanical shaker excitation, such as vibrations of clamps and supports. The results obtained using single, dual and confocal ultrasound transducers in AM and two-beam modes, along with results obtained using a mechanical shaker and audio excitation using a speaker are discussed. © *2006 Acoustical Society of America.* [DOI: 10.1121/1.2171516]

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I. INTRODUCTION

In a variety of academic and industrial applications, modal analysis is an important technique for studying systems. The goal is to excite mechanical vibrations of the system with a driver, and measure the response using some measuring transducer. In the past, the primary instrument used for measuring vibration was the accelerometer. One drawback related to their usage is the fact that they place a mass burden on the object; if the object is small, the mass of the accelerometer can distort the vibrational modes. In recent years, the laser Doppler vibrometer[1] has become the instrument of choice in many applications requiring measuring vibration, since there is no contact between the vibrometer and the device under study. The reed in reed organ pipes is one of numerous systems that has been studied using laser vibrometry.[2]

While the laser vibrometer has allowed noncontact measurements of vibration, there are fewer noncontact methods that can be used for excitation. The primary excitation transducers used in modal analysis are the mechanical shaker and the impact hammer. Especially when a mechanical shaker is used for a relatively small object such as a reed, one area of concern is the distortion of resonances due to mass loading by the shaker. After an impact hammer leaves the surface of an object, there is no mass loading. With appropriate care in setting up a miniature hammer as an excitation source, it would be possible to measure the frequency response and deflection shape of an object such as the organ reed. Other techniques, such as electromagnetic driving or using an acoustical speaker, are sometimes used for noncontact excitation. However, these are limited in terms of the frequency response, or the composition of the object of interest.

Described below is a technique using the radiation force resulting from the interference of ultrasound beams[3] to induce audio-range vibrations of an organ reed. These vibrations were then detected using a laser vibrometer. Both the excitation method, using ultrasound radiation force, as well as the detection method are noncontact. There have been several studies which used ultrasound radiation force for modal analysis in water,[4] however the current study is the first which demonstrates the feasibility of using this technique in air.

A. Previous studies of vibrational modes of pipe organ reeds

The current study is a practical application of the ultrasound radiation force in air to validate results obtained in a recent study of the resonances and deflection shapes of an organ reed.[5] In an organ reed pipe, the air flows past a thin brass reed, through the shallot (a tube with a slot to which the reed is clamped), and into a resonator. For the study of Ref. 5, the reed was excited both by a conventional air blower, as well as with a mechanical shaker, and the resonance frequencies and deflection shapes were measured using a scanning laser vibrometer.

When an organ reed pipe is excited with an air blower, similar to the method that would be used in a conventional pipe organ, the acoustic spectra measured using a microphone as well as the velocity spectra of the reed measured using a vibrometer shows a series of integer-multiple harmonics of the fundamental.[2,5,6] Measurements with a scanning vibrometer revealed that the deflection shapes measured at these integer-multiple harmonics of the fundamental

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showed complicated deflection shapes that included torsional and higher-order transverse deflection shapes.[5]

To understand the deflection shapes observed for the air-driven reed, the simplest model that one might consider for an organ reed is a cantilever fixed at one end and free at the other end. For this type of cantilever, theory predicts a set of nonharmonic modes that include both transverse and torsional mode shapes. To verify this, the resonance frequencies and deflection shapes of the reed excited with a mechanical shaker were measured.[5]

One concern about using a shaker to measure the vibrational modes of the reed was that the driving is indirect. The mechanical shaker, attached to the back of the shallot, caused a small vibration ($<1\ \mu$m) of the entire pipe; when the driver was at a resonant frequency of the reed, it led to an increased signal from the laser vibrometer. However, since the driving was indirect, vibrations of any portion of the pipe, as well as supports or clamps were also detected by the vibrometer. As is the case with many relatively small objects, it was not possible to attach a shaker directly to the reed. Since the mass of the shaker is significantly larger than the reed, it would distort the reed's vibrational modes. The ultrasound excitation method described in the current paper is a direct method to drive the reed in a noncontact manner; the results obtained are compared with those obtained with a more conventional mechanical shaker and excitation using a speaker.

B. Outline of the paper

The following section discusses the physical mechanism that leads to audio-range excitation of structures using ultrasound stimulation. In Sec. III, the apparatus and techniques used in this study are described. These are followed by results of the experiment in Sec. IV, and discussion of these results in Sec. V.

II. THEORY: RADIATION FORCE DUE TO ULTRASOUND STIMULATION

Previous papers have described in detail the mechanism for ultrasound stimulated audio-range excitation, particularly in water.[3] The object of study, in the current experiment an organ reed, was excited by two different frequencies f_1 and $f_2=f_1+\Delta f$ where f_1 and f_2 are ultrasound frequencies, and Δf is the audio-range frequency of interest. When the two frequencies impinge on the reed, interference between the two frequencies produces a radiation force[3] that results in a vibration of the reed at the audio-range frequency Δf.

The radiation force[7] is caused by changes in the energy density of an acoustic field. The total ultrasound pressure field at a point from a pair of CW ultrasound sources of frequency f_1 and f_2, with pressure amplitudes $P_1(\bar{r})$ and $P_2(\bar{r})$ and phases $\varphi_1(\bar{r})$ and $\varphi_2(\bar{r})$ may be written as

$$p(\bar{r},t) = P_1(\bar{r})\cos[2\pi f_1 t + \varphi_1(\bar{r})] + P_2(\bar{r})\cos[2\pi f_2 t + \varphi_2(\bar{r})]. \tag{1}$$

This causes an instantaneous energy density given by $e(\bar{r},t)=p(\bar{r},t)^2/\rho c^2$; this energy density will have a time-independent component, a component at the difference frequency Δf, and high-frequency components at multiples of f_1 and f_2. The radiation force of interest for the current technique is the energy density component at the difference frequency, which can be written as

$$e_{\Delta f}(\bar{r},t) = \frac{P_1(\bar{r})P_2(\bar{r})}{\rho c^2}\cos[(2\pi\Delta f)t + \Delta\varphi(\bar{r})]. \tag{2}$$

Assuming that $P_1(\bar{r})$ and $P_2(\bar{r})$ are plane waves, this will impart a force in the beam direction on an object of area dS with drag coefficient $d_r(\bar{r})$ given by[3]

$$F_{\Delta f}(\bar{r},t) = e_{\Delta f}(\bar{r},t)d_r(\bar{r})dS = \frac{P_1(\bar{r})P_2(\bar{r})}{\rho c^2}\cos[(2\pi\Delta f)t + \Delta\varphi(\bar{r})]d_r(\bar{r})dS. \tag{3}$$

The total radiation force as a function of time is the integral of Eq. (3) over the entire surface of the object; this radiation force can cause a vibration of the object at a frequency Δf. Object vibration due to this radiation force is a function of the size, shape and mechanical impedance of the object. If the radiation force at frequency Δf corresponds to one of the resonant frequencies of the object, it will induce a larger amplitude vibration. The difference frequency Δf is swept through a range of frequencies, and the response is measured at each frequency.

III. EXPERIMENTAL SETUP

A. Scanning laser doppler vibrometer

To measure the vibration of the organ reeds, a Polytec PSV-300 scanning laser vibrometer was used.[8] A vibrometer uses the Doppler shift of reflected laser light to determine the speed of the vibrating reed. The tremendous advantage in using a laser vibrometer is that, unlike a conventional accelerometer, no physical contact is needed to measure the vibration of the object. This makes a laser vibrometer ideal for measuring the motion of a small object such as an organ reed.

With a scanning laser vibrometer, the laser can be deflected across the surface to measure the amplitude and phase at many points on the surface of the reed. Instead of measuring the motion of a single point, a scanning vibrometer and its software can reconstruct the vibrational deflection shapes of the surface. To determine these deflection shapes, the software calculates the phase shift between the electrical signal creating the driving force and the vibrational response at many positions on the reed. A primarily transverse mode will have a constant phase across the entire width of the reed, whereas a torsional mode will have a 180-degree phase shift across width of the reed.

B. Reed organ pipes

The apparatus used in this experiment is shown schematically in Fig. 1. The reed pipe that was the primary focus of the current study, as well as a previous study,[5] was a $\mathrm{G}_5^{\#}$ trumpet pipe with a conical resonator 14 cm in length with a diameter that went from 1.1 cm to 4.6 cm. In order to enable imaging of a larger fraction of the reed, the 1.45 mm diameter tuning wire was bent in such a fashion that it did not

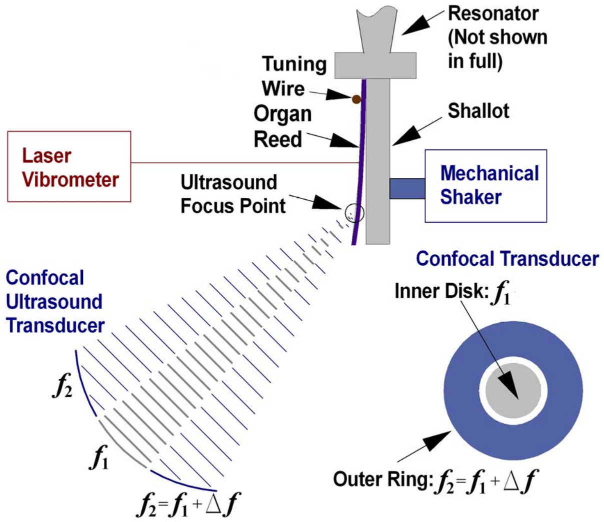

FIG. 1. (Color online) Apparatus used to compare ultrasound stimulated excitation with other excitation methods. The inner disk and outer annulus of the confocal ultrasound transducer, shown in this illustration, could be driven at two different frequencies. The vibrational deflection shapes of the reed were measured using a scanning laser vibrometer. For comparison, the system could be excited using a mechanical shaker placed in contact with the back of the shallot.

obscure the bottom section of the reed. The tuning wire was adjusted by blowing the pipe at its nominal blowing pressure of 3 in. of water and tuning it to a $G_5^{\#}$ with a Korg chromatic tuner. The reed in this pipe is 0.091 ± 0.02 mm thickness brass with a width of 4.57 ± 0.02 mm, and a length of 12.2 ± 0.1 mm from the wedge to the semicircular free end of the reed. After tuning the pipe, the center of the tuning wire was 9.2 ± 0.2 mm from the free end of the reed. Two other pipes were also used, including one with a significantly larger reed that was 6 mm × 36 mm.

For the $G_5^{\#}$ trumpet pipe used in both the current study and Ref. 5, the three lowest modes that are expected for a clamped-free cantilever are a simple transverse cantilever mode, a torsional mode, and a second-transverse cantilever mode that has a nodal line roughly 1/3 of the way from the free end of the reed.[9] To estimate the modal frequencies for this reed, the tables of Ref. 9 were used for a rectangular cantilever with an effective length of 8.7 ± 0.3 mm, which accounts for the semicircular end of the reed; this results in predictions of 670 ± 50 Hz for the fundamental mode, 2.8 ± 0.2 kHz for the torsional mode, and 4.2 ± 0.3 kHz for the second-transverse cantilever mode. The modal frequencies for the reed, including its semicircular end, were also calculated using the finite element modeling package[10] in ME'Scope; the first three modal frequencies predicted using this program were 730 ± 20 Hz, 3.2 ± 0.2 kHz, and 4.5 ± 0.2 kHz, respectively. These predictions are in good agreement with the measured frequencies of 726 ± 2 Hz, 2.95 ± 0.01 kHz, and 4.54 ± 0.02 kHz for the fundamental, first torsional, and second transverse modes when the pipe was driven with a mechanical shaker in the absence of air in a vacuum chamber.[5] The goal of the current study was to compare these results to the measurements obtained using noncontact ultrasound excitation.

C. Excitation using confocal transducer

There were two different types of ultrasound transducers used in the current study. As shown in Fig. 1, the primary transducer used was a custom-made confocal ultrasound transducer for operation in air (MicroAcoustics Instruments, Broadband Air-Coupled Transducer sBAT-5). This transducer produces a focused ultrasound spot with a roughly Gaussian beam profile 1 mm in diameter with a focal length of 7 cm. This transducer has an inner disk that can be driven at one frequency, and an outer annulus that can be driven at another frequency; both elements have broadband performance, with a central maximum located near 600 kHz and a bandwidth of over 200 kHz. As shown in Fig. 1, in order to avoid blocking the beam from the scanning vibrometer, this transducer was mounted below the reed and pointed upwards at a roughly 45° angle. When used in dual-beam mode, the inner disk was driven at one frequency f_1, and the outer annulus was driven at a different frequency $f_2 = f_1 + \Delta f$; this requires a separate function generator and amplifier for both of the two transducer elements.

Another method of producing the difference frequency Δf was to emit a single waveform that was a superposition of the two frequencies, i.e., using a double-sideband suppressed-carrier amplitude modulated (AM) waveform.[11,12] In the case of AM excitation, both the inner disk and outer annulus of the confocal transducer were driven with the same AM waveform. This method has the distinct advantage of requiring only a single ultrasound transducer and amplifier.

D. Diverging (ex-focal) excitation

In addition to using the confocal ultrasound transducer, another excitation method involved using a pair of diverging ultrasound transducers (Prowave 328ST180) which were directed towards the organ reed. These transducers had a central frequency of 32.8 kHz and a bandwidth of about 1 kHz; instead of emitting a focused ultrasound beam, these transducers are diverging with a full beam angle (at 6 dB below the maximum) of 45°. As shown in Fig. 2, a pair of these transducers were placed 5 cm from the reed surface and oriented at a 45° angle of incidence relative to the surface of the reed. This leads to an interaction region about 3 cm wide where there was significant overlap between the two ultrasound beams; it is only within this region that excitation at the difference frequency Δf can occur. This overlap region was centered on the reed. Because they were mounted to the left and right of the reed surface, the transducers did not block the beam from the scanning vibrometer.

As shown in Fig. 2, there is also a region behind the reed where the ultrasound beams could have overlapped, which might induce a radiation force on the supports that held the organ pipe. In that region, the intensity of each beam separately was 3 dB or more below the maximum, so the ultrasound radiation stress in that region would be a small fraction of the radiation stress arriving at the reed. Also, the supports were positioned such that the mechanical shaker placed directly behind the reed shielded this region of over-

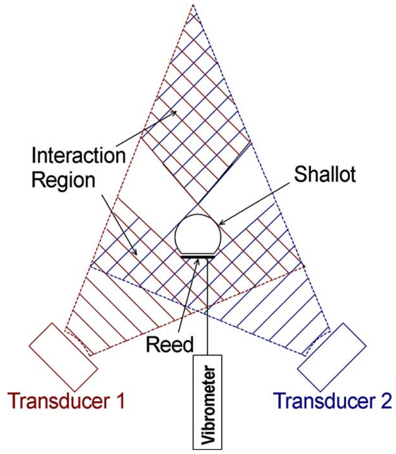

FIG. 2. (Color online) Excitation of reed using a pair of ex-focal (diverging) ultrasound transducers as viewed from above; the vibrometer is not drawn to scale. Excitation can only occur in the cross-hatched interaction region where there is an overlap between the output of the two ultrasound transducers. In the region behind the reed, the ultrasound radiation force is much smaller than the region in the vicinity of the reed, since the intensity from each transducer separately was at least 3 dB smaller. Not shown is the mechanical shaker, that was attached to the shallot opposite from the vibrometer. This shaker blocked the interaction region behind the reed, and thus prevented ultrasound from reaching any supports behind the reed pipe.

lap. Thus, even though the ultrasound beams were diverging, essentially only the organ reed experienced the ultrasound radiation force directly.

E. Waveform generation

To generate waveforms, a pair of Hewlett Packard 33120A function generators were used. For the pair of transducers or when the two elements of the confocal transducer were excited separately, one of the function generators generated a sine wave with a fixed frequency f_1 and the other was set to sweep a chirp sinusoidal waveform of frequency $f_2=f_1+\Delta f$. To generate a reference signal, that was needed to determine the vibrometer phase, the two signals were mixed and filtered using a bandpass filter at $f_2-f_1=\Delta f$. The signals from the two function generators were directed to a pair of power amplifiers; for the 32.8 kHz transducers a Crown 150A stereo amplifier was used, and when the confocal transducer was used, a pair of ENI 240L RF amplifiers served to amplify the signals.

To generate an amplitude modulated waveform, one of the function generators generated an audio-range waveform; this was connected to the second function generator to produce a double-sideband, suppressed carrier amplitude modulated signal. Because the generator produced two sidebands, the difference frequency produced is twice the frequency of the audio-range input frequency.

F. Shaker and audio excitation

The organ reed could also be excited using two conventional methods: a mechanical shaker, and an audio speaker. First, similar to previous studies, a Brüel-Kjær 4810 mechanical shaker was attached to the back of the shallot with a small piece of wax at the point of contact. This shaker caused a very small vibration of the entire pipe. These vibrations were transmitted to the reed by its contact with the shallot, causing a larger amplitude output from the vibrometer when the driving frequency matched one of the reed's resonance frequencies. The shaker and reed pipe were attached by a series of rods and clamps to a vibration isolation table. The clamp system has its own resonant frequencies; since the shaker vibrated the entire system, resonances in this support system would also be observable in the vibrometer spectra.

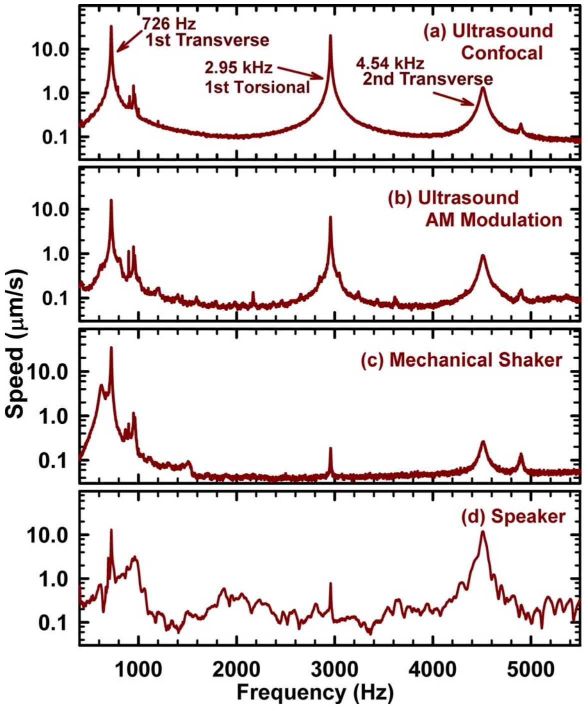

FIG. 3. (Color online) Vibrometer measurements of frequency response of the reed showing the first three resonances. (a) Ultrasound stimulated excitation using confocal transducer; (b) Ultrasound stimulated excitation using the same confocal transducer in AM mode; (c) excitation using a mechanical shaker; (d) audio excitation by nearby speaker. The peaks observed near 900 Hz and 4.8 kHz are from a previously observed noise source in the system.

The other method used to excite the reed was acoustic excitation using an audio speaker. To perform this excitation, an Altec Lansing speaker was placed roughly 10 cm from the pipe.

IV. RESULTS

A. Modal analysis using ultrasound stimulated vibrometry

Figure 3 shows the vibrometer spectra, averaged over the 50 points distributed over the surface of the reed, obtained for a $G_5^{\#}$ trumpet pipe; this was the same pipe characterized in a previous study.[5] The ultrasound transducer used for excitation was a confocal transducer. The position of the transducer was adjusted using a translation stage to obtain the maximum signal from the vibrometer; the maximum signal was obtained when the transducer was about 3 cm from the reed, which is consistent with its focal length. Figure 3(a) shows the spectrum obtained when the inner disk was driven with a frequency $f_1=550$ kHz and the outer annulus was driven with a frequency f_2 which was varied with a sinu-

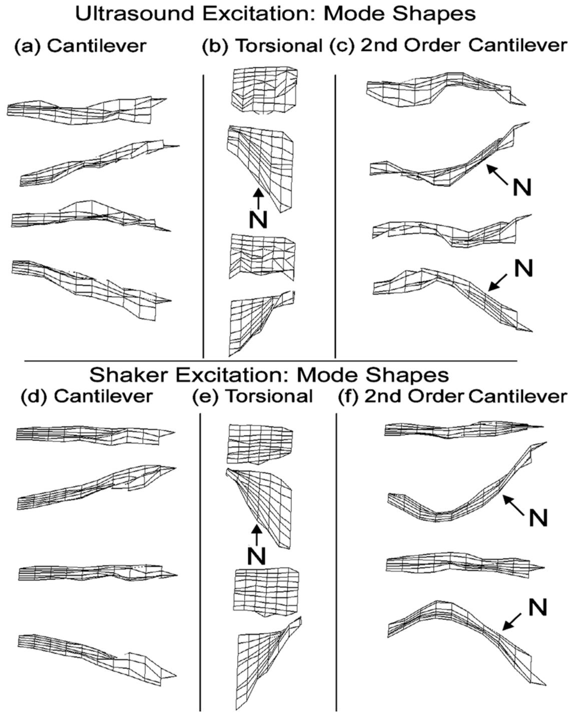

FIG. 4. Scanning vibrometer measurements of the displacement of the reed from its equilibrium position. Successive images downwards show displacement after 90° phase shifts during the cycle; the N in the figures illustrates the location of the nodal line for the torsional and second-transverse modes. (a) and (d) are the first transverse mode of the cantilever at 726 Hz; (b) and (e) are the first torsional mode at 2.95 kHz, and (c) and (f) are the second transverse mode of the cantilever at 4.54 kHz. The deflection shapes of (a)–(c), using ultrasound stimulated excitation, were nearly identical to (d)–(f) that were obtained using a mechanical shaker.

soidal chirp waveform from 550.5 kHz to 556 kHz over a 1.25 s period. This gave a difference frequency that ranged from 500 Hz to 6 kHz that excited the reed. The vibrometer spectra clearly shows peaks at 726 Hz, 2.95 kHz, and 4.54 kHz; these are in agreement with the predicted frequencies for a clamped-free cantilever.

Figures 4(a)–4(c) show the deflection shapes measured by the scanning vibrometer for these three resonances; these shapes are consistent with the mode shapes expected for the first three modes of a clamped-free cantilever. In particular, the peak at 2.95 kHz has a very clear torsional motion, and the peak at 4.54 kHz has a nodal line about 1/3 of the distance from the free end of the reed, which is expected for the second transverse mode.

There are two other regions of interest that can be observed in the spectra of Fig. 3(a); the region near 900 Hz, and the region near 4.8 kHz also show evidence of a resonance. These same peaks have been observed in spectra of other experiments using the same apparatus including vibrometer, electronics, and isolation table. Thus, they appear to be a noise source in either the electrical system, or an unrelated resonance in some portion of the mechanical system. Looking at the deflection shapes at 900 Hz and 4.8 kHz, the reed does not show a collective vibrational shape similar to those in Fig. 4. Instead, the phase at these frequencies for each measurement point on the reed appears to be uncorrelated to the phase of the driving force, which is consistent with a noise source.

Figure 3(b) shows the vibrometer spectrum when the reed was excited with the same ultrasound transducer using amplitude modulation. Both the inner disk and outer annulus were driven using an amplitude-modulated waveform with a carrier frequency of 550 kHz and a modulation frequency that was swept from 250 Hz to 3 kHz. Thus the difference frequency ranged from 500 Hz to 6 kHz. The spectrum of Fig. 3(b), with excitation by a single amplitude modulated ultrasound signal, is nearly identical to the spectra observed in Fig. 3(a) with the two beams from the confocal transducer. This is consistent with previous comparisons of confocal and amplitude modulated ultrasound excitation in water.[12] In contrast to the silent operation when the two elements of the transducer were driven with different frequencies, there was some small emission of audible sound because of recombination of the two waveforms in the transducer itself.

To demonstrate the ability to excite a larger reed, the 1 mm diameter ultrasound beam driven with an AM signal was focused on a much larger 36 mm × 6 mm brass reed. Even for this larger reed, the expected transverse and torsional deflection shapes of the entire reed were excited. Displacements and velocities in excess of 5 μm and 4 mm/s could be imparted at the fundamental frequency of 145 Hz.

B. Comparison with mechanical shaker and acoustical speaker

Figure 3(c) shows the vibrometer spectrum when a mechanical shaker was used as an excitation source. This shaker, in contact with the back of the shallot of the pipe, was driven with a chirp excitation from 500 Hz to 6 kHz. The amplitude of the driving force was attenuated to produce a vibrometer spectrum with about the same amplitude as for the ultrasound excited case; the amplitudes used in this experiment were roughly 1/100 of the maximum amplitude that could be obtained using this mechanical shaker. The frequencies of the three primary peaks in the shaker spectrum are similar to the peaks observed in the ultrasound excited spectra. As expected for an uncorrelated noise source, the background peaks at about 900 Hz and 4.8 kHz were observed with roughly the same amplitude in this spectra as in the other spectra. Figures 4(d)–4(f) show the deflection shapes measured for the three primary resonances. Figures 3(a)–3(c) and Fig. 4 demonstrate that noncontact ultrasound stimulation produces the same resonance frequencies and deflection shapes as are produced using a mechanical shaker.

One significant difference between the shaker spectrum of Fig. 3(c), and the ultrasound spectra of Figs. 3(a) and 3(b) was the relative amplitude of the peaks. In the shaker spectrum, the torsional peak was significantly smaller in amplitude than the two transverse peaks. One possible explanation was that the shaker was more efficient at exciting transverse modes than torsional modes. Since the shaker was moving the entire shallot, the driving force on the two sides of the reed were in phase instead of a 180° phase difference needed for a torsional mode. When the shaker was used, there was little lateral asymmetry in the driving force that would be needed to excite a torsional mode. In contrast, the ultrasound source that was used comes to a relatively small focus. Since the ultrasound spot was not focused along the axis of the reed, this causes a left-right asymmetry in the driving force which may be more efficient at exciting torsional vibrations.

Figure 3(d) shows results of another noncontact method for exciting the reed, namely using a nearby audio speaker. Because of the poor low-frequency response of the speaker used, there was very little excitation of the fundamental mode. It would be difficult to obtain reasonably uniform frequency response across the entire audio spectrum using a single speaker element. The output from an audio speaker, especially for low frequency, cannot be focused. This means that only a small fraction of the acoustical power needed to excite a small object, such as a reed, will be incident on the object. The remainder of the acoustical output is emitted in other directions.

C. Localized nature of the ultrasound stimulated excitation using divergent beams

In addition to being noncontact, another unique characteristic of ultrasound stimulated excitation is that it can be localized. By using a focused ultrasound transducer, the driving force is applied to a small region; another way to achieve a localized excitation is to use a pair of diverging ultrasound transducers oriented such that the interaction region of the beams from the two transducers is relatively small. Oscillations of support structures were highly suppressed by using ultrasound stimulation instead of a mechanical shaker.

As shown in Fig. 2, the ultrasound transducers used were a pair of diverging transducers that were driven at two different frequencies; one was fixed at 32.4 kHz, and the other was swept from 32.5 kHz to 33.2 kHz. The region of overlap from the two transducers was sufficiency large to ensonify the reed, but did not ensonify the clamps or supports that were holding the pipe. Figure 5(a) shows the vibrational spectra of a reed that was excited using ultrasound stimulation; the reed of the pipe used for this test had a resonance frequency of 580 Hz. The major peak observed at 580 Hz was the fundamental transverse resonance of this reed. There were also some small peaks observed between 200 and 450 Hz.

In Fig. 5(b), the same system was driven with a mechanical shaker using a swept sine wave from 100 Hz to 800 Hz. In addition to the main peak, the peaks between 200 and 450 Hz were much larger than the ultrasound stimulated case. These peaks appear to originate in resonances of the supports and clamps used to hold the reed pipe in place; there was very little damping material that was used in setting up the apparatus for this experiment. By making adjustments such as moving or tightening the clamps and supports, these resonances changed. For example, the only difference between Figs. 5(b) and 5(c) was that a 100 g mass was placed on one of the clamps. This caused a shift of roughly 25 Hz in the 240 Hz resonance. These results indicate that these additional peaks between 200 and 450 Hz originate from the fixtures and support structures holding the reed pipe.

Since the overlap of ultrasound does not include the supports holding the pipe, very little energy was transferred to the vibrational modes of the clamps and supports. This is in contrast to the shaker, which vibrated the entire system, and thus drove a significant amount of energy into these modes. Since the energy is proportional to the square of velocity, squaring the spectrum for the ultrasound stimulated excitation shown in Fig. 5(a), the area under the main peak region from 520 to 640 Hz is 270 times the area in the region due to the support clamp resonance from 200 to 300 Hz. A similar analysis of the square of the spectrum in Fig. 5(b), produced using the mechanical shaker, shows that the primary peak contains only six times the area of the region from 200 to 300 Hz. This demonstrates that ultrasound radiation force is much more effective than a mechanical shaker for exciting the reed without exciting the corresponding background vibration of the supports.

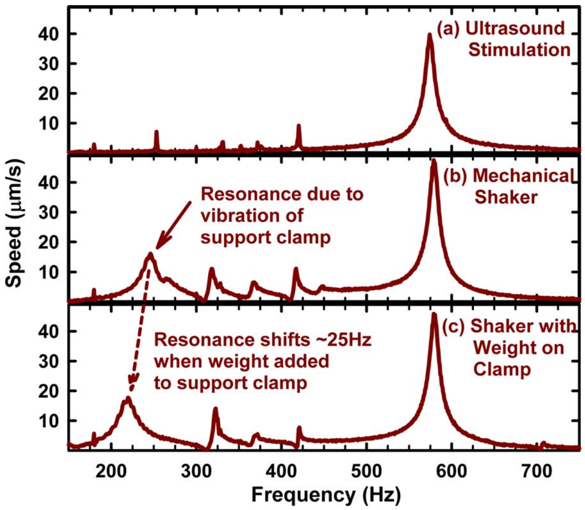

FIG. 5. (Color online) Illustration of efficacy of ultrasound stimulated excitation in suppressing background resonances. (a) Shows vibrometer spectrum for ultrasound stimulated excitation; (b) and (c) show excitation using a mechanical shaker. The background resonances of support structure in region between 200 and 450 Hz were strongly suppressed in the ultrasound stimulated spectrum. The difference between spectra (b) and (c) was that a 100 g weight was placed on one of the support clamps to demonstrate that the support system was origin of these resonances. The ~10 Hz shift in the primary resonance at 580 Hz between Figs. 4(a) and 4(b) was caused because the tuning wire was bumped slightly between these two runs, not because of difference in the resonances for ultrasound and shaker excitation.

V. CONCLUSIONS

In Ref. 5, the vibrational modes of an organ reed were excited using a mechanical shaker, and measured with a scanning laser vibrometer. The resonance frequencies measured in the current study, using ultrasound stimulation excitation are consistent with those previous measurements, as well as theoretical predictions. In the previous study, there was some concern about the validity of using a mechanical shaker to determine the vibrational modes, since the driving mechanism was indirect and there was some mass-load when the shaker was attached. The current study, which demonstrated that the modal frequencies were the same for both shaker and ultrasound stimulated excitation, appears to validate the previous measurements.

More importantly, the current study has demonstrated the efficacy of using airborne ultrasound stimulated vibrometry for modal analysis. Ultrasound stimulated excitation appears to have many advantages, including the noncontact nature of the interaction, relatively large bandwidth, and the ability to focus the excitation into a relatively small region, in contrast to a shaker which is much more homogeneous. The combination of an ultrasound excitation source and a vibrometer allows for completely noncontact modal testing. This method may be advantageous over conventional techniques, particularly for items that would be significantly affected by the mass loading of a mechanical shaker. Also, if a broadband ultrasound transducer is used, it may be possible to excite structures at much higher frequencies than can be obtained using conventional mechanical shakers which are generally limited to less than about 20 kHz.

ACKNOWLEDGMENTS

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