Noncontact Modal Excitation of Small Structures Using Ultrasound Radiation Force

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ABSTRACT: Modal analysis of MEMS and other small structures is important for many applications. However, conventional excitation techniques normally require contact, which may not be feasible for small objects. We present a non-contact method that uses interference of ultrasound frequencies in air to produce low-frequency excitation of structures. Objects studied included a MEMS mirror, MEMS gyroscope, hard drive suspensions, and a brass cantilever. The vibration induced by the ultrasound radiation force was varied in a wide range from 0 Hz to over 50 kHz. Object motion was detected using a laser vibrometer; measured frequencies agreed with expected values. Also demonstrated was the unique capability to selectively enhance or suppress modes independently. For example, for a MEMS mirror, the relative amplitude of a torsional mode could be enhanced by a factor of 10 by changing the ultrasound focus spot position. Similarly, the ratio of the vibrational amplitudes of the torsional modes of a MEMS mirror around two axes could be changed from in excess of 20:1 to less than 1:2 by shifting the ultrasound modulation phase 90 degrees.

I. NOMENCLATURE

c	Speed of sound in air
$d_r(\mathbf{r})$	Drag coefficient on object at location $\mathbf{r}$
$e_{\Delta f}(\mathbf{r},t)$	Instantaneous energy density at frequency Δf at location $\mathbf{r}$ at time t
f_1, f_2	Two ultrasound frequency components emitted by ultrasound transducer
Δf	Difference frequency between ultrasound components: the frequency of the radiation force
$F_{\Delta f}(\mathbf{r},t)$	Instantaneous radiation force at frequency Δf at location $\mathbf{r}$ at time t
$P(\mathbf{r})$	Amplitude of the ultrasound pressure field incident at position $\mathbf{r}$
$p(\mathbf{r},t)$	Instantaneous pressure at location $\mathbf{r}$ and time t
$\Delta\varphi(\mathbf{r})$	Phase difference between frequency components f_1 and f_2 at position $\mathbf{r}$
ρ	Density of air

II. INTRODUCTION

In modal testing of small objects, such as MEMS devices, one challenge can be to excite the vibrational modes without distortions due to mass loading. Using a laser Doppler vibrometer, it is relatively straightforward to measure the vibration in a non-contact manner; however it is not always possible to excite these vibrations without contact. While many devices include electronic methods to excite the structure, some devices are passive, and thus require an external excitation source. It may also be desirable to study the vibration of structures independent of their actuators. In most cases, because of their small size, the only option available is base excitation, where the entire device is vibrated, instead of just the region of interest.

The results described below demonstrate that it is possible to use ultrasound radiation force to excite the vibrational modes of MEMS and similar devices. With this technique, there is no contact between the object and ultrasound source, so there is no distortion of the vibrational modes due to mass loading; the combination of ultrasound excitation and a laser Doppler vibrometer makes for completely noncontact modal testing. As shown in section V.B., since the ultrasound can be focused to a small section of the surface of the object, this method does not excite vibration of the fixture used to hold the object. Sections V.B. and V.C. show that by varying the focus point and phase of the ultrasound excitation, it was possible to selectively excite or suppress different vibrational modes.

III. THEORY

Previous papers have described in detail the mechanism for ultrasound stimulated audio-range excitation, both in air [1] and in water.[2] If an object is ensonified with a pair of ultrasound frequencies, f_1 and f_2, interference between the two frequencies produces a radiation force that results in a vibration of the object at the difference frequency $\Delta f = f_2 - f_1$. One method that has been used to produce excitation of small structures is a pair of ultrasound transducers, one emitting the frequency f_1, and the other producing the frequency f_2.[2] However, in the measurements described below, both frequency components were emitted from a single transducer using a double-sideband suppressed-carrier amplitude modulated (AM) waveform.[3] As shown in Figure 1, an object was excited by a transducer emitting two different ultrasound frequencies $f_1 = f_c - \Delta f/2$ and $f_2 = f_c + \Delta f/2$ where f_1 and f_2 are ultrasound frequencies which are symmetrical about a central frequency f_c. In the course of the experiment, the difference frequency Δf is swept through a range of frequencies, and the response is measured at each frequency. If the radiation force at frequency Δf corresponds to one of the resonance frequencies of the object, it will induce a larger amplitude vibration that will be detected using the laser Doppler vibrometer.

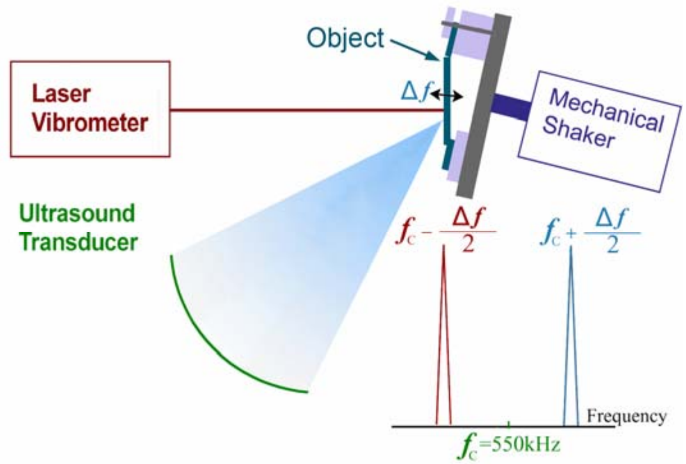

Figure 1: Diagram illustrating ultrasound radiation force as an excitation method for a hard drive suspension. A modulated signal from the ultrasound transducer, with two frequency components equally spaced around a 550 kHz central frequency, was focused on the suspension. The velocity was measured using a laser Doppler vibrometer; for comparison purposes, a mechanical shaker could be used for excitation instead of ultrasound.

The radiation force[4] is caused by changes in the energy density of an acoustic field. In the following derivation, it is assumed that the total ultrasound pressure field $P(\boldsymbol{r})$ at a point $\boldsymbol{r}$ will be the same at both frequencies f_1 and f_2 that are emitted by the transducer. However, as the waves of different frequencies traverse the distance between the transducer and the arrival point $\boldsymbol{r}$, they will arrive with different phases $\varphi_1(\boldsymbol{r})$ and $\varphi_2(\boldsymbol{r})$, thus the total pressure field due to the two frequency components may be written as

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

This causes an instantaneous energy density given by $e(\boldsymbol{r},t)=p(\boldsymbol{r},t)^2/\rho c^2$; 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

$$e_{\Delta \mathrm{f}}(\boldsymbol{r},\mathrm{t}) = P(\boldsymbol{r})^2 \cos[(2\pi\Delta f)t + \Delta\varphi(\boldsymbol{r})]/\rho c^2. \tag{2}$$

Assuming that $P(\boldsymbol{r})$ is a plane wave, this will impart a force in the beam direction on an object of area dS with drag coefficient $d_r(\boldsymbol{r})$ given by [4]

$$F_{\Delta \mathrm{f}}(\boldsymbol{r},\mathrm{t}) = e_{\Delta \mathrm{f}}(\boldsymbol{r},\mathrm{t})\, d_r(\boldsymbol{r})\, dS = P(\boldsymbol{r})^2 \cos[(2\pi\Delta f)t + \Delta\varphi(\boldsymbol{r})]/\rho c^2\, d_r(\boldsymbol{r})\, dS. \tag{3}$$

The total radiation force as a function of time is the integral of Equation 3 over the entire surface of the object; this radiation force can induce a vibration of the object at a frequency Δ*f*. Object vibration due to this radiation force is a function of the size, shape and mechanical impedance of the object. Previous studies have shown that this radiation force can be used for modal analysis of a variety of systems[5] including hard-drive suspensions.[6]

IV. EXPERIMENTAL SETUP

To measure the vibration, a Polytec PSV-300 scanning laser vibrometer was used.[7] A vibrometer uses the Doppler shift of reflected laser light to determine the speed of the vibrating part. With a scanning laser vibrometer, the laser can be deflected across the surface to measure the motion at many points on the surface of the object; this allows measurement of 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. A primarily transverse mode will have a constant phase across the entire width of the part, whereas a torsional mode will have a 180 degree phase shift across its width.

In many cases, the results of ultrasound excitation were compared to base excitation using a mechanical shaker. A Brüel-Kjær 4810 mechanical shaker placed in contact with one of the clamps caused a very small vibration of the entire support system. These vibrations were transmitted to the object under study, causing a larger amplitude output from the vibrometer when the driving frequency matched one of the parts resonance frequencies. However, 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.

A. Modal testing using focused transducer.

The apparatus used to obtain results in Section V.A. is shown schematically in Figure 1. The transducer used in this portion of the testing 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. In the testing described below, both the inner disk and outer annulus of the transducer were driven with the same double-sideband suppressed carrier AM waveform. As shown in Figure 1, for most experiments where it was not possible to ensonify from the back of an unsupported part, this transducer was mounted at an angle of roughly 45 degrees, thus it leads to a focus spot that is roughly elliptical with 1mm along one axis and 1.5 mm along the other axis. The transducer was attached to a 3-d translation stage to allow the excitation point to be moved.

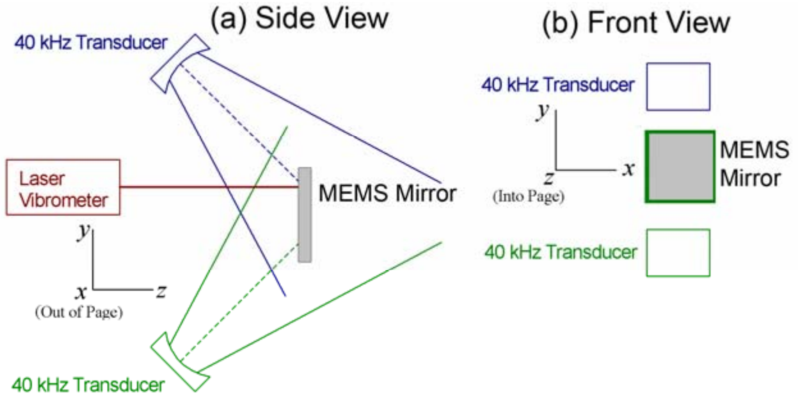

Figure 2: Apparatus used for selective excitation using a pair of 40 kHz diverging ultrasound transducers. The phase angle of the modulated signal between the two transducers was varied to emphasize transverse modes when the transducers were driven in phase, and torsional modes around the *X* axis when they were driven at a phase angle near 90 degrees.

B. Excitation using phase-shifted pair of transducers:

In addition to using the confocal ultrasound transducer, another excitation method involved using a pair of diverging ultrasound transducers [Prowave 400ST160] which were directed towards the object.[8] These transducers had a central frequency of 40 kHz and a bandwidth of about 2 kHz; instead of emitting a focused ultrasound beam, these transducers are diverging with a full beam angle (at 6dB below the maximum) of 45 degrees. As in Figure 2, a pair of these transducers were placed about 1.5 cm from the object under study (in the case illustrated, a MEMS mirror); these transducers were oriented at a 45 degree angle of incidence relative to the surface of the object. The modulated waveforms sent to these two transducers were produced using a National Instruments NI6040-E data acquisition board; there was an adjustable phase difference between the waveforms generated in software for the two transducers. As shown in Section V.B., when the modulation waveform sent to the two transducers was the same, the radiation force from the two transducers would be in phase, which tends to reinforce vibrational modes that have a transverse displacement (vibrations of the structure causing forward/backwards motion in the direction of the *Z* axis of Figure 2) while suppressing torsional modes (vibrations that involve torsion of the object around its midline parallel to the *X* axis of Figure 2) that have a 180 degree phase difference from one side to the other. In contrast, if the modulation phase between the two transducers differs by about 90 degrees, there will be a 180 degree phase difference between the radiation forces imparted by the two transducers, which will tend to reinforce *X* torsional modes while suppressing transverse modes.[8]

V. RESULTS

A. MEMS Gyroscope

One of the devices tested was an ADXRS MEMS Gyroscope from Analog Devices. This device consists of a pair of ¾ mm square test masses separated by 1.5 mm. In normal operation, these test masses are oscillated in the XY plane at a resonance frequency of 14 kHz. The goal of this testing was to determine whether there was out-of-plane motion of the masses, and the frequency of this motion.

A conventional test was performed, using a shaker for base excitation of the entire gyroscope integrated circuit. Out of plane vibration of the test masses was detected in the 13.5 kHz region. However, this vibration was difficult to observe because the entire structure was in motion from the base excitation. The amplitude of vibration of the test masses was less than 50% larger than the vibration of neighboring regions of the integrated circuit.

In contrast, using an ultrasound source focused on the gyroscope, it was possible to cause significant excitation of the test masses with only minimal excitation of the remainder of the device. This is because the excitation primarily occurred in the ultrasound focus spot, which was roughly an elliptical region 1.5x1 mm; therefore adjacent portions of the device were relatively unaffected. Using an amplitude modulated 600 kHz ultrasound source with a difference frequency of 13.5 kHz, the out-of-plane vibration of the test masses was in excess of 100 μm/s, whereas an adjacent section of the integrated surface substrate, less than 2 mm away, had an amplitude less than 1 μm/s. This demonstrates the capability of ultrasound stimulation to excite only small regions on a part without excitation of adjacent regions.

B. MEMS Mirror.

Figure 3 shows a DuraScan MEMS mirror manufactured by Applied MEMS. This 3mm square mirror is designed for 2-dimensional scanning; it accomplishes this by a hinge mechanism that allows rotation around two separate axes. Using a mechanical shaker, these vibrational modes were measured. As shown in the dashed curve in Figure 4(a), these two modes are a torsional mode around the *X* axis with a frequency of 60 Hz, and another torsional mode around the *Y* axis with a frequency of about 829 Hz; in normal operation, the mirror is scanned by electrically exciting it at these frequencies.

In addition to the two torsional modes, there were two other resonances observed in the dashed curve. There was a 329 Hz transverse mode where the mirror moved out of the plane (*Z* direction); this mode is not

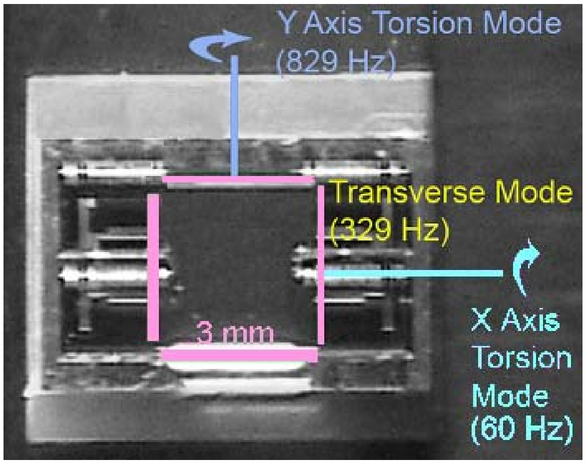

Figure 3: 3mm square Applied MEMS DuraScan mirror, with illustration of vibrational modes around *X* and *Y* axis. A transverse mode was also present

used for scanning applications. The resonance at about 164 Hz is a “fixture mode” that results from vibration of some portion of the support structure or clamps that hold the mirror and shaker assembly.

1. Results using focused ultrasound transducer

The mirror was ensonified using the focused ultrasound transducer; the ultrasound spot was about 1.5 mm long in the *X* direction and 1 mm high in the *Y* direction. As shown in solid curves in Figure 4, ultrasound excitation produced the same resonance frequencies as were observed using the mechanical shaker. This provides strong evidence that the ultrasound radiation force can be used to measure the same resonances and vibrational modes that can be observed using a conventional mechanical shaker. This is consistent with previous measurements demonstrating the efficacy of using ultrasound as an alternative to a mechanical shaker. [1,6]

As has been shown in previous studies, ultrasound excitation is much less likely to excite resonances in the fixture used to hold the part than traditional base excitation. [1,6] This is because the ultrasound ensonifies only the region of interest, in this case the mirror itself. Unlike the spectrum for the mechanical shaker, the fixture resonance at 164 Hz is hardly present when the ultrasound radiation force is used.

When a focused ultrasound source is used, this technique has the additional capability to perform selective excitation of different modes. Figure 4b demonstrates that excitation of the torsional mode around the *X* axis can be significantly enhanced by focusing the ultrasound transducer near the top of the mirror; similarly, in 4c, the *Y* torsional mode is enhanced when the transducer is focused near the right edge of the mirror. Figure 5 shows the ratio of the amplitude of the *X* torsional mode at 60 Hz and the transverse mode at 329 Hz as the focus position of the transducer is varied along *Y* axis. When the transducer is focused near the center of the mirror, the amplitude of the transverse mode is largest; as the transducer is moved vertically from the center, a smaller fraction of the ultrasound beam ensonifies the mirror, leading to a decrease in the amplitude. In contrast, the *X* torsional mode has the smallest amplitude when the ultrasound is focused near the center of the mirror (since there is a smaller lever arm for rotating the mirror), and peaks when the ultrasound focus point is located near the edge of the mirror. This leads to about a 10x enhancement of the relative amplitude of this mode.

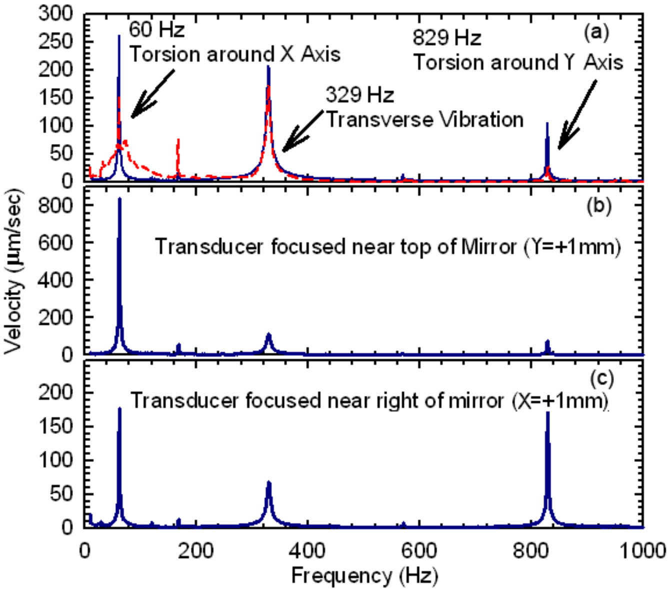

Figure 4: Vibrational spectra observed for MEMS mirror. (a) dotted line indicates spectra obtained using mechanical shaker, and solid line is for ultrasound focused at center of mirror; spectra for ultrasound focused near top (b) and right edge (c) of mirror

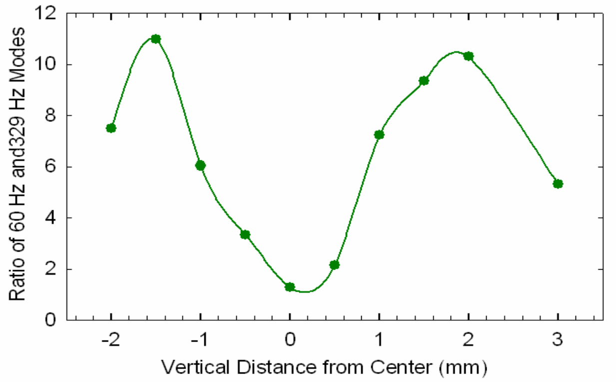

Figure 5: Demonstration of selective excitation by varying ultrasound focus position. The *X* torsional mode and transverse mode have nearly the same amplitude when the ultrasound focus point is near center, but is over 10x larger when focused near edges of mirror.

These tests demonstrate that it is possible to selectively excite different vibrational modes by moving the ultrasound focus point. Focusing the ultrasound near a region where a mode has an antinode can lead to an enhancement of excitation of this mode relative to other modes. This capability may be useful in cases where there are two or more vibrational modes that have similar resonance frequencies, but different mode shapes.

2. Phase Shifted Diverging (Ex-Focal) Excitation of MEMS Mirror:

An even more effective method of selective excitation of transverse versus torsional modes can be accomplished by using a phase-shifted pair of transducers.[8] Using the apparatus shown in Figure 2, the pair of ultrasound transducers were driven with the same magnitude signal, but with a phase angle between the modulation signal (the difference frequency at Δ*f*) that could be varied. The solid blue curve in Figure 6 shows the spectrum obtained when the two transducers were driven in phase. The amplitude of the 329 Hz transverse mode and the 829 Hz *Y*-torsional mode were over twenty times larger than the 60 Hz *X*-torsional mode. The *X*-torsional mode is strongly suppressed in this case because the ultrasound radiation force arriving from transducers above and below the mirror are in phase; this means that there is an essentially uniform radiation force across the object. This uniform radiation force will tend suppress the *X* torsional mode, since this mode requires a 180 degree asymmetry along the *Y* axis. In contrast, the dashed red line in Figure 6 shows that when the phase difference between the two transducers was 90 degrees; the resulting 180 degree phase difference in the radiation force between the two transducers tends to selectively excite torsional mode around the *X* axis while suppressing the transverse and *Y*-torsional modes. The amplitude of the torsional mode resonance is over twice as large as the corresponding transverse mode. Figure 7 shows the relatively large changes in amplitude of these two modes that could be obtained simply by adjusting the phase angle between the two transducers.

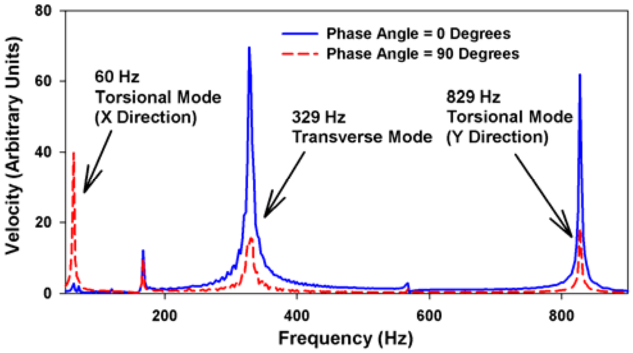

Figure 6: Demonstration of selective excitation by varying phase shift between two transducers. A phase angle of 0 degrees excites the transverse and *Y*-torsional mode while suppressing the *X*-torsional mode. In contrast, a phase difference of 90 degrees enhances the *X*- torsional mode while suppressing the other modes.

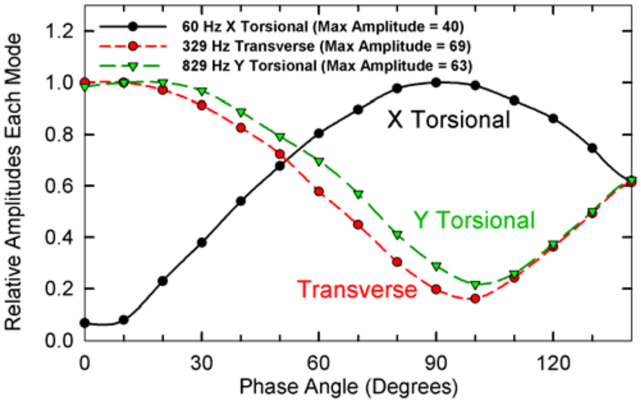

Figure 7: Relative amplitude of vibrational modes as a function of phase shift between two transducers. A phase angles near 0 degrees strongly excite the transverse and *Y*-torsional, whereas phase differences near 90 degrees enhances the *X*- torsional mode.

C. Ultrasound excitation of other objects.

This noncontact technique of position and phase adjustment offers the unprecedented capability, which cannot be accomplished using a mechanical shaker, to selectively excite or suppress either torsional or transverse modes. In addition to the MEMS devices studied above, other devices have been extensively studied using the ultrasound excitation technique. Reference [6] discusses detailed results for ultrasound excitation of a hard drive suspension.

This capability may be especially useful in resolving transverse and torsional vibrational modes that nearly overlap in frequency. In a series of tests, a brass cantilever which had a second transverse mode at 1540 Hz, and a torsional mode at 1610 Hz was driven using a mechanical shaker; these modes nearly overlapped. It was possible to use this same phase shifted pair of ultrasound transducers to selectively suppress one or the other of these modes by changing the phase difference. The ratio of the amplitudes of these modes changed from about 1:2 when the phase angle was 0 degrees to 10:1 when the phase angle was 90 degrees.

VI. CONCLUSIONS

The experiments described demonstrate that it is possible to perform noncontact excitation of MEMS objects using the ultrasound radiation force. Ultrasound excitation has the unique ability to selectively excite or suppress transverse or torsional modes by varying either the focus position of the ultrasound excitation, or the phase difference between two transducers. These tests have shown that the ultrasound radiation force is a unique method that may be advantageous for modal testing of MEMS devices and other small structures.

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