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Noncontact modal testing of hard-drive suspensions using ultrasound radiation force

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ABSTRACT: The head-gimbal assembly suspension is a cantilever-like structure that holds the heads on a hard drive. A noncontact method for modal testing, in air, of suspensions is discussed. This method utilizes the radiation force at the difference frequency generated by two intersecting ultrasound beams. The resulting low-frequency excitations were measured using a scanning vibrometer. This excitation technique has been demonstrated for MEMS and other small devices. There are several unique advantages of the ultrasound radiation force relative to mechanical shakers. Since the ultrasound radiation force is noncontact, a specialized test fixture was not needed; the technique was relatively insensitive to distracting resonances of fixtures and support structures. Another advantage is broadband excitation; a 550-kHz confocal ultrasound transducer excited suspension resonance frequencies from under 1 kHz to at least 50 kHz. Other advantages include the ability to selectively excite different modes. For example, the amplitude of one suspension's 5.0-kHz torsional mode was suppressed by an order of magnitude by shifting the modulation phase between the two ultrasound beams by 90 degrees. In another test, the amplitude of the 6.0-kHz torsional mode was doubled by moving the ultrasound focus point from near the center to near the edge of the suspension.

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

Head gimbal assembly suspensions are a roughly 10-14.5 mm length cantilever structure with an average width of about 4-6 mm; on the end of the suspension is a roughly 2-3 mm square gimbal that holds the read/write head for a hard drive. These suspensions are engineered to vibrate at specific frequencies. Modal testing during the manufacturing process is essential, since if the resonance frequencies of the suspension deviate from the design tolerances, it can lead to failure to properly read or write information, or even a head crash. The testing procedure that is currently used involves using a mechanical shaker to vibrate the suspension between 500 Hz and 20 kHz, and a laser Doppler vibrometer to detect the resulting motion of the suspension.

There are a few problems with the current testing protocol used during the manufacturing of suspensions. As the physical size of hard drives decreases, there is a desire to extend the resonance testing of the suspensions to between 20 kHz and 50 kHz, which is beyond the frequency range of the mechanical shakers currently used. Also, to perform the testing, the suspension must be mounted in a fixture attached to the mechanical shaker; the laser vibrometer detects the resonance frequencies of the suspension, but also detects any resonance frequencies of the fixture. Finally, since the suspension must be physically connected to a mechanical shaker, it is not possible to do *in situ* testing of a suspension in a working hard drive.

The results described below demonstrate that it is possible to use ultrasound radiation force to produce vibration of these suspensions; similar studies have shown that this technique can be used for modal analysis of organ-pipe reeds,[1] a MEMS mirror and a MEMS gyroscope,[2] as well as numerous studies of modal testing of structures in water.[3] This ultrasound radiation force technique appears to have some unique advantages over the use of a conventional mechanical shaker as an excitation source. With this technique, there is no contact between the suspension and ultrasound source, so there is no distortion of the vibrational modes due to mass loading; the combination of ultrasound excitation and laser Doppler vibrometer makes for completely noncontact modal testing. As shown in section V.A., since the ultrasound can be focused to a small section of the surface of the suspension, this method does not excite vibration of the fixture used to hold the suspension. Sections V.A. and V.B. show that by varying the focus point and phase of the ultrasound excitation, it was possible to selectively excite or suppress different vibrational modes. By using an ultrasound transducer with a wide bandwidth, it was possible to excite resonances in the suspension from below 500 Hz to at least 50 kHz. Finally, Section V.C. demonstrates the possibility of doing *in situ* excitation of the suspension while flying above a rotating disk without attaching it to any fixture, which makes it feasible to resonance test the suspension in a fully functioning hard drive.

III. THEORY

Previous papers have described in detail the mechanism for ultrasound stimulated audio-range excitation, particularly in water.[4] If an object, in this case the hard drive suspension, 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 suspension 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.[1] 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 [5]. As shown in Figure 1, a hard drive suspension 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 suspension, it will induce a larger amplitude vibration that will be detected using the laser Doppler vibrometer.

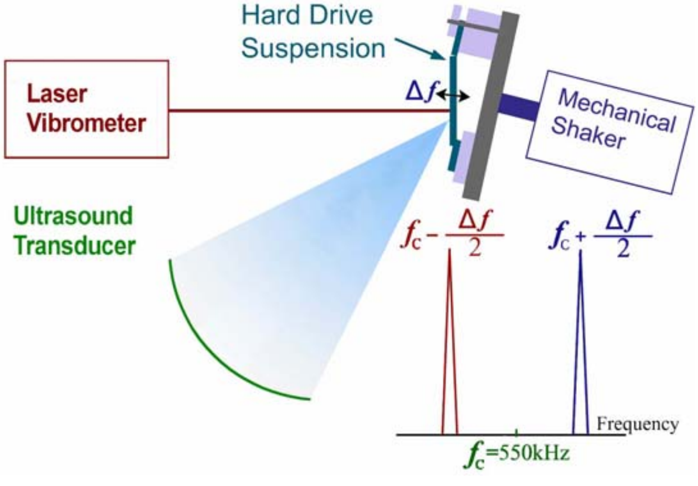

Figure 1: Diagram illustrating ultrasound radiation force as an excitation method for a hard drive suspension. A modulated signal from the ultrasound transducer, with two frequency components equally spaced around a 550 kHz central frequency, was focused on the suspension. The velocity was measured using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

The radiation force[6] 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

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

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

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

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]

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

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 Δf. Object vibration due to this radiation force is a function of the size, shape and mechanical impedance of the object.

IV. EXPERIMENTAL SETUP

To measure the vibration of the suspensions, 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 suspension. 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 suspension; 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 width of the suspension.

A. Modal testing for a simply supported suspension.

The apparatus used to obtain results in Section V.A. is shown schematically in Figure 1. The suspension was clamped at one end, and the gimbal was resting on the flat surface of a micrometer caliper. The caliper was adjusted such that the downward force produced by the flex of the hinge on the suspension was the same force as when this suspension is used in an operating hard drive. 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. For the current experiment, 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, in order to avoid blocking the beam from the scanning vibrometer, this transducer was mounted below the suspension and pointed upwards at a roughly 45 degree angle, and it was attached to a 3-d translation stage to allow the excitation point to be moved on the suspension.

The suspension could also be excited using a mechanical shaker. A Brüel-Kjær 4810 mechanical shaker was placed in contact with one of the clamps that held the suspension support. This shaker caused a very small vibration of the entire support system. These vibrations were transmitted to the suspension, causing a larger amplitude output from the vibrometer when the driving frequency matched one of the resonance frequencies of the suspension. 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.

B. Phase Shifted Diverging (Ex-Focal) Excitation of suspension:

In addition to using the confocal ultrasound transducer, another excitation method involved using a pair of diverging ultrasound transducers [Prowave 400WB160] which were directed towards the suspension. These transducers had a central frequency of 40 kHz and a bandwidth of about 10 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 a suspension that was clamped at one end but free at the other end; these transducers were oriented at a 45 degree angle of incidence relative to the surface of the suspension. 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 *y* axis of Figure 2) while suppressing torsional modes (vibrations that involve torsion of the suspension around the midline of the suspension parallel to the *z* 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 torsional modes while suppressing transverse modes.

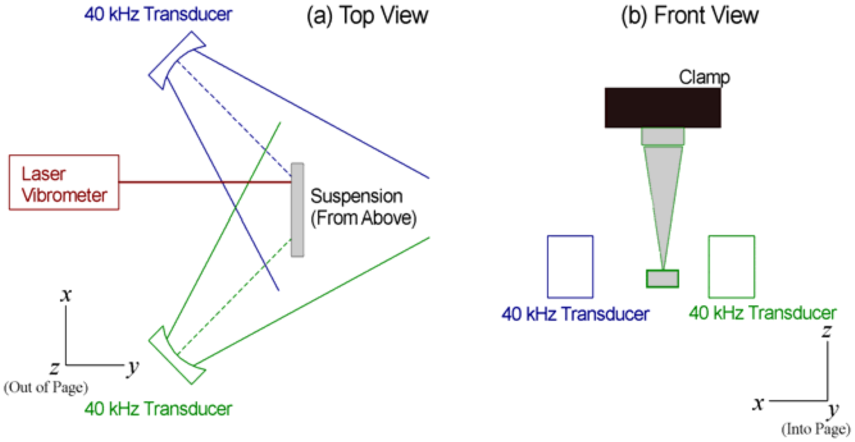

Figure 2: Apparatus used for selective excitation using a pair of 40 kHz diverging ultrasound transducers. The phase angle of the modulated signal between the two transducers was varied to emphasize transverse modes when the transducers were driven in phase, and torsional modes when they were driven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

V. RESULTS

A. Modal testing for a simply supported suspension.

Figure 3 shows a comparison of the velocity spectra measured by the vibrometer when the excitation source, as shown in Figure 1, was a mechanical shaker (solid line) or the focused ultrasound transducer (dotted line). The amplitude of the signal sent to the mechanical shaker was adjusted such that the response curves for both the shaker and ultrasound had similar amplitudes; when driven at its maximum driving voltage, the mechanical shaker could produce velocities over two orders of magnitude larger than those illustrated here. Based on the test results, there are several observations that can be made.

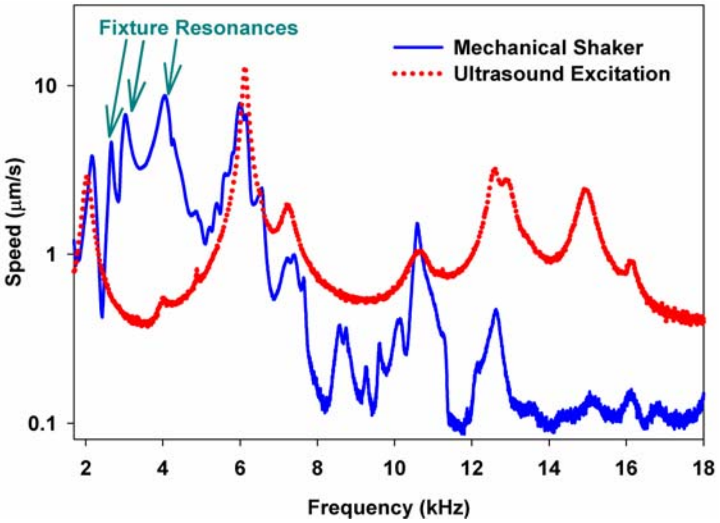

Figure 3: Comparison of velocity spectra obtained using mechanical shaker (solid line) versus ultrasound radiation force (dotted line) as a function of frequency. The mechanical shaker spectrum is significantly more complicated, and includes undesired fixture resonances.

First, it was shown that the ultrasound excitation produced the same resonances of the suspension as were generated using the mechanical shaker. All of the peaks observed in the ultrasound excitation were present at the same frequency in the spectrum produced using the mechanical shaker. For all resonances that were common to both the shaker and the ultrasound excitation, the deflection shapes observed were essentially identical. 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. [1,2] Additional tests demonstrated that this ultrasound transducer could excite resonances of the suspension to at least 50 kHz.[8]

In addition to the resonances that were common to both excitation techniques, the response curve obtained using the ultrasound excitation was smoother and has many fewer peaks than the corresponding response curve for the mechanical shaker. In particular there were several large peaks between about 2.5 kHz to 4 kHz. These additional peaks were consistent with fixture resonances that were caused by vibration of some portion of the micrometer, clamps and support structure that hold the suspension and shaker in place. These fixture resonances were present in all runs that involved a shaker, but were absent in runs using an ultrasound transducer (this included runs where the transducer was focused on different portions of the suspension, and runs that did not use an AM signal to produce the two ultrasound components, but where they were produced by driving the inner disk of the confocal transducer with one frequency f_1 and the outer annulus with a different frequency $f_2=f_1+\Delta f$). In the deflection shapes produced by the scanning vibrometer, these fixture resonances did not appear to have a well-defined shape and phase relationship. This lack of a clear structure to the deflection shape is characteristic of a background vibration, in contrast to the uniform deflection shapes that are related to the vibrational modes of the suspension. In the current experiment, we did not attempt to identify the exact source of these fixture modes. However, in a recent experiment[1] where resonances were observed in the shaker spectrum that were absent in the ultrasound excitation spectrum, in some cases it was possible to isolate the particular clamps or supports that led to fixture resonances.

Figure 4 illustrates another unique capability of ultrasound excitation. The dashed curve in Figure 4 shows the response when the transducer was focused near the center of the suspension, and the solid curve shows the response when the transducer was moved about 1.5 mm so the ultrasound focus point was near the edge of the suspension. As might be expected, the amplitudes of the resonances that correspond to torsional modes of the suspension were larger when the ultrasound was focused near the edge of the suspension than when it was focused near the center. Thus, by moving the transducer, it was possible to change the relative amplitude of different resonances. Specifically, for the torsional resonance at 6 kHz and transverse resonance at about 7 kHz, it was possible to change the ratio from about 2:1 when the transducer was near the center of the suspension to about 4:1 when the transducer was located near the edge of the suspension. Similarly, note the large change in the relative amplitude of the two peaks at about 15 and 16 kHz.

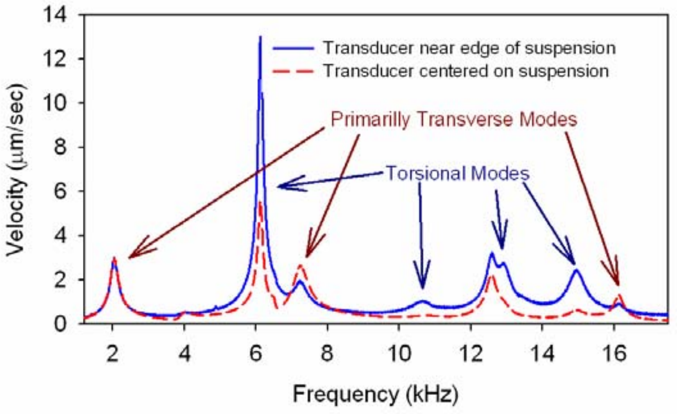

Figure 4: Selective excitation showing increased amplitude of torsional modes when transducer was focused near the edge of suspension instead of near the center of the suspension.

B. Phase Shifted Diverging (Ex-Focal) Excitation of suspension:

An even more effective method of selective excitation of transverse versus torsional modes can be accomplished by using a phase-shifted pair of transducers. 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 Δf) that could be varied. The solid curve in Figure 5 shows the spectrum obtained when the two transducers were driven in phase. The amplitude of the transverse mode at 2.85 kHz was about 3x larger than the amplitude of the first torsional mode at 5.0 kHz. The transverse mode dominates, because the ultrasound radiation force arriving from transducers to the left and right of the suspension are in phase; this means that there is an essentially uniform radiation force across the object that will tend to accentuate transverse modes which have no asymmetry between the two sides of the suspension. In contrast, the dotted line in Figure 5 shows results that when the phase difference between the two transducers was on the order of 90 degrees; the resulting

180 degree phase difference in the radiation force between the two transducers tends to selectively excite torsional modes while suppressing transverse modes. The amplitude of the torsional mode resonance is over 10x larger than the corresponding transverse mode. Figure 6 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.

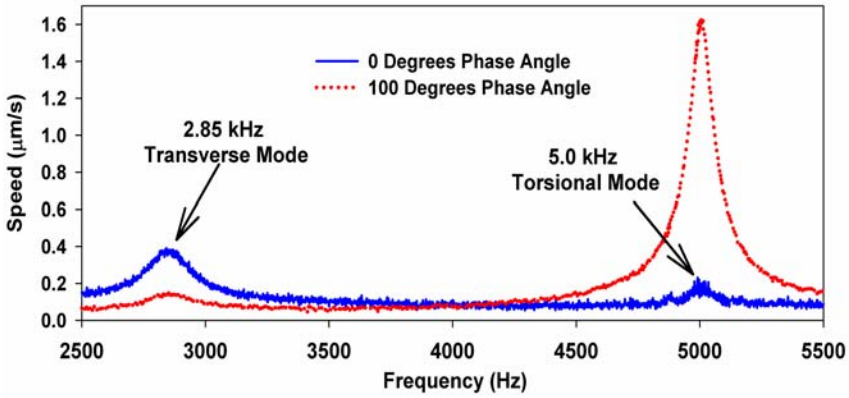

Figure 5: Spectra showing selective excitation of suspension for phase angles of 0 degrees (showing enhancement of transverse mode and suppression of torsional mode) and 100 degrees (showing enhancement of torsional mode and suppression of transverse mode).

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. This capability may be especially useful in resolving transverse and torsional vibrational modes that nearly overlap in frequency.

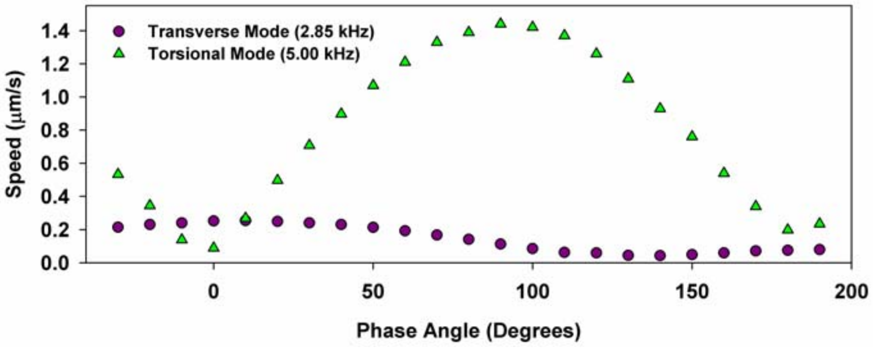

Figure 6: Amplitude of transverse and torsional modes as a function of phase angle between the modulation signals sent to the two transducers of Figure 2. The transverse mode peaks for angles near 0 degrees, and the torsional modes peaks when the angle is near 90 degrees, which corresponds to a 180 degree phase difference between the radiation force produced by the two transducers.

C. *In-situ* excitation of suspension in a rotating disk:

When the tests are performed as part of the quality control procedure, the suspension is clamped into a fixture that is attached to a mechanical shaker. Because the suspension must be attached to a shaker, this conventional testing protocol makes it impossible to test a suspension that is flying in an operating hard drive. Since the ultrasound excitation technique requires no physical contact between the ultrasound transducer and the suspension, it is possible to excite a suspension that is flying in a fully operational hard drive. To perform this test, the beam from the focused ultrasound transducer was directed at a suspension that was flying over a rotating disk, and the vibrometer measured the vibration. Figure 7 shows the velocity spectra for a suspension flying above a disk rotating at 4500 RPM. The solid curve shows the velocity spectrum when the suspension was being excited by the ultrasound radiation force. In contrast, the dotted curve shows the velocity spectrum when the ultrasound transducer was turned off; this velocity spectrum is due to the windage (aerodynamic forces between the flying head and disk that can cause vibrations) as well as the excitation induced by flutter vibrations of the rotating disk surface. The resonances visible in Figure 7 demonstrate that it is possible to use the noncontact ultrasound radiation force to produce excitation of the suspension in excess of the windage when the suspension is not in any special fixture. If the cover on a hard drive is removed to expose the suspension to an ultrasound transducer and vibrometer, this test demonstrates it is possible to do modal testing on a fully functional hard drive.

VI. CONCLUSIONS

The experiments described demonstrate that it is possible to perform noncontact excitation of a hard drive suspension using the ultrasound radiation force. This method minimizes the influence of fixture resonances, and can produce excitation to at least 50 kHz. In addition to these capabilities, ultrasound excitation has the unique ability to selectively excite or suppress transverse or torsional modes of the suspension, and can be used to excite resonances in a fully operational hard drive. These tests have shown that the ultrasound radiation force is a unique method that may be advantageous for modal testing of hard drive suspensions and other small structures.

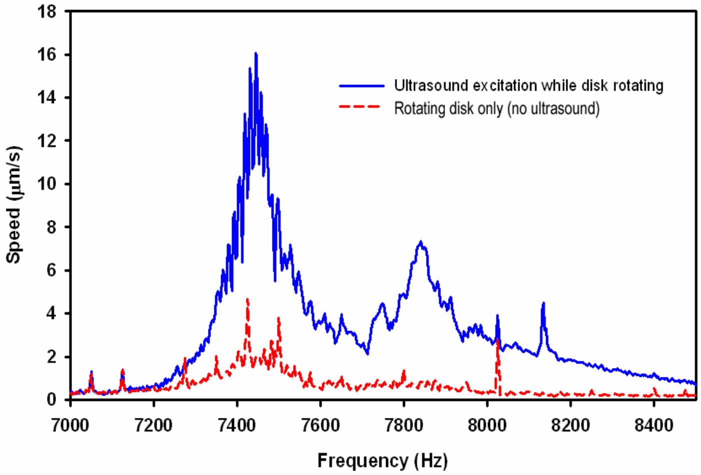

Figure 7: Comparison of velocity spectra observed for a suspension flying above a disk spinning at 4500 RPM with ultrasound excitation on (solid line) and ultrasound excitation off (dashed line). The narrow peaks observed with separation of 75 Hz are harmonics of the 4500 RPM revolution frequency.

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