

Apparent nonlinear effect of the microscope on the laser Doppler vibrometer

Hartono Sumali^{*a}, Matthew S. Allen^b

^aSandia National Laboratories, MS 1070, PO Box 5800, Albuquerque, NM 87111, USA;

^bUniversity of Wisconsin-Madison, 535 Engineering Research Building, 1500 Engineering Drive, Madison, WI 53706-1609, USA

ABSTRACT

One powerful method for measuring the motion of microelectromechanical systems (MEMS) relies on a Laser Doppler Vibrometer (LDV) focused through an optical microscope. Recent data taken under a very simple and common condition demonstrate that the velocity signal produced by the LDV with an optical microscope may be different from the velocity signal produced by the LDV without a microscope. In this study, the time derivatives of the two signals are compared against the signal from an accelerometer. The signal from the LDV without the microscope is almost identical to the accelerometer signal. In contrast, the signal from the LDV with the microscope exhibits a nonlinear relationship with the accelerometer signal. Both the LDV and the accelerometer were measuring a sinusoidal velocity generated by an electromechanical shaker. The Fourier transform of the acceleration from the LDV with the microscope shows a multitude of high harmonics of the excitation frequency, which have much higher amplitudes than the harmonics present in the accelerometer signal. Without the microscope, the LDV gives a much less distorted sinusoidal signal, even after time differentiation. The distortion of the signal from the LDV is periodic, with the same period as the sinusoidal drive signal. The largest distortion occurs near points of maximum negative acceleration, corresponding to the positive displacement peak of the sinusoidal oscillation. Because the measured oscillation is out of plane, pseudo-vibrations caused by speckle noise do not explain the distortion. Instead, the distortion appears to be caused by the optics of the microscope.

Keywords: Velocimeter, vibration, harmonic distortion

1. INTRODUCTION

For about two decades, laser Doppler vibrometry (LDV) has been used to measure the vibration of various structures because of its many advantages, such as non-contact measurement, high signal to noise ratio, ease of acquiring area mode shapes, etc... For the last decade or so, LDV has also been used with microscopes for measuring vibrations of micro-scale structures. In this realm there are few other methods, if any, that are capable of measurements with similar resolution, accuracy and ease of use.

It is important to ascertain that the velocity signal produced by the LDV is accurate. On the macro scale, one can verify this by comparing the LDV velocity signal with, say, the time-integrated signal produced by an accelerometer. Previous studies have shown that the two signals correlated very well, in fact, calibration laboratories often use LDVs to calibrate accelerometers, because the frequency shift in the Doppler signal can be tied to the velocity of the vibrating structure using first principles.

On the other hand, recent experiments have suggested that the use of a microscope may distort the LDV measurement. This is thought to have been a major hindrance in the Authors' previous work in which nonlinear system identification was applied to a MEMS system [1]. Figure 1 shows a sample response from [1] that may exhibit spurious harmonic distortion. The motion of a MEMS cantilever, forced to vibrate at 82 kHz, was measured with an LDV, focused through a 20X objective lens. The actual average velocity signal is shown over one cycle (bottom) as well as the integrated (middle) and differentiated (top) velocity. The physical reason for this MEMS system to exhibit this kind of velocity dependent nonlinearity is yet unknown. Part of the nonlinearity may have been an artifact of the LDV. This paper

* hsumali@sandia.gov

investigates the accuracy of a microscope LDV system by testing it on a simple setup, and shows that the LDV measurement may contain higher levels of harmonic distortion than their specifications lead one to believe.

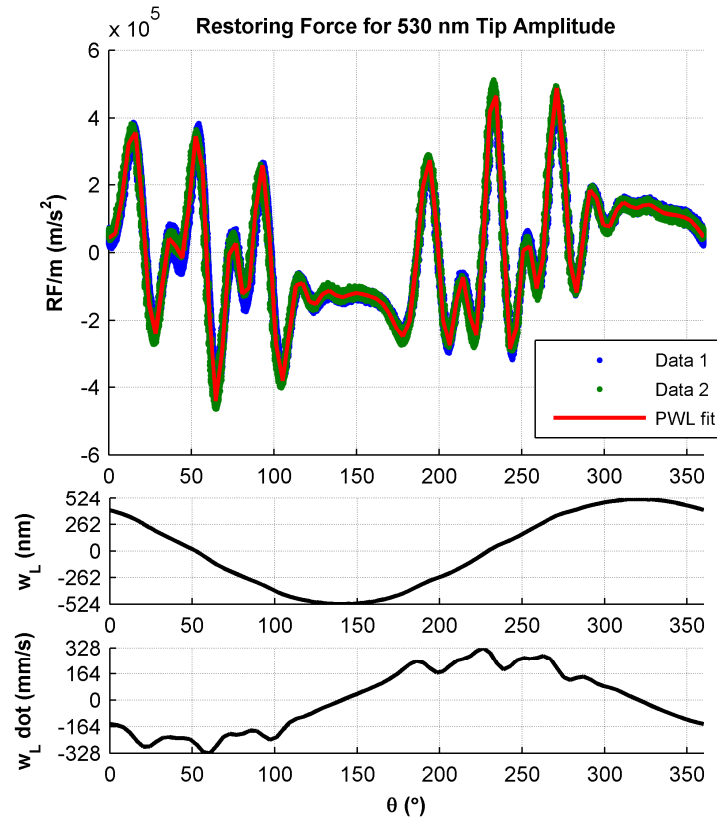


Figure 1: Measurements of a vibrating MEMS surface from [1] showing harmonic distortion measured using an LDV focused through an optical microscope. The signal was periodic with a frequency of 82 kHz, so only one representative cycle is shown. The dots show the measured, time-differentiated LDV signal, the lines show the averaged displacement (middle), velocity (bottom) and acceleration (top).

Laser vibrometer systems have improved significantly over the past few decades, and current commercial systems are commonly used and though to be trustworthy under most circumstances. One exception is when the velocity of a rough surface is measured and that surface is translating in plane. Rothberg noted that the LDV signal could become badly distorted if the surface velocity was large enough, and called the distortions “pseudovibrations” [2]. He showed that the surface roughness results in a speckle pattern that can modulate the intensity of the laser as seen by the LDV’s photodetector. While the vibrometer is somewhat insensitive to intensity modulations, the phase of the Doppler signal is also distorted, so the speckle pattern affects the demodulated velocity signal as well. The distortion that results is often called “speckle noise.” One important property of this noise is that the distortions tend to be harmonic if the motion of the structure is harmonic. They manifest themselves at the frequency at which the structure is moving in plane and may be significant out to the hundredth harmonic or higher [3].

Rothberg’s initial work contained a model for speckle noise that has been developed more extensively in subsequent works [3, 4]. The most recent work discusses how the transitions were approximated as speckles enter or exit the laser spot and showed good agreement with LDV measurements. Figure 2 shows a representative LDV measurement from a surface that was moving in plane (rotating at constant speed) but not vibrating from Rothberg [3]. The surface was rotating, so the surface roughness can be expected to be periodic with the rotational frequency of the surface and hence the speckle noise is also periodic. The fundamental speckle noise frequency is 31 Hz, and 12 other harmonics of varying amplitudes are also visible.

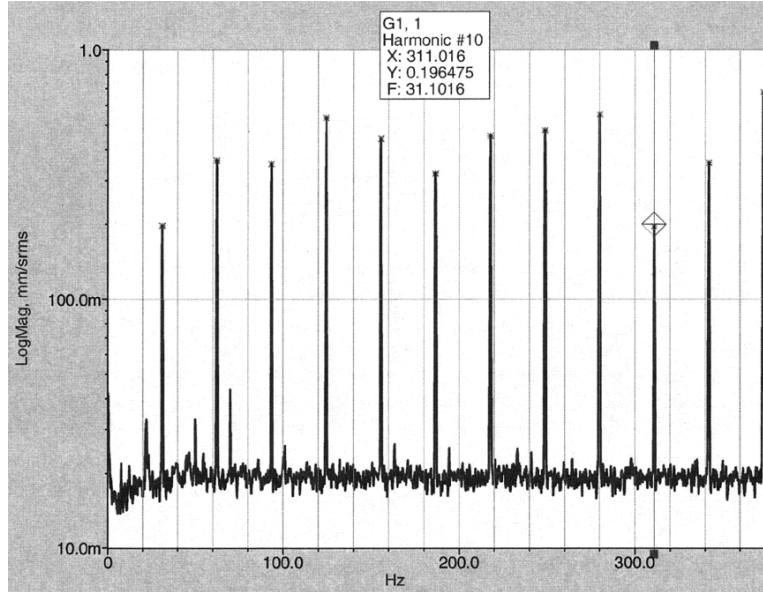


Figure 2: Spectrum of speckle noise from Rothberg [3]. This is an actual LDV measurement from a surface that was moving with constant velocity in plane but not vibrating significantly out of plane.

The harmonic distortions of interest in this work (shown later in Figure 6) have the same character as those presented by Rothberg, but the microscope LDV system of interest in this work does potentially have some significant differences. The laser beam employed in LDV is expected to be speckled whenever the surface of interest is rough on the order of the wavelength of the laser (typically hundreds of nanometers, 630 nm for the system used here). The size of the laser spot on the subject must also be large enough relative to the roughness of the surface so that the returning beam is speckled. Dainty provides a detailed discussion of the relationship between surface roughness and laser speckles [5]. Rothberg showed that the severity of speckle noise was related to size of the photodetector in the direction of the speckle motion. In principle, one can determine whether speckle noise might be a problem if the surface roughness and LDV properties are known.

Unfortunately, existing models for speckle noise do not seem to be applicable to the microscope LDV system of interest in this work. On the microscope LDV system, the laser passes through a lens with a much shorter focal length than on typical macro-scale systems. A geometric model would suggest that the laser beam enters the lens with a diameter of about 3mm and then focuses to a point at the specimen. Actually, the beam is diffraction limited as it approaches the sample, so the interaction of the beam with the sample is more complicated. The size of the laser spot depends on the wavelength of the illuminating light and the aperture of the lens. This work takes an experimental approach and presents a set of conditions under which a speckle noise type of harmonic distortion is observed for this particular LDV system. Future works will seek to develop analytical models for the observed phenomena.

2. EXPERIMENTAL SETUP

The experimental setup is shown in Figure 3. An LDV system was used to measure the motion of an accelerometer mounted on the top of an electromagnetic shaker. The LDV and Accelerometer signals were recorded simultaneously, so they represent the same motion. The shaker was carefully aligned so that the motion of the accelerometer was in the direction parallel to the laser beam. In-plane motion of the accelerometer should be minimal. The input to the shaker was sinusoidal at 503Hz, with an amplitude of about 200m/s². The laser beam was focused on the accelerometer through a microscope optical system in one setup. In the second setup the laser beam was focused on the accelerometer with a small lens at the end of the fiber, without a microscope.



Figure 3: An accelerometer was mounted on a shaker. The LDV laser beam sensed the velocity through the microscope optics. In a different test setup (not shown), the LDV laser beam sensed the velocity without a microscope.

The shaker was a B&K™ model 4809; the accelerometer was a PCB™ model 356A02 with a calibrated sensitivity of 9.74mV/g multiplied by a gain of 10 on its battery-powered signal conditioner. The microscope was a Mitutoyo™ M-Plan APO 5X magnification. The LDV was Polytec™ MSA 400 Micro System Analyzer, with a Polytec OFV552 fiber laser generator and a VD-02 velocity decoder set at a sensitivity of 25mm/s/V. The data acquisition system was a Polytec Data Management system. The sampling rate was 128kHz.

3. COMPARISON BETWEEN LDV SIGNAL AND ACCELEROMETER SIGNAL

Figure 4 shows the velocity signal measured by the LDV with a microscope (dotted line) and the time integral (with zero initial condition) of the acceleration measured by the accelerometer (solid line). The LDV measurement was taken using the MSA 400 vibrometer head with a 5X objective lens. The LDV velocity signal is fairly close to the time-integrated accelerometer signal, but the peaks of the two signals differ by more than the 1.5% linearity error specified by the LDV manufacturer [5]. Therefore, the error is not likely to be caused by the nonlinearity of the LDV itself.

The signals discussed in this paper are mainly accelerations. Accelerometers are routinely used for macro-scale vibration measurements, but for micro-scale measurements, the size of available accelerometers rules out their application. The LDV is the only practical instrument for many micro-scale applications. However, in many cases acceleration signals are required rather than velocity [1, 6]. For example, the acceleration of a discrete mass system is equal to its restoring force [7], so acceleration is sometimes sought to characterize the nonlinear restoring forces acting on a dynamic system. The only recourse is to estimate the structure's acceleration by differentiating the velocity signal produced by the LDV. (Rothberg et al. [8] have investigated the use of Laser Doppler Accelerometry, but instruments capable of this measurement mode have not yet become widely available.) As is commonly known, differentiation magnifies noise and inaccuracies. Figure 5 compares the accelerometer signal with the time-differentiated LDV signal. The harmonic distortion in the LDV signal has been greatly magnified by differentiation, so the two signals differ substantially. The lower plot shows a detailed view, revealing that the two signals agree most of the time, but that the LDV signal contains a number of short duration spikes in which it deviates wildly from the accelerometer signal.

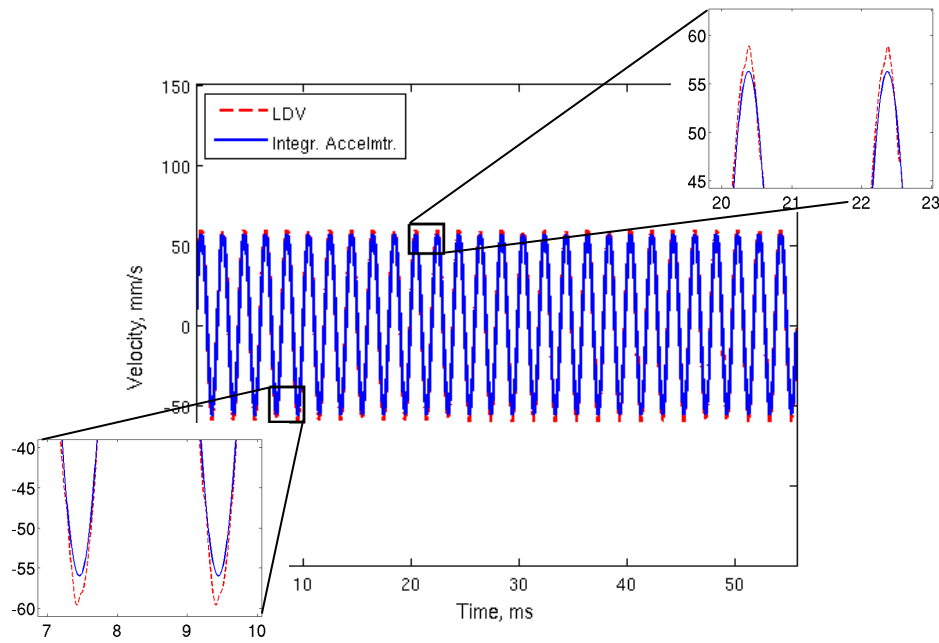


Fig. 4. The velocity signal from the LDV with a microscope compares quite well with the time-integrated accelerometer signal, except near the peaks where some distortion is visible.

The spectra of the two signals, shown in Figure 6 are also revealing. Some harmonic distortion is present in the Accelerometer signal, but all of the spurious harmonics are almost three orders of magnitude smaller than the intended acceleration. On the other hand, the differentiated LDV signal shows a number of harmonics that are 7% of the actual acceleration. These harmonics continue out at approximately the same level to the end of the bandwidth of the signal.

The measurements were repeated without the objective lens and the MSA head. In this case, the only lens employed was a small lens that attaches to the end of the LDV fiber, which produces a near collimated beam. Figure 7 shows the spectra of the LDV and Accelerometer signals. In this setup, the two signals are very similar, except for the first harmonic of the vibration at 1006 Hz.

Figure 8 presents a different view of the measurements. The differentiated signals of the LDV with and without the microscope are both plotted against the accelerometer signal. Over many cycles, each differentiated signal traces almost the same loop, indicating good repeatability. The dotted red line shows the differentiated LDV signal using the microscope objective, while the solid blue line shows the differentiated LDV signal when the microscope is not employed. The latter shows almost a one-to-one correspondence with the accelerometer signal. On the other hand, when the LDV beam passes through the microscope lens, the signal is greatly distorted. Interestingly, the worst distortion seems to occur when the acceleration is most negative. This corresponds to the largest positive displacements of the accelerometer, but the distortion begins when the accelerometer is near the equilibrium position. The velocity is minimum when the acceleration is maximum, so the velocity signal would be relatively small in the region where the distortion is worst. On the other hand, the velocity is also small when the acceleration is large and positive, so the discrepancy cannot be explained by small velocity alone.

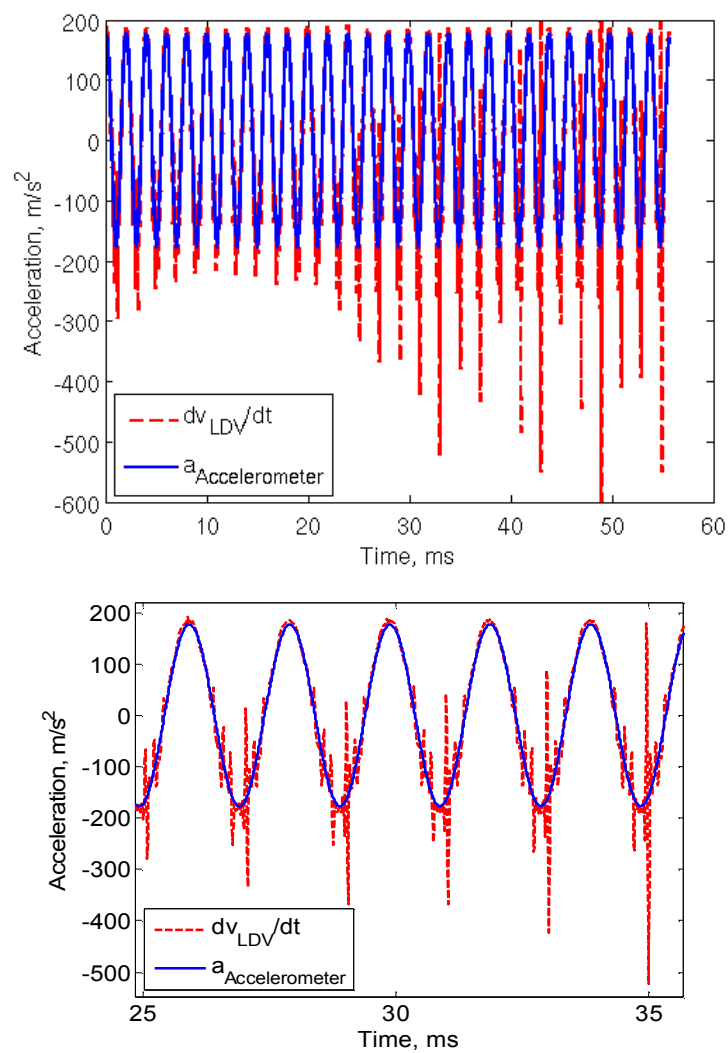


Fig. 5. The time-differentiated signal from the LDV with microscope is very different from the accelerometer signal.

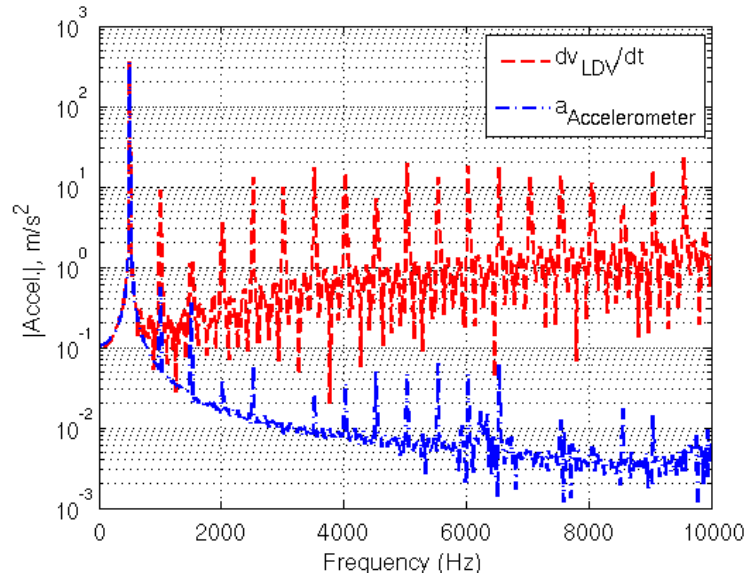


Figure 6: Acceleration obtained by time-derivation of signal from LDV with a 5X microscope objective (dotted curve) exhibits much greater harmonic distortion than the acceleration obtained by an accelerometer.

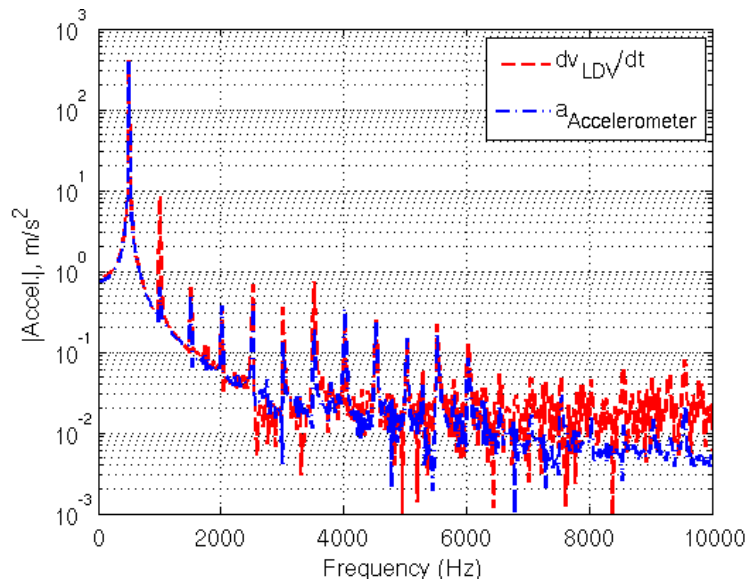


Figure 7: Acceleration obtained by time-derivation of signal from LDV without microscope. The harmonics of the time derivative of LDV signal roll off with frequency.

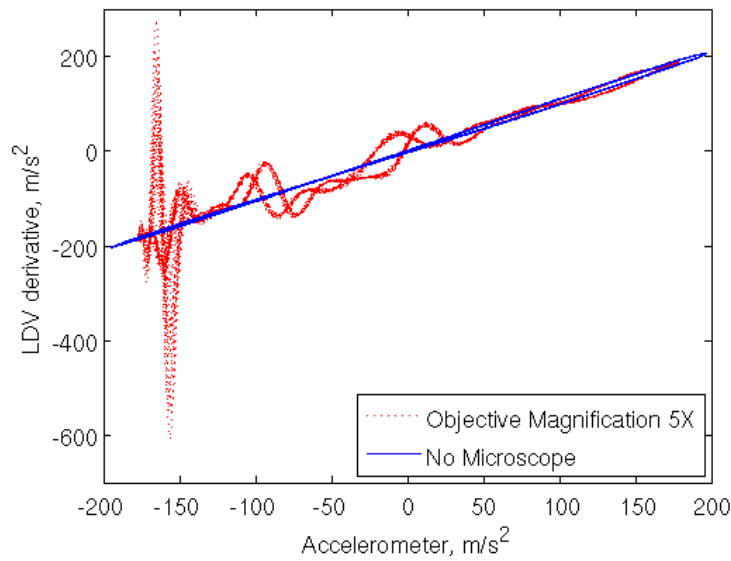


Figure 8: Time derivative two LDV signals compared to the Accelerometer signal at the same instants (accelerometer acceleration is shown on the horizontal axis, a straight line would be observed in the absence of any distortion.) The red dotted trace shows the LDV derivative when a 5X microscope objective is used, the blue curve shows the LDV derivative when the microscope is not used.

4. DISCUSSION AND CONCLUSIONS

This work has compared measurements obtained by a microscope LDV system with those obtained simultaneously by an accelerometer. The LDV measurements are seen to exhibit harmonic distortion that exceeds the manufacturer's specifications for nonlinearity, especially if the LDV signal must be differentiated to estimate the acceleration of the surface. Several inquiries were made with the LDV manufacturer regarding the measurements presented in [1], which had a similar character. The manufacturer repeatedly asserted that they were accurate, which is probably true of the LDV by itself. The results presented here indicate that the harmonic distortion obtained by the LDV exceeds the manufacturer's specifications only when the laser is focused through a *microscope* system. The distortion observed here was approximately 3.5% of the actual vibration, although the distortion in [1], obtained with a 20X objective was 10% or more. These distortions can be greatly magnified if the LDV signal must be differentiated, making the estimated acceleration very inaccurate. In this study, the distortion in the LDV signal was largest only when the acceleration was near zero or negative.

One potentially important difference between the measurements obtained with and without the microscope head is the fact that the laser spot is much larger when the microscope head is not used. If one assumes that the photodetector collects most of the laser light in both cases, then one would expect that there would be far more speckles in the reflected beam when the microscope is not used, and so the laser light might be affected less dramatically when a bright speckle enters or exits the photodetector. The signals presented in this paper exhibit the harmonic distortion that seems to fit the characteristics of speckle noise. However, one would expect that there is little, if any in-plane motion of the sample; every effort has been made to assure that there was none. Furthermore, the signal obtained without the microscope does not seem to be strongly affected by speckle noise, confirming that the surface is probably not moving in plane. There does not seem to be any reason for speckles to enter or leave the spot illuminated by the laser due to in-plane motion. The same was true of the MEMS system in [1], and the surface there was very smooth on the order of the optical wavelength, so there is not any reason for the beam to be significantly speckled.

Another important difference between the two setups is the focal lengths. The microscope has a very short focal length (20 mm), while the focal length of the beam in the other setup is very large (the beam is nearly collimated). The focal depth of the 5X objective is 14 μm . The amplitude of the displacement of the surface is about 17.4 μm , which exceeds the depth of focus. Such a large motion may cause a harmonic distortion that resembles speckle noise. An indicator bar on the fiber laser generator indicated that the strength of the signal returning to the vibrometer remained very good

throughout the measurement, so one would hope that the signal would remain strong even if the amplitude of the motion is large relative to the focal depth of the objective lens. However, it is possible that the indicator bar shows a time-smoothed signal strength and does not show short drops of signal strength. With the short focal depth of the microscope, the moving surface possibly moves out of focus repeatedly but for short durations. Even though the velocity history in Fig. 4 shows no clear sign of a drop in signal strength, the acceleration plots in Figs. 5 and 8 suggest that some form of signal degradation may have occurred at positive displacement (negative acceleration). The worst distortion occurred around the highest positive displacement.

The harmonic distortion discussed here is different from the measurements that the authors presented in [1], some of which are repeated in Figure 1. In [1], significant distortion occurred when the displacement was 500 nm or less compared to a depth of field of 1.6 μm . The laser signal strength was excellent at zero displacement where the LDV was focused. Therefore, the harmonic distortion in [1] could not be attributed to the test object going out of focus. Most of the harmonic distortion in [1] may be attributed to non-sinusoidal motion of the structure itself around zero deflection, not to the nonlinearity of the microscope LDV. On the other hand, the distortion in the present case is worst around the highest deflections, suggesting that the test object may move out of focus.

Beyond the above conjecture, the true cause of the harmonic distortion when a microscope is used with the LDV is still subject to research. This paper attempts to raise awareness to that issue, and to stimulate the interest in the vibrometer and MEMS testing communities to more fully explore the issue and to come up with a solution.

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