Dynamic MEMS Measurement Using a Strobed Interferometric System with Combined Coherence Sensing and Phase Information

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1. INTRODUCTION

While computer modeling of MEMS systems is becoming increasingly sophisticated, the delicacy and complexity of many MEMS components requires accurate metrology of the final devices to assure proper performance. Stiction, motion versus drive signal, shape changes during actuation, angular repeatability, and resonant frequencies are all items of interest. By obtaining topographic information as the drive signal phase, frequency, and voltage are varied, MEMS devices can be fully characterized over their range of operation. Strobed holographic interferometry has been employed for more than 25 years to characterize a variety of vibrating structures.[1] Only recently, however, has strobed illumination been combined with more sophisticated interferometric techniques to produce quantitative data for a large class of moving devices.

Phase-shifting interferometers and white-light profilers have gained popularity in measuring surface topology due to their generality, speed, and accuracy.[2] Phase shifting interferometry (PSI), produces topographic data with extremely low noise and high accuracy, but is limited in that height and slope of the surface to be measured must be less than one quarter of the source wavelength from pixel to pixel to avoid errors; typically the point-to-point height change limit is about 160nm. Coherence sensing interferometry, also known as white-light or vertical scanning interferometry (VSI), is based on the detection of the peak contrast of fringes which are narrowly localized about the plane of best focus. VSI techniques avoid the height and slope limitations of PSI methods, measuring steps of up to 8mm[3], but typically sacrifice some accuracy and noise rejection. The two techniques, however, may be combined for relatively smooth surfaces with large discontinuities, in a method known as enhanced VSI (EVSI), to obtain the benefits of both methods simultaneously[4]. MEMS devices are generally ideal surfaces for this combined technique, as individual features are generally high-quality, but with large steps or gaps between regions.

2. STROBED ILLUMINATION INTEGRATION FOR MEMS METROLOGY

Measuring even a slightly vibrating structure with any degree of accuracy is difficult with a standard optical profilometer configuration. The interference pattern to be measured will blur or distort even at low frequencies and amplitudes. The most common error associated with small vibrations is print-through of the interference fringes into the calculated surface shape, as shown in Figure 1. Thus, standard optical profilers can not accurately measure MEMS devices under actuation. However, by making the assumption that the vibrations are periodic and of primarily one frequency, which are generally design goals for MEMS products, one can use illumination strobed to match the MEMS drive frequency to effectively freeze the motion[5]. This permits standard scanning techniques and algorithms to be employed even on these moving devices.

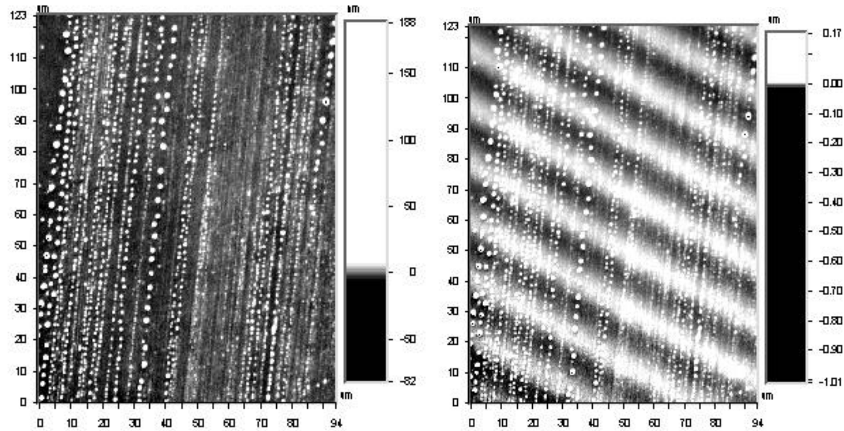

Figure 1. Measurement of a machined surface with (left) and without (right) motion of the test piece.

Traditional strobed illumination systems employed either pulsed lasers or varied the illumination with acousto-optic modulators or mechanical shutters. However, each of these techniques has limitations: laser illumination can lead to coherent imaging artifacts, shutters have relatively low maximum frequencies and are potential sources of vibration, and acousto-optic modulators are generally high in cost. Fortunately, recent advances in LED technology have dramatically increased their brightness; with proper integration into an optical system, they are now a viable light source for optical profilers. Also, with spectral bandwidths on the order of 30nm, LED's provide proper coherence length for EVSI techniques. Finally, rapid rise-times for LED's permit strobing at greater than one megahertz frequency, so most MEMS devices can be tested over their entire frequency range.

A standard arrangement for a white-light optical microscope is shown in Figure 2. The illumination source is traditionally a tungsten-halogen bulb, and is coupled into the system such that it best matches the various microscope objectives used to measure the test piece. The illumination is generally split in the microscope objective, with half the beam travelling to the device under test and the other portion to a high-quality reference surface. The reference surface is translated relative to the test surface, and the resulting intensity scans are analyzed using PSI, VSI, or EVSI techniques to calculate the surface profile of the device.

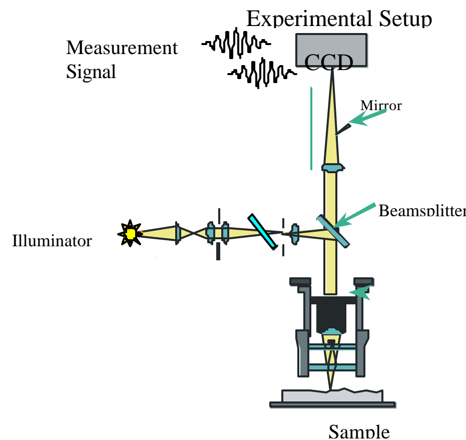

Figure 2. Example of a white light interferometer

To employ an LED as a strobed source for a profiler requires both careful selection of hardware as well as carefully designed software to allow efficient operation. Achieving light levels on the camera which nearly saturate it is important to maintain the quality of the surface measurement. The viewing angle of the LED must be carefully matched to the existing optical design, as even the brightest single LED's emit less than 35 candelas. By contrast, a 100W tungsten-halogen bulb emits approximately 30 times this amount.

Combinations of multiple LED's on one chip require higher currents and introduce potential pulse spreading and so are generally avoided for high-speed strobing. Thus, the optical system design becomes critical for ensuring sufficient light at high magnifications using a single LED source. The system employed in the final MEMS interferometer uses a modified Kohler illumination scheme, to allow for high efficiency and nearly uniform illumination.

While an efficient optical design is critical, the amount of light which strikes the test sample may be increased further by overdriving the pulsed LED beyond the normal maximum current or by lengthening the duty cycle of the pulse. However, higher drive currents require lower duty cycles to avoid overheating the LED, which is their primary failure mode. In addition, increasing the duty cycle of the illumination can lead to blurring of the resulting image, and this can lead to errors in the surface shape calculation. These two factors must be carefully balanced in the drive software such that good results are achieved.

3. EVSI TECHNIQUE WITH STROBED LED OPERATION

While the EVSI technique, which combines phase calculations and coherence peak sensing algorithms, provides high accuracy and large dynamic range, there are sensitivities to the technique which must be addressed in a MEMS measuring system. One potential source of error is having a known wavelength of the source under different operating conditions. Another is ensuring a known scanner speed throughout the scan, a requirement for accurate PSI, VSI, and EVSI measurements.

Although LED's have relatively stable center wavelengths, like tungsten-halogen bulbs and other non-laser sources, the wavelength can drift significantly with temperature and operating current. Even a few nm change in effective wavelength on a MEMS device with 100μm steps, could lead to several hundred nanometers of error. This is significantly higher than the noise floor of most optical profilers, which is generally a few nanometers or less. Combined phase and coherence sensing techniques are often more sensitive to wavelength errors, with print-through of the interference fringes when incorrect wavelengths are used. Similarly, errors in the scanner speed during the scan, or from one measurement to the next, will cause erroneous results. While either a known wavelength or scanner speed can be used to calibrate the errors in the other, one of the variables must be determined to ensure the best measurements.

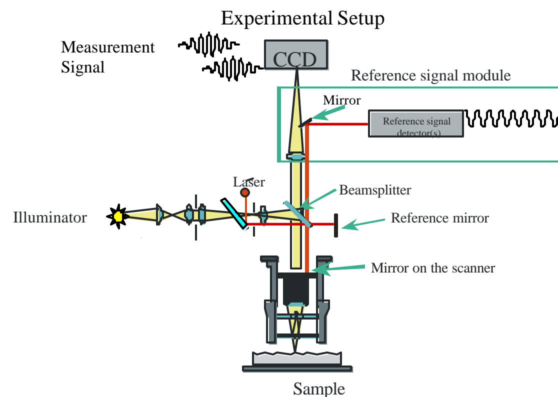

Figure 3. White light interferometer with internal reference signal.

Common methods for creating known correct scanner steps for PSI measurements is to employ a well-characterized narrow-band filter in the system, and use the known wavelength to adjust the scanner until steps of the correct phase difference are generated. Similarly for VSI measurements a high-quality step is measured, with the scanner speed adjusted until it measures accurately. Both techniques produce acceptable results on many parts, but suffer from effectively using the average scanner step for their calculations. Also, both calibrate the system only over one range of the scanner motion, and measuring parts at different points of the scanner's range can lead to errors.

For production systems, or ones where correlation and accuracy tolerances are tighter, it is possible to integrate a second interferometric signal into the instrument to perform real-time calibration of the scanner wavelength[3]. Such a configuration is shown in Figure 3. Such a system allows for accurate determination of the scanner motion over any range, and also can use the wavelength of the laser to ensure the effective wavelength is properly known for any scan. Thus, nanometer-level accuracy and system-to-system correlation are maintained for any surfaces within the scan range of the profiler.

4. EXPERIMENTAL RESULTS

A variety of devices were measured using strobed illumination for an optical profiler. Figure 4 below shows a representative measurements of an in-plane resonator provided by Sandia National Laboratories. The plot on the right shows translation of the large center section at various frequencies of actuation, but constant voltage and phase. The greater deflection at 4500 Hz represents a resonant frequency of the device. By stepping through various combinations of frequency, amplitude, and phase, MEMS devices can be completely characterized. Other plots of interest show step response of devices, translation vs. voltage for linearity calculations, and shape calculations to examine deflections in the device under the stress of actuation.

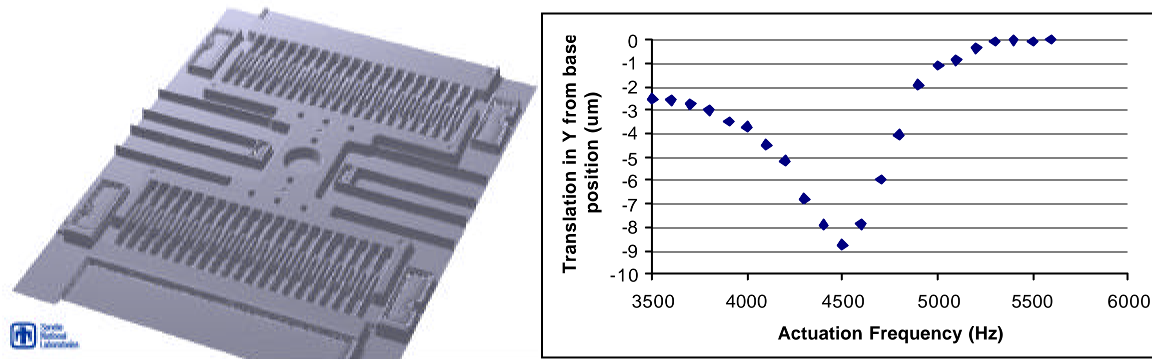

Figure 4. Left: in-plane resonator as measured using strobed interferometer, actuated at 4000Hz. Right: plot of translation vs. frequency at a 45 degrees phase, showing 4500 Hz resonant frequency. Resonator is courtesy Sandia National Laboratories, SUMMiT ™ Technologies, www.mems.sandia.gov

4. CONCLUSIONS

As more types of MEMS devices move from the laboratory to full production products, metrology for quality control and process yield improvement becomes increasingly important. Creating a system with the hardware and software required to measure these devices rapidly and accurately in a static state and during actuation is critical. Through careful opto-mechanical design and thorough software control of the strobing and device motion, an interferometric optical profiler can provide the required flexible, high-accuracy measurements needed for full MEMS characterization.

5. REFERENCES

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