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MEMS METROLOGY USING A STROBED INTERFEROMETRIC SYSTEM

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Abstract − Accurate measurements of MEMS surfaces, geometries and motions are crucial to achieving the desired performance of the devices. The wide variety of MEMS devices in development and production requires very flexible metrology for single-platform characterization. In addition to having greatly varying geometries, devices must also be characterized statically and under actuation.

White-light interferometry, fortunately, is a technique flexible and accurate enough to meet MEMS metrology needs. This high-speed, non-contact measurement method allows both large lateral and vertical ranges with nanometer-level vertical resolution and positional accuracy. When standard illumination is complemented with strobed light, dynamic measurements of MEMS can also be carried out.

This paper presents some of the hardware and software design considerations for producing a single metrology platform with the required flexibility for production MEMS metrology. Several static and dynamic MEMS measurements are presented to illustrate the design requirements.

Keywords: interferometer, surface metrology, profilometry, MEMS, white-light scanning, phase-shifting

1. INTRODUCTION

Accurate measurements of MEMS surfaces, geometries and motions are required to achieve proper performance[1,2]. As MEMS devices continue the move from laboratory experiments to full production devices, achieving acceptable yield requires not only adequate modeling of device performance before fabrication, but robust testing of the devices in production. The large variety of MEMS devices, including pressure sensors, accelerometers, gyroscopes, motors, and micromirror arrays, requires hardware and software that are extremely flexible in their ability to fully characterize the components.

Some measurement parameters are general across most MEMS devices, such as surface shape and roughness or relative heights of features. Others are more appropriate only for some components, such as radius of curvature changes for micromirror arrays, diaphragm radii for pressure sensors , trench depth and width for microchannels, or relative heights of interleaved cantilevers for accelerometers. In some situations, particularly in arrayed devices such as spatial light modulators, the positions of each component with respect to other components on the device in all three dimensions must be calculated to assure proper functionality.

White-light optical interferometry is one of the preferred methods of precision surface characterization. [3] This non-contact technique offers vertical ranges of up to 8mm and vertical scan speeds of over 100µm/sec[4]. Fields of view range from 60µm to over 10mm, accommodating a wide range of parts sizes; multiple measurements may also be stitched together for large-area, high lateral resolution characterization. Further, these instruments are available anywhere from low-cost manual configurations to fully automated systems with staging and wafer handling capabilities, to meet nearly any required volume of measurements.

The challenge for such instruments in MEMS-related measurements is two-fold: achieving measurement of not only static devices but also of moving parts, and creating a software and hardware design flexible enough to meet the needs of a large variety of devices.

2. DYNAMIC MEASUREMENTS USING STROBED ILLUMINATION

Measuring even a slightly vibrating structure with any degree of accuracy is difficult with a standard optical profilometer. The interference pattern to be measured will blur or distort even at low frequencies and amplitudes, since vibration is one of the principal sources of error in these instruments.. 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.

Because of this sensitivity to vibration, standard optical profilers can not accurately measure MEMS devices under actuation. However, by making the assumption that the vibrations are periodic, as when the device is tested with a known waveform, one can use illumination strobed to match the MEMS drive frequency, effectively freezing the motion[5]. This permits standard scanning techniques and algorithms to be employed even on moving devices. By stepping the device through it’s operating voltage and frequencies, and varying the relative phase of the strobe and device drive signal, complete characteristics of its motion including resonant frequency, step response, lateral motions, and deformation may be obtained.

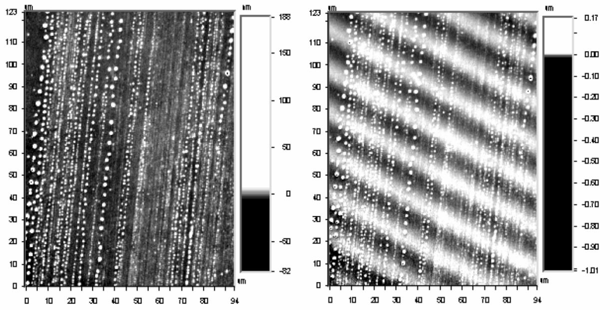

Figure 1. Measurement of a machined surface with (left) and without (right) motion of the test piece.

Traditional strobed illumination systems employ either pulsed lasers or vary the illumination with acousto-optic modulators or mechanical shutters[6,7]. However, each of these techniques has limitations. Laser illumination can lead to coherent imaging artefacts and makes use of white-light algorithms inaccurate; shutters have relatively low maximum frequencies and are themselves potential sources of vibration; acousto-optic modulators, meanwhile are generally high in cost.

Fortunately, LED's have many preferred properties for strobed illumination. Recent advances in LED technology have dramatically increased their brightness; with proper illumination optics, 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 phase shifting calculations, standard white light profilometry techniques, and combined phase and coherence sensing methods. 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. Finally, low cost and 100,000 hour lifetimes make them attractive from a cost standpoint.

A schematic of a white-light optical profiler with integrated LED illuminator is shown in Figure 2. The standard source, much brighter than the LED, is retained to allow measurement of extremely rough surfaces. The illumination is 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 various techniques to calculate the surface profile of the device[8].

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 are possible, but 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.

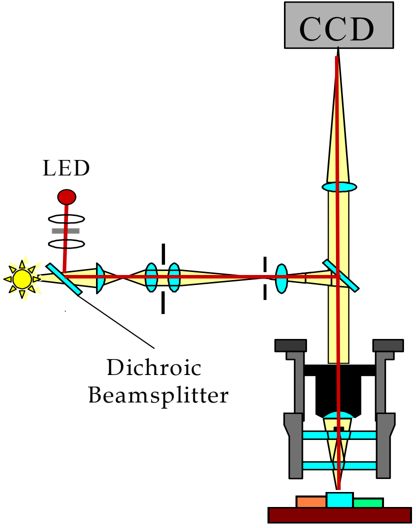

Figure 2. Example of a white light interferometer

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, and the LED is not overdriven to the point of device failure.

The final challenge for strobed illumination integration involves properly synchronizing the strobed light with the measurement scan. For optical profilers, it is important that each camera frame encompass the same amount of scanner motion, or that motion be known and corrected. With strobed illumination during a measurement scan, if the strobe frequency and camera frame rate are not matched, some frames of data will contain different numbers of pulses than others. At high speeds, over 1kHz or so the effect on the measurement is minimal. However, at slower speeds, the camera must be properly triggered with respect to the strobe and the scanner speed adjusted to ensure equal numbers of strobed pulses per camera frame. Without this synchronization, height errors of up to 10% on an 8µm step were observed when employing strobed illumination.

3. SOFTWARE FOR MEMS CHARACTERIZATION

3.1. Template Based Analysis Software

White-light optical profilers, due to their speed, accuracy, and flexibility, have been employed in numerous metrology applications, from surface roughness calculations on chocolate, machine-part wear characterization, to thick film calculations in the semiconductor industry. As such, there is a large variety of parameter calculations available to handle most standard surface metrology. Several aspects of dynamic MEMS metrology, however, require enhanced capabilities for proper part characterization.

Foremost among these capabilities is the need to segment surfaces in an intelligent and efficient manner. For instance, Figure 3 below shows a three dimensional output plot from a Veeco NT1100 profiler measurement of a MEMS pinwheel. Parameters of interest may include the roughness of each of the raised sections, the relative position of the sections, the roughness of the bottom later, and the heights of each section with respect to each other and the bottom surface. Ideally, calculation of each of these parameters would be automatic, and insensitive to potential errors in lateral positioning or rotation due to how the device is placed within the field of view.

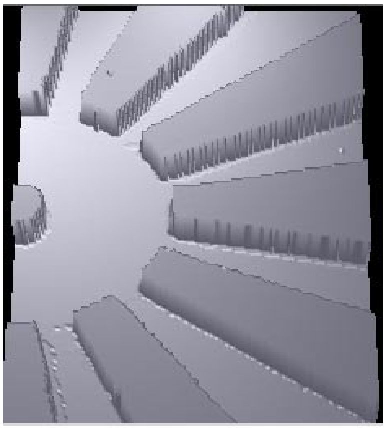

Figure3. Portion of a MEMS pinwheel.

One way to accomplish such automated calculation is to employ template software which will automatically segment and align a part to a known orientation. First, a good part is measured or ideal measurement mathematically created. This data is segmented into islands based on slope, separation, or intensity, shown in Figure 4 for the pinwheel. Unique alignment features are chosen manually or automatically, with potential for further masking data. Last, the segmented islands are placed into analysis regions which comprise one or more islands. Various analyses can then be chosen for each region independent of the others. When a measurement is taken in the future, the part is automatically aligned, masked, and analyzed based on the predefined part template.

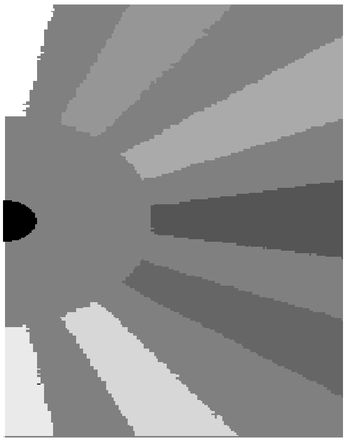

Figure 4. Segmentation of the pinwheel into different data islands.

3.2. Calculations of MEMS Properties Across Multiple Measurements

Another unique aspect to MEMS metrology is the requirement to calculate parameters not only from a single measurement, but across many measurements, encompassing varying frequencies, voltages, and phases. While any calculated parameter can be logged to a database, in order to fully characterize a device, parameters must be tracked with respect to the drive signal. For instance, Figure 5 below shows a static measurement of a MEMS resonator device, (resonator provided by Sandia National Laboratories). While linewidths, roughness, relative heights, spacings, and tilts are important, it is also important to understand the surface shape and motion properties at various frequencies, voltages, and phases of actuation.

One key parameter related to dynamic calculations is resonance frequency. The device is measured at various drive frequencies with fixed amplitude and phase. Lateral displacement can be calculated using the template software described previously. For rapid visualization of performance, calculating displacement versus voltage or other database parameters in real time is required. Traditionally, parameters could be tracked and plotted as measurements are taken, but not one against another in a real-time manner. However, for MEMS metrology in a production environment, such calculations are required for rapid feedback into the process.

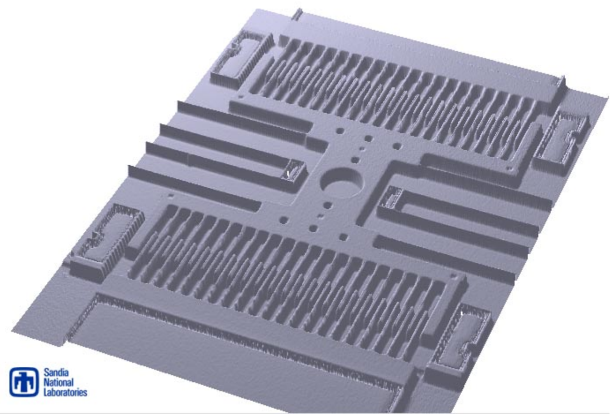

Figure 5: MEMS resonator device.

Two resonance frequency plots generated in this manner are shown in Figure 6, both taken on a Veeco NT1100 with strobed illuminator. Both devices were from the same wafer and die. Designed resonance frequency was 4kHz. Both devices show considerably higher resonance frequencies than the design, and differ from each other by 10%. In addition, one device translates a total of 9 µm while the other translates less than 7 µm. Rapidly assessing such differing properties is important to improve the overall production process.

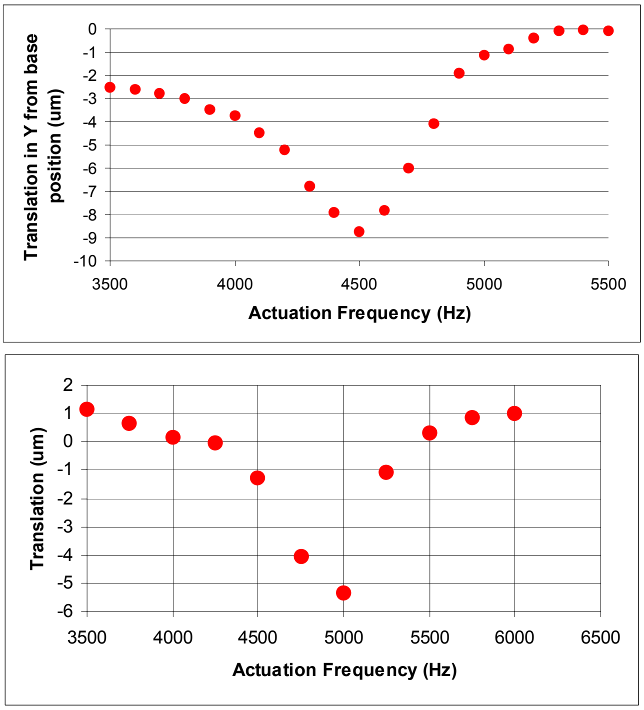

Figure 6: Motion vs. actuation frequency for two resonator devices.

3.3. External Software and Hardware Control

The last aspect of software to be addressed for ease of integration into production environments is the ability to integrate various hardware platforms and custom analyses. Often, a given MEMS device is to be tested on a specific hardware platform provided by the producer, rather than the drive electronics offered as an option with the optical profiler. In addition, due to either cost, time, or intellectual property considerations, it is not always feasible to have a the profiler manufacturer, code custom analyses into the base software.

Exporting data and performing separate analyses is a common solution to the software analysis problem. For hardware control, a non-integrated computer platform could be separately used, with limited communication with the optical profiler. Neither approach, however, allows for clean integration into a production environment where automation and ease of use are of high importance. Towards this end, it is important that the profiler software allow easy and rapid two-way communication with external software packages so that a single program can be used for all of the required functionality.

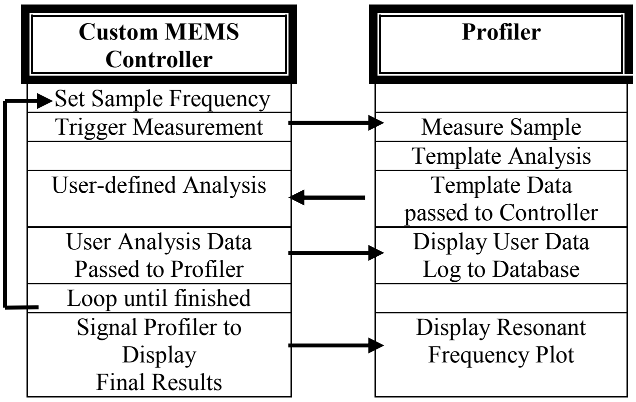

Figure 7: Flow chart showing possible implementation of TCP/IP interface. Communications between external world and profiler represented by center arrows.

The method chosen by Veeco to allow this functionality is to integrate a TCP/IP interface capability into the optical profiler. In this manner, a single software package can be used to control the profiler and separate hardware elements seamlessly. In addition, the profiler software has the capability of exporting data to programs such as Matlab®, allow the external program to perform separate analysis functions, and then receive back into the profiler code the analysis results.

Figure 7 presents a flow chart of one way in which this functionality could be used. With the external interface, results can be displayed, logged to database, and used in pass/fail evaluations without requiring the analyses actually be calculated in the main software package. This approach allows the maximum flexibility for the end user in terms of both how devices are controlled and evaluated. In addition, by supporting multiple hardware and software platforms, it is easy for the hardware features and calculations to be optimized as the production process matures, ensuring maximum value from the metrology tool.

4. CONCLUSIONS

As MEMS production capabilities improve, the variety of devices is steadily increasing. Each device has unique geometries and different parameters critical to its proper functioning. White light interferometric profilers present a highly general platform for surface metrology. However, both hardware and software changes are required to the standard commercial product in order to accommodate the ability to measure moving devices, and to analyze these devices in a highly flexible manner.

By employing strobed interferometry, with an LED as a pulsed source, one can effectively freeze the device motion and perform standard measurement scans on the object under test. Device actuation beyond 1MHz is achievable, and full characterization of the device can be accomplished by varying drive voltage, frequency, and phase.

A template-based software approach allows automatic segmentation of measurements such that different regions can be compared, and different calculations performed on each data island or group of islands. Allowing different measurement parameters to be plotted with respect to one another in a real-time mode allows rapid assessment of performance. Finally, implementation of a TCP/IP interface allows any hardware to be used as well as rapid implementation and changing of custom analyses to suit any given situation.

White light interferometric profilers offer sub-nanometer vertical resolution, customizable fields of view, high speed, and vertical ranges up to 8mm. In addition, the level of automation can be customized from a manual configuration up to systems including full wafer handling. With proper hardware and software, these tools can be customized to suite MEMS metrology needs in almost any production environment.

REFERENCES

[1] J.P. Blanc, M. Belleville, F. Mieyeville, and H. Bono, "Automatic evaluation of sensors geometrical parameters," Design, Text Microfab. MEMS MOEMS Symp Dig. vol 3680, '00 pp 94-102, Paris, France

[2] W. Hemmert, M.S. Mermelstein, D.M. Freeman, "Nanometer Resolution of Three-Dimensional Motions Using Video Interference Microscopy" , Proceedings of the 12th Annual IEEE International Micro Electro Mechanical Systems, Orlando, Flordia, January '99

[3] P. Caber, "Interferometric profiler for rough surfaces," Appl. Opt. 32, pp 3438-3441, 1993.

[4] J. Schmit, A. Olszak, "High-precision shape measurement by white-light interferometery with real-time scanner error correction," Appl. Opt. 41, pp 5943-5950, 2002

[5] R. Gutierrez, K. Shcheglov, T Tang; "Interferometric system for precision imaging of vibrating structures," US Patent 6,291,145, 2001

[6] Y. Nishikura, A. Torii, A. Ueda, K. Hane, "Transient Vibration Measurement of an Ultrasonic Motor Using Stroboscopic Phase-shift Interferometry" International Symposium on Michromechatronics and Human Science, 225-230, 1998.

[7] C. Vest, *Holographic Interferometry,* New York: Wiley, 1979

[8] J. Schmit, A .Olszak , "Some challenges in white light phase shifting interferometry," in *Interferometry XI: Techniques and Analysis*, Katherine Creath and Joanna Schmit, Editors, Proc. SPIE 4777, 118-127, (July 7-11, 2002)

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