Micro Motion Analysis System for MEMS Characterization

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ABSTRACT

Laser Doppler Vibrometry (LDV) is a widely accepted tool for dynamic characterization of MEMS. Using automated scan capability, the Polytec system can measure structural resonance and display out-of-plane deflection shapes with amplitudes down to the picometer level and frequencies to 30 MHz. By adding stroboscopic video microscopy for in-plane motion analysis, our combined Micro Motion Analysis (MMA) system is capable of three-dimensional dynamic characterization. The MMA system opens up new possibilities to measure in-plane actuators previously difficult or impossible for LDV measurements. To exemplify the use of this technology, we present characterization measurements on MEMS devices fabricated by Sandia National Labs SUMMiT V process. Multi-axis measurements reveal the complex motions exhibited by an electrostatic comb drive driven at resonance. Also, ultra-high resolution displacement measurements are made on passive cantilever structures oscillating under thermal excitation. Picometer resolution makes possible detection of these purely mechanical resonances. This study demonstrates the unique performance of our hybrid LDV / strobe video measurement system for quick, accurate, high-resolution dynamic response measurements.

Keywords: MEMS, laser Doppler vibrometer, mechanical, dynamic characterization, vibration, machine vision

1. INTRODUCTION

Use of LDV technology has been demonstrated as a valuable technique for non-contact, out-of-plane deflection measurements of MEMS devices\textsuperscript{1}. The advantages of LDV technology for microscope-based measurements are real-time analog output, high resolution (picometer), small spot size (\(\mu\text{m}\)), wide frequency range (MHz), wide dynamic range (160 dB) and high accuracy. With the scanning ability to automatically acquire, analyze and reconstruct complex vibration modes, the Micro Scanning Vibrometer (MSV) is an ideal tool for displaying out-of-plane deflections.

However, there has been one major limitation to the instrument. It has been difficult or impossible to measure in-plane motions since Doppler shift is derived from a velocity vector normal to the surface. Polytec has overcome this limitation by using stroboscopic video microscopy to measure in-plane motion of periodically moving structures. This expands the measurement capability to full 3-dimensional motion analysis. In this paper, we present a characterization study using this new Micro Motion Analyzer system on a test set of comb-drive resonators and passive cantilever structures.

2. POLYTEC MICRO MOTION ANALYZER SYSTEM

Both scanning laser vibrometry and stroboscopic video microscopy can be combined into a single setup. The basis of this hybrid system is to add a stroboscopic video imaging system to the already existing microscope-based scanning vibrometer. The schematic of this combined system is presented in Figure 1.

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Out-of-plane measurements are made using the Laser Doppler Vibrometer. Its principle of operation is based on Doppler shift measurements using a modified Mach-Zehnder interferometer. By coupling the laser beam into a microscope and using piezo-based scanners to position it in the x and y direction, the scanning LDV technique can be extended to full area measurement at the microscopic scale. Figure 1 shows a schematic of the scanning unit coupled to a microscope. Scan measurements are taken on a point-by-point basis to measure the velocity field of the structure. From this data, the operating deflection shape at any given frequency or time sample can be determined and displayed as a three-dimensional deflection shape.

Planar motions are measured by stroboscopic video microscopy. The system uses a special strobe unit that is connected to the c-mount of a microscope and couples the strobe light into the microscope beam path. A digital camera captures the strobe images to allow visualize rapid motions. Time resolution of the system is defined by the pulse width of the LED-strobe flash such that events can be recorded with a time period even shorter than the exposure time of the camera. Thus periodic motions out to 1 MHz frequency can be measured. The signal driving the specimen, the LED-strobe flashes and the camera exposure have to be accurately synchronized.

A data set of strobe images is obtained and pixel deviations among frames are determined by machine vision analysis. In-plane motion algorithms calculate the position shifts ($\delta x, \delta y$) of a user defined search pattern between successive images through correlation functions. The system automatically steps through user-defined frequencies, and image sets are recorded to obtain frequency response. Displacement versus phase delay data is extracted for every measured frequency automatically by employing image-processing techniques. Phase and amplitude are computed for every frequency record through a sine-function fit of displacement versus phase delay data.

3. COMB DRIVE MEASUREMENTS

The test subjects for this study are MEMS devices produced by Sandia National Laboratories SUMMiT V surface micro machining processes. To illustrate the capability of the Micro Motion Analyzer we characterize the in-plane electrostatic comb drive actuator. The comb drive resonator is illustrated in Figure 2 below.
The comb drive is electromechanically actuated by applying voltage to either of two comb electrodes on both sides of the center shuttle mass. The center mass is grounded through substrate connections and the electrostatic force pulls it towards the fixed electrode. Two sets of bifold springs anchored to the substrate provide a mechanical restoring force that pulls the shuttle back to its rest position when the voltage is removed. The natural frequency is given as

\[
\omega_d = \frac{1}{2\pi} \sqrt{\frac{E w^3 (1 - \zeta^2)}{\rho L^3 A_{\text{eff}}}}
\]

where E is Young’s Modulus of elasticity (165 Gpa), w is the spring width, \(\rho\) is the density, L is the spring length, \(\zeta\) is damping ratio and \(A_{\text{eff}}\) is the effective area of the shuttle, springs and truss determined by energy equivalence models.

### 3.1 Out-of-plane Measurements

Out-of-plane motion measurements are made first using Laser Doppler Vibrometry. Although the resonator is designed to move only in the in-plane direction, some residual out-of-plane motion exists that can be detected through the high sensitivity of the LDV sensor. The comb drive resonator is excited by a chirp waveform (i.e. fast sine sweep) out to a frequency of 500 KHz. The time response from the LDV analog velocity is sampled and Fast Fourier Transformed to reveal resonance frequencies. A complete frequency response for one point can be made in 25.6 milliseconds. By scanning the laser beam and sampling this response over measurement points on the area of the shuttle, the operating deflection shape measurement is made in less than 11 seconds. The results are shown in Figures 3 and 4 below.
The result reveals a fundamental resonance at 5 KHz, as well as some higher order resonance modes at 340 and 440 KHz. Three-dimensional animations resulting from the scan show operating deflection shapes for the structural response. The deflection shape for the fundamental resonance at 5 KHz is shown in Figure 4. Bending modes of the shuttle at the higher 340KHz and 440 KHz frequencies are determined by similar scan measurements.

### 3.2 In-plane Measurements

In-plane measurements are made on the same comb drive switching to the stroboscopic system. Strobe measurement is limited to synchronized sine excitation and frequency response measurements are obtained by data intensive stepped sine video capture. Having determined the resonance frequency already with the LDV, the in plane measurement can be focused also at the 5 KHz frequency range. With a positive voltage drive signal set to a 5 KHz sine and 10 Volts peak, a data set of 15 strobe images is obtained and pixel deviations among frames are determined by machine vision analysis (Figure 5).

**Figure 5.** In-plane Analysis of MEMS comb drive actuator using strobe video microscopy.

**Figure 6:** Sensitivity Curve showing in-plane displacement (x) versus applied voltage (V).

A distinct feature on the shuttle (an upper, left corner highlighted by the inner box in the Figure 6 above) was chosen for shot-to-shot pattern recognition. A peak-to-peak displacement of 3.2 μm was observed for the x motion. Sensitivity measurements were performed to determine amplitude versus voltage. The force from electrostatic actuation is non-linear following a voltage-squared relationship. The sensitivity curve is shown in Figure 6 above with second order polynomial fit to show voltage square relationship.

A Bode Plot revealing magnitude and phase is determined from stepped sine measurements centered on the 5 KHz resonance frequency. Strobe video capture was performed for stepped sine waves from 2000 to 8000 Hz in 50 Hz increments. The same pixel x, y deviation is automatically processed for all saved images, and the Bode Plot for x direction is shown in Figure 7 below.
A dynamic model was fit to the data using the equations

\[ x(\omega) = 20\log \frac{A/1m}{\sqrt{(\omega_0^2 - \omega^2)^2 + 4D^2\omega_0^2\omega^2}} \]

\[ \phi(\omega) = \arctan \left( \frac{-2\omega\omega_0\zeta}{\omega_0^2 - \omega^2} \right) + \phi_{\text{offset}} \]

where \( \phi_{\text{offset}} \) is a slight phase offset and \( A \) is the amplification factor. From curve fitting, we obtained a resonance frequency of 5036.1 Hz and a damping factor of 0.062.

### 3.3 Transient Response

Dynamic characterization of the comb drive resonator is not limited to sinusoidal response measurements. Step response measurements are made to determine settling time dynamics. A comb drive resonator different than the one used in the sections above was actuated with a voltage step of 10 Volts. First, the out-of-plane response was measured on a single point of the shuttle. The result is shown in Figure 8 below. The comb drive responded deflecting upward 150 nm and ringing at a natural frequency of approximately 7 KHz. The comb drive undergoes damped oscillation as it settles into position.

The corresponding in-plane measurement taken by stroboscopic video microscopy is shown in Figure 9. The comb drive has a 5 um excursion and initially overshoots its settling position as it resonates at the same fundamental frequency. Both in-plane and out-of-plane measurements form a complete characterization of the step response of the actuator.
3.4 Analysis

From the measurements, the both z and x motions are characterized individually. The comb drives behaves predictably in the in-plane x direction using both sinusoidal and step drive signals. The peak, micron level displacements $x_{\text{max}}$ are proportional to $V^2$ as governed by the electrostatic force. While orders of magnitude smaller in the nm range, the out of plane motion is significant. Residual out of plane motion exists because of parasitic effects of the electrostatic fields interacting with the ground plane. This complicates the overall motion of what should ideally be a strictly lateral actuator.

Scan measurements reveal the complex movement of the resonator. The 3D animation of what is illustrated in Figure 4 shows a combination of vertical translation (lift) and torsion about an axis of rotation. The leading edge of the comb drive first lifts up 250 nm as it is pulled into the comb electrodes. The opposite edge of the comb drive lags the leading edge by a phase angle of 60 degrees and pulls itself up to 70 nm displacement. The phase lag produces the torsional movement of the comb drive. The axis of rotation is off center towards the far edge, approximately parallel to the furthest set of springs. On top of this, the axis of rotation translates up and down with 120 nm peak to peak amplitude and approximately 110 degrees phase lag.

4. CHARACTERIZATION OF CANTILEVER ARRAY

Part of this Sandia SUMMiT V MEMS die set includes an array of graduated cantilevers ranging in length from 100 to 1800 $\mu$m in 100 $\mu$m increments. Previous studies on these cantilevers include stress gradient measurements to characterize deformation caused by deposition and annealing steps, and anodic oxidation-induced delamination. Cantilever structures are often built to determine mechanical properties such as Young’s modulus of elasticity by measuring the resonance frequency. The modulus of elasticity E as a function of fundamental resonance frequency $f_1$ for a rectangular cantilever fixed at one end is given by

$$E = \frac{4 \pi^2 f_1^2 L^4 \rho}{I \lambda_1^3} \quad \text{with} \quad I = \frac{1}{12} WT^3$$

where $L$ is the length, $\rho$ is the density, $I$ is the moment of Inertia, $W$ is the width, $T$ is the thickness and $\lambda_1$ is 1.875.

The cantilevers are suspended above and grounded to the substrate poly0, and voltage applied to an electrode at the poly0 layer bends the electrode down. The first method of measurement was to apply the same broadband chirp waveform and observe the resulting FFT spectrum. The result was a disappointingly flat FFT response and it appeared that the cantilever was forced into oscillation at whatever frequency was applied. It was clear that this response was more electrostatic in nature than mechanical. Also, since cantilevers were suspended 6 microns above
the substrate, they were subject to considerable air damping. These factors made the typical method of dynamic characterization difficult.

Previous studies on cantilevers indicated that resonance can be excited by thermal oscillation alone. This is possible because this thermal kinetic energy of the low mass cantilever is sufficient to excite very small vibrations. These infinitesimal vibrations can be detected using our highest resolution digital displacement decoder capable of detecting movements down to the picometer range. Digital vibrometer measurements at the tip of the cantilever yielded a thermal noise spectrum that can be decomposed by a dynamic spectrum analyzer (Figure 9). These measurements were made for the poly3 cantilevers with 6 µm air gap. The spectrum of the poly3 400 µm cantilever is shown in Figure 10 below.

These measurements were performed for the poly3 cantilevers from 100 to 800 µm lengths. Squeeze film damping effects were determined by measuring the width of the resonance peak at –3dB (half-power method). Measurements at 900 µm length and beyond were difficult because the resonance frequencies were comparable to the background acoustic noise at low kHz frequencies. The results are graphed in Figure 11 below.

Figure 9: poly3 400 µm cantilever with laser measurement spot located at tip.

Figure 10: Thermal noise spectrum for poly3 400 µm cantilever showing resonance at 17.8 KHz.

Figure 11: Resonance frequency versus length for cantilever array. Squeeze film damping affects (Δf) are shown by red bars.
The resonance frequency $f_1$ is proportional to $L^{-2}$, as expected from Equation 4. More interesting are the effects on damping. The damping is much more significant for cantilevers due to the small 6 micron gap. Air molecules are squeezed more tightly in this constricted space and form a pressure gradient that strongly damps the movement. From fitting the data of damping versus length, the damping is proportional to $L^2$ with considerable damping for the longest cantilevers.

5. CONCLUSIONS

Laser Doppler Vibrometry is already an established non-invasive characterization tool for a multitude of MEMS applications. Our new hybrid MMA system uses the advantages of two measurement principles (vibrometry and stroboscopic video microscopy) and is state-of-the-art for dynamic characterization of MEMS. The real-time response capability of LDV allows use of fast broadband excitation for determining frequency response, rather than time intensive stepped sine techniques. Pre-characterization of resonance frequencies by LDV allows planar motion analysis of in-plane behavior “right on the spot” without the need to hunt around at discrete frequencies. Therefore, the MMA system offers an optimal solution for quick, accurate three dimensional vibration measurements of MEMS. Our experiments on the Sandia Comb Drive show the unique measurement capability of this combined system.

Furthermore, the unique high-resolution capability of the LDV is demonstrated by thermal noise vibration measurements of cantilevers. Picometer level vibrations are detected and correlated to device parameters, allowing mechanical characterization without use of any active excitation techniques.

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REFERENCES