# MEMS Geometry *and Vibrations*

**POLYTEC APPLICATION NOTES**

A Aerospace
B Audio & Acoustics
C Automotive
D Data Storage
G General Vibrometry
**M MEMS & Microstructures**
P Production Testing
S Scientific & Medical
T Structural Testing
U Ultrasonics

## Measuring 3-D Geometry and Vibrations on a MEMS Comb Drive for Model Verification

*Determination of 3-D dynamics and static topography is necessary for MEMS design revision and the verification of mathematical design models. Polytec has combined three measurement techniques for measuring surface topography and 3-D vibrations with one single setup. The MSA-400 Micro System Analyzer uses scanning laser-Doppler vibrometry for fast, broadband, out-of-plane dynamics; stroboscopic video microscopy for in-plane motion; and white-light interferometry for high resolution topography. These technologies are integrated into a compact, all-in-one measurement head. In this paper, we describe example measurements of in-plane and out-of-plane vibration spectra and static characterization of surface topography.*

### System Performance

The schematic of the MSA-400 Micro System Analyzer is shown in Figure 1. The integrated microscope system employs:

1. **Confocal scanning laser-Doppler vibrometry for the measurement of out-of-plane vibration patterns**
2. **Stroboscopic video microscopy for in-plane motion detection**
3. **White-light interferometry to measure surface topography**

For white-light interferometry, an interference objective is used. For in-plane and out-of-plane vibration measurements, the interference objective is exchanged with a bright-field objective by rotating the microscope's revolving nosepiece.

The white-light interferometer can measure surface profiles with a lateral pixel resolution as small as 129 nm. The vertical resolution can be as small as 200 pm (rms) for a single measurement and 30 pm (rms) for 50 averages at a vertical scan range of 250 µm and 0.25 % accuracy.

In-plane vibration measurements are performed using stroboscopic video microscopy and image processing. The time resolution of the system is defined by the pulse width of the LED strobe flash which is 100 nanoseconds.

**Polytec GmbH**
**Laser Measurement Systems**
**Application Note**
**VIB-M-05**

**July 2006**

Thus, periodic motions with frequencies up to 1 MHz can be measured. Amplitude resolutions of 1 nm can also be obtained.

Laser-Doppler vibrometry is a widely accepted tool for dynamic characterization of MEMS. Using automated scan capability, the Polytec system can measure structural resonances and display out-of-plane deflection shapes with amplitudes down to the picometer level and frequencies up to 30 MHz. All the advantages of this technology are realized for microscope-based measurements including real-time analog output, high resolution, small spot size, wide frequency and dynamic range, and high accuracy. The smallest spot size ($1/e^2$) for the confocal scanning laser-Doppler vibrometer is 900 nm. The rms resolution depends on the bandwidth.

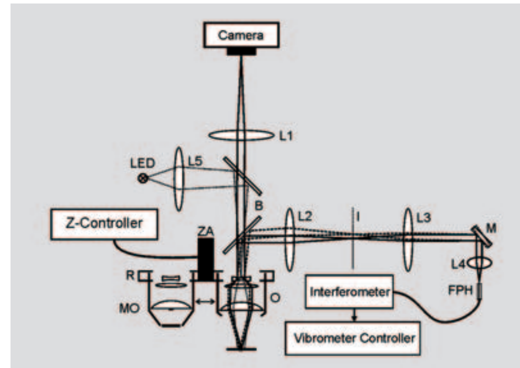



**Figure 1: Schematic of the MSA-400 measurement system. O is an objective; MO is a Mirau-interference objective; FPH is a fiber which acts as pinhole; L1, L2, L3, L4, and L5 are lenses; B are beam splitters; I is an intermediate image; R is the revolving nosepiece; ZA is a Z-positioning stage, and M is the scanning mirror.**

## The MEMS Comb Drive

Electrostatic comb drives are actuators where two interdigitated comb structures can be moved together or apart by applying voltage to either of the two comb electrodes.

The MEMS device under test (Figure 2) was fabricated by Sandia's SUMMiT V process.

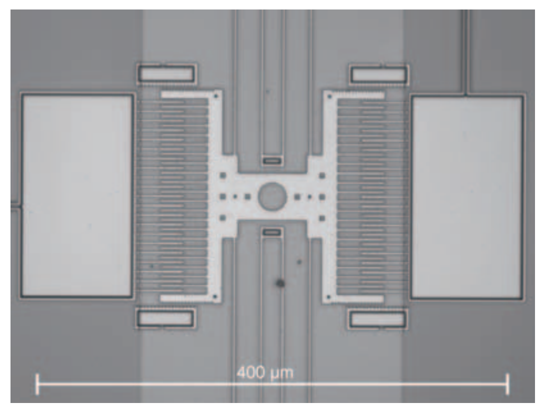



**Figure 2: MEMS comb drive actuator (courtesy Sandia Nat. Labs)**

Multi-axis measurements reveal the complex motions exhibited by the comb drive driven at resonance. Although the drive is designed for in-plane motion, the amount of residual out-of-plane motion is easily measured by laser vibrometry, giving a measure of the success of the design and manufacturing processes. The natural frequencies are determined by various parameters such as Young's Modulus, the mass density, the damping ratio and the geometry of the mass-spring system. As seen in previous studies, resonance modes are a sensitive indicator of repeatable geometry and material properties from fabrication processes. The comb drive was examined first using the MSA-400's scanning white-light interferometer. After that, out-of-plane vibration measurements were made using the laser-Doppler vibrometer mode. Focusing on the resonance frequency determined by laser vibrometry, in-plane measurements were made on the same comb drive using the stroboscopic system.

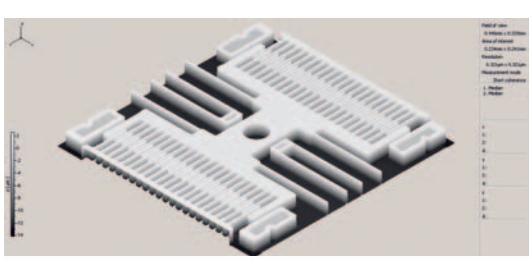


**Figure 3: Topography measurement of the comb drive; the area of interest is 234 µm times 241 µm**

## White-Light Measurement of Topography

Figure 3 shows a measurement performed with the white-light interferometer tool in the MSA-400 system on the comb drive actuator. Structure heights, shape and cross-section profiles on both rough and specular surfaces can be determined at high spatial resolution.

## Out-of-plane Motion Measurements

Out-of-plane motion measurements are made using laser-Doppler vibrometry. Although the resonator is designed for in-plane motion, some residual out-of-plane motion exists and can be detected with the high sensitivity of the vibrometer. The real-time measurement capability of the vibrometer allows the use of any suitable broadband, non-synchronized waveform source to drive the device.

In Figure 4, a resonance graph is shown which demonstrates the high amplitude resolution of the laser-Doppler technique. Using a white-noise signal to drive the device, the time response from the analog velocity is sampled by the vibrometer. A fast Fourier transformation (FFT) of the data using 12,800 FFT lines reveals resonance frequencies up to 20 MHz. This parasitic out-of-plane component of the in-plane motion has an amplitude < 100 pm and can be clearly identified.

By scanning the laser beam to 200 discrete measurement points on the shuttle, the operating deflection shape (ODS) measurement is made in less than 11 seconds.

In Figure 5, a snapshot from the ODS animation of the fundamental resonance at 5 kHz is shown. For a 10 V peak excitation, a 250 nm displacement amplitude is determined for the tip of the shuttle fingers.

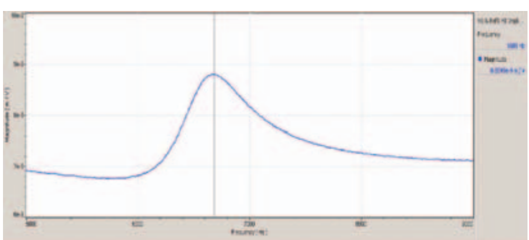


**Figure 4: Out-of-plane vibration spectrum**

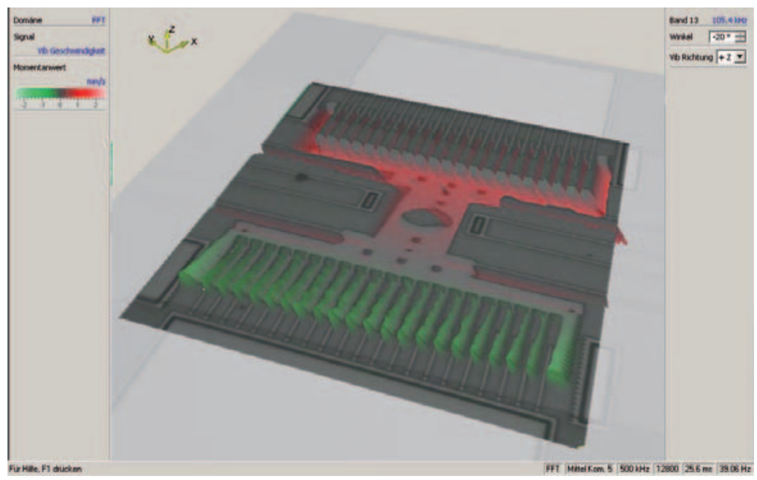


**Figure 5: 3-D ODS animation of the fundamental resonance at 5 kHz**

## In-Plane Measurements

Using the stroboscopic video system, in-plane measurements are made on the same comb drive. Using the parasitic out-of-plane resonant frequency quickly determined by the vibrometer, the in-plane measurement can be focused around 5 kHz avoiding the extra effort to search over a broad frequency range. Strobe video capture was performed for stepped sine waves from 2000 Hz to 8000 Hz in 50 Hz increments.
At each frequency, the position shifts (δx, δy) of a user defined search pattern (Figure 6) are determined using image processing with sub pixel resolution.

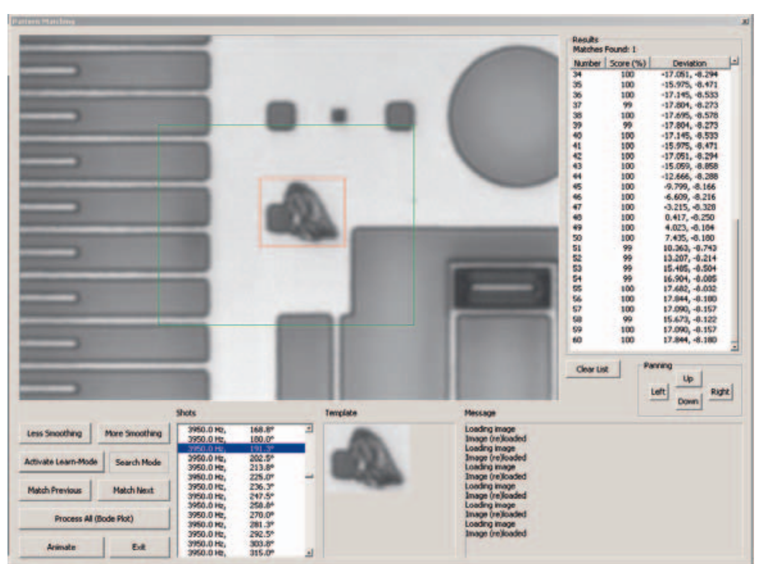


**Figure 6: Image processing determines in-plane motion parameters from stroboscopic video data (search pattern: red box; region of interest: green box)**

## Simple Example for Parameter Identification

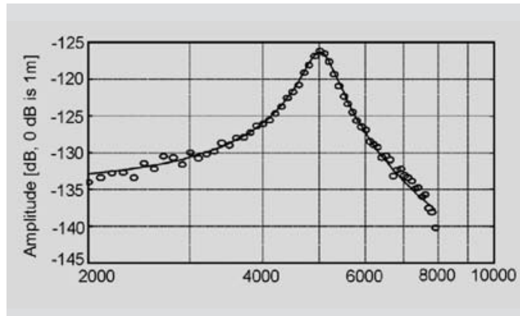
A Bode plot revealing magnitude and phase is determined from stepped sine measurements centered on the 5 kHz resonance frequency. Strobe video capture was performed for stepped sine waves from 2000 to 8000 Hz in 50 Hz increments. The same pixel x, y deviation is automatically processed for all saved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

Fitting the resonance curve from Figure 7 gives the resonance and the damping factor. A dynamic model was used to fit the data consisting of the following equations

$$\hat{y}(\omega) = 20\log\frac{A}{\sqrt{\left(\omega_0^2-\omega^2\right)^2+4D^2\omega_0^2\omega^2}},$$

$$\varphi(\omega) = \arctan\left(\frac{-2\omega\omega_0 D}{\omega_0^2-\omega^2}\right)+\varphi_{offset}$$

where $\varphi_{offset}$ is a slight phase offset, A is the amplification factor and $\hat{y}$ is the amplitude in dB (0 dB is 1 m).
From curve fitting, a resonance frequency of $f_0 = \omega_0/2\pi = 5036.1$ Hz and a damping factor of $D = 0.062$ were computed. This simple example shows that data obtained using the MSA-400 is suitable to determine model parameters from mathematical models by employing methods of parameter identification.



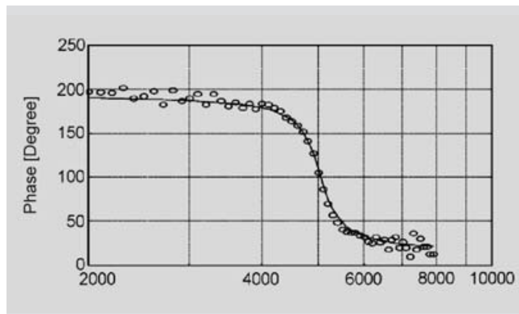




**Figure 7: Bode plots for amplitude and phase of x direction in-plane response determined by stroboscopic video measurement. Individual measurement points are shown (circles) along with the curve fit (straight line).**

## Conclusions

By fully integrating a microscope with scanning laser-Doppler vibrometry, stroboscopic video microscopy and white-light interferometry, the MSA-400 is designed with an all-in-one combination of technologies that clarifies real microstructural response and topography of MEMS devices.

Laser-Doppler vibrometry is an established tool for non-invasive characterization of MEMS devices. Its real-time response allows very fast broadband analysis of frequency response, rather than time intensive stepped sine methods. Pre-characterization of resonance frequencies by vibrometry allows planar motion analysis of in-plane behavior "right on the spot" without the need to hunt around at discrete frequencies. A simple example of parameter estimation by computing natural frequency and damping from an in-plane Bode plot measurement has been demonstrated.

In addition to this unique capability to measure MEMS and micro system dynamics, the MSA-400 Micro System Analyzer can also perform high resolution topography measurements on MEMS and micro-components. Incorporated in the MEMS design and test cycle, the MSA-400 provides precise 3-D dynamic and static measurement data that simplifies troubleshooting, enhances and shortens design cycles, improves yield and performance, and reduces product cost.

**For more information about Polytec Microscope-based Systems and their application to MEMS characterization, please contact your local Polytec sales/application engineer or visit our web page www.polytec.com/usa/microsystems**

**Polytec GmbH (Germany)**
Polytec-Platz 1-7
76337 Waldbronn
Tel. + 49 (0) 7243 604-0
Fax + 49 (0) 7243 69944
info@polytec.de

**Polytec-PI, S.A. (France)**
32 rue Délizy
93694 Pantin
Tel. + 33 (0) 1 48 10 39 34
Fax + 33 (0) 1 48 10 09 66
info@polytec-pi.fr

**Lambda Photometrics Ltd. (Great Britain)**
Lambda House, Batford Mill
Harpenden, Herts AL5 5BZ
Tel. + 44 (0) 1582 764334
Fax + 44 (0) 1582 712084
info@lambdaphoto.co.uk

**Polytec KK (Japan)**
Hakusan High Tech Park
1-18-2 Hakusan, Midori-ku
Yokohama-shi, 226-0006
Kanagawa-ken
Tel. +81 (0) 45 938-4960
Fax +81 (0) 45 938-4961
info@polytec.co.jp

**Polytec, Inc. (USA)**
North American Headquarters
1342 Bell Avenue, Suite 3-A
Tustin, CA 92780
Tel. +1 714 850 1835
Fax +1 714 850 1831
info@polytec.com

Midwest Office
3915 Research Park Dr.
Suite A-12
Ann Arbor, MI 48108
Tel. +1 734 662 4900
Fax +1 734 662 4451

East Coast Office
25 South Street, Suite A
Hopkinton, MA 01748
Tel. +1 508 544 1224
Fax +1 508 544 1225