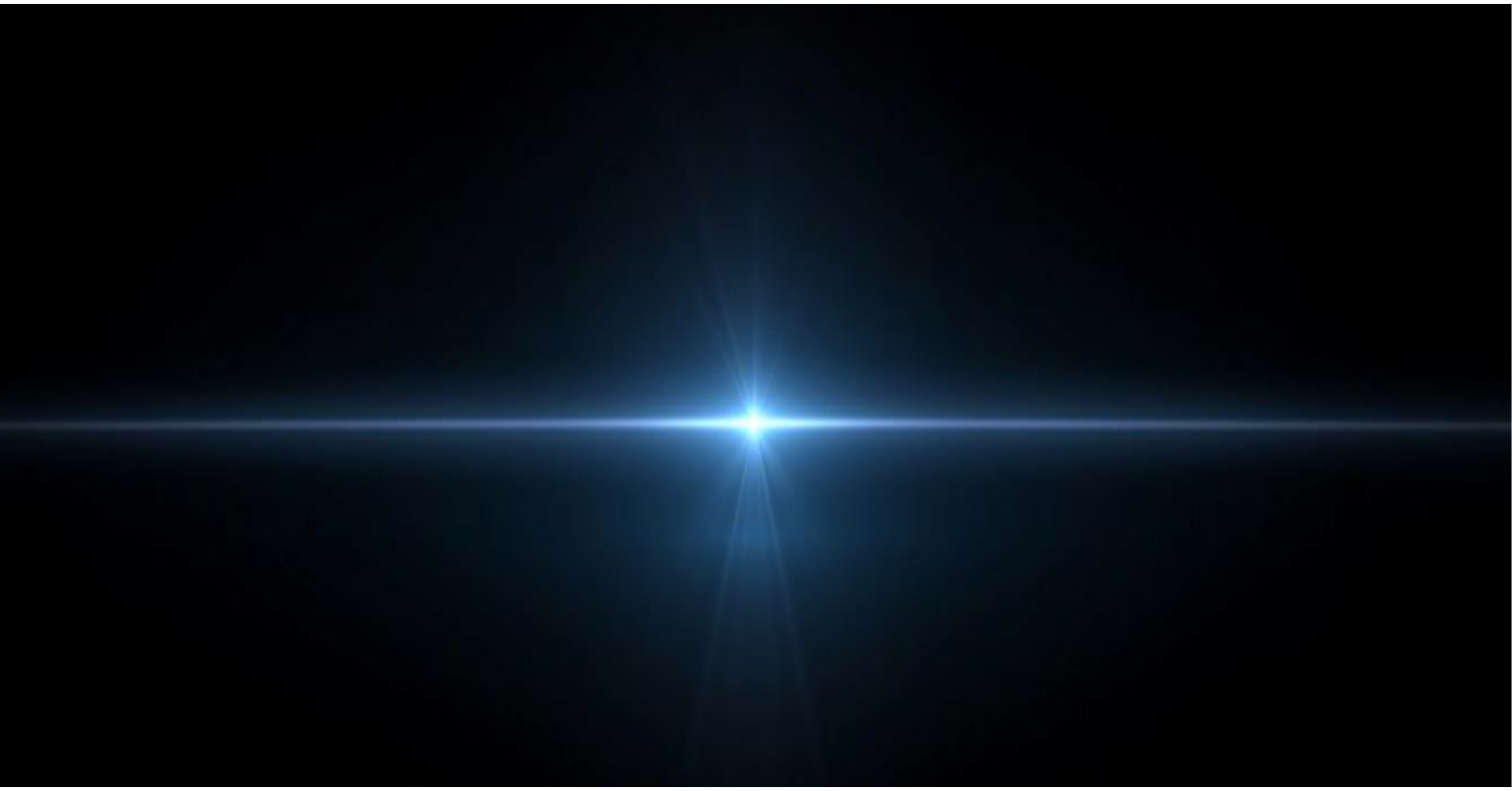

Characterizing Dynamics of MEMS Devices

Using Optical Measurement Techniques

Whitepaper

Abstract

Advanced optical measurement techniques are key for characterizing MEMS devices (microelectromechanical systems) during the development process. Electrical tests provide functionality tests, but do not provide complete measurements of physical properties. This paper details the state-of-the-art optical measurement capabilities available for full-field dynamic response and surface topography measurements of MEMS devices. This includes the use of laser Doppler vibrometry (LDV) that enables real-time dynamic response measurements with a resolution down below the picometer level and a frequency bandwidth up to 25 MHz. A range of characterization studies are presented that exemplify the use of this technology for micro mirror array, pressure sensor, cantilever beam and accelerometer applications.

Whitepaper topics

MEMS testing, characterization, dynamic response, vibration, resonance, settling time, displacement, deflection shape, micro mirrors, RF switches, cantilevers, inertial sensors, resonators, actuators, FE model validation, production test, surface topography.

About Polytec

For over 50 years Polytec provides high-technology, optical measurement solutions to researchers and engineers. Our commitment is to provide the most precise and reliable optical instruments and sensors available for non-contact measurement of vibration, length, speed, surface topography and for process analytics. Polytec instruments help to solve pressing application challenges in R&D, engineering and manufacturing quality and process control and help our customers to maintain the leading position in their field.

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Technology | Optical measurement systems

For characterizing MEMS devices optically, a wide range of measurement systems are available. This follows diverse technologies that are available to measure a wide range of physical properties (dimension, film thickness, step height, cross section, roughness, stress, stiction, modulus elasticity, response time, thermal expansion, resonance frequency, etc.…). For example, basic optical microscopy with digital image processing can provide dimensional analysis and measure deformations. More advanced optical measurement systems are tailored towards specific capabilities (3D shape measurement, dynamic response, high lateral resolution and / or high vertical resolution). Table 1 shows a comparison of commonly available techniques.

Table 1: Comparison of MEMS optical measurement tools

Technique	**Lateral Resolution** (typical)	**Vertical Resolution** (typical)	**Static Shape**	**Dynamic Response**	**Realtime Response**
AFM (Atomic Force Microscopy)	0.0001 µm	0.0001 µm	3D	No	No
SEM (Scanning Electron Microscope)	0.001 µm	-	2D	No*	No
OM (Optical Microscopy)	<1 µm	<1 µm	2D	No*	No
CM (Confocal Microscopy)	<1 µm	<0.01 µm	3D	No	No
WLI (White-light Interferometer)	<1 µm <0.01 µm **	<0.001 µm	3D	Yes**	No
DHM (Digital Holographic Microscopy)	<1 µm <0.01 µm **	<0.001 µm	3D	Yes**	No
SVM (Strobe Video Microscopy)	<1 µm <0.01 µm **	<1 µm	2D	Yes**	No
LDV (Laser Doppler Vibrometry)	<1 µm $<10^{-6}$ µm ***	$<10^{-6}$ µm ***	No	Yes	Yes

* *Dynamic response possible using video capture technique*
** *Dynamic response possible using strobe technique*
*** *Resolution for real-time dynamic response – not static*

The real-time capability of an LDV allows for measurement times approx. 6 orders of magnitude smaller than any method based on strobe techniques or offers for a comparable measurement time an amplitude resolution of approx. 6 orders of magnitude better.

Technology | Polytec optical measurement system

Polytec's optical measurement system specializes in dynamic response measurements. MEMS devices usually involve actively moving elements for sensing and actuation. Dynamic response measurements provide critical information that cannot be determined by electrical testing alone. Examples of dynamic response measurements include settling time dynamics of micro mirrors, displacement amplitudes of resonators and resonance frequency of cantilevers. Here, non-invasive measurement techniques are needed that are precise, real-time and high resolution.

Three technologies are used in the Polytec microscope-based measurement system: 1) Laser Doppler vibrometry (LDV) is used to measure out-of-plane motion. Measurements of in-plane motions are done by adding two additional vibrometer channels angled to the surface. By automated scanning, deflection shapes can be measured and displayed as 3D animations. 2) Strobe video microscopy is another approach to measure in-plane motions and again extends the analysis to the planar direction to provide a complete 3D motion measurement. 3) White-light interferometry (WLI) adds the capability of surface topography measurement for static shape.

This instrumentation is presently being used throughout the MEMS community to characterize the devices such as micro mirrors, cantilevers, accelerometers, gyros, actuators, RF switches, ultrasonic transducers, ink jets, microphones, pressure sensors and resonators. Applications include:

- Dynamic testing of device response to determine mechanical parameters such as resonant frequency, stiffness and damping.
- Characterization of device response during design development and release processes.
- Design validation of performance versus expected FE model predictions.
- Measurement of settling time dynamics to determine precise movement versus time and show 3D visualization of response.
- Calibration of actuator and sensor displacements versus drive voltage over wide range of motion and frequencies.
- Topography measurement to determine surface characteristics after fabrication process (shape, geometry, curvature, roughness, step height, film stress, delamination)

This paper describes how the Polytec optical measurement system is used for several of these examples. The principles of operation are important for understanding the inherent advantages and disadvantages of the technology used. A detailed summary of this technology is included in the next several sections, followed by examples showing how the above mentioned techniques are used for key applications.

Technology | Laser Doppler vibrometry

The laser Doppler vibrometer (LDV) is an optical instrument using laser technology to measure velocity and displacement at selected points on a vibrating structure. Laser vibrometers measure without contact and are not affected by surface properties or environmental conditions. The laser beam can be focused to a spot down to 1 µm in diameter, allowing investigation of MEMS structures visible under an optical microscope. Diffraction limitations prevent measurements of devices smaller than the wavelength of light used (532 nm). LDV is a very sensitive optical technique with the overall capability of measuring displacements from centimeters to picometers at frequencies from near DC to GHz. In addition to their broad frequency range, LDVs also have a high dynamic range (over 170 dB) for velocity amplitudes from 0.02 µm/s to 10 m/s. These features allow measurements not possible using holographic or other techniques.

The LDV uses the Doppler effect, where light backscattered from the moving target carries information about the motion quantities velocity and displacement at the point of incidence. Displacement of the surface modulates the phase of the light wave while instantaneous velocity shifts the optical frequency. Using interferometric techniques, the received light wave is mixed with a reference beam so that the two beams recombine at the photo detector. The basic arrangement of a modified Mach-Zehnder interferometer is depicted in figure 1.

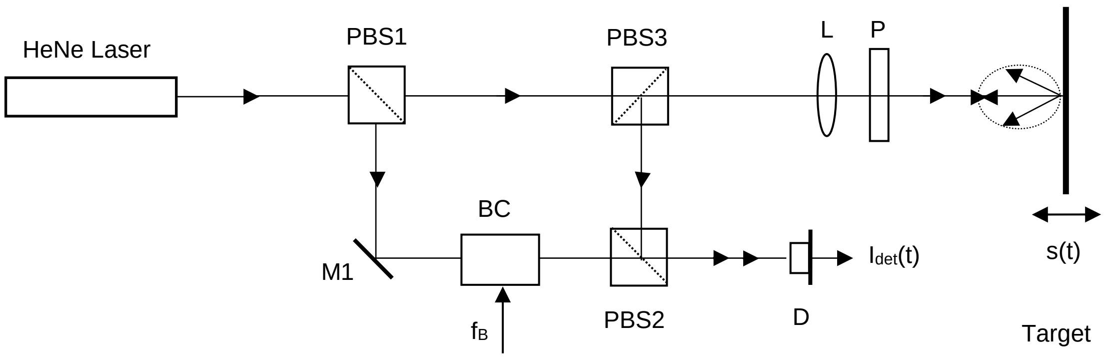


Figure 1: Optics schematic of a modified Mach-Zehnder Interferometer.

The signal measured at the photo detector carries direction sensitive frequency and phase modulation from the moving target. Target displacement s(t) results in a phase modulation

$$\varphi_m(t) = \frac{4\pi s(t)}{\lambda} \qquad (\lambda \text{ - laser wavelength}) \qquad (1)$$

According to the basic relationships $d\varphi / dt = 2\pi f$ and $ds / dt = v$, that phase modulation corresponds to a frequency deviation

$$\Delta f(t) = \frac{2v(t)}{\lambda}, \qquad (2)$$

known as the Doppler frequency. The resulting frequency of the detector output signal correctly preserves the directional information (sign) of the velocity vector.

The measurements taken by LDV are dynamic by nature and do not carry information about static shape (as is possible using other techniques like digital holography or white-light interferometry). Displacement and velocity are encoded in phase and frequency modulation of the detector output signal. In order to recover the displacement and velocity time histories from the modulated detector signal, phase and/or frequency demodulation techniques are used in the signal decoder blocks of a laser vibrometer. Both digital and analog frequency demodulators directly convert the instantaneous Doppler frequency into voltage proportional to vibration velocity. The high quality demodulation electronics used provide critical accuracy, linearity, sensitivity and signal-to-noise ratio for complete vibrometer system.

The LDV measurement instruments can be extended to a 3D vibrometer setup enabling pm-resolution for both out-of-plane and in-plane motion. The optical setup is based on heterodyne Mach-Zehnder interferometry with three linearly independent interferometer paths (see figure 2). The laser beam directed on-axis through the main interferometer is frequency-shifted acousto-optically with respect to the three reference beams by a Bragg-cell. The scattered light is then collected on-axis and in two off-axis directions. The three detector signals contain the complete broad-bandwidth 3D vibration spectra at the measurement spot. A coordinate transformation is employed to derive the vibration data in Cartesian coordinates.

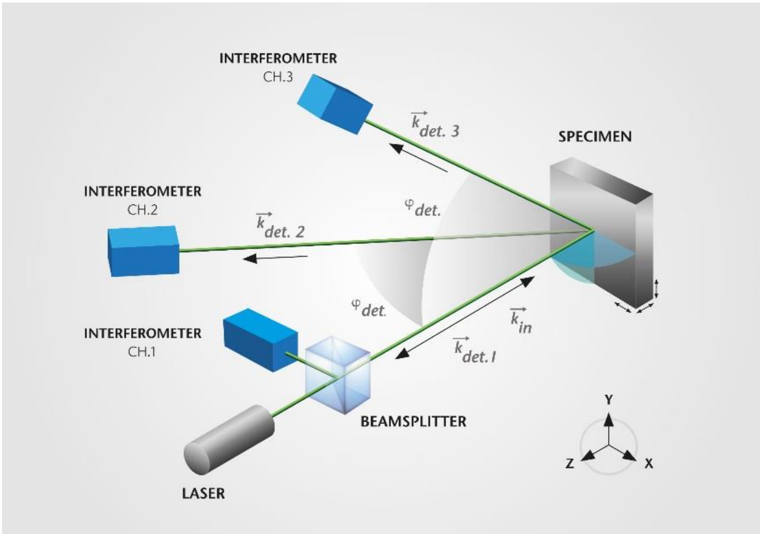


Figure 2: Optical layout of 3D laser vibrometer

One disadvantage of using LDV is that the measurements are at a single point, rather than captured on a full field as done using video interferometry techniques. Deflecting the laser measurement beam in x and y direction using scanning mirrors extends the LDV technique to full area scanning. The schematic for this is shown in figure 3 below with scanning mirror M. The laser measurement beam can be positioned to any point visible on the live microscope video. This technique is used to scan an area point by point to measure the velocity field of the structure. Though a single point LDV can be treated like a conventional sensor (i.e. analog output recorded by oscilloscope or other data acquisition systems), the scanning LDV requires system software to create a scan measurement grid, control of the scanning process and simultaneous acquisition of the measurement data. The phase of each point is determined by simultaneous measurement of an additional reference channel (typically the drive signal produced by the internal signal generator). From this data, 3D deflection shapes are calculated. The end result comprises the mapping of the velocity and / or displacement field over the structure that allows 3D animations of the response either in the frequency or time domain (see figures 12 and 14).

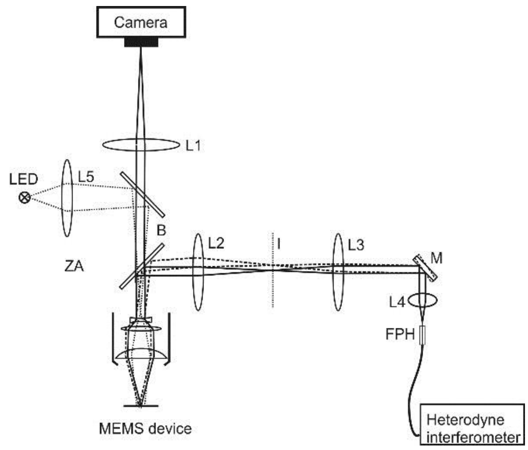


Figure 3: Optical layout of microscope scanning laser vibrometer.

Technology | Strobe video microscopy

Strobe video microscopy measures *in-plane* periodic motion of MEMS. This technique can be used in combination with LDV. An integrated CCD camera captures the strobroscopic images as shown in figure 4. The signal driving the specimen, the LED-strobe flashes and the camera exposure have to be accurately synchronized. A timing diagram of the strobe synchronization is shown in figure 4 for two camera shots at two different phases relative to the periodic excitation.

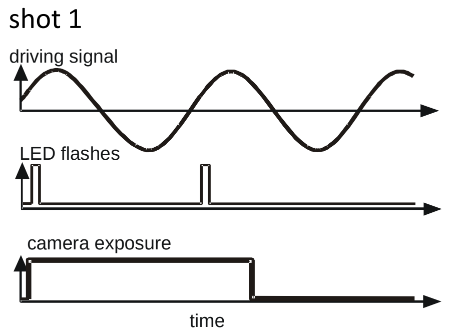


Figure 4: Timing diagram of the strobe signals.

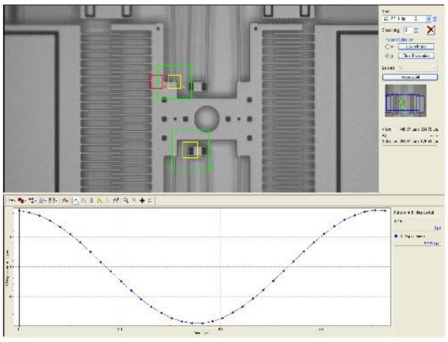


Figure 5: In-plane motion of comb drive device.

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 (δx, δy) of a user defined search pattern between successive images through correlation functions. The values of δx and δy can be calculated down to sub-pixel resolution by employing image-correlation techniques. This requires post-processing and is not captured in real-time, as done for the LDV.

Figure 5 shows the pattern match and displacement of a comb drive MEMS device at resonance. 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 and displayed as a Bode plot. In-plane motion analysis can be performed not only with sine excitation but also for a step response.

Technology | White-light interferometry

Static surface topography measurements are enabled using white-light interferometry (WLI). This provides x-y-z mapping of the device surface to determine key parameters such as flatness, curvature, step heights, roughness, parallelism, angles and volumes. The result can be displayed as 2D or 3D mappings for evaluation, defect analysis and/or processing to extract parameter values for given areas.

The WLI uses a Michelson interferometer using the optical configuration shown in Figure 6. The white-light source used has a coherence length in the µm range. The collimated light beam is split at a beam splitter into an object beam and a reference beam. The light scattered back from the mirror and the object respectively are superimposed at the beam splitter again and imaged to the CCD camera. This interference results in a fringe patterns that is mapped out for each pixel in the camera image. By moving the position interference lens using a z-stage, the interference signal is modulated for each pixel resulting in a correlogram. The maximum value of the correlogram occurs when the distance to the reference mirror is exactly the same as the distance to the device surface. After a measurement run, the correlograms from the camera frames are analyzed and a true topographical representation of the surface can be reconstructed as a 3D topography map as shown in the figure 7.

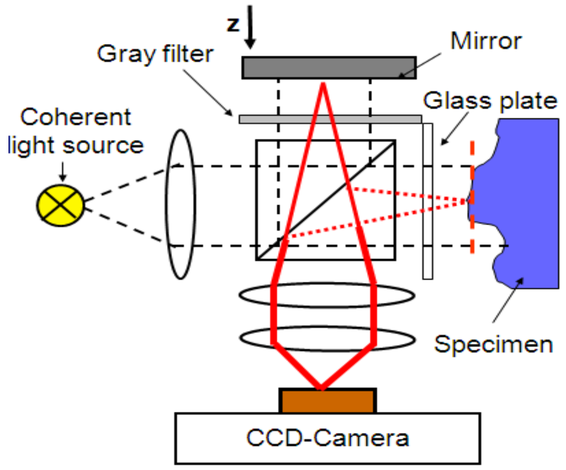


Figure 6: White-light interferometer schematic.

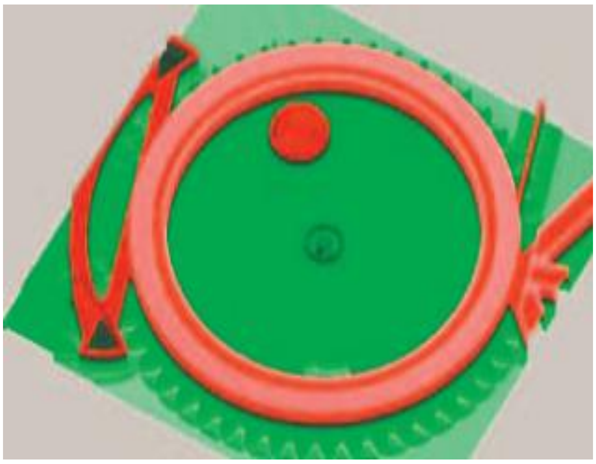


Figure 7: Topography measurement of a micro gearwheel

Application | Texas Instruments digital mirror device (DMD)

Settling time is an important parameter for the micro mirror applications where mirror orientation is rapidly switched from one tilt state to another. Here, speed and accuracy are key indicators of performance. Complex factors in the mirror design such as damping coefficients, resonance frequencies and optimization of drive control signals affect settling time response. These can be measured using laser Doppler vibrometry for real-time response with high sampling rate and accuracy. Scan measurements provide 3D visualization of mirror response as time animated sequences.

Measurements are made on Texas Instruments DMD arrays .The array consists of millions of 12-micron mirrors. Each mirror rotates +/- 12 degrees about a primary axis by twisting about a hidden hinge as shown in figure 8. Moving the mirror from “-“ to “+” state controls the illumination projected for an individual pixel, and the amount of time at the “+” state controls the grey level brightness. The mirrors are capable of switching on / off at a rate of approximately 50,000 times per second. Further improvement of the switching speed would increase the range of color scales available in the projected image.

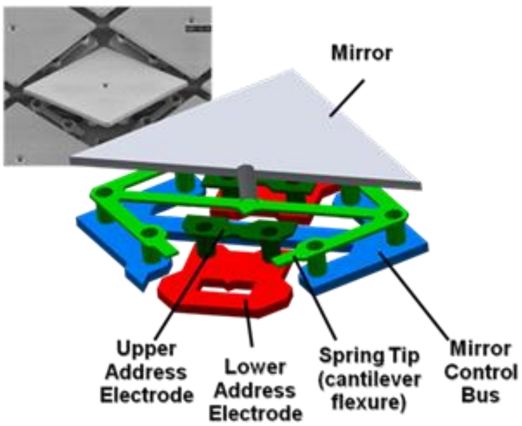


Figure 8: Structure of a Texas Instruments micro mirror.

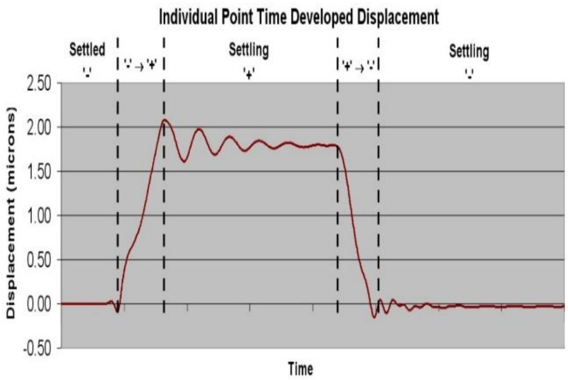
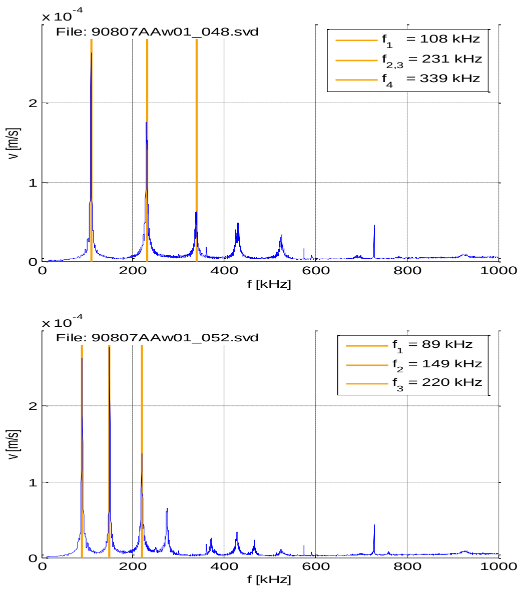


Figure 9: Time response of an individual point on a mirror.

Scan measurements are taken on the DMD array using LDV to measure settling time response and provide a 3D time visualization of movement. Figure 9 shows the displacement of a point targeted by the laser measurement spot in the corner of the mirror. When transitioned to the “+” state by rotating 12 degrees, the corner of the mirror displaces upwards and takes a characteristic time to settle to a stable orientation. During the settling, the mirror has a damped oscillation at the fundamental torsional resonance. Repeating this measurement at coordinate locations over the full surface, a full 3D dynamic representation of the mirror movement is determined for the primary tilt motion, as well as orthogonal roll and sag motions. The result is a 3D animation showing the exact time sequence for all three axes. Extending the measurement over multiple mirrors in the array allows comparison of the relative phase of the motion from mirror to mirror. These measurements served as a critical gauge of design settling time performance and are used to guide future design development.

Application | Testing pressure sensors on wafer-level

Wafer level testing can provide an effective means of quality control and reduce costs related to packaging MEMS devices that do not meet specifications. Identification of geometrical and material parameters using LDV provides real-time measurements that can be quickly automated at the wafer-level on a probe station. The measurement microscope head used mounts easily on any probe station. Resonance frequency can be measured at a single point on the structure in milliseconds. The probe station steps to the next device and the same measurement is repeated. The process takes approximately 2 seconds per die, and the end result is a wafer map displaying quantitative Estimated Identification Error used for “pass/fail” criteria.



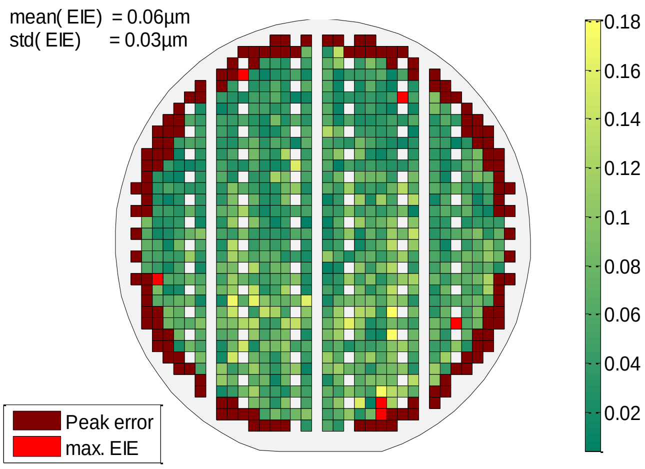


Figure 10A (upper): Frequency response of good device.
Figure 10B (lower): Frequency response of bad device.

Figure 11: Wafer map of Estimated Identification Error. Bad Devices are shown in red.

Measurements are taken for pressure sensors consisting of 1300 µm x 1300 µm devices, processed by KOH etching. An algorithm for membrane thickness based on frequency response measurements made by LDV is used as the basis of the parametric testing. The membranes are excited using contactless electrostatic probes. Figure 10 shows the frequency response of two devices: The first one (figure 10A) shows the frequency response of a “good” die with resonances at expected frequencies, and the second one (figure 10B) shows the frequency response of a “bad” die with shifted resonance frequencies. Calculation of an Estimated Identification Error (EIE) provides a quantitative evaluation that permits the classification of processing errors. These are mapped on the wafer as shown in figure 11, with criteria for maximum error used to screen out “bad die” (shown in red).

Application | FE model validation

During the design phase of MEMS devices, FE models are used to simulate mechanical response. Typical models take in complex electrical and mechanical parameters to predict device response and are used to design the device towards target specifications. Since many of these parameters have variations due to fabrication processes, it is important to validate them through testing. This is especially true at the initial phases of fabrication where the process is not well controlled and there are greater uncertainties.

A basic example is shown below for a MEMS cantilever beam. The silicon beam is 225 microns long, 40 microns wide and 4 microns thick. The resonance frequency f is given by:

$$f_i(Hz) = \frac{k_i}{2\pi L^2}\sqrt{\frac{EI}{m}} \tag{3}$$

where L is the length, E is the elasticity, I is the moment of inertia and m is the mass . An ANSYS model of the silicon beam is derived using 1000 node points based on the modeled geometry. The first bending mode is predicted to occur 94,153 Hz (Figure 12, right). Experimental validation of this model is made using scanning LDV measurements on the beam, using the same density of measurements points as node points for the model. The experimental results are compared for validation and the model is updated based on the data. Complex effects such as geometric errors, non-uniformities, damping, residual stress, mismatching boundary conditions and torsional compliance are often not accounted for in an idealized model. In this case, the experimental results give the first bending mode at a lower frequency of 66,718 Hz (Figure 12, left). This is explained by inaccurate geometrical values that are used in the model.

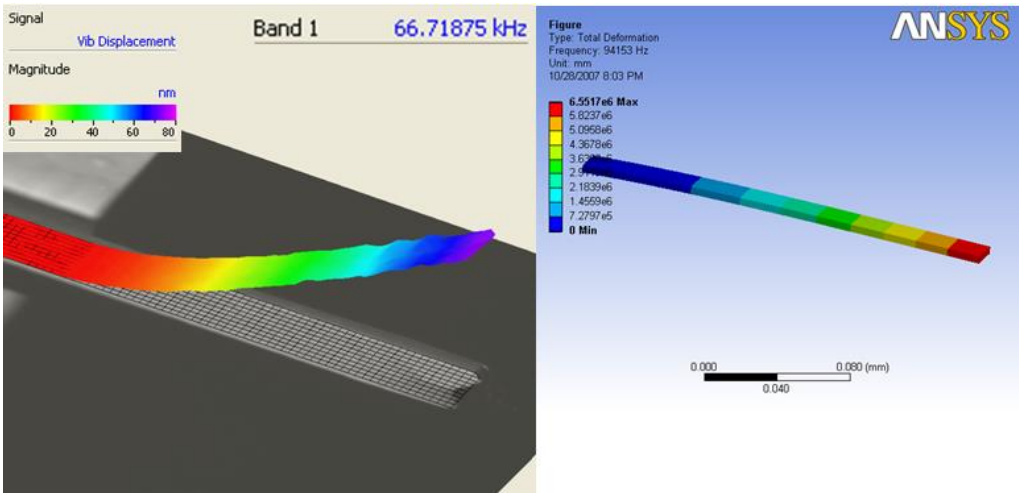


Figure 12: Comparison of cantilever first bending mode determined experimentally (left) and from FE model (right).

For inertial sensors, modeling can be even more complex for drive and sense modes using, for example, comb drive or tuning fork resonators. These modes are typically designed at specific frequencies that need to be validated through experimental measurements.

Application | Optimizing the design of accelerometers

MEMS devices have integrated electrical and mechanical components to form electro-mechanical systems. When characterizing and troubleshooting these devices, it is often difficult to determine whether an observed behavior is purely mechanical, purely electrical, or inherently both. LDV measurements allow direct mechanical measurements uninfluenced by electrical effects.

An example measurement is shown for a stable, robust MEMS low-g servo accelerometer previously manufactured by Applied MEMS. The accelerometer has a noise floor near 30 ng/√Hz and a dynamic range of >115dB. The sensor is developed for demanding environments of oil exploration for seismic exploration and monitoring, but is also used for inertial navigation, as well as vibration monitoring and analysis.

In the early stages of development, a spurious resonance near 20 kHz is observed in the output of the accelerometer. Although this frequency is well outside of the desired performance band, this mode is suspected as a cause of reduced sensor performance. The source of the mode is unknown at the time; however, there are several suspected causes. Mechanical sensor modes around this frequency are known to exist from FEA simulation, though it is unclear how these modes might manifest in the closed-loop output of the sensor. Artifacts from the control loop as well as package induced modes are also considered as a source of the 20 kHz tone.

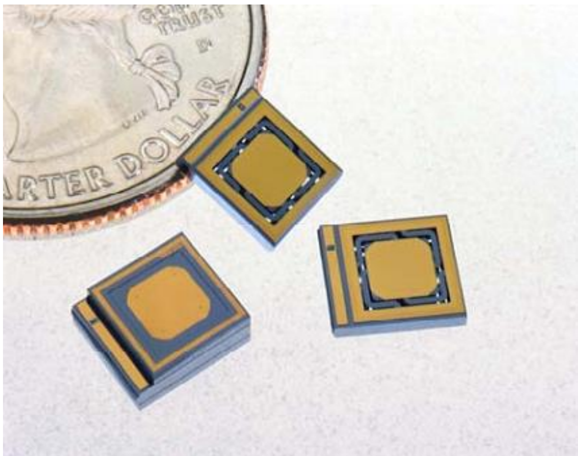


Figure 13: MEMS accelerometer die from Applied MEMS.

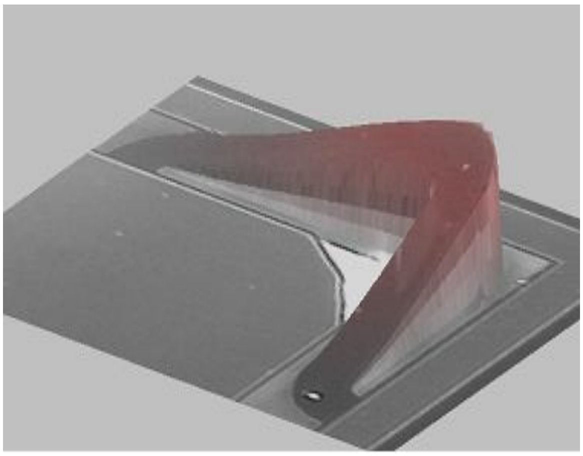


Figure 14: Bending mode of flexure at 23 KHz.

To further investigate the cause of the tone, scanning vibrometry is used to scan the surface of the bare die shown in figure 13. Since the device is a variable capacitor with sensing and forcing electrodes on either side of the moving proof mass, one of the electrode caps had to be removed in order to scan the moving parts inside. The de-capped die is attached to a high-frequency shaker and mechanically stimulated in the band of interest. The entire surface is scanned using broadband input to the shaker to excite all modes in the band of interest. This revealed the general location and frequency of the modes for the device under test. With this information, higher resolution fast scans are performed at single frequencies for specific modes at various locations on the die. The results of a fast scan over a

1.5 x 1.5 mm section containing the accelerometer spring elbow are shown in figure 14. The peak displacement of the spring elbow is 800 nm. The scan clearly revealed a mechanical resonance of the spring elbow. Since the LDV measurement is made using only mechanical excitation, electrical causes of the spurious mode can be further eliminated. The scan also reveals additional higher-order modes of the spring arm at frequencies approaching 1 MHz. As a result, the sensor is redesigned to reduce the negative effects of this mode. The subsequent sensor designs leads to improved device performance and higher yields.

Conclusion

Polytec provides valuable measurement tools used for the research and development of MEMS devices used in real-world applications. Laser Doppler vibrometry provides real-time, broadband measurements of dynamic response with resolution down to the picometer level. The examples in this paper show how this is used for characterization, troubleshooting and design optimization of the Texas Instruments DMD array and applied MEMS accelerometer. Furthermore, this capability can be extended to fast, automated production test measurement on wafer level. Use of our measurement techniques uniquely gives inside view of MEMS devices, shorten design cycles, improve yield and performance, and ultimately reduce product cost.

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As Polytec, we offer application services and support by our engineers that have experience with MEMS applications and the relevant test requirements.