Application Note *M-02*

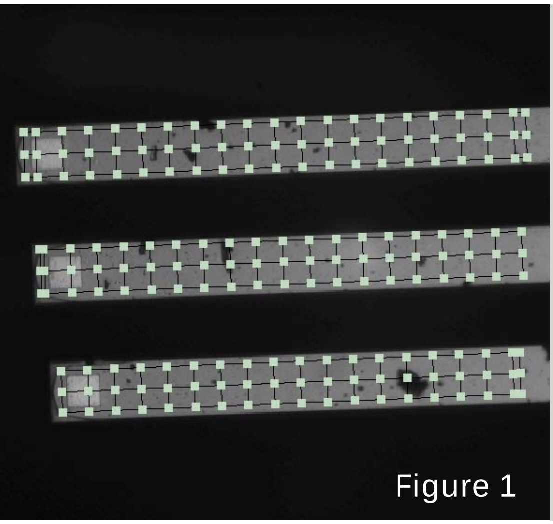
Figure 1

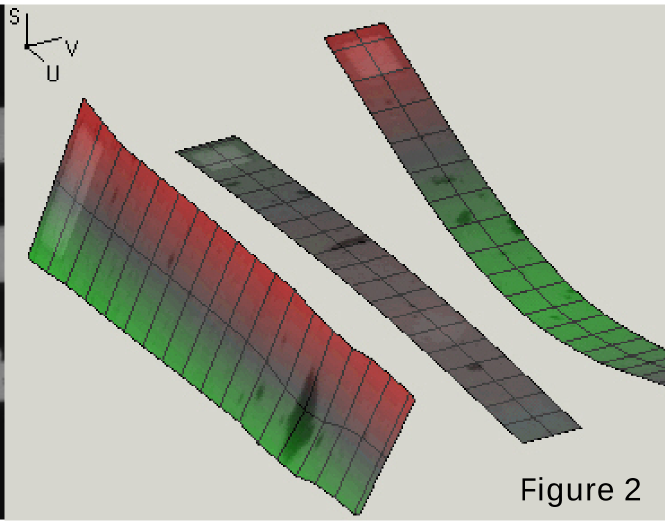

Figure 2

FIELD OF APPLICATION

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

Identification and Characterization of the 3-Dimensional Vibration Behavior of a MEMS Cantilever Structure

MEMS sensors find their use in wide fields of applications, among them aviation, automotive and data storage. Here we present the analysis of the complete dynamical behavior of a standard MEMS device in order to demonstrate the capabilities of the optical state-of-the-art measurement technology. The MMA is Polytec's new hybrid measurement system. To the widely known microscope based Laser Scanning Doppler Vibrometry (SLDV), stroboscopic video microscopy is added for in-plane analysis. The outstanding capabilities of the SLDV for frequency response and operational deflection shape measurements in out-of-plane direction is thus expanded to full 3-dimensional motion analysis.

Introduction

The device under test is a common cantilever structure as it is used in airbag sensors. The properties of such cantilevers are tuned to give each cantilever isolated resonance frequencies. Each cantilever has a different geometry (e.g. length). Consequently resonance occurs for one lever only when its specific resonance frequency is excited. Because the sensor is passive, it is mounted onto a piezoelectric exciter that is connected to the MMA internal HF signal generator.

Measurement Setup

As can be seen in figure 3 the specimen is placed under a standard microscope. In order to measure its out-of-plane response, a "pseudo random" broad band signal is applied to the exciter.

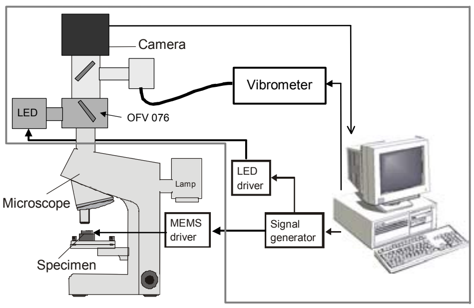

Figure 3: Polytec MMA system

A HeNe laser beam is coupled into the microscope optical path and focused onto the specimen. Any surface vibration modulates the frequency of the reflected laser light (FM modulation; Doppler effect). Demodulation of the interference signal provided by a Mach-Zehnder interferometer gives an output-signal proportional to the

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velocity vector normal to the measurement surface (out-of-plane measurement).

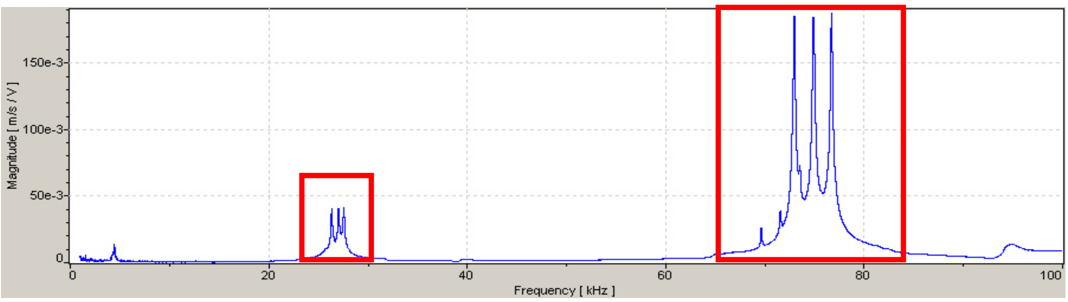
In order to obtain the operational deflection shapes (ODS), the laser beam is scanning the surface point-by-point, using two piezo-driven mirrors. The generator signal is looped back into the acquisition channel thus providing the reference phase.

To overcome the limitation of out-of-plane analysis, the final MMA setup incorporates a strobe unit with a flash LED as well as a digital high resolution progressive scan camera to sample the in-plane movements of the specimen. The LED and the camera are synchronized with the excitation source.

Out-of-Plane Analysis

Figure 1 (title page) shows a live video image from the progressive scan camera. We limited the analysis to three cantilevers although the sample contained more than thirty. The scan-point grid for each lever is defined rapidly with a freehand tool on the video image. Density is chosen to give 180 scan-points on a rectangular grid (figure 1). A measurement with a bandwidth of 100 kHz is then performed point-by-point. Figure 4 shows the averaged frequency response function (FRF).

Figure 4: Averaged FRF, 100 kHz BW



The spectrum represents the average over all 180 scan-points. Using a 3,200 FFT-line analysis gives a frequency resolution of 31.25 Hz and a total measurement time of about 20 seconds for the complete structure including complex averaging. As expected we find two resonance triplets, one around 27 kHz another around 75 kHz corresponding to two orders of bending modes of the three cantilevers.

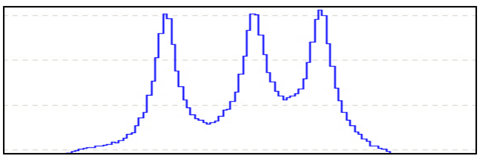


Figure 5: Triplet around 27 kHz

First we take a look at the ODS of the 27 kHz triplet (figure 5). The resonances are situated at 26.3 kHz, 27.1 kHz and 27.6 kHz with similar displacement amplitudes of about ± 1.5 nm. The deflection modes are displayed in figure 6, 7 and 8. The red color indicates maximum elongation, the light green color marks a knot.

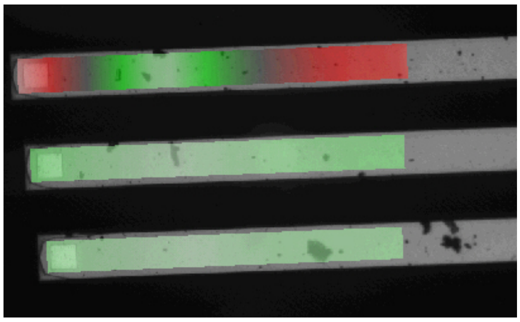


Figure 6: ODS at 26.31 kHz

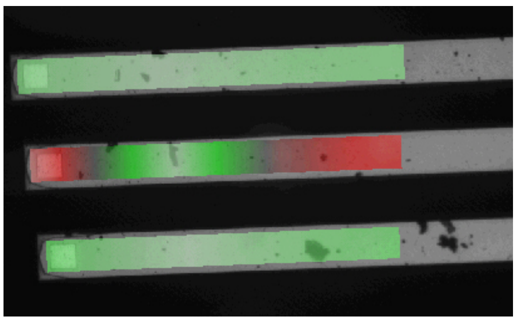


Figure 7: ODS at 27.09 kHz

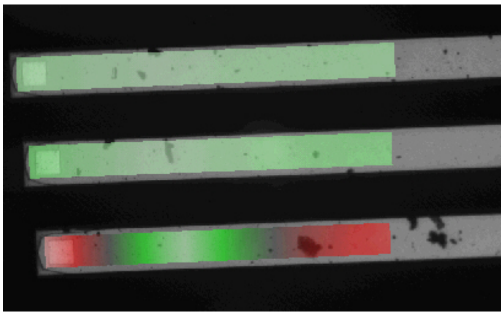


Figure 8: ODS at 27.59 kHz

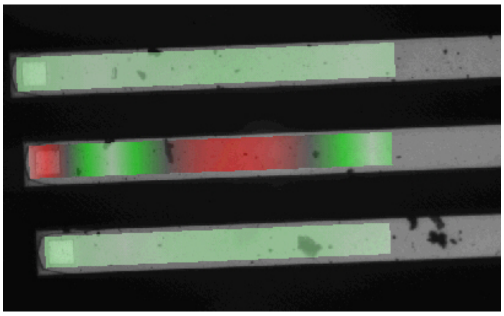


Figure 11: ODS at 74.94 kHz

These results are quite useful when it comes to validate resonances obtained by finite element models (FEM). The resonance triplet around 75 kHz however reveals some new particularities (figure 9).

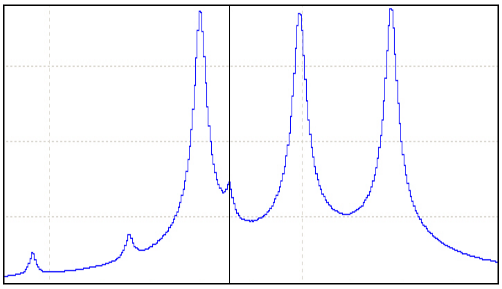


Figure 9: Triplet around 75 kHz

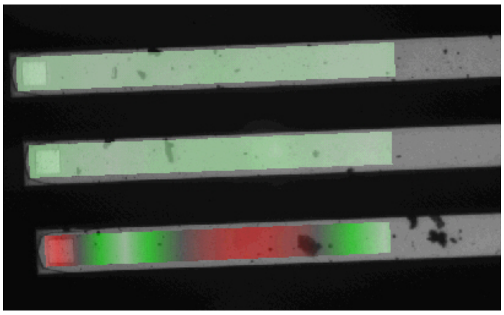


Figure 12: ODS at 76.78 kHz

First we observe the higher order bending mode triplet with similar displacement amplitudes of ± 20 nm. The corresponding ODS are displayed in the figures 10, 11 and 12.

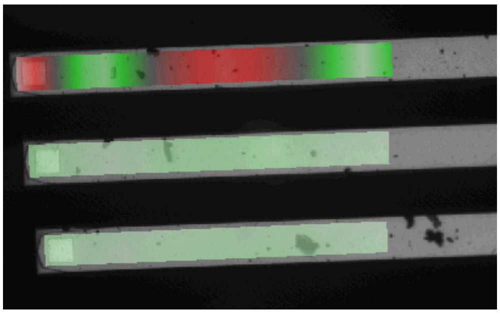


Figure 10: ODS at 72.97 kHz

Apart from these higher order bending modes, the FRF spectrum in figure 9 contains a superposed third triplet of inferior amplitude. Figure 13 shows the first resonance of this third triplet revealing a tilt motion of the first cantilever at 69.7 kHz.

The two following resonances at 71.53 kHz and 73.56 kHz show the tilting of the second and the third cantilever respectively. A snapshot from the 3-D ODS-animation of the third tilt mode (± 2 nm) is displayed in figure 2 (title page).

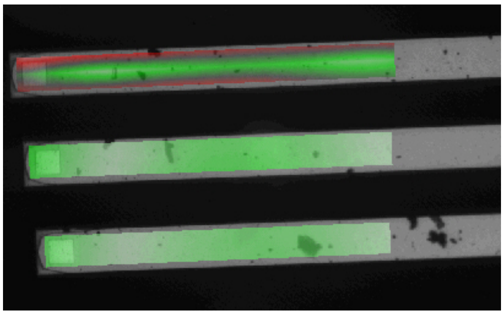


Figure 13: ODS at 69.66 kHz

We suppose that in reality the tilting of the three cantilevers corresponds to a combined in- and out-of-plane mode. A rotary movement for example where in- and out-of-plane motions are 90° phase-shifted would appear as such a tilting in an out-of-plane-only measurement. Therefore we chose the 73.56 kHz resonance for an in-plane analysis using strobe video.

In-Plane Analysis

In opposite to SLDV systems a broadband excitation is now only possible as repeated hammer blow. Here we use a sinusoidal excitation and frequency stepping. For every frequency a set of N images is captured at N different phase angles between 0° and 360°. Synchronization of the flash LED, the CCD camera and the excitation signal allows to record a few thousand flashes, corresponding to the same phase during one camera exposure. Thus frequencies up to 1 MHz can be analyzed with at least 10 shots (i.e. phases) per period.

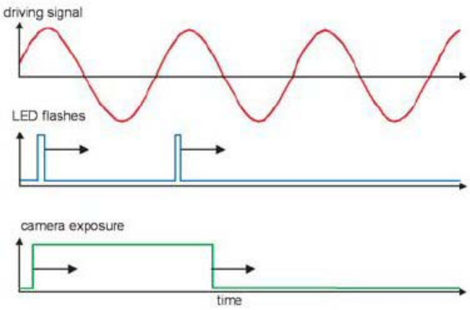


Figure 14: Principle of strobe video

For our example we recorded images at frequencies from 72.5 kHz to 75 kHz with 50 Hz steps, capturing 16 images per period per frequency, thus giving a total set of 800 images to be analyzed. Acquisition took ~2 minutes.

Analysis is done by choosing a small template (red box in figure 15) of the moving structure in the image as well as a region-of-interest (ROI, green box in figure 15) in order to reduce time for calculation. Displacement (δx, δy) is obtained for each phase by image-image correlation algorithms.

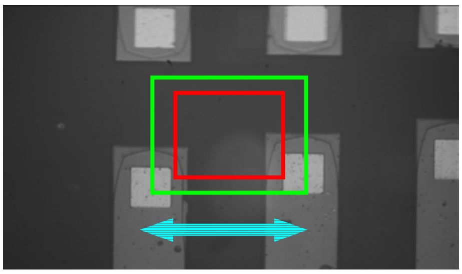


Figure 15: Image-template and ROI

This technique has been shown to determine the position shifts with a noise level below 0.03 pixel, i.e. with 4 nm resolution in the case of a 50x objective. Results are plotted in Bode plots (see figure 16 and 17).

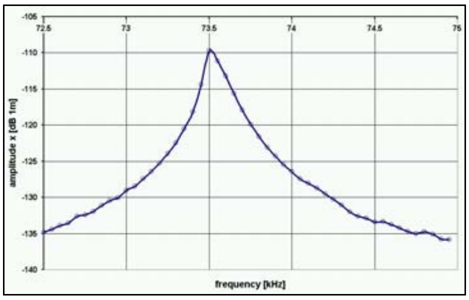


Figure 16: Bode-plot of δx-Amplitude

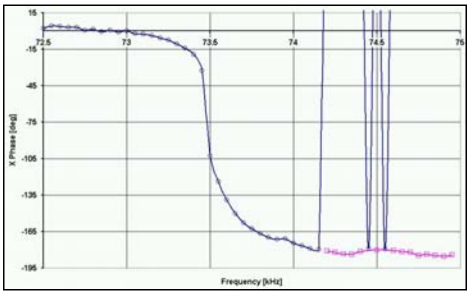


Figure 17: Bode-plot of δx-Phase

The trajectory analysis shows finally a sinusoidal in-plane motion with 6.5 µm peak-to-peak amplitude. These results are a perfect match to the previous out-of-plane analysis (± 2 nm amplitude) and show the important benefit of a hybrid system for 3-D motion analysis on MEMS-structures.

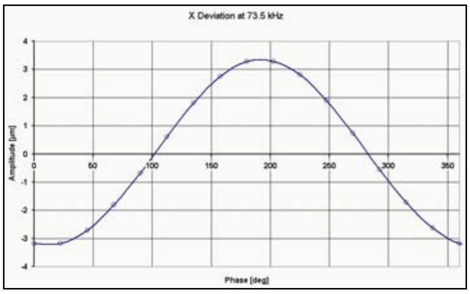


Figure 18: Trajectory-plot of δx

Conclusions

Microscope based SLDV allows ultra-precise (MHz motions with picometer resolution) and fast determination of every out-of-plane resonance. The high sensitivity reveals also residual motion from in-plane modes.

Thus in-plane analysis can be carried out "right-on-the-spot" avoiding time and data consuming imaging analysis and broadband sine-stepping.

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