3-D Vibration and Motion Analysis of Microstructures

While originally developed for macrostructures, the full-field vibration mapping technique of laser scanning vibrometry can be applied successfully to microstructures by using microscope optics and high grade piezo scanners instead of camera lenses and galvo scanners. Polytec’s laser vibrometers operate on the Doppler principle, measuring back-scattered laser light from a vibrating structure to determine its vibrational velocity and displacement. Please find detailed information on the basics of vibrometry in issue 1/2003 of this tutorial series (for more information see page E16).

Surfaces of silicon micro devices are usually optically flat and light is specularly reflected and not diffusely scattered. Therefore, the incident laser beam must be near normal incidence to assure that the reflected beam is captured by the probe optics. Given this fact, a vibrometer is preferentially used to study motions along the optical axis of the imaging optics (out-of-plane). To find and measure resonances of mechanical structures oscillating in all three dimensions, vibrometry must be combined with machine-vision techniques. Stroboscopic video microscopy is such a technique that can acquire the in-plane motion data to complete the three-dimensional measurement.
A Smart Combination for Rapid Results
Normally, the highly sensitive laser-Doppler technique (picometer resolution!) is applied first to the device to rapidly find all mechanical resonances using wide-band excitation. “Pure” in-plane resonances will be detected because of small, parasitic coupling to out-of plane modes and the high sensitivity of vibrometry. A frequency signal that does not fall in a FFT line is distributed over the neighboring lines, and therefore even a narrow vibration peak, which falls between two FFT lines, can be discovered. One of the great advantages of this approach is that the in-plane analysis can be limited to the already determined resonance bands in the spectrum.

Optical Setup
The vibrometer’s laser beams and the strobe illumination must be coupled into the beam path of the same microscope optics to integrate the two techniques in one setup. This can be realized by designing two beam splitters between the microscope objective and the microscope tube lens. The first beam splitter is used to couple the vibrometer laser beam into the microscope beam path. The second splitter couples the strobe light source into the microscope. A possible arrangement is shown in Figure 1.

Figure 1: Schematic of an optics arrangement for a combined vibrometer and machine vision measurement.
L1 is the scanner lens, L2 the microscope tube lens that images the specimen on the camera chip C. Lens L3 images the strobe lamp SL to the backside focus IL of the objective O. B1 and B2 are beam splitters, and M is the scanning mirror.

Functional Principle
A stroboscopic video microscope measures in-plane motions of periodically moving structures with stroboscopic machine vision and can measure frequencies as high as 1 MHz. The camera used is typically a CCD sensor for video frame rates and not a high-speed detector; therefore, the stroboscopic principle must be applied to visualize rapid motions. A pulsed LED is used as a reliable light source that ensures constant illumination power of the strobe pulses. The time resolution of the system is defined through the pulse width of the strobe flash. No light is collected through the CCD sensor when the strobe light is off. Therefore, events can be recorded with a period time shorter than the exposure time of the camera.

The drive signal of the device is the timing reference and synchronizes the strobe flashes and the camera exposure. The timing diagram of the strobe synchronization is shown in Figure 2 for an example of three camera shots. The shots are recorded at three different phases of the periodic excitation for the specimen.

Two LED flashes are used in Figure 2 within the exposure time of the camera. The number of flashes per camera shot can be used to adjust the image brightness. The time between two shots is the cycle duration of the camera-framing rate. The phase delay of the strobe illumination with respect to the driving signal is adjusted by setting the duration $T_{\text{shot}}$ between the shots to

$$T_{\text{shot}} = nT_{\text{excitation}} + \tau_{\text{phase delay}}.$$ 

Here, $n$ is an integer, $T_{\text{excitation}}$ is the period length of the excitation signal, and $\tau_{\text{phase delay}}$ is the time shift that corresponds to the phase delay. The maximum frame rate $F_c$ of the digital camera limits the shot frequency to $F_c \geq 1/T_{\text{shot}}$.

The procedure demonstrated in Figure 2 is completed when all images, necessary to derive the displacement response with image processing, are captured. Short strobe pulses are necessary to freeze a rapidly moving structure. Blur is generated if the device moves a longer distance than the distance that corresponds to the diameter of a camera pixel during the strobe illumination. It is necessary to use only a few flashes per shot (best is one flash) if the device does not perform a precise periodical motion but has a jitter. In this case, blur is generated if the jitter is higher than the distance that corresponds to one pixel.
Calculating Displacement: The Numerical Algorithm

Modern video-microscopy systems can automatically record frequency responses. Image sets are recorded for a number of frequencies to obtain a frequency response. Displacement-versus-phase-delay data is extracted for every measured frequency automatically by employing image-processing techniques. Phase and amplitude are computed through a sine-function fit from the displacement-versus-phase-delay data for every frequency record.

In-plane shifts $d_i$ and $d_j$ between image 1 ($I_1$) and image 2 ($I_2$) are computed with sub-pixel resolution by image correlation. Two images are matched if the displacement-dependent, normalized correlation coefficient $r$ at $(d_i, d_j)$ is a maximum: $\max(r(d_i, d_j))$.

The in-plane-motion algorithm computes $d_i$ and $d_j$ with sub-pixel resolution. The Nyquist-sampling theorem can be employed to calculate a resampled image $I_r(i, j)$ which is the key to understand the idea of sub-pixel-displacement computation.

Here $\bar{I}$ denotes the average intensity value of the pixels in $I$ and $(k, l \in \mathbb{N}; d_i, d_j \in \mathbb{R})$.

If $r$ is maximum the difference between the image-pattern template $I_2(k, l)$ and the shifted image $I_2(k, l)$ is a minimum. Therefore, the displacements $d_i$ and $d_j$ are the estimation parameters for an optimization algorithm that computes the maximum of $r$.

Figure 2: Timing diagram of the stroboscopic method for in-plane analysis
Practical Implementation

In Figure 3 the schematic of the MSA-400 Micro System Analyzer is shown. The superimposed block diagram indicates how stroboscopic video microscopy and laser vibrometry have been combined. The strobe light and the vibrometer beam are coupled with modular units via the microscope C-mount into the microscope beam path. The computer in collaboration with the vibrometer controller and the signal generator controls the motion of the laser beam, the stroboscopic illumination, the processing of both the interferometric signals and the camera image, and the sample excitation. The acquisition, evaluation and presentation of the data is managed by individual PSV and PMA software programs that utilize the hardware differently.

More Info:
www.polytec.com/usa/microsystems

Figure 3: Schematic of the MSA-400 Micro System Analyzer. OOP: out-of-plane, IP: in-plane