

Dynamic metrology of MEMS devices

Time-resolved optical microscopy can be used to visualise and measure nano-scale motion in functioning MEMS devices. Frequency-dependent responses up to the megahertz range can be examined. Stroboscopic image capture and advanced feature recognition software can be used to follow tiny displacements, and to scan frequency spectra to determine resonances, mode shapes and other critical performance parameters such as Q-factor under a range of operating conditions.

Advanced design and manufacturing techniques for microfabricated silicon-based microelectromechanical systems (MEMS) are providing a broadening range of electronics functions available for application in miniaturised devices. At the heart of these lies accurate control of the motion of a micromechanical sensor or actuator element, operating responsively or driven within tight tolerances.

MEMS devices typically comprise surface micromachined membranes or cantilevers that exhibit vertical (out-of-plane) motion, or bulk micromachined beams or inertial masses that undergo lateral (in-plane) motion. Measurement of these displacements under realistic operating conditions is necessary to fully characterise the functionality and performance of devices, and to validate software models used in device design.

Dynamic displacement measurements have been undertaken on two example functional MEMS devices using a combination of instruments available through CEMMNT.

Measurement of Vertical Motion

Vertical motion is measured using the complementary techniques of White Light Interferometry (WLI) and Laser Doppler Vibrometry (LDV). The former is undertaken using a Veeco NT3300 DMEMS interferometer, while the latter employs a Polytec MSA-400 Microscope scanning vibrometer instrument.

WLI measures vertical displacements by focusing a low coherence light beam on to the sample using an interferometric lens that is translated vertically through the point of focus. The reflected light recombines with a second light path resulting in an interference pattern referenced to the vertical position of the lens. Stroboscopic synchronisation with the WLI source allows the capture of a topographic image of the surface during a motion cycle. In contrast, LDV senses the velocity of vertical motion, rather than displacement. The basis of the technique is again optical interference, but here the Doppler shift of a laser source reflected from a vibrating area is detected, providing the velocity of its motion along the axis of the laser light. Displacements are measured by integration relative to the surface at rest and 2D scanning is employed to build a topographic image of the motion.

The capabilities available within CEMMNT are demonstrated by analysis of the vertical motion of a capacitively-driven MEMS membrane. This device features a 2 mm diameter metal/nitride membrane of 2 μm thickness with fundamental resonant frequencies in the range of tens of kilohertz.

WLI is an effective tool with which to capture a series of snapshot images displaying vertical motion. These are acquired stroboscopically by locking in to a selected drive frequency and modulating the phase offset across the cycle. Figure 1 compares WLI images of the membrane topography at rest and at the extreme of an electrostatically driven motion at 5 kHz in air. Dynamic measurements taken at steps throughout the

phase cycle allow the tympanic motion of the membrane to be followed in detail. The peak displacement is 80 nm under the drive conditions employed in this example.

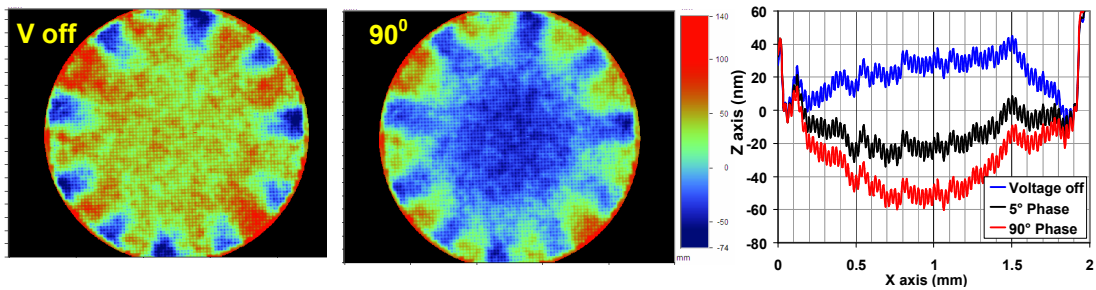


Figure 1. WLI height-contrast images and line-traces from a 2 mm diameter membrane driven at 5 kHz in air comparing maximum displacement (90° phase) and rest (V off) positions.

Laser Doppler vibrometry is well-suited for rapid measurement of frequency spectra, and figure 2 shows the spectra obtained from the 2 mm diameter membrane under a range of environmental conditions. The effects of damping on resonant peak frequencies and widths are evident, with critical damping observed in air.

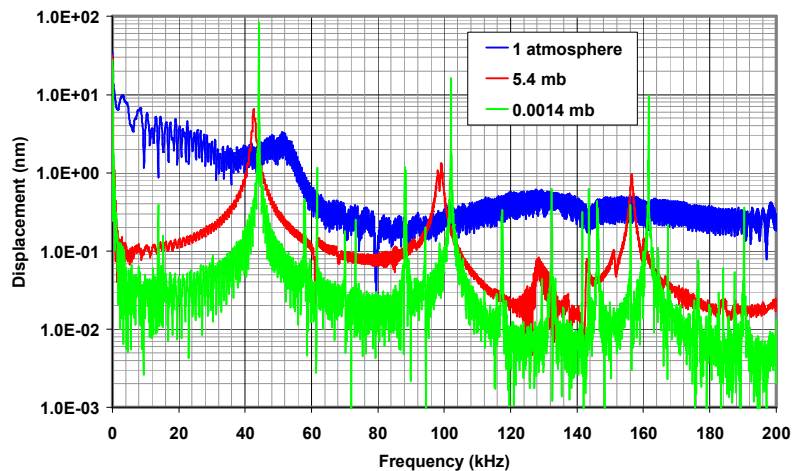


Figure 2. LDV frequency scans of the MEMS membrane device in different environments.

LDV can also be used to extract measurements at multiple sites across a device in order to construct mode shape images of the motion at specific frequencies. Examples are shown in figure 3 for several of the resonant peaks in figure 2.

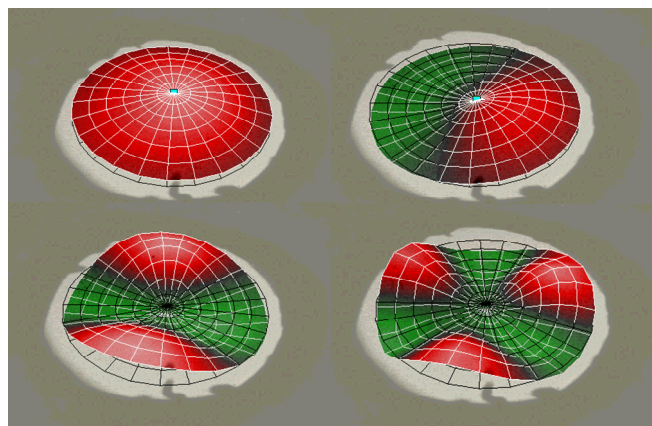


Figure 3. LDV images of mode shapes. These have been obtained by mapping displacement amplitudes from a grid of 150 sites across the circular membrane when driven under vacuum at four different resonance frequencies shown in figure 2.

The spatially resolved visualisation of vertical motion is invaluable in revealing device defects, providing a wealth of information not available from electrical testing. An example is shown in figure 4 for a membrane found not to be moving, the result of a surface defect visible using dynamic WLI. In this case, after the identification of this defect a simple means of defect avoidance was developed, proving the utility of these metrology tools for device and process development.

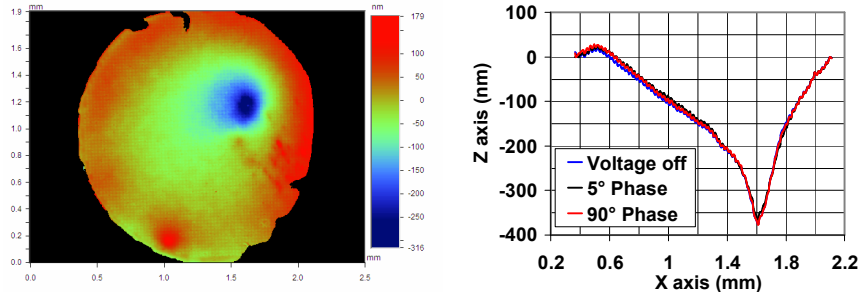


Figure 4. WLI image and line-profiles from a pinned membrane.

Measurement of Lateral Motion

Using stroboscopic illumination in combination with digital microscopy imaging, the lateral motions of oscillating structures can be frozen and their positions captured at discrete phase points through the cycle. Feature recognition software is then used to compare sequences of digital images, enabling the measurement of displacements well below the theoretical optical resolution of the microscope used within the system.

The application of this capability is demonstrated by monitoring the lateral motion of a comb-drive MEMS device that is shown in the static WLI image in figure 5 (left). A pair of “snapshot images” (right) show a sub-region of this device at the extreme points (0° and 180° phase) of its lateral motion whilst driven at 5 kHz (the device fundamental resonant frequency) in air. The images contain two $15\ \mu\text{m}$ wide beams, the left which is fixed and the right which is driven. The displacement of the driven beam (δx) is clearly visible, and accurate characterisation, yielding key performance characteristics, can be undertaken.

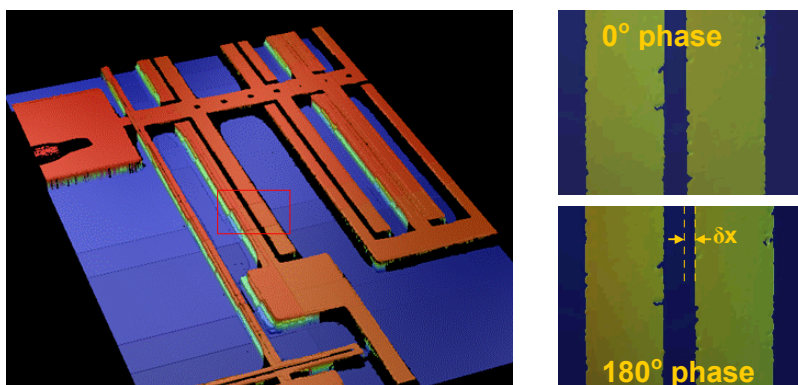


Figure 5. Static (left) and dynamic (right) images from beams of a comb-drive device driven at 5 kHz in air.

Graphs of lateral motion scanning the phase cycle are shown in figure 6(i) for a range of sinusoidal drive voltages. Displacement is seen to increase with drive voltage and the data shows that 10 nm lateral resolution is possible. The peak displacement is shown for each drive voltage in figure 6(ii), demonstrating the square-law relationship between peak displacement and drive voltage.

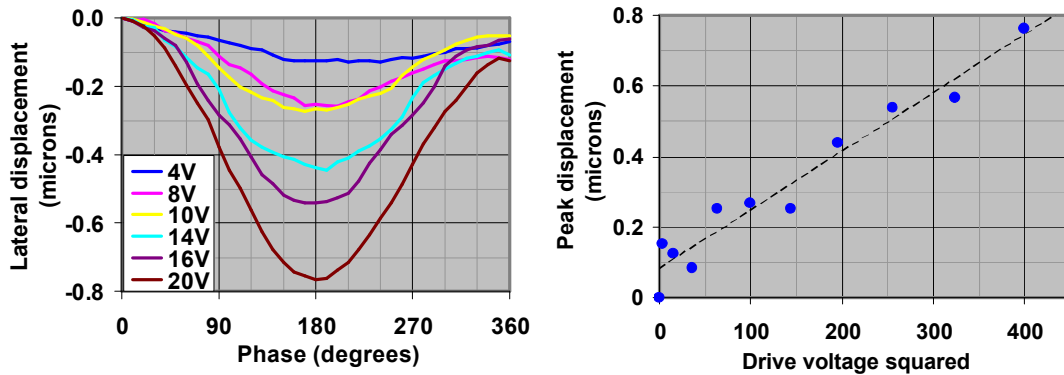


Figure 6. Left: lateral displacement curves measured during the phase cycle at 5 kHz in air, for different drive voltages. Right: the dependence of peak displacements on drive voltage.

The Q-factor associated with oscillating structures can also be obtained using this technique by scanning through drive frequencies and calculating the peak width (Δf) associated with the resonance. The dependence of this on ambient pressure, as shown in figure 7, is a further important operational parameter.

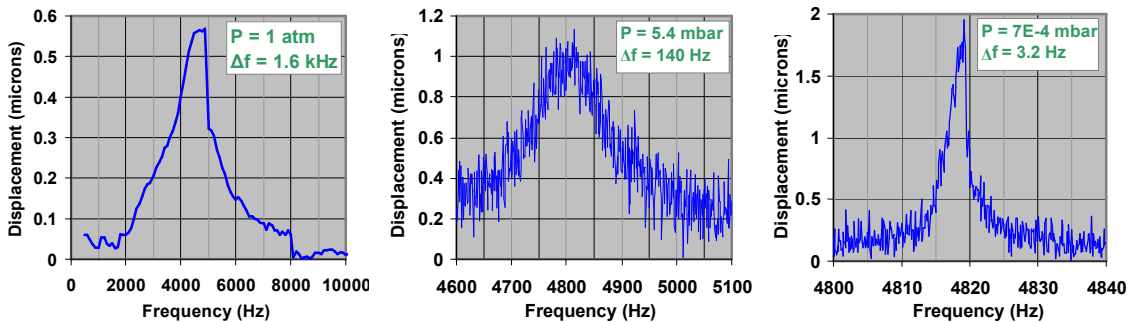


Figure 7. In-plane resonance peaks measured at different operating pressures.

Summary

White light interferometry and laser Doppler vibrometry are complementary techniques allowing sensitive measurement and visualisation of MEMS device motions under operating conditions. These techniques are able to provide engineers with detailed spatial and functional information that is not available from electrical characterisation. Directly measured device response can be compared against design specifications, with data derived from real devices and not test structures. The techniques are also valuable tools for revealing defects that impact on device performance, assisting trouble-shooting, device development and quality control. Such dynamic measurements facilitate a greater understanding of the effects of physical characteristics and uniformity on device performance, which can in turn be used to refine the assumptions and parameters used for device design and software simulation.

The analysis of vertical and lateral motion measurements of MEMS devices undertaken using advanced metrology systems is just one of the many services and techniques of core value to the MEMS device engineer, and to engineers and developers in many other fields. Such services are available through CEMMNT.

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