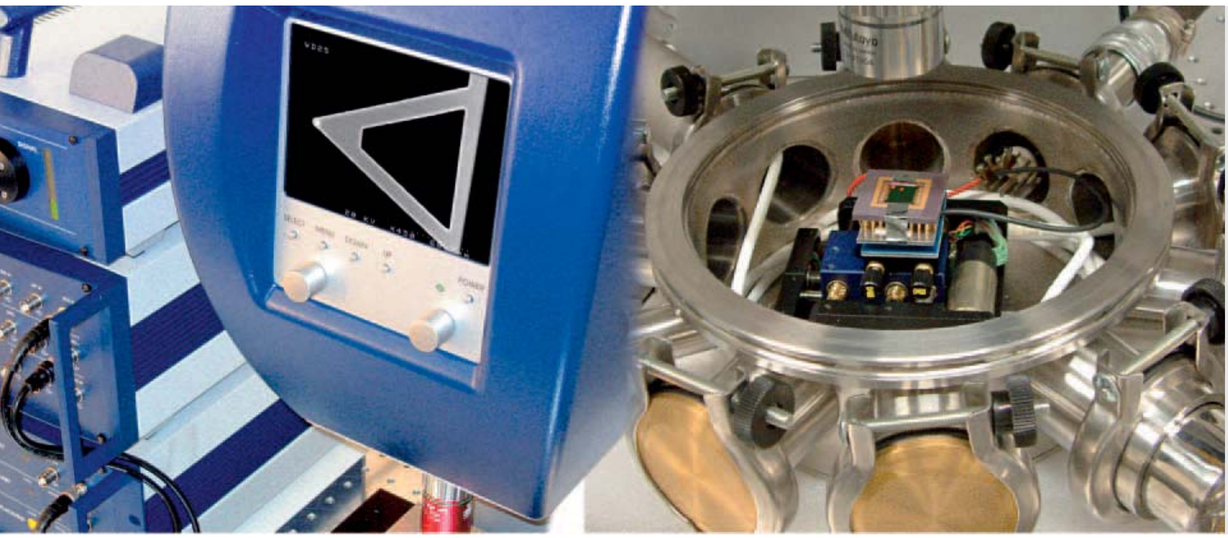
Polytec

Monitoring MEMS Motion Under Vacuum



Field of Application

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

An Environmental Chamber Integrated with a Polytec MSA-400 Micro-Scanning Laser Doppler Vibrometer for Use in Characterizing MEMS Devices

With the increased use of MEMS devices, characterization of their motion is becoming essential, both to evaluate their performance and to develop process improvement strategies. The addition of integrated functionality within MEMS devices, such as the incorporation of thin piezoelectric layers, is leading to novel devices that require detailed measurement and characterization, in environmental conditions representative of the operational state of the device. Additionally, manufacturing processes may lead to changes in residual stresses, which can result in degradation of device performance, representing further measurement challenges. There is a pressing need for a methodology to assess the performance of these functional materials at such miniaturized sizes.

Introduction

The National Physical Laboratory (NPL) is the United Kingdom's national standards laboratory, an internationally respected and independent centre of excellence for R&D, and knowledge transfer in measurement and materials science. The Functional Materials group at NPL has integrated an environmental chamber with a Polytec micro-scanning laser Doppler vibrometer for use in characterising MEMS devices at the nano-scale over a wide range of vacuum conditions. They developed a specialized laser Doppler vibrometer (LDV) based test station for examining the motion of MEMS devices over a wide range of pressures, from 1 bar (atmospheric), down to 10^{-5} mbar.

Experimental Setup

Pumping is performed by a diaphragm-backed turbomolecular pump, providing an oil-free environment for sample examination. The LDV laser beam reaches the sample through a specially coated covered glass window, enabling good RFI/EMI shielding whilst retaining optical clarity. The MEMS vacuum chamber, shown in figure 1, includes standard ports allowing computer control of the vacuum stages.
Sample excitation for the dynamic analysis is afforded via electrical feedthroughs. The sample chamber is configured for future upgradeability, including the option to study sample motion as a function of temperature and humidity.

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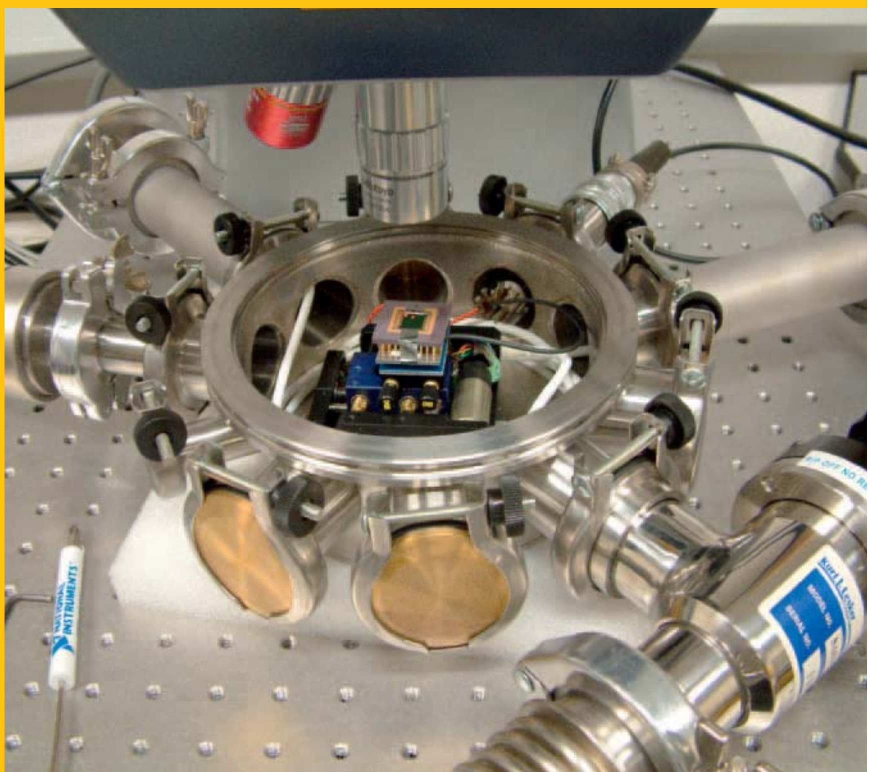

Figure 1: Photograph of the environmental chamber, showing a sample attached to the vacuum-compatible XY stages. The long-focal length lens can be seen above the sample, which is attached to the Polytec Micro Systems Analyzer Differential Vibrometer.

Benefits of Polytec's MSA-400 Micro System Analyzer Combined with a Vacuum Chamber

NPL's system utilizes a Polytec scanning differential vibrometer (Polytec MSA-400-PM2-D Micro System Analyzer, including both out-of-plane and in-plane measurement capability) with long working distance objective optical lenses that reduce the beam size down to 1 µm. This allows samples with lateral sizes of less than 10 µm to be characterized. The Polytec system was chosen because of the small spot size and hence excellent lateral spatial resolution, an ability to measure through a vacuum window and for its differential measurement capability, thus eliminating any relative motion between the tested device and its supporting structure. Device excitation can be achieved by broad-band stimuli like periodic chirp and white noise, or for specific frequencies using single frequency waveforms like sine or square. Scanning the laser across the sample produces velocity or displacement profiles showing the out-of-plane motion, with a resolution of better than 10 pm. In the normal operating mode, scanning of the sample is via the internal optics of the MSA-400. For larger samples (up to 25 mm) NPL has incorporated a set of X-Y vacuum-compatible stages into the MEMS chamber. These stages are normally employed for sample positioning and alignment, but can also be used to scan the sample and generate the motion profile. The combination of a scanning unit with a devoted, flexible design vacuum chamber allows the study of devices under more realistic working conditions, including the option of studying specific effects such as air damping and friction.

Sophisticated Data Processing

For data analysis, the velocity signal from the vibrometer controller was imported into a lock-in amplifier (Stanford Research Systems SR830). This set-up serves two purposes. Firstly, it allows simple extraction of velocity/displacement and phase information. Secondly, the use of lock-in techniques allows for a reduction in noise levels when obtaining vibrational information at a single frequency, permitting far smaller excitation voltages. In the work reported here, a frequency sweep was initially recorded to determine the position of the resonant peaks of a piezoelectric MEMS device, followed by either laser or sample scanning to map the vibration mode.

Example: Piezoelectric (PZT) Transducer Membrane

As an example of the scale over which the scanning vibrometer system can operate, tests have been carried out on a macro-scale PZT membrane (4 mm diameter – see figure 2) and an atomic force microscopy (AFM) tip (see figure 3). For both samples, measurements were recorded in air (data not shown) and in vacuum to compare the effects on their dynamic response. The PZT membrane, excited directly by applying a sinusoidal voltage between top (inner) and bottom electrodes, exhibits a fundamental mode of vibration at a frequency of 20.78 kHz in air and 17.81 kHz under a vacuum of 4×10^{-5} mbar (see figure 4).

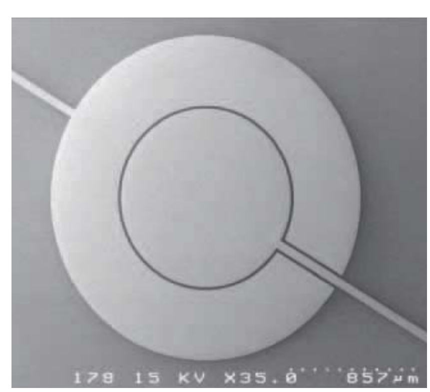

Figure 2: SEM image of the 4 mm diameter PZT circular membrane. Resonant modes are shown in the image to the right.

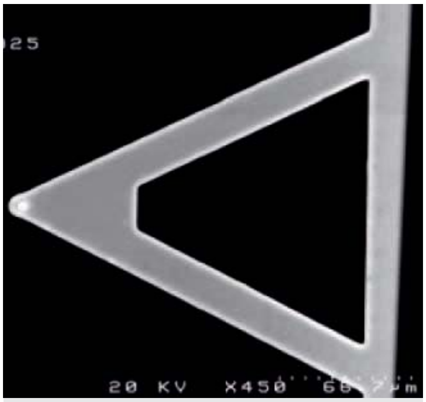

Figure 3: SEM image of the Veeco UltraleverTM AFM tip. Resonant modes are shown below.

This reduction in frequency is caused by a sealed air gap that exists behind the sample membrane and the mounting substrate. For "freely" vibrating samples, an increase in frequency is observed on reducing the pressure, because of the reduction in air damping acting on the sample. As well as the expected higher-order harmonics, further vibrational modes can also be seen, a result that would be more difficult to observe with a single-point vibrometer. For smaller devices, laser scanning can save time when compared to physically scanning the sample and also reduces effects caused by lateral motion and backlash of the scanning stages. Depending upon spatial resolution and frequency range required, a complete scan of the out-of-plane motion can be achieved in a matter of minutes.

Example 2: AFM Tip

Results from the AFM tip (feature size ~ 20 µm – see figure 3) demonstrate the lateral resolution of the system. A typical V-shaped cantilever used for contact mode AFM was scanned in both air and under vacuum. The resonant frequency of the cantilever was found to be 62.12 kHz in air and 62.59 kHz at a pressure of 3 x 10^{-5} mbar, with the amplitude of vibration increasing by a factor of approximately 50 (see figure 5). The increase in resonant frequency and enhanced Quality factor observed at reduced operating air pressures, can be explained as a reduction in the frictional energy dissipating forces that the cantilever experiences as it resonates in its local environment. This data can subsequently be compared to a software-modeled response using tools such as finite element analysis. Knowledge of the fundamental frequency of the tip allows calculation of the force constant which can then be compared with the values provided by the manufacturers – a fundamentally important characteristic of all AFM probes.

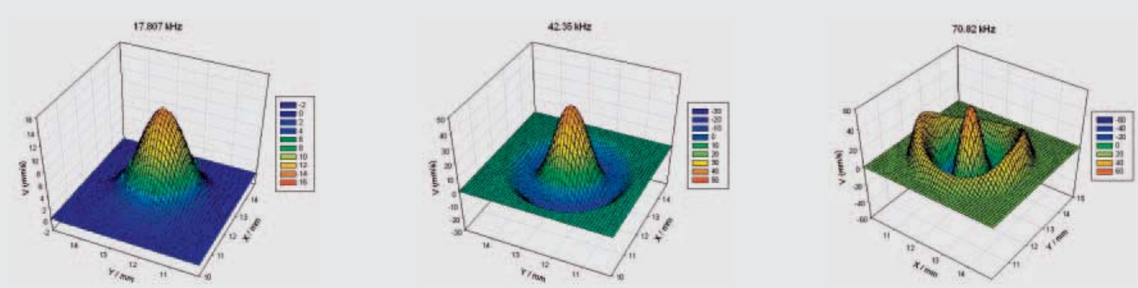

Figure 4: Resonant modes of the PZT membrane obtained under a vacuum of 4 x 10^{-5} mbar (fundamental, first and second order)

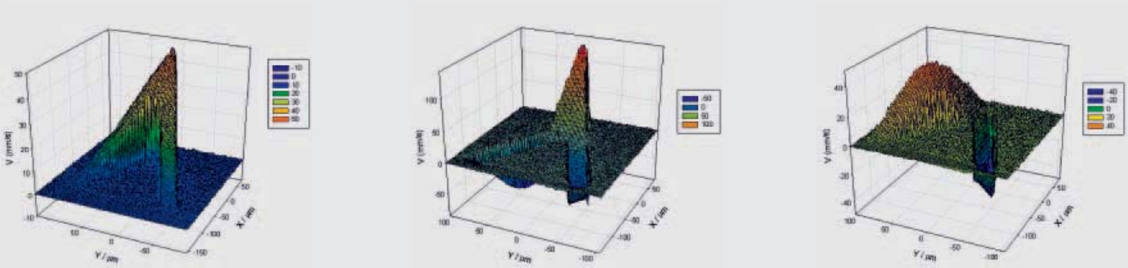

Figure 5: Maximum amplitude resonant modes of the AFM tip obtained under a vacuum of 3 x 10^{-5} mbar

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Example 3: SNOM Gold Probe

An example of the data taken using NPL's system from a 250 µm diameter gold probe used for a scanning near-field optical microscope (SNOM), is shown in figure 6a.

For the SNOM to successfully operate, an etched gold probe is driven at resonance by a small piezo element, with an amplitude of around 1 nm. This amplitude is kept small so as to reduce the area over which information is obtained. Initial work involved examining a relatively long probe (length ~ 6 mm). Scanning over the length of the probe showed that the mode thought to be the fundamental mode of vibration was in fact a higher-order harmonic vibration. This would complicate SNOM operation if the probe was excited at this higher frequency. A shorter probe (length ~ 2 mm) was subsequently fabricated and the frequency response of the apex of this probe is shown in figure 6b. It is found that the probe only requires a voltage of approximate 0.6 mV to produce a tip displacement of 1 nm at a resonant frequency of 22.06 kHz.

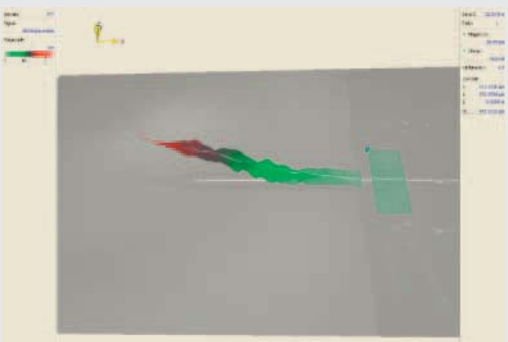

Figure 6a: Scanning LDV of the SNOM gold probe.

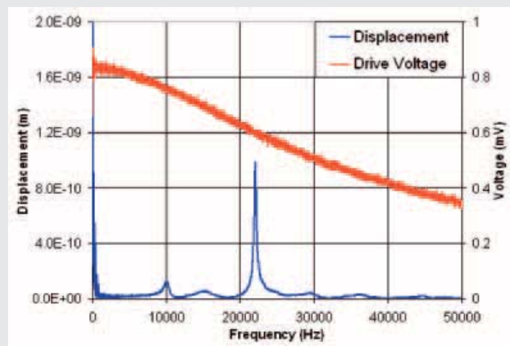

Figure 6b: Frequency response from 2 mm long Au SNOM tip. The LDV image shows that the fundamental mode is indeed being excited, rather than a higher-order harmonic mode of vibration.

Conclusions and Outlook

The work presented here has focused on obtaining high-resolution vibrometry scans from various samples of interest.

NPL's Polytec MSA-400-PM2-D (differential) Micro System Analyzer offers the advantages of rapid data acquisition and processing by utilizing FFT analysis, as well as permitting in-plane vibrational analysis. When combined with NPL's vacuum chamber operating down to 10^{-5} mbar with optional temperature/humidity control,

this provides a unique characterization system for out-of-plane and in-plane dynamic analysis of MEMS and macro-sized devices. As well as these samples, further velocity and displacement profiles have been acquired from a variety of other samples – both active and passive MEMS devices. Animated movies of some of these vibration modes can be found at **www.npl.co.uk/materials/functional/mpp1_3_4.html**

New MSA-500

In addition to the MSA-400 used for this measurements, the new MSA-500 has an Autofocus and Geometry Scan that widen the vertical measurement range and allow a complete 3-D view of the vibrations.

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

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