Dynamic measurements of a micropump using a fibre optic based interferometer

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ABSTRACT

Spatially resolved, non-contact, displacement measurements are reported from the membrane surface of a piezoelectric-driven micropump. The measurement system uses a fibre optic interferometric technique, which incorporates an air path to the pump in the signal arm, allowing measurements to be made remotely. The interferometer operates at 1523nm, has a bandwidth of 200kHz, a focussed spot size of 22μm and a noise equivalent displacement of 0.36nm. Membrane displacement profiles while pumping air and water have been obtained using custom designed automated fringe counting and interpolation software to interpret the digitised fringe patterns from the interferometer.

Measurements show significant differences in membrane velocity, displacement and settling time between the two different pumping media. Transient underdamped vibration of the membrane surface was also detected in the rapid excursion and recursion phases of the pump cycle while pumping air. Analysis of the vibration transients allowed the resonant frequency and damping ratio of the system to be calculated. In addition, the amplitude of the membrane displacement was demonstrated to be dependent on the pumping frequency when pumping air. Analysis of the driving voltage and displacement profiles indicated that this frequency dependant relationship was primarily due to two effects: insufficient settling time between pump cycles and capacitive loading of the driving voltage at high pumping frequencies.

Keywords: MEMS, optical fibre, interferometer, micropump, non-destructive testing.

1. INTRODUCTION

The rapid development of microelectromechanical systems (MEMS) has resulted in a large range of miniature sensors, actuators and other devices which can offer high performance together with low manufacturing cost in a very small package. These devices have a wide range of applications and have the capacity for integration into compact functional systems. While existing microelectronics techniques can often be used for testing electrical elements, further techniques are required for testing small mechanical components and providing information for design improvement.

Typically MEMS devices operate with very high speeds over small displacements and have rather high frequency modes of resonant vibration. Characterisation of the dynamic performance of these moving microstructures is required to better understand their modes of operation, and to be able to optimise their design as well as identify possible causes of failure. Common methods for studying the structural integrity and operating environment of small mechanical devices rely on measurement of changes in the modal resonant frequency or displacement during operation. Measurement systems must perturb the MEMS structures as little as possible as these moving surfaces are generally sensitive to load and damping. The performance of a MEMS device is also strongly influenced by its packaging so that non-contact, high bandwidth measurement systems are essential. Non-contact optical sensing techniques, which produce negligible loading effects are particularly suitable.

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This paper presents a fibre optic interferometric technique, which can be used to make rapid, microscopic displacement measurements from small target areas that are not required to be specularly reflecting. The novelty of this simple interferometric technique is the fact that it is fibre optic based and hence can be used in inaccessible areas which would be generally considered inappropriate for conventional interferometric techniques.

The technique is applied to dynamic displacement measurements from the surface of a micropump actuator. Micropump displacement measurements are presented during operation with two different media (air and water) over a range of different pumping frequencies. Interpretation of these measurements gives information about pump structure and performance.

2. EXPERIMENTAL ARRANGEMENT

The experimental arrangement used for the measurement of pump actuator deflection is shown schematically in figure 1. The fibre optic interferometer is a modified version of one first described by Philp and Booth for the measurement of small amplitude vibrations in a cantilever. The interferometer consists of a standard communications grade 1550 nm single mode optical fibre arranged in a Mach-Zehnder configuration. The fibre is coupled to a Melles Griot 1.2mW 1550 nm HeNe laser source. The source is split into two beams of equal intensity (signal and reference arms) by a 3dB 2x2 fibre optic directional coupler (DC1). The signal arm of the interferometer incorporates an air path to the actuator surface.

![Schematic diagram of the fibre optic interferometer and measurement system.](image)

Light from the actuator surface is reflected back into the signal arm and recombines with the reference beam at a second fibre optic directional coupler (DC2). The output in each arm of this coupler is out of phase by 180 degrees. Hence, any phase modulation of the signal beam induced by actuator movement can be converted to intensity modulation by calculating the differential of the detector outputs. The displacement range of the micropump surface causes intensity modulation over many cycles of the arc cos function and an automated fringe counting and interpolation technique was employed to calculate the surface displacement. Low frequency drift-induced phase changes are compensated for using a feedback-controlled phase shifter in the reference arm that locks the interferometer at the quadrature point. The phase shifts are induced by wrapping the reference arm of the fibre around a piezoelectric cylinder which expands and contracts via the feedback control. The bandwidth of the detection electronics is 200KHz and the measured noise equivalent displacement was 0.36nm.
giving a figure of merit of 0.8 pm/√Hz. For this application, the spot size of the focussed beam on the actuator surface was measured using a scanned edge to be 22µm at FWHM.

The micropump used for experimental measurements was an IMM self-priming membrane micropump. The device has overall dimensions of 12 x 13 x 3 mm³ and a maximum water flow rate of at least 250 µl/min⁸. The operation of the micropump relies on the driving of a piezo-electric actuator by an external 440V pk to pk square wave pulse of approximately 5ms duration. Frequency adjustment is achieved by varying the pulse repetition rate. The positive edge of the pulse induces an upward deflection in the piezo-electric actuator surface. This in turn creates a low-pressure zone under the membrane into which fluid or gas can expand up through an inlet valve from a reservoir below (figure 2B). At the negative edge of the voltage waveform the actuator surface is deflected downwards forcing the liquid or gas out through an outlet valve (figure 2C). The micropump is mounted on a multi-axis translation stage to enable the signal beam from the interferometer to be focussed at a convenient point on the actuator surface (generally the centre).

![Schematic diagram of the membrane micropump illustrating principle of operation. Suction phase (B), Pumping phase (C).](image)

Figure 2: Schematic diagram of the membrane micropump illustrating principle of operation. Suction phase (B), Pumping phase (C).

For the micropump measurements, the output of the interferometer was recorded using a 1GHz LC534AM LeCroy digital storage oscilloscope. The sampled section of the waveform was selected to include at least one complete pump cycle and the total number of samples was chosen to allow faithful reproduction of the high frequency interferometric fringe patterns obtained during rapid transitions of the pump excitation waveform (200 k samples for air ; 100 k samples for water).

2. RESULTS AND DISCUSSION

Figure 3 illustrates the driving voltage waveform for the pump on the primary axis. Typical examples of the intensity modulation of the interferometer output caused by movement of the pump membrane while pumping air and water are shown on the secondary axis. The interferometric waveforms are shown as photovoltages and are offset by 5 and 7 volts respectively to allow all three waveforms to be displayed in phase clearly. The maximum fringe excursion and frequency of fringe movement are dependent on the peak driving voltage and its rate of change respectively. The timescale of Figure 3 is...
chosen to display a complete pump cycle and is not suitable for resolving the details of fringe movement during the rapid transitions in the driving waveform. Under the digitising conditions used, these details are available by expansion of the waveform time scale using a shorter time interval for display.

Figure 3: The Piezoelectric driving voltage is shown on the primary axis. Typical interferometer intensity modulation fringes as a photovoltage waveform are shown on the secondary axis while pumping air and water (offset by 5 and 7V respectively).

Figure 4: Pump displacement waveforms while pumping air and water. Three waveforms recorded under identical conditions are shown for each pumping medium.
Figure 4 shows displacement profiles determined from the stored interferometric fringe pattern using the automated fringe counting routine. For the same repetitively-pumped excitation conditions, the peak displacement for the membrane surface while pumping water was about half that obtained while pumping air. The volume of material that will flow into or out of the pump chamber during a pump cycle is dependant on the material's viscosity and density. Thus increased flow resistance of the liquid as compared to air may explain the observed reduction in the amplitude of the membrane displacement for the former case. In addition to this difference in amplitude of displacement, the variability of displacement between nominally identical pump cycles was much greater while pumping water. This is evident in the figure as distinctly different displacement waveforms while pumping water while the three waveforms displayed while pumping air are indistinguishable. The observed variability while pumping water may be associated with flow instability effects which would be expected to be much more significant when pumping liquids through the system, and in particular through the membrane valves.

The details of the shapes of the pump displacement waveforms are indicative of processes characterising the pump or affecting its operation. To the extent that waveform features can be quantified or modelled, one can obtain information which can assist in understanding or optimising pump operation. For example, while pumping air, the displacement profile exhibited a ringing superimposed on the rise and decay during the rapid excursion and recursion phases of the movement as shown in figure 5. This ringing was characteristic of an underdamped free vibration that can be described by a function of the form,

\[ y = K e^{-\zeta \omega t} \sin(\sqrt{1 - \zeta^2} \omega t + \phi) \]

Where \( \zeta \) is the damping ratio, \( \omega \) is the resonant frequency of the system and \( \phi \) is a phase offset. By fitting just the ringing sections of the displacement profile with this function superimposed on an exponential rise or decay as shown in figure 5, the damping ratio and resonant frequency of the vibrating system can be determined. The damping ratio and resonant frequency for the air pump were found in this way to be 0.122 ± 0.004 and 84.8 ± 0.3 kHz respectively.

![Figure 5: Ringing section of pump displacement profile fitted to characteristic underdamped free vibration equation.](image-url)
While pumping air, the amplitude of the membrane displacement was found to decrease approximately linearly with pump pulse repetition frequency. A decrease of about 15.5% over a frequency range of 10 Hz to 75 Hz was observed as shown in Figure 6. This frequency dependant response may be partially explained by examining the membrane displacement profiles at four different pumping frequencies plotted on the same axis (Figure 6). These displacement profiles show that after the first pump cycle, there is a significant variation between the starting points for the upward motion of the next pump cycle. This variation in starting position is due to insufficient settling time between pump cycles, particularly at high pump frequencies.

![Figure 6: Frequency dependant response of pump displacement while pumping air.](image)

![Figure 7: Variation of pump displacement profile while pumping air at different pumping frequencies.](image)
The magnitude and shape of the driving voltage for the piezoelectric actuator is indicative of an excitory voltage that may suffer from frequency dependent loading effects. The peak to peak voltage delivered by the driver was measured over a range of pump frequencies from 5 to 95 Hz. The relationship between pump voltage was observed to decrease approximately linearly with increasing pump frequency as shown in Figure 8. For the frequency range from 10 to 75Hz a drop of approximately 6% in driving voltage was measured. The displacement of piezoelectric actuators is theoretically predicted to be linearly dependent on the supply voltage. Hence, some of the frequency dependant displacement damping demonstrated for the pump membrane in figure 6 is also likely to be caused by the reduction in supply voltage at higher pump frequencies.

A similar monotonic decrease in displacement amplitude with pump increasing frequency was not observed while pumping water, possibly because it was smaller than the pulse-to-pulse variability in membrane displacement.

![Figure 8: PZT driving voltage as a function of pump frequency while pump air and water.](image)

4. CONCLUSIONS

A simple optical technique has been presented for remote spatially-resolved non-loading measurements of membrane displacement in a MEMS micropump. The technique was used to measure pump actuator deflection while pumping air and water and provided a displacement profile that can be used to help characterise the operation of the pump. The interferometric technique presented may find further application for non-contact measurement of dynamic performance of small mechanical components in MEMS structures.

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