Vacuum performance and control of a MEMS stage with integrated thermal position sensor

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Abstract

A flexure-based MEMS stage with electrostatic actuators and an integrated thermal position sensor was designed and fabricated. Both the thermal conductivity and the viscosity of air decrease for lower pressure. This was measured as a lower sensor response and higher Q-factor of the MEMS stage. For the first time, we considered the control stability of a MEMS stage as a function of decreasing pressure. We conclude that stable position control of the stage is possible for vacuum pressures down to 1 mbar.

1. Introduction

Millimetre sized nano-resolution manipulators for confined vacuum chambers are becoming increasingly important for future applications in scanning and transmission electron microscopes (SEMs and TEMs). Applications include manoeuvrable phase plates, sample manipulators, and in-situ sample straining. Typically SEMs and TEMs operate at vacuum pressures below 1×10^{-6} mbar. Environmental SEMs (eSEMs) offer the possibility to make electron microscopy images in gaseous environments at higher pressures, up to 20 mbar, so that 'wet' samples can be investigated. The main objective of this paper is to investigate the applicability of a closed-loop MEMS-based positioning stage in a vacuum environment.

An overview of the stage is given in Figure 1. The stage is suspended by a flexure mechanism and is actuated by electrostatic comb-drives. Position feedback for control is provided by an integrated sensor based on the conductance of heat through air [1].

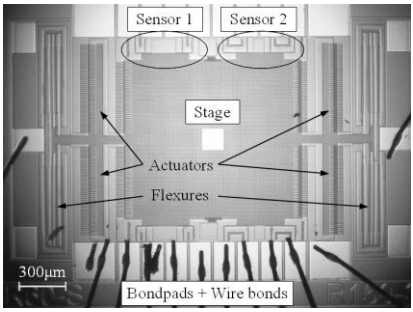

Figure 1: Top view optical microscope image of the MEMS stage. The comb-drive actuators in combination with the flexure mechanism enable stage displacements up to ±30 µm. Differential thermal displacement sensors are included for feedback of the stage position.

2. Vacuum theory

The thermal conductivity of air is independent on pressure for large volumes, since the mean free path length increases inversely proportional with the amount of air molecules [2]. When the mean free path length is limited by geometry, the thermal conductivity will decrease proportional with the pressure [3]. The characteristic dimensions of the MEMS stage are in the transition regime of these two cases; a model for the thermal conductivity in the transition regime is given by Sherman [4]. The thermal conductivity and the viscosity of air are based on the same physical principle, the collision of air molecules with each other and with the surroundings, and are therefore linearly related [2]. The thermal conductivity and viscosity of air are used to model the sensor sensitivity and the Q-factor of our MEMS device.

3. Identification results

The sensor response and Q-factor are measured as a function of the pressure and given in **Figure 2**. The sensor sensitivity is independent from pressure in the range of 800 mbar to 10 bar. Below 800 mbar, the response drops with approximately 20 dB per decade of pressure, reaching the detection limit at 1 mbar. This behaviour was accurately modelled for pressures above 10 mbar. This is shown in Figure 2 (left). The quality factor of the actuator with flexure mechanism in resonance decreases with increasing pressure. The behaviour can be modelled accurately for pressures above 50 mbar. This is shown in Figure 2 (right).

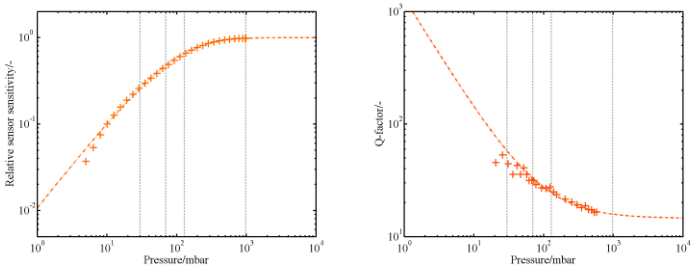

Figure 2: The sensor response for low pressure is normalized towards the sensor sensitivity at ambient pressure (2.17 mV/µm) and is plotted as a function of the vacuum pressure (left). The Q-factor is given as a function of the pressure (right). The markers indicate the measurements and the dash-dotted lines indicate the model.

We have also identified the plant in the frequency domain by performing a frequency sweep at four vacuum pressures; the results are given in Figure 3. The MEMS stage can be described by a mass-spring-damper system with variable sensor gain and Q-factor. A low-pass filter is added to describe the frequency response of the thermal position sensor.

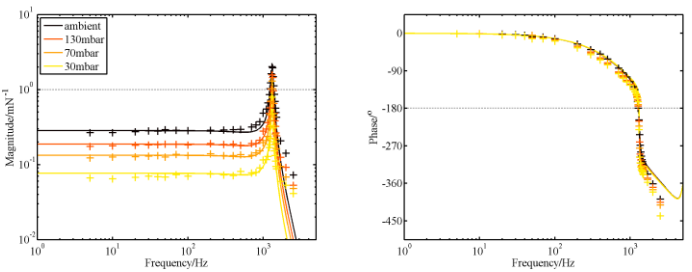

Figure 3: Identification of the MEMS stage (plant) in the frequency domain. The markers indicate the measurements and the lines indicate the model.

4. Control results

The results of the plant identification are used for control of the MEMS stage. An integral controller (C_I) is chosen to control the plant that acts as a stiffness. Due to the high Q-factor in vacuum the crossover frequency of the controller cannot be chosen too high. By adding a low-pass (C_{I+LP}) or a notch filter (C_{I+N}) the crossover frequency can be increased. The closed-loop system with different controllers is validated in time by measuring the step response and the force disturbance response, Figure 4. Simulations show good agreement with the measurements.

The crossover frequency of the controllers is increased to reach the minimum settling time. The integral controller with the notch filter gives the lowest settling time at ambient pressure and at 1 mbar, and therefore it is the preferred controller. The controlled system remains stable at pressures down to 1 mbar, limited by the detection limit of the sensor.

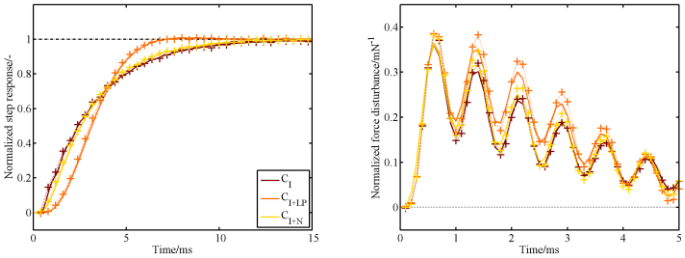

Figure 4: Step (left) and disturbance (right) response at ambient pressure of the closed-loop system with an I-controller, an additional low-pass filter and an additional notch filter are shown. The controllers were set to a crossover frequency of 50 Hz. The solid lines represent the model and the markers represent the measurements.

5. Conclusion

Electrostatically actuated flexure-based microstages with thermal displacement sensors for position control can be effectively used in vacuum environments down to 1 mbar, for example in eSEMs.

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