Influence of Temperature Variations on the Frequency of Two-dimensional MEMS Mirrors

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***Abstract*—The reliability of microelectromechanical systems (MEMS) becomes increasingly important due to the fast market growth, especially in medical, automotive, and aerospace applications, where high reliability performance under harsh environmental conditions is crucial. The aim of this work is to test the behavior and performance of two-dimensional (2D) resonant MEMS mirrors, which are driven electrostatically, under different temperatures. Therefore, six mirrors and their driver application specific integrated circuits (ASIC) are tested inside a temperature chamber, where the temperature is swept between -40°C and 90°C multiple times and different mirror parameters are logged for both axes of the mirrors and the results are evaluated afterwards. Especially the driving frequencies of the axes are monitored. The results show that there is a nearly linear inverse relation between driving frequency of the mirror's fast axis and temperature, as the frequency rises with a decreasing temperature, while for the slow axis the relation between frequency and temperature is more complex. Moreover, the operation of the mirror is stable over the tested temperature range, as no failures are observed.**

***Index Terms*—2D MEMS mirror, temperature, driving frequency, reliability, oscillation angle**

I. Introduction

Electrostatic two-dimensional (2D) microelectromechanical system (MEMS) mirrors consist of gimbal structures, which enable steering actions in two orthogonal directions. Due to the simple design, fast response, ability to enable rotary motion and low power consumption, an electrostatic actuation is favorable. There are several successful applications for MEMS mirrors in recent years. For example the operation in mirror arrays for projection display systems in order to modulate optical signals digitally. Moreover they are also applied as optical switches for telecommunications or as virtual masks for DNA patterning. It is also possible to incorporate them with other micro-optical devices, like micro lenses, micro gratings or optical waveguides [2]. In addition to that MEMS mirrors are widely used in areas like augmented and virtual reality (AR/VR) and for projection displays [3]. The performance specifications for the application of resonant MEMS mirrors typically include mirror size, resonant frequency, quality factor, deflection angle and operation voltage and linearity [2]. Regarding the reliability there are different failure mechanisms for micro-mirrors, like mechanical wear, fracture, fatigue, shock and vibration with failure acceleration factors such as temperature, strain and voltage. Because of the complex moving structures of MEMS elements, their failure modes and mechanisms are different than for integrated circuits (IC) and furthermore also the number of feasible failure modes is higher [1]. For fatigue testing millions to billions of cycles before failure need to be executed. Due to that in order to reduce development time, which saves companies money and time, high temperature testing is used to accelerate failure. It is known that there is a relation between the elasticity of doped silicon and temperature, which may lead to frequency shifts due to temperature deviations [4]. Previous measurements showed that drifts of the driving frequency of 2D MEMS mirrors could be observed prior to breakage, but in order to detect them correctly the influence of temperature on the frequency has to be compensated to distinguish them from deviations due to temperature variations [5].

In the scope of this research the influence of temperature shifts on the operation of 2D resonant MEMS mirrors, which are actuated electrostatically, is evaluated, where especially the relation between temperature and driving frequency is investigated. Therefore a test setup is adapted in order to measure six mirrors and their corresponding drivers inside a temperature chamber, where the temperature is changed between -40°C and 90°C several times, while logging the defined mirror parameters. Afterwards the influence of temperature on the driving frequency is analyzed for both axes of the mirrors. It is also determined how the frequency changes for different oscillations angles over the temperature range. Therefore the presented paper contributes to the following scientific research questions: Which influence do temperature variations have on the driving frequency and operation of MEMS mirrors? How does the relation between driving frequency and temperature look like for both axes for different mirrors and how could it be explained? Do the results changes for a different oscillation angle and how do they change? May temperature shifts influence the lifetime of MEMS mirrors and accelerate failure?

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II. Temperature Influence on MEMS mirrors

A. Background

With the help of deep reactive ion etching the mechanical structures of 2D MEMS mirrors are manufactured on silicon on insulator (SOI) wafers [6], where silicon is chosen as material due to the high stiffness and large yield strength, which enables high oscillation angels and operating frequencies [7]. In order to isolate the mirror and the frames, oxide- or polysilicon-filled trenches are used and the backside silicon substrate and buried oxide layer under the elements are detached to set free the structure [6]. The buried oxide layer fixes the thickness of the mirror, as it is positioned under the silicon and acts as an etch stop [8]. For MEMS devices the two main materials used for the structures are single crystal silicon and polycrystalline silicon. While their electrical properties are well-known, it is not well researched how their mechanical characteristics influence the fatigue of MEMS devices, when it comes to the prediction of their lifetimes. As a brittle material silicon is considered to be fatigue free at room temperature. Nevertheless it was experienced that single crystal silicon and polysilicon show mechanical fractures if they are exposed to different temperature ranges and damp environments because of the fatigue growth rate and cyclic stress. It was observed that the fatigue rates are increased by high temperatures [9]. Over the normal operation temperature range (250-350 Kelvin) the material properties of silicon change quite fast, where the thermal expansion coefficient at 250 Kelvin is only 70% of the value at 350 Kelvin [10]. The resonant frequency of MEMS devices is influenced by temperature due to the thermal expansion of cantilever arms and because the bending stiffness of silicon decreases with temperature [11]. The temperature dependence of the elastic constants of doped silicon is described in more detail in [12] and [13], where it is described that the material constants of silicon also depend on the orientation relative to the crystal lattice and on the doping concentration. In [4] it was shown that there is an inverse relation between temperature and frequency for vacuum encapsulated MEMS resonators, where the correlation value between them was minus 0.94. This means that almost all of the small frequency variations happened due to temperature changes [4].

B. MEMS mirror and ASIC

This work concentrates on two-dimensional resonant MEMS mirrors, which are actuated with the help of electrostatic comb drives, where the corresponding driver application-specific integrated circuit (ASIC) is responsible for sensing, controlling and actuating the mirror. The ASIC consists of a sensing interface, a phased-locked loop (PLL), an amplitude control and a high voltage (HV) driver. With the help of the HV driver the mirror is actuated by switching on and off the HV, where the position of the mirror has ro be sensed precisely in order to perform this. The sensing of the mirror is executed by measuring the capacitance from the comb drives, where the current flows from the capacitors are then converted into voltage levels by transimpedance converters. The PLL follows the movement of the mirror, while the amplitude control keeps the maximum deflection angle constant. The investigated two-dimensional MEMS mirror has one axis, which deflects the laser beam vertically and another, which deflects it horizontally [14]. There is a ratio between the axes, which leads to a so called fast axis with a higher frequency and a slow axis with a lower frequency in order to achieve Lissajous scanning, described in [15]. The two different axes of the mirror are shown in [5]. Because of the response curve of the mirror, the frequency increases with an increase of the oscillation angle in operation [14]. A more detailed description of the mirror and it's operation is given in [14], [16] and [17].

C. Test Setup

The test setup for the measurements consists of a multi-devices under test (DUT) board, where six mirrors and there corresponding drivers could be tested in parallel, which is connected to a HV supply and a micro-controller board. The Multi-DUT board is placed inside a temperature chamber, while the other parts of the setup are placed outside and connected via cables with the board. The tests are executed with the help of a laptop, where a test program runs in order to steer the temperature chamber and the drivers of the mirrors. The test setup is shown in the following Fig. 1.

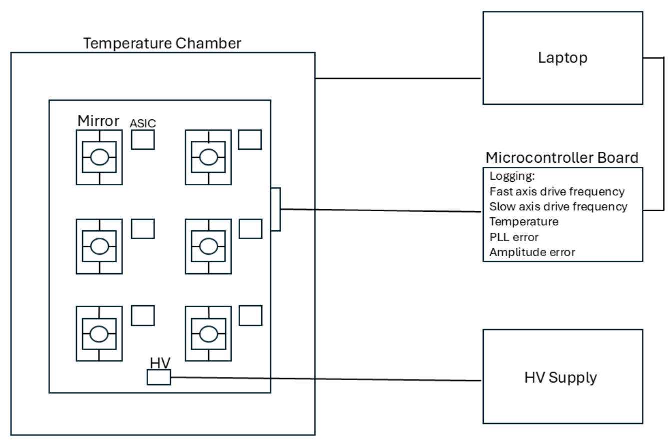

Fig. 1. Test setup for executed temperature measurements with temperature chamber, Multi-DUT Board, HV supply, micro-controller board and laptop.

D. Measurements

The measurements were executed for six mirror and their corresponding drivers, where the temperature was swept several times between -40°C and 90°C with the help of the temperature chamber. Two of the mirrors were started on the outer or so-called slow axis at 70% of the maximum target angle, while four mirrors were started on the inner or fast axis at the same angle. For some of the tests the fast axis deflection angle was increased to the maximum target angle in order to see how this influences the results. Different parameters were logged by the drivers during the temperature sweeps like driving frequency, PLL error, amplitude error and driver temperature, which deviations over the temperature range are then analyzed. The drive frequency is the actuation frequency of the respective axis, which is in the kHz range. Furthermore the PLL error is calculated as the difference between expected and measured zero-crossing of the mirror in ticks, while the amplitude error is the error of the deflection angle detector. The driver temperature is the temperature measured by the ASIC and therefore the actual temperature at the IC.

III. Results

First the results for the behavior of the driving frequencies of both axes over temperature are discussed, which are in the kHz-range. The following Fig. 2 shows the frequencies of the fast axis for four different mirrors for an oscillation angle of 70% of the maximum angle and the maximum angle, where the temperature of the chamber was swept between -40°C and 90°C six times. In Fig. 2 the actual temperatures measured by the ASICs of the mirrors are shown, which go from -35°C up to 88°C. It is visible that the total frequency drift over the temperature range is about -90Hz, where the frequency decreases nearly linearly with an increase of temperature for a constant angle, as the correlation value is calculated as minus 0.99, like in [4]. The total frequency drift is a bit larger for the higher oscillation angle. Moreover the frequency increases approximately 20Hz for an increase of the angle from 70% to the maximum angle at the same temperature, due to the resonance curve in [14].

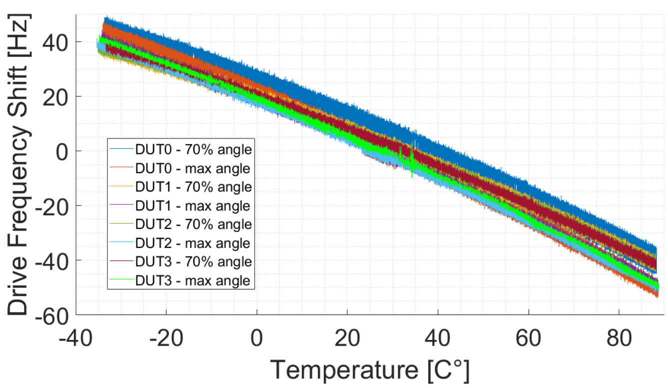

Fig. 2. Fast axis drive frequency of four mirrors for 70% angle and maximum oscillation angle over temperature

For the following Fig. 3, a linear fit was determined for all curves for both oscillation angles with the help of Matlab and the mean of these linear fits was taken to approximate the relation between fast axis frequency drift and temperature. It was determined that the frequency of the fast axis changes on average -0.7Hz/C° and approximately -90Hz over the temperature range from -40°C to 90°C. The next Fig. 4 shows now the slow axis frequencies for two different mirrors for an oscillation angle of 70% of the maximum angle, where the temperature was again swept between -40°C and 90°C six times. The total frequency drift over the temperature range for the slow axis is approximately 25Hz, which is lower than for the fast axis, but ratio between the axes frequencies is about 1 to 4. The

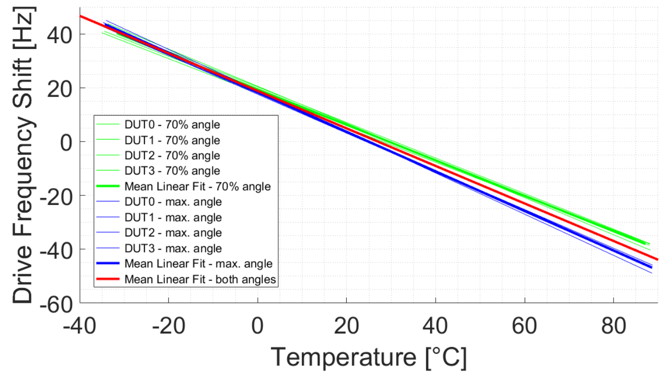

Fig. 3. Linear fit for fast axis frequencies of four mirrors over temperature

drive frequency increases with an increase of temperature until 45°C, as the slow axis is connected to the package-frame, which stiffness decreases and thermal expansion rises with temperature, which influences the slow axis. Therefore the slow axis frequency increases with temperature until 45°C in order to keep the oscillation angle constant. At approximately 45°C the glue of the package becomes viscous, like in [18], which leads to a plateau and for higher temperatures the slow axis frequency decreases then with increasing temperature. For the slow axis a polynomial fit was determined for both mirrors with the help of Matlab and the mean of these fits was taken to approximate the relation between slow axis frequency drift and temperature, which is shown in Fig. 4. It was determined that the frequency of the slow axis changes on average 0.35Hz/°C between -40°C and 0°C, 0.15Hz/°C between 0°C and 45°C and -0.07Hz/°C between 45°C and 90°C. Over the whole temperature range the frequency changes approximately 20Hz and the correlation value between slow axis frequency and temperature is determined as 0.75.

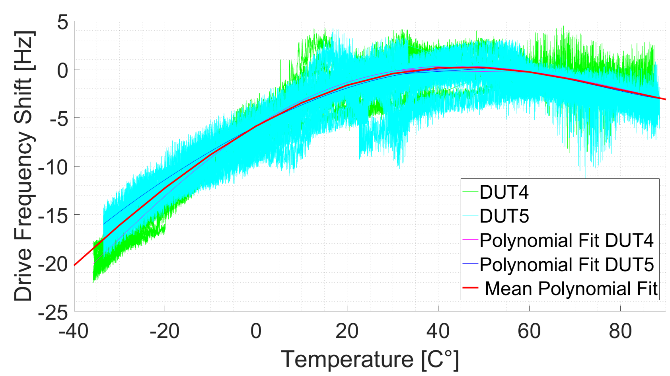

Fig. 4. Slow axis frequencies of two mirrors over temperature with polynomial fit

Finally the results for the PLL and amplitude error over temperature are evaluated. Both error values stay low and stable over the whole temperature range within a normal range. The results indicate that the operation of the mirrors was stable over the entire temperature range and the function was not affected by the temperature variation.

IV. Conclusion

In conclusion it was determined that the operation of 2D resonant MEMS mirrors over temperature for both tested axes, where it was swept between -40°C and 90°C several times, is reliable and stable. The PLL error is quite low, as the PLL is able to follow the movement of the mirror accurately. Furthermore, the amplitude error remains low over the entire measurement, which means that the deflection angle is kept constant. In addition to that the behavior of the fast and slow axis drive frequency over temperature was analyzed, where a indirect proportional linear relation was approximated between fast axis frequency and temperature, as the frequency decreases with an increase of the temperature with about -0.7Hz/°C. This relation could be explained by the fact that the bending stiffness of silicon decreases for lower temperatures and in order to keep the oscillation angle stable the drive frequency increases. The correlation value between temperature and fast axis frequency was calculated as minus 0.99, which indicates a strong negative relation. Moreover the total frequency drift over the temperature range is -90Hz and it was determined that the drift gets slightly larger for a higher oscillation angle. On the other hand now for the slow axis a polynomial function was approximated with the help of Matlab, where the drive frequency increases with about 0.35Hz/°C between -40°C and 0°C and 0.15Hz/°C between 0°C and 45°C, as the slow axis is connected to the package-frame, which stiffness decreases and thermal expansion increases with increasing temperature. Therefore the drive frequency of the slow axis has to increased to keep the deflection angle stable between -40°C and 45°C. At around 45°C the glue of the package gets viscous, which leads to a plateau of the frequency and between 45°C and 90°C the frequency decreases with approximately -0.07Hz/°C. The results for the slow or outer axis are more complicated due to the complexity of the structure of the MEMS mirror and its connection to the outer frame of the device. The total frequency drift for the slow axis was determined as 20Hz over the temperature range, where it has to be taken into account that ratio between the axes is approximately 1 to 4, so the total drift is similar related to the drive frequency. Regarding the lifetime and reliability of MEMS mirrors, temperature may be an accelerating factor for failure due to the deformation of the structures, which is caused by thermal expansion or contraction and different bending stiffness for different temperatures. Especially high temperatures may shorten the lifetime due to increased fatigue rates. As an outlook the relation between temperature and frequency drifts could be further analyzed for a larger number of mirrors and different oscillation angles in order to create more statistical data. In addition measurements could be executed, where both axes are actuated at the same time and the results could be compared. Moreover, mirrors could be tested under elevated or reduced temperatures over longer time to investigate the influence of temperature on the lifetime of MEMS mirrors in more detail. Therefore, the cycles until failure could be compared to the results at room temperature to evaluate the failure acceleration.

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