JMEMS Letters

Parallel Averaging for Thermal Noise Mitigation in MEMS Electrothermal Displacement Sensors

Ali Mohammadi, S. O. R. Moheimani, and Mehmet Rasit Yuce

***Abstract*— The sensitivity of an electrothermal displacement sensor increases with its temperature, whereas a higher temperature range leads to higher thermal noise level, which imposes a tradeoff on the sensor's achievable resolution. We have developed a multiple sensor displacement measurement technique on a 1-degree-of-freedom silicon-on-insulator microelectromechanical systems nanopositioner that mitigates the mentioned tradeoff. To obtain maximum improvement, it is necessary to supply equal power to all of the sensors to ensure equal sensitivity. By combining three identical sensors, we have successfully achieved a 4-dB improvement in signal-to-noise ratio, which is in a good agreement with the averaging theory. Experiments show that the displacement resolution is improved from 0.3 to 0.15 nm/$\sqrt{(\mathrm{Hz})}$ in the prototype nanopositioner. Furthermore, improvement is possible by increasing the number of sensors around the stage. [2014-0120]**

***Index Terms*— Electrothermal sensor, microelectromechanical systems (MEMS), thermal noise, averaging, nanopositioning.**

I. INTRODUCTION

Nanopositioning has emerged as an indispensable technology in nanosystems. A nanopositioner consists of a microactuator and a displacement sensor operating in a closed loop [1]. The performance of nanopositioning systems is strongly dependent on the resolution of the sensor. Microelectromechanical systems (MEMS) offer a high-speed and low-cost solution compared to existing mesoscale approaches. Smaller footprint and higher sensitivity make the electrothermal sensing a viable method for displacement measurement compared with other techniques available in MEMS [2]. The sensitivity of an electrothermal sensor increases proportional to its temperature according to the models proposed in [3]. However, the thermal noise floor also increases with temperature, which forces the user to strike a compromise between the thermal noise and sensitivity. Thermal noise reduction by averaging repetitive measurements known as serial averaging is routinely used in instrumentation by processing the recorded data [4]. However, real-time parallel averaging has been reported only in a few cases. A general purpose averaging system was first patented in [5], where a digital circuit is utilized to examine the polarity of multiple analog inputs and inputs with similar polarity were amplified by a variable gain amplifier. In [6], sixteen piezoresistive elements are combined to reduce the thermal noise of a tactile sensor but no quantitative improved figure was reported. In another work diffraction grating is used for two optical displacement measurements to reduce the sensor noise by a factor of $1/\sqrt{2}$ [7]. We propose a new architecture for MEMS electrothermal displacement sensing based on on-chip parallel averaging. The SEM image of a prototype nanopositioner implemented in standard SOI technology for this purpose is shown in Fig. 1. The sensor noise phenomena and theoretical expectations of the proposed technique are described in section II. The experimental details and measurement results are reported in section III and section IV concludes the letter.

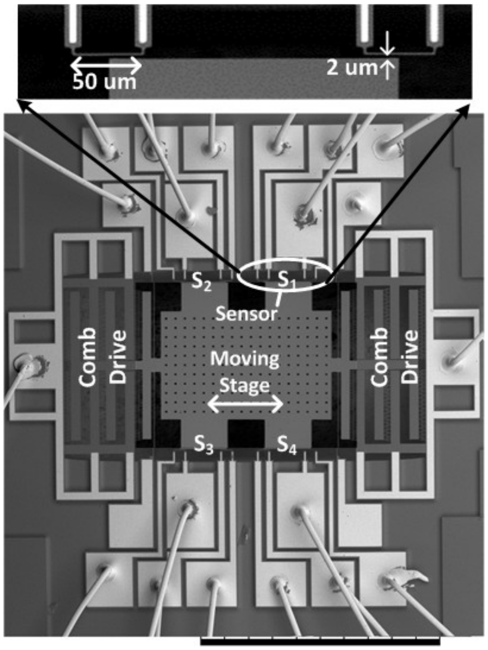

Fig. 1. Proposed multiple-sensor displacement measurement system on a 1-DOF SOI MEMS nanopositioner, (one electrothermal sensor magnified at top.)

II. PROPOSED MULTI-SENSOR ARCHITECTURE

The operating principle of electrothermal sensors can be described as in Fig. 1. Applying electrical power to doped silicon resistors (see S_1 magnified) increases their temperature. The heat conduction through a thin air gap ($2\,\mu$m) between the stage and sensors is proportional to the overlapped area. The stage movements changes the area overlapped and consequently the sensors temperature. The resistance of sensors varies as a function of temperature. Hence, the stage displacement translates to resistance variations. The surface micromachined devices are vulnerable to mechanical noise while bulk micromachined transducers are predominantly influenced by the electrical noise, originating in their resistive elements and the readout circuit. The chopper and lock-in amplifier are used to alleviate the flicker noise in the readout circuits [8]. The electrical noise of a MEMS resistor made of doped silicon consists of thermal noise

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Manuscript received April 9, 2014; accepted September 21, 2014. Date of publication November 12, 2014; date of current version January 30, 2015. Subject Editor A. M. Shkel.

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Digital Object Identifier 10.1109/JMEMS.2014.2364588

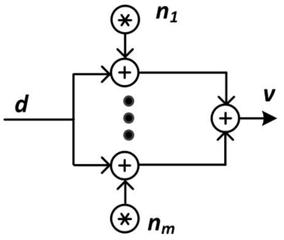

Fig. 2. Uncorrelated noise sources ($n_1, \ldots, n_m$) added to the desired displacement signal (d).

and flicker noise. A high frequency excitation method to mitigate the flicker noise in electrothermal displacement sensors was reported in [9]. The thermal (Johnson) noise is the result of thermal agitation of charge carriers and its white power spectrum is described as

$$V_j = \sqrt{(4k_B T R)} \tag{1}$$

where k_B is the Boltzmann constant, R is the resistance and T is the temperature of the device. The resolution of an electrothermal displacement sensor at higher frequencies is limited by its thermal noise. In particular, it is a crucial factor in high speed nanopositioning [2]. A trade-off between the thermal noise and the sensitivity sets the resolution limit, i.e. to achieve a higher displacement resolution it is essential to improve the signal-to-noise ratio (SNR) of the sensor. The differential configuration improves the transducer linearity and rejects the common mode interferences. However, the thermal noise is a random variable, which is impossible to be mitigated by the differential architecture.

Signal averaging provides a means of estimating the shape of repetitive response buried in non-coherent interference. SNR can be improved by using the redundant information inherent in multiple measurements [4]. The averaging approach to sensor white noise reduction is depicted in Fig. 2, where the desired displacement signal, sensor noise and output voltage are represented by d, n and v, respectively and m is the number of measurements. Let σ be the rms value of the random variable n. Then the total noise (N) and signal power (S) at the output are

$$N = \sigma\sqrt{m} \tag{2}$$

$$S = md \tag{3}$$

Thus, the resulting SNR is

$$SNR_{avg} = \frac{mS}{\sqrt{m}N} \tag{4}$$

which is $\sqrt{m}$ times larger than what would be by each sensor alone. This technique is routinely implemented by sampling the signals at certain time intervals and storing the data in a memory (serial averaging). In comparison, parallel averaging is based on combining independent measurements using multiple sensors. In nanopositioning applications, the delay generated by serial averaging may adversely affect the performance of the closed-loop system. In addition, it may add quantization noise to the measured quantity, which further deteriorates the SNR. Parallel approach is immune to quantization noise and time delays that may arise in serial methods.

Here we propose a real-time analog averaging method that avoids the complications arising from the digitization and storage of data. The 1-DoF nanopositioner designed for this purpose is illustrated in Fig. 1. Four pairs of sensors are on the two opposing sides of the moving stage. Each sensor is independently measuring the same displacement. Hence, they translate the same amount of movement to resistance variations. However, imperfections in the MEMS fabrication process lead to different resistance values. Consequently, even with the same excitation voltage or current the sensors may heat up to different temperatures leading to different sensitivities and unequal output signals. It is known that the sensor temperature is determined by various parameters such as the level of injected electrical power, the air-gap between sensors and the stage etc. However, once fabricated the only parameter that can be tuned to set the sensitivity is the injected electrical power. Therefore, in order to have sensors with identical sensitivities, the applied electrical power is kept constant during the measurements. This is achieved by operating the sensors in constant voltage mode and monitoring the sensors bias current and voltage simultaneously. The proposed readout circuit consists of two transimpedance amplifiers (TA) that add the sensor outputs and a differential amplifier to provide the required gain as shown in Fig. 3. R_{1p} and R_{1n} are nominal resistances of a differential sensor (See S_1 in Fig. 1) and V_h represents the heating voltage. Resistance variations result in a change in the current flow in each resistive sensor. The effect is modelled here by V_i as a differential voltage.

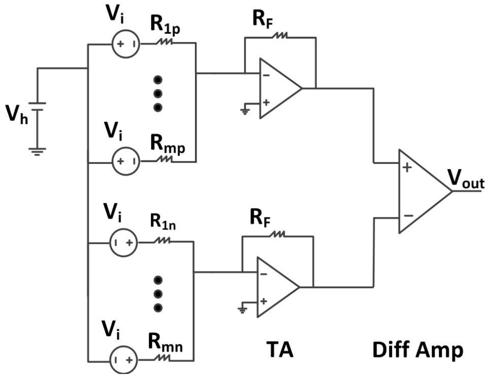

Fig. 3. Readout circuit designed for multiple sensor outputs.

III. EXPERIMENTAL RESULTS

The 1-DoF nanopositioner shown in Fig. 1 is fabricated in a standard SOI MEMS process [10]. The sensors length, width and thickness are 50 μm, 2 μm and 25 μm, respectively, and their spacing from the stage is 2 μm. A 3 V dc voltage is applied to heat up the sensors. Larger voltages are avoided due to the current limit of the following amplifiers. The stage is moved by the electrostatic forces generated by the comb drives. A 110 Hz actuation signal is applied to the electrostatic actuator in order to operate the device sufficiently away from the low frequency noise and the power line 50 Hz noise. Despite monitoring the electrical power delivered to sensors to ensure equal sensitivity, S_4 showed significantly different characteristic, which is most likely due to damages happened in the test process. Therefore, three sensors were utilized in the experiments. The power spectrum of each sensor (S_1, S_2 and S_3) and their combination (S_{123}) were measured. These are depicted in Fig. 4. The signal level is increased by about 9 dB. In order to measure the noise level a separate noise floor (nf) measurement was carried out by removing the actuation signal. The integrated noise floor over a 10 Hz bandwidth shows that the noise floor of the combined output is increased by about 5 dB. Therefore the SNR is improved by approximately 4 dB, which is very close to the theoretical prediction of $20\log(\sqrt{3})$.

The bandwidth of sensors is about 6.6 kHz in both cases, which was determined by applying a step input to the sensor bias and measuring the settling time, assuming that the sensor resembles a

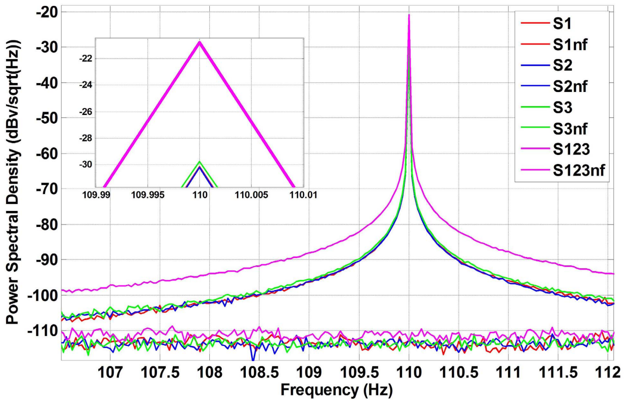

Fig. 4. Measured power spectral density for three sensors and their combination.

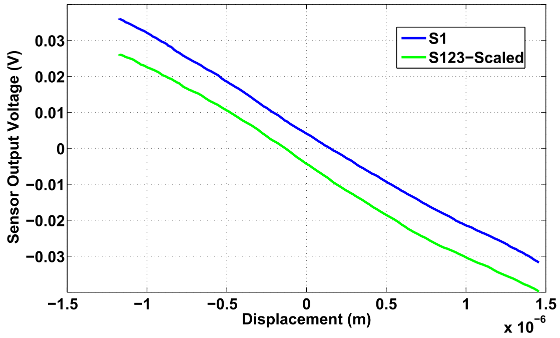

Fig. 5. Sensor transfer characteristic.

first order transfer function. The sensor output voltage was measured versus the stage displacement by an optical microsystem analyzer (MSA-050-3D) for a single sensor (S_1) and combination of three sensors (S_{123}). This was achieved by applying a slowly varying triangular signal to the actuator and recording the stage displacement and the sensor output voltage simultaneously. The transfer characteristics are shown in Fig. 5. S_{123} is scaled down to match its sensitivity with S_1. In order to compare the linearity, the maximum residual of a linear fit is divided by the full scale of the sensor output which leads to 2.32% and 3.12% for S_1 and S_{123}, respectively. The three sensors were operated independently, therefore the increased nonlinearity can be attributed to the limited output current of transimpedance amplifiers. Three sensors draw higher currents, which drives the amplifier closer to its non-linear region. The sensor dynamic range (maximum displacement input/sensor resolution) is limited by the actuator displacement to 40.5 dB. As illustrated in Fig. 5 the stage maximum travel range is less than 3 μm.

IV. CONCLUSION

The positioning accuracy of a MEMS nanopositioners is strongly dependant on its sensor specifications. The SNR of an electrothermal displacement sensor was investigated through a device level approach. A multiple sensor based 1-DoF MEMS nanopositioner was designed to cope with the thermal noise of the sensors. We have successfully obtained a 4 dB SNR enhancement, which is close to the theoretical improvement attainable by the averaging technique and leads to resolution enhancement from 0.3 nm/$\sqrt{Hz}$ to 0.15 nm/$\sqrt{Hz}$. The number of sensors can be increased to achieve a higher resolution. However, the limited space available around the stage and higher power consumption must be considered in the design process.

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