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A Low-Flicker-Noise MEMS Electrothermal Displacement Sensing Technique

A. Mohammadi, M. R. Yuce, and S. O. R. Moheimani

Abstract—The sensitivity of an electrothermal displacement sensor is heavily dependent on its noise profile, particularly on the flicker noise inherent to the doped silicon heater. We show that the flicker noise in a microelectromechanical systems (MEMS) electrothermal displacement sensor can be reduced by driving the silicon heaters with a high-frequency voltage. The proposed technique has been applied to a MEMS electrothermal sensor fabricated in the standard silicon-on-insulator process. Experimental results demonstrate an 8-dB improvement in noise level compared to the conventional measurement technique. The achieved noise floor is less than -100 dBVrms around the 20-Hz measured signal. [2012-0153]

Index Terms—Electrothermal sensor, flicker noise, microelectromechanical systems (MEMS), nanopositioning.

I. INTRODUCTION

The ongoing research toward miniaturization of high-precision positioning devices has led to increasing efforts to fabricate microactuators using microelectromechanical systems (MEMS) processes [1]. High-density probe storage [2], [3] and high-speed atomic force microscopy [4] are two prominent applications for MEMS nanopositioners. In order to achieve high-bandwidth, robust, and repeatable operation, these nanopositioners are equipped with feedback control loops. Hence, they need highly accurate displacement sensors that can be integrated on the MEMS device. Capacitive [5], piezoresistive [6], and electrothermal sensors [7] have been used for displacement sensing in MEMS. Piezoresistive and electrothermal sensors have much smaller footprints compared to capacitive sensors and hence are under intense investigation. In these transducers, the actuator displacement is mapped to resistance variations as a function of mechanical stress and temperature change, respectively. Resistivity of the doped silicon is an order-of-magnitude stronger function of its temperature than its mechanical stress [8], which makes electrothermal sensing a viable method for displacement measurement. However, the sensitivity of electrothermal sensors, particularly at low-frequency measurements, is significantly limited by the noise associated with their silicon heaters [7].

The concept of electrothermal sensing is discussed in [7] and [9]–[11]. The one-degree-of-freedom (1-DOF) nanopositioner shown in Fig. 1 is fabricated in silicon-on-insulator (SOI) Multi-User MEMS Processes (MUMPs) standard technology [7]. The objective is to measure the displacement of the moving stage that is actuated elec-

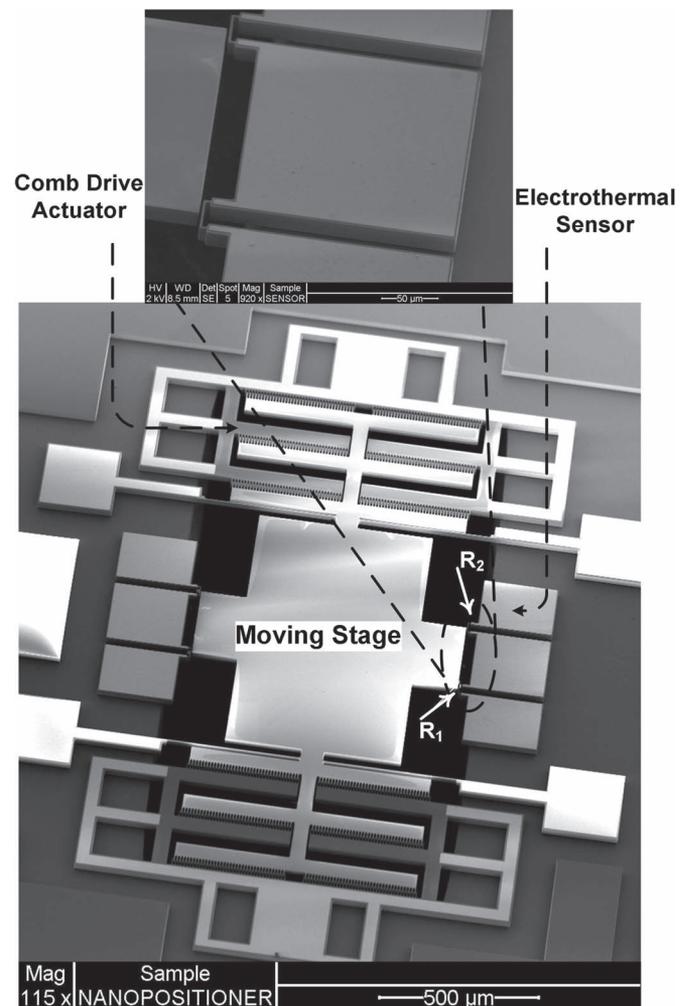


Fig. 1. Differential electrothermal displacement sensor in a 1-DOF electrostatic microactuator, implemented in standard SOI MUMPs technology.

trostatically by comb drives. R_1 and R_2 are two sets of doped silicon resistors whose resistance is a function of temperature. They are heated up by passing a dc current through them. The moving stage is acting as a heat sink, and its movements change the sensor temperature and thereby its resistance. A readout circuitry measures the resistance changes and maps them to displacements. The sensitivity of this system is drastically influenced by the noise associated with the two sensing resistors.

We propose a method for reducing the flicker noise component of the sensor noise. In Section II, we discuss the contributing factors to the noise in a MEMS electrothermal sensor. The proposed method is described in Section III and then verified by experiments. Section V concludes this paper.

II. ELECTROTHERMAL SENSOR NOISE

Conventional low-noise readout techniques for low-frequency measurements, including chopper modulation and auto-zeroing, are designed to cope with the amplifier imperfections [12], [13]. These

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techniques up-convert the signal to higher frequencies, so that the amplifier is operated over its low noise range (away from low frequencies where $1/f$ noise is dominant). The signal is then down converted back to the original frequency. As a consequence, the noise originating from the electronics is reduced; however, the noise arising from sensors will persist.

The noise in MEMS devices can be of mechanical or electrical origin [14]. The mechanical noise (Brownian noise) is more crucial in surface micromachined devices. In bulk micromachined devices, the electrical noise is dominant [15]. The electrical noise in MEMS consists of the thermal noise (also known as Johnson noise) and flicker noise. Johnson noise is the result of thermal agitation of charge carriers. The flicker noise is believed to be a result of fluctuations in conductivity in a semiconductor device. Power spectral density (PSD) of the thermal noise is described as

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

where k_B is the Boltzmann constant, R is the resistance, and T is the temperature of the device. The PSD of flicker noise is known to be

$$V_f = \sqrt{\left(K R^2 \left(\frac{I^a}{f^b} \right) \right)} \quad (2)$$

where K is a constant for the device, I is the current, f is frequency, and a and b are constants.

It can be inferred from (1) and (2) that the power spectrum of the thermal noise is white and the flicker noise reduces with increasing frequency of the applied voltage. The electrothermal sensors investigated in this work are doped silicon devices. It is known that they suffer from both flicker noise and thermal noise [3], [16] and [17]. Nanopositioners are often operated at low frequencies [18]. Hence, in a MEMS nanopositioner that uses electrothermal sensing flicker noise is dominant.

III. PROPOSED TECHNIQUE

The temperature of resistors rises when conducting the electrical power [9]. The power is proportional to the rms value of the applied voltage. To the authors' best knowledge, in all previous research reported in the literature, a dc voltage is used to heat up the electrothermal sensors [3], [7], [10], [11]. An alternative current (ac) voltage source can achieve the same temperature provided that its rms value is identical to the applied dc voltage. As stated in (2), the flicker noise of doped silicon is inversely proportional to the frequency [16]. As a result, the noise power generated by the doped silicon due to the high-frequency input (i.e., frequency of interest) is lower. Hence, a lower noise floor can be expected by increasing the frequency of the heating voltage. Thus, we use a high-frequency voltage source to heat up the sensors. The proposed readout technique is shown in Fig. 2(a), which converts the resistance (R_{MEMS}) variation to the voltage output (V_{out}). The high-frequency voltage source (V_h) is used to heat up the resistors. The voltage V_a actuates the stage. V_a is typically a low-frequency voltage source. The stage displacement changes the temperature of the resistors via thermal conduction through a thin air gap. The equivalent circuit corresponding to the proposed technique is shown in Fig. 2(b). The resistor variation is modeled as a voltage source (V_i) in series with a constant resistor. V_i has the same frequency as V_a but a smaller amplitude.

The signal at the transimpedance (TI) amplifier input in Fig. 2 is a high-frequency and high-amplitude voltage. This voltage is added by (V_i) which is a low-frequency and low-amplitude signal. The resistance variations are differential while the heating voltage is common

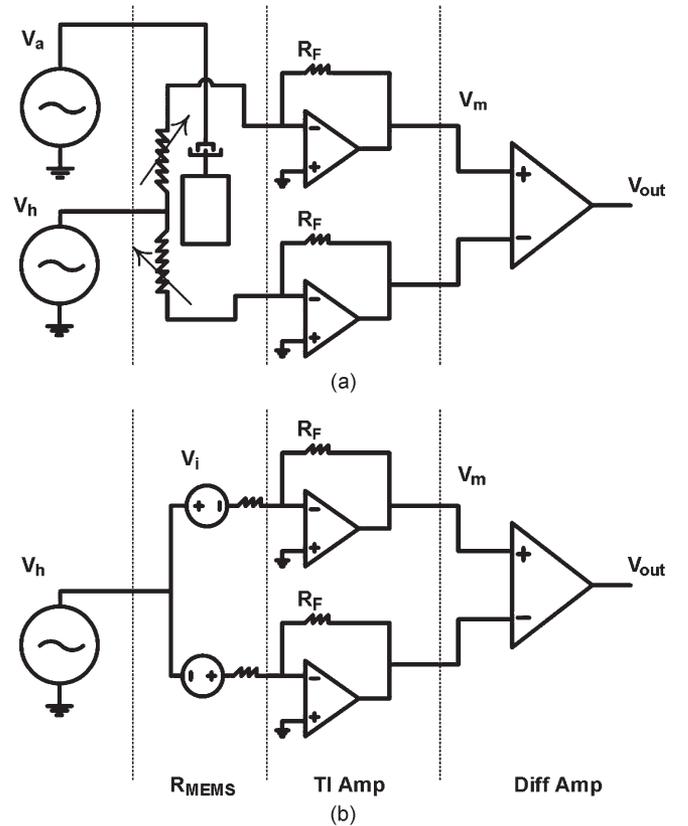


Fig. 2. (a) Proposed readout technique and (b) equivalent circuit, for flicker noise reduction.

for the differential amplifier inputs. Therefore, the output voltages of the TI amplifiers are as follows:

$$V_m = A(V_i \pm V_h) \quad (3)$$

where A is the gain of the TI amplifier. The differential amplifier, also a gain stage, amplifies the resistance variation as a desired signal and attenuates the heating signal with regard to its common-mode rejection ratio. The simulation results of the model are shown in Fig. 3. V_m is the output of the TI amplifier. The high-frequency high-amplitude component of this signal (V_h) is attenuated by the differential amplifier, while the low-frequency and low-amplitude component (V_i) is amplified at the output (V_{out}).

IV. EXPERIMENTAL RESULTS

The proposed method was tested on the 1-DOF nanopositioner shown in Fig. 1. A 12-V (peak-to-peak) 5-kHz sinusoidal voltage (V_h) was applied to the sensor resistors (heaters). The resistors were heated up to the same level as a 4.3-V dc voltage. A 20-Hz actuation voltage (V_a) was applied to the electrostatic actuator to move the stage. The V_{out} signal in Fig. 2(a) and (b) is a measure of stage displacement. The differential amplifier, which is the main gain stage, is a low-noise instrumentation amplifier (INA128) which offers a gain of 100 at 200-kHz bandwidth. The PSD of the output signal is plotted in Fig. 4. V_a is the actuator input signal, which is supplied to the comb drives. V_{outAC} is the sensor output attained by applying V_h to the heaters. In another experiment, with the same setup, a 4.3-V dc voltage is applied to the heaters, and the sensor output is recorded as V_{outDC} in Fig. 4. This experiment shows that the noise floor around the 20-Hz signal is about 8 dB less than what is measured with the dc heating signal.

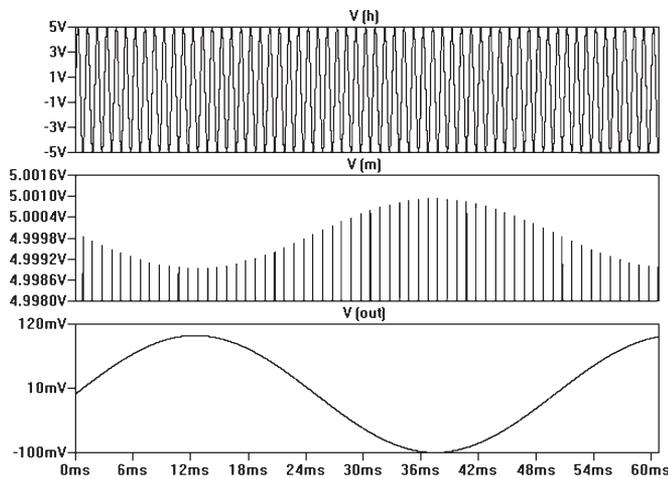


Fig. 3. Heating voltage (V_h), added voltages at the TI output (V_m), and differential amplifier output (V_{out}).

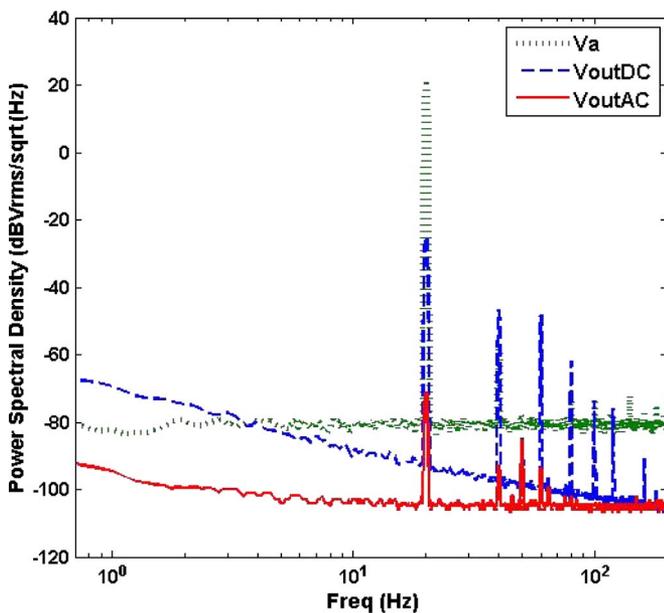


Fig. 4. Comparison of the output power spectrums by applying dc and ac heating voltages to the sensors.

In terms of positioning measurement accuracy, this translates to an improvement from $0.2 \text{ nm}/\sqrt{\text{Hz}}$ to about $0.1 \text{ nm}/\sqrt{\text{Hz}}$. The 50-Hz noise and the 20-Hz harmonics can be easily removed by applying a low-pass filter to the output signal. The PSDs were recorded by an HP35670A spectrum analyzer.

The bandwidth of the sensor was determined by measuring its step response. This was found to be 10 kHz. The resonance frequency of the stage was determined to be 1.6 kHz. The heating signal's frequency (5 kHz) was chosen so that it is above the bandwidth of the mechanical system but low enough to avoid excessive phase noise due to the signal generator, which increases with the drive frequency.

V. CONCLUSION

The displacement measurement accuracy of electrothermal sensors in MEMS nanopositioners is limited by their flicker noise. An alternative sensing procedure has been introduced to reduce the flicker noise. Driving the electrothermal sensors with an ac source instead of the commonly used dc source led to a lower noise level in the low frequency range. The effectiveness of the method was verified experimentally with electrothermal sensors on a 1-DOF nanopositioner.

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