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MEMS-based voltage detector

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ABSTRACT

A novel principle of low-noise voltage measurement based on microelectromechanical systems (MEMS) is introduced and experimentally demonstrated. The method is based on parametric conversion of voltage via electromechanical force to the amplitude of the RF signal of the capacitive measurement circuit that detects the displacement of a moving-plate MEMS capacitor. Both theory and experiments show that the noise of voltage measurement can be considerably decreased by biasing the MEMS device near its pull-in point. Experimental results are in agreement with theoretical predictions and they indicate the potential of the method as a competitor of state-of-the-art low-noise voltmeters in special applications.

1. Introduction

Macroscopic electromechanical devices, both inductive, such as DC and AC moving coil voltmeters and galvanometers, and capacitive, such as electrostatic voltmeters and quadrant electrometers, were commonly applied to measurement of electrical quantities in the past [1]. Presently, semiconducting electronic devices have almost completely substituted for them due to easier processibility, smaller size, lower cost and better integrability of semiconducting electronics.

Microelectromechanical systems (MEMS) are used widely as sensors of mechanical quantities such as acceleration or pressure [2,3]. They share the advantages of semiconducting devices and have thus replaced macroscopic sensors in many applications. However, capacitive MEMS sensors are sensitive not only to mechanical quantities, but they enable also detection of electrical quantities through the electromechanical force. It was recognized already in 1990s that this enables important potential applications of MEMS devices in electrical precision measurements and metrology [4]. Applications considered so far include AC–DC converters, RF and microwave power meters, AC and DC voltage references, and reference oscillators [5]. In this paper, we describe a new application of MEMS devices in electrical precision measurements, a low-noise voltage detector that can be used e.g. as a sensitive null detector.

When a voltage or charge is applied on a moving-plate MEMS capacitor, an electromechanical force is generated that tends to pull the capacitor plates together. This force is balanced by the spring force of the elastically suspended moving plate, and that leads to the so-called pull-in phenomenon: the voltage has a maximum, pull-in voltage, as a function of displacement of the moving plate (or, equivalently, as a function of charge). When the MEMS capacitor is biased at the pull-in point, its effective spring constant vanishes and force-to-displacement gain becomes infinite.

In force-measurement applications, the noise of the electrical readout circuit can limit the resolution of the MEMS sensor. We have shown previously that the increased force-to-displacement gain of the MEMS component near the pull-in point can be utilized to eliminate the noise of the readout electronics [6]. This concept was demonstrated with a microphone. Here we study the suitability of the same principle to measurement of small electrical quantities. As an example, we introduce a sensitive voltmeter based on a MEMS capacitor. We show both theoretically and experimentally how its voltage resolution can be improved by biasing the MEMS capacitor at the pull-in point.

2. MEMS capacitor as a voltage detector

2.1. Mechanical noise

The operating principle of the MEMS voltage detector is based on converting the measured voltage first to force. This force leads to a displacement of the moving plate of the MEMS capacitor, and that can be detected as a change in capacitance. A realization of

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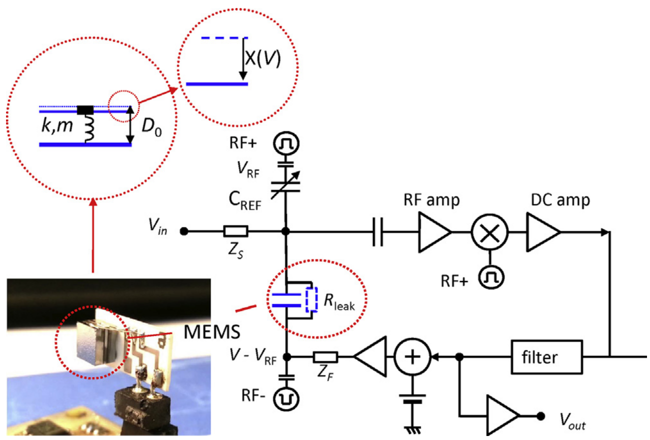

Fig. 1. Measurement scheme: a capacitance bridge with electromechanical feedback. Bottom left: the MEMS accelerometer used as the voltage sensing element. A seismic mass is suspended with cantilever beams between two symmetric electrodes. Top left: the used mechanical model.

electromechanical voltage measurement is shown in Fig. 1. An RF capacitance bridge measures the MEMS capacitance C_{MEMS} and through feedback keeps it at the desired operation point determined by the reference capacitor C_{REF}. Feedback enables stable operation at and beyond pull-in. The excitation frequency of the RF bridge $\omega_{\text{RF}} \gg \omega_0$, where ω_0 is the resonance frequency of the MEMS component

$$\omega_0 = \sqrt{k/m}, \tag{1}$$

and k is the spring constant and m is the mass of the moving plate. Thus the RF excitation does not affect the dynamics of the MEMS component, but it causes a constant bias that adds quadratically to the applied DC bias.

The voltage to be measured V_{in} is applied to one of the MEMS plates. It causes a force

$$\begin{aligned} F &= -\frac{VC_0D_0}{D^2}V_{\text{in}} \\ &= -\frac{\sqrt{2kC_0x}}{1-x}V_{\text{in}} \end{aligned} \tag{2}$$

where $V \gg V_{in}$ is the bias voltage, C_0 is the capacitance of the MEMS without bias voltage, and $D = D_0 - X$ (D_0) is the gap between the MEMS capacitor plates with (without) bias voltage. In the latter form of Eq. (2) the bias is expressed in terms of the relative MEMS displacement $x = X/D_0$.

The power spectral density of the thermal force noise of the component is described by the (generalized) Nyquist equation [8] according to the fluctuation-dissipation theorem [9]

$$S_{F,\eta} = 4k_BT\eta, \tag{3}$$

where T is the temperature and η is the damping coefficient that describes mechanical dissipation in the device. In the case of squeezed film damping, η depends on the gap as $(1-x)^{-3}$ [7]. Substituting in (2), we end at corresponding voltage noise spectral density

$$S_{V,\eta} = \left(\frac{\partial V_{in}}{\partial F}\right)^2 S_{F,\eta} = \frac{2k_BT\eta(x)}{kC_0}\frac{(1-x)^2}{x}. \tag{4}$$

In addition, there is a thermal voltage noise component due to the leakage resistance R_{leak} of the MEMS device. In a good MEMS device $R_{\text{leak}}(>10^9\,\Omega) \gg |Z_F + Z_S|$, the series combination of the feedback and source impedances Z_F and Z_S. At signal frequencies $1/\omega C_{\text{MEMS}} > |Z_S|$ and $1/\omega C_{\text{RF}} > |Z_F|$ (valid ranges for the relevant impedances are given at the end of the next subsection). Thus the main return path for the current noise of R_{leak} is through Z_F and Z_S. The voltage noise due to the leakage resistance becomes then

$$S_{V,\text{leak}} \simeq \frac{4k_BT}{R_{\text{leak}}}\left|Z_F + Z_S\right|^2. \tag{5}$$

In practice, this contribution can be usually neglected.

2.2. Operation at pull-in

In [6] it was shown that by operating the MEMS near the pull-in point, electronics contribution to system noise can be fully suppressed in comparison with the mechanical noise. Let us bias the component at the pull-in point, which, in the damped harmonic spring-mass approximation, is described by voltage

$$V_{\text{pi}} = \sqrt{\frac{8kD_0^2}{27C_0}} \tag{6}$$

and by relative displacement of the moving plate

$$x_{\text{pi}} = 1/3. \tag{7}$$

At pull-in, the MEMS voltage noise spectral density (4) is then

$$\begin{aligned} S_{V,\eta,\text{pi}} &= \frac{8k_BT}{3C_0}\frac{\eta(x_{\text{pi}})}{k} \\ &= \frac{8k_BT}{3C_0}\frac{1}{Q\omega_0}, \end{aligned} \tag{8}$$

where

$$Q = \frac{k}{\omega_0\eta(x_{\text{pi}})} = \frac{m\omega_0}{\eta(x_{\text{pi}})} \tag{9}$$

is the Q factor of the resonance. The equivalent current noise is obtained by dividing the voltage noise by the capacitive impedance of the component $1/(\omega C_{\text{MEMS}})$.

We describe the dominant electronics noise contribution to the system resolution by a finite displacement (or, equivalently, capacitance) fluctuation of the RF bridge, $S_{X,\text{RF}}$. We assume that it is caused by the noise in the first stage RF amplifier. As described in Ref. [6], this corresponds to an equivalent force noise spectral density

$$S_{F,\text{RF}} = ((k' - m\omega^2)^2 + (\eta\omega)^2)S_{X,\text{RF}} \tag{10}$$

where k' is the effective spring constant, softened by the bias voltage:

$$k' = k - \frac{C_0V^2D_0}{D^3} = \frac{1-3x}{1-x}k \tag{11}$$

which vanishes at the pull-in $x = 1/3$. Combining Eqs. (2) and (10), the effect of the electronics noise on the voltage resolution becomes

$$S_{V,\text{RF}}(\omega) = \left(\frac{D^2}{VC_0D_0}\right)^2((k' - m\omega^2)^2 + (\eta\omega)^2)S_{X,\text{RF}}. \tag{12}$$

At low frequencies we get

$$S_{V,\text{RF}}(0) = \frac{k}{2C_0}\frac{(1-3x)^2}{x}S_{X,\text{RF}}(0). \tag{13}$$

When approaching pull-in, $S_{V,\text{RF}}(0) \to 0$. Thus the mechanical noise Eq. (8) becomes the dominant noise mechanism independent of the resolution of the RF bridge.

As frequency increases, the motion of the MEMS plate starts to be limited by the dissipation and inertia instead of the spring constant. As described in [6], this sets a limit to the noise suppression at pull-in. By equating Eqs. (8) and (12) at pull-in, a criterion can be