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Low-noise real-time measurement of the position of movable structures in MEMS

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ABSTRACT

A low-noise, low-perturbing electrostatic position measurement system for capacitive MEMS sensors is described.

A small-amplitude, high-frequency voltage signal is applied between the movable and fixed plates of the sensing capacitance. The resulting current is modulated by the external forces applied to the structure. This high-frequency-shift makes it possible to filter low-noise contributes and minimize readout electrostatic perturbations on the device.

Experimental results are reported for a comb-type MEMS test structure with quasi-static, sinusoidal, and impulsive forces. Resolution and long-term stability of nanometric values have been obtained.

1. Introduction

Several kinds of MEMS devices have a mobile structure, with springs or other constrains, which move under the effect of external actions or internally generated electrical forces. It is, for instance, the case of accelerometers, gyroscopes, pressure sensors, and many test structures.

The measure of the instantaneous position, or of the displacement, of this mobile structure, gives the information on the intensity and the time behaviour of the external action. In the case of test structures the information required is the behaviour of the MEMS as a result of a known force. This measurement not only has to be fast and accurate but must not affect the behaviour of the device. The last condition might not be trivial to achieve owing to the very small masses (10–1 μg) and elastic constants (0.1–0.01 N/m) typical of scaled MEMS [1]. Optical position measurements [2] generally satisfy these requirements, but have several practical limitations and are usually useful only during test stages.

Electrical techniques for MEMS displacement measurement, based on resonant frequency changes, have been utilized in several cases [3–5]. Resonance might be affected by changes in mass, in the case of measurement of very small amounts of various molecules; by some nonlinear effects in the retracting forces, as in the case of accelerometers; or by changes in material properties, as in the case of fatigue test structures. Other electrical techniques rely on the measurement of a variable capacitance between fixed and moving plates. Electrical capacitance measurements are typically performed applying a test voltage, generally at the resonance frequency, and measuring the corresponding current [6]. In this way, however, electrostatic force is generated, which can perturb the mobile structure position. As MEMS size scales, this effect becomes more important. As a matter of fact the unwanted force cannot be proportionally reduced because the applied voltage cannot scale beyond a certain value. Very small capacitances have to be measured with good resolutions.

In this paper an electronic system, for capacitive MEMS movable part position readout, is described in detail. A small-amplitude, high-frequency voltage signal is applied between the movable and fixed plates of the sensing capacitance, measuring the resulting current modulated by the external forces applied to the structure. The current is proportional to voltage derivative and therefore low amplitude test voltages may be applied reducing the electrostatic force effects but still with high resolution. As it relies on a lock-in-based electronics, signals are shifted to high frequencies before they reach the first electronic stage. Filtering of low-frequency noises, including flicker noise, is possible [7]. The method has been initially developed for the study of fatigue in test structures and, for this application it has the advantage of enabling continuous data acquisition when compared with resonant frequency techniques, often employed. The same system is suitable for other MEMS characterizations and has been employed in quasi-stationary force response (force–displacement plots) and precise impulsive force response (damping measurements). The measurement scheme would also be of interest for MEMS sensors as accelerometers or gyroscopes.

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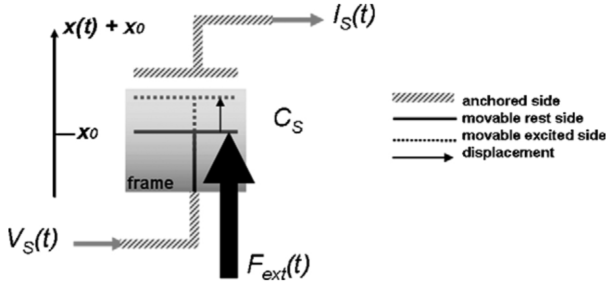

Fig. 1. Schematic view of an electrostatic MEMS sensor capacitance with a movable part (frame) under the effect of a force action causing a displacement $x(t)$.

In the following paragraphs basics principles of the method and the implementing electronics will be described. Measurements on a capacitive comb test structure will be presented, where forces of the desired intensity and time law are generated by an actuating section of the same MEMS device.

2. Electronically read MEMS capacitive sensors

Consider a simplified electrostatic capacitive MEMS structure (be it of the parallel plates or of the interdigitated combs type) as the one depicted in Fig. 1. There is a variable capacitance, which we call synthetically the sensor, indicated by C_S, suitably designed to detect the position variation of the moving frame under the effect of the force $F_{ext}(t)$. One of its two plates is part of a single suspended structure, the frame, which constitutes the movable part of the MEMS, while the other plate is fixed. The capacitance value is modified as a geometrical dimension (the gap in parallel plate and the facing area in the interdigitated comb-type MEMS capacitive sensors) changes.

If the frame absolute position is indicated by $x(t)+x_0$, being x_0 the rest position, the motion is described by the Newton's equation in which the damping forces, the elastic forces and the other external forces appear:

$$m\ddot{x} + \frac{\sqrt{km}}{Q(1-(Q/(Q+Q_{el})))}\dot{x} + [k+k_{el}]x = \sum f_{ext,n}(t) = F_{ext}(t) \qquad (1)$$

In the expression above m is the frame mass. $F_{ext}(t)$ indicates the external forces acting on the device due to external phenomena (acceleration, pressure or other mechanisms) or suitable electrostatic generated test forces. k is the mechanical elastic constant and Q the mechanical damping quality factor due to external losses (viscous friction, acoustic waves) or internal losses (various processes in the bulk, at the surface and in the anchors). The quality factor Q is related to the mechanical damping coefficient $b = \sqrt{km}/Q$.

The terms Q_{el} and k_{el} represent possible influence of the electrical readout apparatus. k_{el} is due to the electrostatic energy dependence from the distance between the plates of the sensing capacitor; in the case of parallel plates the force is nonlinear with $x(t)$ and therefore k_{el} may be itself function of x, apart from the very common case of little displacements from mechanical equilibrium in differential structures [2,7]. In the ideal case of interdigitated combs k_{el} is null. The term Q_{el} is the electronics quality factor due to the extra dissipation caused by the current flow in the reading circuit, forced by the variations of the capacitances [2].

3. Basics of the displacement monitoring method

Capacitive position measurements can be obtained measuring the current I_S flowing through the plates of C_S after a voltage V_S is applied:

$$I_S(t) = \frac{d}{dt}Q_S(t) = C_S(t)\frac{dV_S(t)}{dt} + V_S(t)\frac{dC_S(t)}{dt} \qquad (2)$$

If the applied voltage V_S is constant the first term in the equation above is null and the second term gives information on the capacitance variations which, in MEMS devices, can be due, as described above, to displacements $x(t)$ of the movable part. The applied voltage V_S however determines an unwanted electrostatic force proportional to V_S^2 which can perturb the structure [9,10]. The flow of electric current in the reading circuit is related to the change in capacity due to mechanical movement and this causes a damping related to dissipative effects in the electronics. Moreover this kind of measure does not provide full position information but only displacement data.

If instead an ac voltage signal centred on the zero level (as in Fig. 2a):

$$V_S(t) = V_2\cos(2\pi f_2 t)$$

is applied to the frame contact as in Fig. 1, leaving the output node at a zero voltage, with f_2 much bigger than the mechanical resonance frequency, the second term in Eq. (2) can be neglected. The current flowing through C_S can be written as

$$|I_S(t)| = C_S(t)\frac{dV_S(t)}{dt} = C_S(t)V_2 2\pi f_2 \sin(2\pi f_2 t) \qquad (3)$$

As the sensor capacitance current is proportional to the derivatives of the voltage signal $V_S(t)$, that is both to V_2 and to f_2, it is possible to hold a good sensitivity increasing the signal frequency f_2 while decreasing the signal amplitude V_2 by the same factor, in order to minimize the effect of this electrical signal on the frame position sensibly lowering the k_{el} value.

The output signal is a high-frequency signal (f_2) modulated by the external force, whose frequency spectral range Δf will be consistently lower than f_2, as in the example of Fig. 2. From the sensor current waveform the sensor capacitance value $C_S(x, t)$, and then the absolute frame position $(x(t)+x_0)$, can be reconstructed after rectifying and averaging (Fig. 2d).

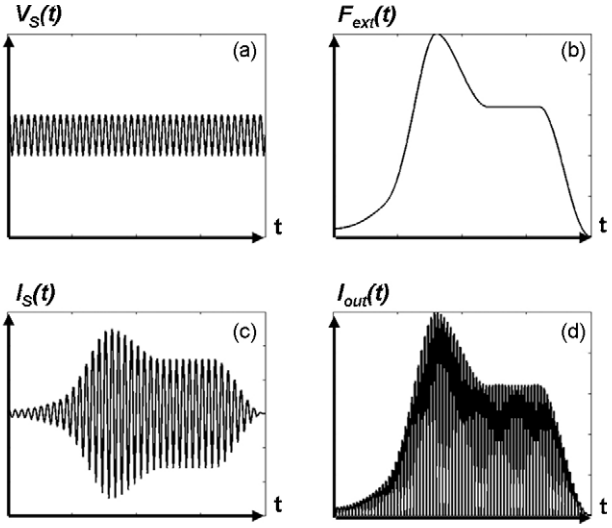

Fig. 2. The high-frequency harmonic signal $V_S(t)$ (a) is modulated by the force $F_{ext}(t)$ acting on the frame (b), whose spectrum harmonics are much lower than $V_S(t)$. The result is the current signal (c). The rectified and low-pass filtered signal (d) has the shape of the incoming force.