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Sensors and Actuators A 123–124 (2005) 185–193
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

A method for cross-sensitivity and pull-in voltage measurement of MEMS two-axis accelerometers

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Received 13 September 2004; received in revised form 18 March 2005; accepted 26 April 2005
Available online 22 June 2005

Abstract

An electronic circuit for the characterization of two-axis accelerometers is presented, implementing a non-linear method which reduces the effect of parasitic signals. Single-ended and differential measurements were used to extract a value of 0.15 for the cross-sensitivity of the device. Other parameters, like the pull-in voltage, the quality factors and the resonance frequencies, are extracted as well. Curves of the frequency response at different pressure levels, and with different dc bias voltages are presented.

Keywords: MEMS accelerometers; Electronic interfaces; Cross-sensitivity; Pull-in voltage

1. Introduction

Characterization methods for accelerometers are of paramount importance both for research purposes, and for industrial testing. They are especially convenient if they can be implemented with an automated, computer controlled system. Inertial testing methods based on shakers or turntables [1,2] and capacitive sensing are the obvious choice for the measurement of several accelerometer parameters, even if they require specific hardware. Methods based on interferometry [3] or image processing [4] provide extensive information on the dynamical behaviour of the device, but they probably are of a more limited use for industrial testing because of, among other reasons, higher cost of instrumentation and more complex measurement set-ups.

Electrostatic techniques, based on the capacitive actuation of the moving mass with specifically designed electrodes or with the actual sensing electrodes, are widely used [5,6], especially for built-in self test [7,8], even if it has been recently suggested that electrostatic driving cannot identify every possible defect [9]. Electric methods have the advantage of being based on readily available instrumentation, already used in other testing applications. Electric testing can be routinely performed at the wafer level, reducing costs and improving reliability. Finally, plenty of commercial hardware and software automation solutions are available. The development of methods to measure specific parameters of a MEMS accelerometer with an all-electrical method is thus justified.

A difficulty with electric testing of two-axis MEMS accelerometers is that electrostatic driving along one of the channels (used to mimic the effect of an external acceleration) may produce a deflection of the moving mass along the orthogonal direction even if the mechanical structure is symmetrical, because of possible asymmetries in the driving electrodes. In this paper we propose a method to discriminate the various components of the cross-axis output signal. Our approach allows the measurement of the cross-axis sensitivity of the accelerometer, defined as the ratio between the outputs of the two channels when acceleration is present along one of the two orthogonal directions, without the need of actually exciting it with external accelerations. The method also exploits the intrinsic non-linearity of electrostatic actuation to reduce the effect of parasitic capacitances [10]. The measurements are performed with an experimental set-up,

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doi:10.1016/j.sna.2005.04.028

which allows the measurement of both in-channel and cross-channel response of the accelerometer. Other parameters, like the resonance frequency and the quality factor, are measured as well. We also give a characterization of the dependence of the resonance frequency on the dc bias voltage caused by the electrostatic softening [11]. This last measurement is used to extrapolate the resonance frequency of the structure at zero dc bias and its pull-in voltage as well.

2. Measurement method

The measurement principle is based on the square-law relationship between the actuation force and the driving voltage, typical of every voltage-driven electrostatic actuator. As a consequence of this non-linear relationship, if the actuator is driven with a sinusoidal voltage at frequency $f/2$, it is excited with a sinusoidal force at frequency f, at least as long as the relationship between the deflection and the capacitance can be supposed linear, i.e. as long as the deflection is small [10].

To introduce the method, we begin with a fairly general model for an electrostatic system, constituted by a first fixed electrode (the *driving stator*), a spring-suspended movable mass (the *rotor*) and a second fixed electrode (the *sensing stator*). As long as the deflection of the rotor is small, if we apply a sinusoidal voltage (at frequency $f/2$) to the driving stator with respect to the rotor, the latter will show a harmonic oscillation at twice the driving frequency; if the *sensing stator* is capacitively coupled with the rotor and it is biased with a dc voltage with respect to the rotor, the current at this electrode will have a component at frequency f, which can be used to reveal the rotor movement. This current is used as the output signal. It is straightforward to show that the amplitude of this component is proportional to the amplitude of the rotor deflection. The main advantage of this method is to eliminate the parasitic component at frequency $f/2$, due to direct capacitive coupling between the two stators, without using an external frequency conversion [6]. A possible drawback is that the bias dc voltage on the sensing stator produces a static deflection of the rotor.

This method was used to characterize a two-axis MEMS accelerometer. A simplified scheme of the device under test and a SEM image of the actual device are shown in Fig. 1. The rotor is suspended by two orthogonal systems of springs, nominally equal, which allow independent movements along x and y directions. Four parallel-plate stators X_1, X_2, Y_1, Y_2, each duplicated for symmetry reasons, are present. During operation as a sensor, acceleration along x is detected by measuring the differential capacitance variation between X_1 and X_2, and similarly for y acceleration.

Two different measurements, both based on the aforementioned approach, were implemented: in the first one, which we will call *single-ended*, the rotor is driven along x and its movement is detected along the same axis, i.e. X_1 is used as the driving stator, and X_2 as the sensing stator. In the second kind of measurements (or, from now on, *differential* measurements), X_1 is again the driving stator, but the movement is detected using the Y electrodes as sensing stators. Although no signal should be detected in this second configuration (because the rotor should not move along y), electrical and mechanical asymmetries produce a detectable signal. This can be ascribed both to unexpected displacements along y caused by asymmetries in the driving electrode and/or the mass and springs, and to asymmetries in the coupling between the rotor and the sensing electrodes, that make them sensitive to x displacements as well. As both Y electrodes are available (i.e. they are not used for driving), the differential current between Y_1 and Y_2 is chosen as the output signal. This choice gives two advantages: first, the aforementioned parasitic current at $f/2$ is mainly a common mode signal, and it is thus partially rejected; second, the dc bias voltages on the Y electrodes are symmetric, thus their effect on the static deflection of the rotor along y is reduced with respect to single-ended measurements.

A comparison between the two measurements can be used to measure the cross-axis sensitivity of the device: details about the theory used for its determination are presented in the measurements section.

3. Circuit description

A printed circuit board, including the accelerometer and the driving/sensing electronics, was fabricated: its simplified schematics is given in Fig. 2. The board, 16 cm × 10 cm in size, can be inserted into a vacuum chamber to allow characterization of the accelerometer at different pressure levels. The driving electrode X_1 is driven with a sinusoidal input signal V_{in} at frequency $f/2$ through a dc blocking capacitor and the buffer U9, while the rotor is grounded.

In the *single-ended* measurement, X_2 is biased at a constant voltage E. The current at X_2 is converted to a voltage by the transresistive amplifier U5 and further amplified by U6 and U7. The output signal $V_{out,single}$ is fed to a lock-in amplifier, which uses the input signal V_{in} as frequency reference. The instrument is set to detect signals at twice the reference frequency. The dc component of the output is blocked by a CR filter after U5.

In the *differential* measurement, X_1 is driven as above, while Y_1 and Y_2 are biased at a constant voltage E. The current flowing from Y_1 and Y_2 is converted into a voltage by two transresistive amplifiers (U1 and U2); CR filters are inserted in this configuration as well, in order to reject the dc component. This is required to eliminate the dc common mode input signal fed to the following differential stage U3. This stage is implemented with an AD620 monolithic instrumentation amplifier (U3), followed by a non-inverting amplifier (U4). Its output voltage $V_{out,diff}$ is fed to the lock-in amplifier as well. The parasitic currents at frequency $f/2$ fed to U1 and U2 are largely rejected thanks to the high CMRR of the AD620. This reduces the parasitic signal level in the output