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A high-resolution micro-electro-mechanical resonant tilt sensor

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ABSTRACT

This paper reports on the design and experimental evaluation of a high-resolution micro-electro-mechanical (MEM) tilt sensor based on resonant sensing principles. The sensors incorporate a pair of double-ended tuning fork (DETF) resonant strain gauges, the mechanical resonant frequencies of which shift in proportion to an axial force induced by variations in the component of gravitational acceleration along a specified input axis. An analysis of the structural design of such sensors (using analytical and finite element modelling) is presented, followed by experimental test results from device prototypes fabricated using a silicon-on-insulator (SOI) MEMS technology. This paper reports measurement conducted to quantify sensor scale factor, temperature sensitivity, scale factor linearity and resolution. It is demonstrated that such sensors provide a $\pm 90^{\circ}$ dynamic range for tilt measurements with a temperature sensitivity of nearly 500 ppb/K (equating to systematic sensitivity error of approximately 0.007°/K). When configured as a tilt sensor, it is also shown that the scale factor linearity is better than 1.4% for a $\pm 20^{\circ}$ tilt angle range. The bias stability of a micro-fabricated prototype is below 500 ng for an averaging time of 0.8 s making these devices a potentially attractive option for numerous precision tilt sensing applications.

1. Introduction

Tilt sensors or inclinometers are widely utilized in a number of applications such as industrial machine alignment, attitude control systems, user interfaces in smart phones, human body motion detection, ground motion and land subsidence detection and several consumer electronics applications [1–8]. A majority of these tilt sensors however, comprise simply of a fixed casing and a movable mass. When the sensor is subjected to a small angular tilt, the mass displaces relative to the fixed casing due to the induced inertial force arising from gravity, the transduction of which allows for an estimation of the angular tilt.

Various methods of proof mass displacement transduction have been reported to date in such tilt sensors. A few methods that have gained visibility in recent years include fibre-optic interferometric displacement sensing, variable resistance or impedance based detection, electrolytic sensing, thermal-convection based sensing, and variable capacitance based displacement transduction [9–15]. MEMS accelerometers have also been shown to operate as tilt sensors with the incorporation of specially designed encoders [16]. Tilt sensing in a MEMS accelerometer is typically achieved by recording the change in the quasi-static response of the device as the sensitive axis is oriented at different angles with respect to earth's gravitational field. As opposed to measurements of dynamically varying acceleration signals, tilt measurement in a MEMS accelerometer is a quasi-static measurement and the response can be decoupled from dynamic loading through low-pass filtering of the resulting signals, either by tailoring the mechanical response of the device or through the external electronics or through a combination of both approaches.

Although many of these methods of displacement transduction allow for accurate angular tilt measurements, the detection range and resolution achievable from such sensors still remain limited [17]. Another limitation for some tilt sensors is their sensitivity to environmental parameters such as temperature and humidity, especially for sensors realized using thermal-convection or variable impedance based sensing principles. In what follows, we report on the design and experimental characterization of a tilt sensor based on resonant sensing principles [17,18] that not only provides a large detection range but also allows for high resolution and improved environmental (viz. temperature) rejection.

2. Design

The micro-machined resonant tilt sensor reported in this work uses a pair of structurally symmetric double-ended tuning fork (DETF) resonant sensing element, the resonant frequencies of which shift proportionally with the applied axial force resulting

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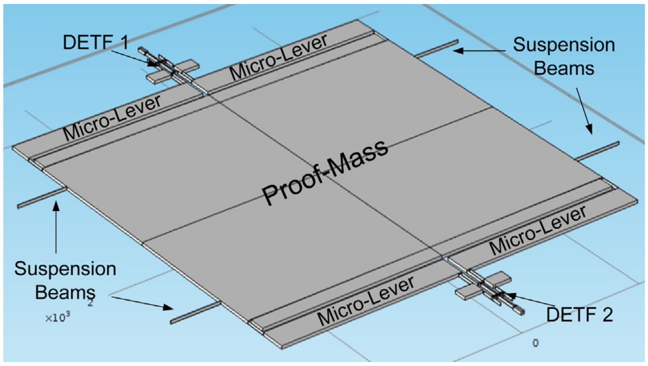

Fig. 1. Schematic view of the resonant tilt sensor.

from any angular tilt applied on the tilt sensor. Additionally, the sensor comprises of two single-stage micro-levers that connect the pair of DETFs to a suspended poof mass (supported by four straight beam suspensions).

When the sensor is subjected to angular tilt about the sensing axis (see Fig. 2), the suspended proof-mass displaces, inducing axial tensile and compressive stresses on the two symmetric DETFs attached at the two opposite ends consequently tuning their mechanical resonant frequencies by equal magnitudes but in opposite directions. The differential measurement of frequency enables a first-order cancellation of common-mode effects such as temperature. The out of plane stiffness of suspension beams is designed being significantly higher than the in-plane stiffness to make the axial tensile and compressive forces applied on the DETFs closely relate to the sine of tilt angle. In order to further increase the sensitivity of the tilt sensor, single-stage micro-levers are used to linearly amplify the induced axial force communicated onto the tuning fork pairs. The sensor output will hence correspond to a mechanically amplified differential measure of the frequency variations arising from the two tuning fork resonators.

The scale factor of this tilt sensor, S_{Tilt}, can be estimated by:

$$S_{Tilt} = \frac{|\Delta f_{out}|}{\sin\theta} \cong S_{Res} \times EA_{Lvr} \times M_{proof}\, g \qquad (1)$$

where S_{Res} is the scale factor of resonant sensing element in the unit of 'Hz/N', EA_{Lvr} is the effective amplification factor of micro-levers, M_{proof} is the proof-mass, g denotes gravitational acceleration, θ is the tilt angle and Δf_{out} is the frequency shift of the tilt sensor. In order to achieve high sensitivity, the parameters on the right side of Eq. (1) should be designed as large as possible. However, simultaneously, impact of design parameters on other performance metrics such as the intrinsic noise floor, dynamic range, bandwidth, mechanical robustness and constraints imposed by fabrication limitations also need to be considered in design.

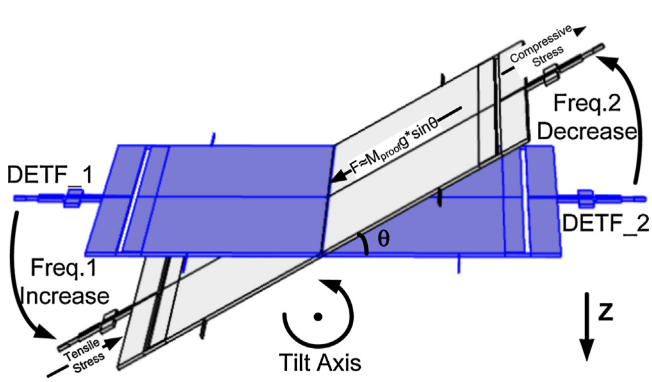

Fig. 2. Operation principle of resonant tilt sensor.

2.1. Design of the resonant element

The MEMS DETF translates the inertial force on the proof mass into a resonant frequency shift and electrostatic transduction is employed to translate the motional response into an electrical format. The design of the DETF therefore directly impacts both scale factor and sensor resolution and both aspects are addressed in this section.

2.1.1. Scale factor

The resonant frequency of tuning fork can be shown to vary as a function of the axial force acting on the free end [17,18]. The variation in the resonant frequency thus induced may be evaluated as [17]:

$$S_{Res} = \frac{\Delta f}{F_{Axial}} \approx \frac{1}{4} S \cdot f_c, \quad \text{where} \quad S = 0.293\left(\frac{L_T^2}{E t_T w_T^3}\right)$$
$$\text{and} \quad f_c = \frac{2}{\pi} \cdot \sqrt{E\left(\frac{w_T}{L_T}\right)^3 \cdot \frac{1}{\rho(A_{Ele} + 0.375 \cdot L_T w_T)}} \qquad (2)$$

where, F_{Axial} is the axial force applied to the DETF, f_c is the resonant frequency of DETF without axial force load, E is the modulus of elasticity of the material, ρ is the density of the material, A_{Ele} is the area of attached electrode and L_T, w_T and t_T are the length, width and structural thickness of the laterally vibrating device. As shown in Eq. (2), the scale factor of the DETF is determined by material properties and beam dimensions. Since the choice of material parameters are often constrained by the fabrication process (and taken to be single-crystal silicon in this paper), optimization of the critical dimensions of the DETF sensing element is considered. The scale factor dependency on the dimensions is derived from Eq. (2) and summarized below:

$$S_{Res} \propto \frac{L_T^{1/2}}{t_T w_T^{3/2} (A_{Ele} + 0.375 \cdot L_T w_T)^{1/2}} \qquad (3)$$

According to the Eq. (3), the scale factor of the DETF can be increased by decreasing the width and thickness of tuning fork tines.

2.1.2. Non-linearity of scale factor

The above modelling and analysis assume that the scale factor of DETF sensing element is constant, regardless the direction and magnitude of input force. However, if the input force becomes large, the frequency shift of DETF sensing element will exhibit deviation from linear behaviour. For large tensile input force, the frequency shift will increase whereas for large compressive input force, the frequency shift will decrease. For same input force, the DETF sensing element with thin, narrow tines will exhibit more non-linearity in the frequency response relative to thick, wider tines. This non-linear relation between the input force and frequency shift of the DETF sensing element can be studied by numerical simulation (COMSOL® 4.2a) with summary results shown in Fig. 3. Representative dimensions of the single-crystal silicon DETF sensing element used in the simulation are:

$$L_T = 350\,\mu\text{m}, \quad w_T = 4\,\mu\text{m}, \quad t_T = 30\,\mu\text{m} \quad \text{and} \quad A_{Ele} = 1250\,\mu\text{m}^2$$

When the tine width (w_T) is reduced from 5 μm to 2 μm, the frequency shift notably deviated from an expected linear response. The asymmetry of frequency shift between compressive and tensional input force is also evident in the sensing element with narrower tines. The simulation results also indicate that the 2 μm tines may potentially buckle under about 2 mN compressive input force.