A MUMPs angular-position and angular-speed sensor with off-chip wireless transmission

W. Sun, W. J. Li, Y. Xu

Abstract A novel surface-micromachined non-contact high-angular-speed sensor with total surface area under 4 mm² was developed using the multi-user MEMS processes (MUMPs), and was integrated with a commercial RF transmitter with carrier frequency of 433 MHz for wireless signal detection. This piezoresistive sensing system is capable of wirelessly measuring rotation speeds with sensitivity of ~2 Hz/rpm/V using 5 V input in the 100–6000 rpm rotation range. Further experimental analyses showed that a sensor designed with a 13 µg seismic mass has high enough sensitivity to detect angular position of a rotating disk if the disk rotation axis is tilted away from the vertical direction. Experimental results from simultaneous detection of angular position and average angular speed for the sensor are reported in this paper.

1 Introduction

Tachometers have been widely used to measure angular speeds of rotating objects. In general, contact mechanical-based tachometers, although capable of giving measurements conveniently, are less accurate than AC or DC electromagnetic-based tachometers. Nevertheless, as discussed by Nachtilag (1990) and Haslam et al. (1993), each type has its own advantages and shortcomings depending on the applications. Optical tachometers are also available to give relatively accurate readings with a wider rpm range. An example of this optical measurement method is given by Spooncer et al. (1991). However, Kwa and Wolffinbuttel (1991) pointed out that some optical sensors are quite sensitive to background light and contamination.

Recently, many new rotation-sensing devices were developed based on different principles. Watanabe and Kim (1994) measured rotation speed from magnetized axes, Powell and Meydan (1996) used magnetic sensors based on Faraday induction to measure rotation rate, and Fabian and Brasseur (1997) developed a capacitive sensor for angular motion detection. These techniques, however, impose restrictions on the material properties or geometry of the rotational components to be measured, and they also limit the effective measurable rotation speed. In addition, all these sensors must be accompanied with a stationary reference, which is externally mounted to the system’s housing for proper operation.

Many micro motion sensors have also been fabricated recently which can be used for rotation sensing. Söderkvist (1990), Madni et al. (1996), and Voss et al. (1997) used piezoresistive, piezoelectric, and capacitive principles, respectively, for angular rate sensing. Nonetheless, the existing sensors are designed mainly for low rotation speeds (i.e., <1000 rpm) and acceleration measurements.

We have previously developed a MEMS high-speed rotation sensor with no external mounted reference and it was packaged with a commercial wireless-transmission system for signal detection. Results of this work can be obtained from Sun et al. (1999, 2000). This piezoresistive sensor is capable of wirelessly measuring rotation speeds with sensitivity of ~2 Hz/rpm/V using 5 V input in the 100–6000 rpm rotation range. To the best of our knowledge, no one has reported successful integration of high-speed rotation sensors built using the MCNC (renamed to CRONOS Integrated Microsystems Inc.) MUMPs commercial foundry service with wireless transmitted output before our work.

In the current work, we have tested several structural and seismic mass designs for the above sensor to observe if the sensing system has enough sensitivity to detect gravitational effect if the system is rotated about an axis parallel to the ground. We have found that, for certain seismic mass and structural design combinations, the sensing system is capable of detecting gravitational force, and hence, can be used simultaneously as a angular-position sensor. It is well known that, for surface-micromachined devices, gravity force is less important when compared to surface forces. However, for our sensor design and high-speed measurement range, centrifugal force will overcome surface forces, and hence, making the sensor angular-position sensitive. The result from the current work is reported in this paper.

2 MUMPs fabricated rotation sensor

Concept and design

The concept for measuring rotation speed of a spinning body using embedded micro-sensors is illustrated in
Fig. 1. A three dimensional illustration of the developed MCNC sensor is shown in Fig. 2. Details of the MCNC layers and post-fabrication processes used were reported by Sun et al. (1999). Scanning electron microscope (SEM) picture of a pair of the surface-micromachined sensors is shown in Fig. 3. The mass platforms are sacrificially released and are curved due to residual stresses between different thin film layers in this case. Three MUMPs thin film layers which make up the platforms are apparent in this picture: Poly 1, Poly 2, and Au. A reference sensor that was not sacrificially released is shown in Fig. 4. The reference sensor can be used for temperature dependence adjustment of the sensing system eventually.

**Theoretical analysis**

As shown in Fig. 5, a set containing two identical sensors in opposite directions is oriented so that the axes of the cantilevered beams are perpendicular to the axis of rotation. As will be discussed later, a set of two sensors can be used to measure the angular acceleration of the rotating element.

If no linear motion exists along the rotation axis then lateral deflection of the beams, or transverse stress, can be neglected. Excluding the substrate, a MCNC fabricated sensor is less than 5.1 μm thick (platform) and weighs about 3–15 μg (theoretical value based on the density and geometric dimensions of the materials). As shown in Fig. 5, the initial moment arm from the centroid c to the fixed end F is a constant. When centrifugal force is induced on the seismic mass by an angular velocity (ω) or acceleration (α), the length of this moment arm will change. The vertical load \( P = m \cdot r \cdot \omega^2 \) induced by rotation and the axial load \( N = m \cdot r \cdot \alpha \) caused by angular acceleration \( (r \text{ is the distance from the axis of rotation to the neutral axis of the cantilever}) \) both act on the centroid c of the platform. The distance \( e_c \) is a constant depending on the number of polysilicon layers. It is measured from the

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**Fig. 1.** Conceptual drawing of micro sensors embedded in a rotating structure to measure rotation (not to scale)

**Fig. 2.** Three-dimensional drawing of a surface-micromachined rotation sensor using polysilicon as cantilever beams supporting a multi-layered mass platform

**Fig. 3.** SEM picture of a pair of fabricated sensors. The curvature of the mass plate is due to residual stress between different layers of materials making up the plate. The MUMPs layers shown are Poly 0, Poly 1, Poly 2, and Au

**Fig. 4.** SEM picture of a reference sensor. MUMPs layers shown in the SEM include Poly 0, Poly 1, Poly 2, and Au

**Fig. 5.** This illustration shows a pair of rotation sensors. The design parameters are also shown in this figure.