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Analog-CMDA based interfaces for MEMS gyroscopes

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ABSTRACT

This work moves toward the state-of-the-art for the interfaces usually employed for three-axes micromachined gyroscopes. Several architectures based on multiplexing schemes in order to extremely simplify the analog front-end which can be based on a single charge amplifier are analyzed and compared. This paper presents a novel solution that experiments an innovative readout technique based on a special analog-CDMA (Code Division Multiplexing Access); this architecture can reach a considerable reduction of the analog front-end with reference to other multiplexing schemes. Many family codes have been considered in order to find the best trade-off between performance and complexity. System-level simulations prove the effectiveness of this technique in processing all the required signals. Finally, a case study is analyzed: a comparison with the SD740 micro-machined integrated inertial module with a tri-axial gyroscope by SensorDynamics AG is provided.

1. Introduction

A gyroscope usually consists of a mechanical structure, typically a polysilicon proof mass mounted on elastic suspensions, which can vibrate along two (ideally) orthogonal directions (two degrees of freedom); for each degree of freedom, the system can be considered as a Mass–Spring–Damper oscillator. In a non-inertial reference system fixed with the sensor frame, the two modes of vibration experience a dynamic coupling whenever the sensor undergoes a rotation, because of the onset of the Coriolis acceleration [1].

Fig. 1 represents a non-inertial reference system fixed with the sensor frame, whose x- and y-axes are aligned with the two orthogonal directions of vibration of the proof mass. The in-plane equations of motion of the proof mass in the sensor-fixed frame can be written as follows:

$$M\ddot{q}(t)+D\dot{q}(t)+Kq(t)=F(t)+2\Omega(t)MS\dot{q}(t) \quad (1)$$

where $q(t)=[x(t),y(t)]^T$ is the in-plane displacement vector, $F(t)=[F_x(t),F_y(t)]^T$ is the vector of external actuating forces, and $\Omega(t)$ represents the sensor angular velocity along the z-axis (orthogonal to the x–y plane). The 2×2 real, positive definite matrices

$$M=\begin{bmatrix} m_x & 0 \\ 0 & m_y \end{bmatrix},\quad D=\begin{bmatrix} d_{xx} & d_{xy} \\ d_{yx} & d_{yy} \end{bmatrix},\quad K=\begin{bmatrix} k_{xx} & k_{xy} \\ k_{yx} & k_{yy} \end{bmatrix}$$

denote the mass, damping and stiffness matrices. The off-diagonal terms d_{xy} and d_{yx} in the damping matrix D and k_{xy} and k_{yx} in the stiffness matrix K represent non-proportional viscous damping and anisoelasticity effects. S is the antisymmetric matrix

$$S=\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$$

that explains how the Coriolis acceleration couples the dynamics of the two modes of vibration. In the following, for a sake of simplicity, only anisoelasticity effects are considered while non-proportional damping is neglected. The conventional principle of working consists of driving the mass with a simple harmonic motion along the direction of the primary mode (*drive-mode* or *driving*) and of detecting the motion generated along the direction of the secondary mode (*sense-mode* or *sensing*) while the sensor is rotating. If x- and y-axes denote the directions of the drive-mode and the sense-mode respectively, the equations of the motion can be written as follows:

$$x(t)=-X_0\sin(\omega_x t) \quad (2)$$

$$\ddot{y}(t)+\frac{\omega_y}{Q_y}\dot{y}(t)+\omega_y^2 y(t)=-2\Omega(t)\dot{x}(t)-\omega_{yx}x(t) \quad (3)$$

where $\omega_x=\sqrt{k_{xx}/m_x}$ and $\omega_y=\sqrt{k_{yy}/m_y}$ are the natural frequencies of the drive-mode and the sense-mode respectively, $\omega_{yx}=k_{yx}/m_y$ is the coupling factor between the two modes, and $Q_y=m_y\omega_y/d_{yy}$ is the quality factor of the sense-mode.

In (2) it has been assumed that the amplitude of the harmonic motion along the driving is regulated and kept constant to a specific

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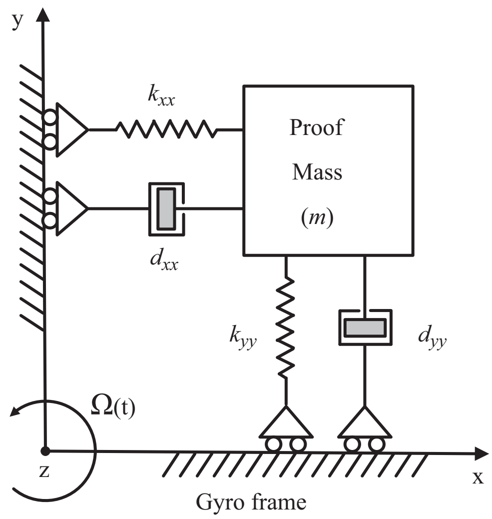

Fig. 1. Mechanical model of a one-dimensional gyroscope.

value X_0 by an external circuitry; in (3) it has been assumed that the sensing is not forced by the outside. Still in (3), the first forcing term $a_\Omega(t) \overset{def}{=} -2\Omega(t)\dot{x}(t)$ represents the Coriolis' acceleration that depends directly from the angular rotation $\Omega(t)$ of the sensor. When $x(t)$ is a harmonic oscillation, $a_\Omega(t)$ is a double-sideband signal with carrier $\dot{x}(t)$ and $\Omega(t)$ as a modulating wave.

The second forcing term in the quadrature acceleration $a_q(t) \overset{def}{=} -\omega_{yx}x(t)$ is due to a partial coupling of the drive-mode along the sensing axis (caused by imperfections of the manufacturing process). The motion $y(t)$ along the sensing axes is hence characterized by two different contributions: $y_\Omega(t)$ due to the Coriolis' acceleration and $y_q(t)$ due to the quadrature acceleration. The last contribution is usually called *quadrature error* or *Qbias*. For constant angular rates, the two contributions are proportional to $\dot{x}(t)$ and $x(t)$; under this condition, those terms are in quadrature and a synchronous demodulation is required.

In the industrial field, the driving signal is called *motor* and is represented by (4) with $\omega_d = \omega_x$; the sensing signal instead is called *sense* and is represented by (5), again with $\omega_d = \omega_x$, where I_B, Ω, and Q_B represent the *in-phase bias*, the *applied rate*, and the *in-quadrature bias* respectively.

$$m(t) = M_0 \sin(\omega_d t) \tag{4}$$

$$s(t) = (I_B + \Omega)\cos(\omega_d t + \phi) + Q_B \sin(\omega_d t + \phi) \tag{5}$$

For sake of clarity, the dynamics of a triaxial gyroscope is reported below (according to [36]) assuming that the gyroscope is moving with a constant linear speed, the gyroscope is rotating at a constant angular velocity, the centrifugal forces are negligible, the gyroscope undergoes rotations along x-, y- and z-axes, $m_x = m_y = m_z = m$.

$$m\ddot{x} + d_{xx}\dot{x} + k_{xx}x + k_{xy}y + k_{xz}z = F_x + 2m\Omega_z\dot{y} - 2m\Omega_y\dot{z}$$
$$m\ddot{y} + d_{yy}\dot{y} + k_{xy}x + k_{yy}y + k_{yz}z = F_y - 2m\Omega_z\dot{x} + 2m\Omega_x\dot{z}$$
$$m\ddot{z} + d_{zz}\dot{z} + k_{xz}x + k_{yz}y + k_{zz}z = F_z + 2m\Omega_y\dot{x} - 2m\Omega_x\dot{y}$$

where m is the proof mass; Ω_x, Ω_y, and Ω_z are angular velocities in the x-, y-, and z-direction respectively; k_{xy}, k_{xz}, and k_{yz} are asymmetric spring terms; k_{xx}, k_{yy}, and k_{zz} are spring terms in the x-, y-, and z-direction respectively; d_{xx}, d_{yy}, and d_{zz} are damping terms in the x-, y-, and z-direction respectively; F_x, F_y, and F_z are the control forces in the x-, y-, and z-direction respectively. As previously underlined the asymmetric damping terms have been neglected for a sake of simplicity. From the previous considerations, the modern mixed-signal architectures for three-axes capacitive gyroscopes have to manage principally four signals: one primary signal for keeping the sensor in resonance (motor) and three sensing signals (x-/y-/z-sense) [2,3]. The motor signal is used to reach and maintain sensor lock by the primary chain feedback loop; instead x-, y-, and z-senses are used to extract the angular motion information from the sensor [4–7].

A fully decoupled 3D gyroscope [8] is shown schematically in Fig. 2 and implementation details are presented in Fig. 3.

The gyroscope consists of eight radially driven segments angularly spaced by 45°. Four segments that are angularly separated by 90° are not paired by the central suspension but suspended directly from the substrate. The high z-stiffness of the suspension neutralizes out-of-plane Coriolis forces. Two opposite segments of the other four plates are linked by the Cardan suspension (or equivalent) in two pairs, either of which may tilt about the y- or x-axis in response to the corresponding components Ω_x and Ω_y. Electrodes placed underneath allow independent differential capacitive measurement for any of the in-plane rate signals. The four Ω_z–sensitive frames nest sub-frames that can be deflected orthogonally to the radial movement. The sensing boxes within the sub-frames capture the Coriolis deflections stemming from the Ω_z component. All segments perform a common drive motion that is enforced by the eight radially arranged synchronization springs.

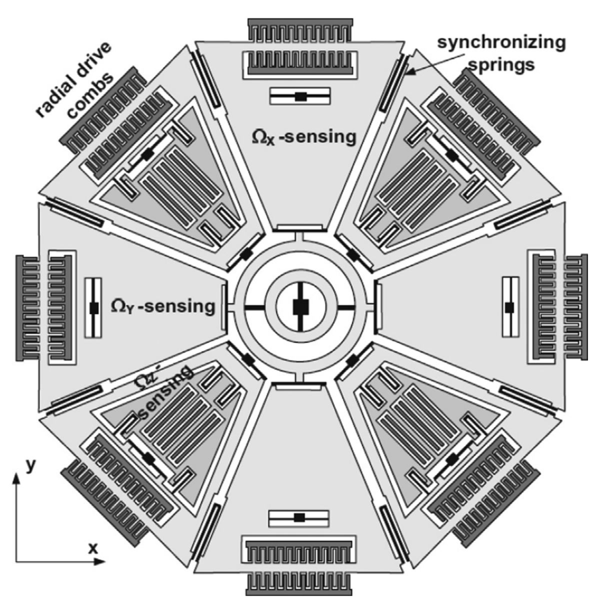

Fig. 2. A fully decoupled 3D gyroscope.

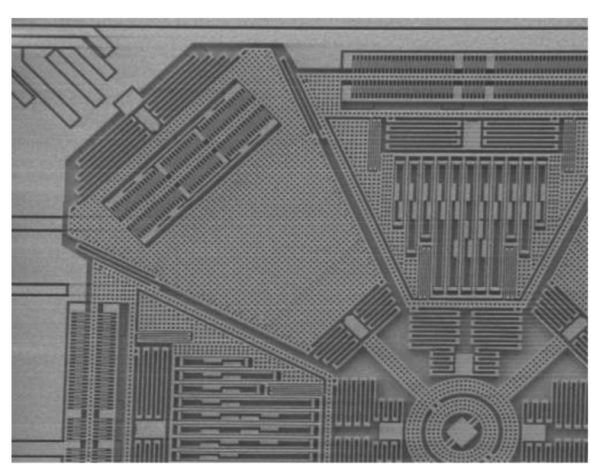

Fig. 3. Implementation details of a fully decoupled 3D gyroscope.