MEMS Inertial Sensors and Their Applications

Kazusuke Maenaka
Graduate School of Engineering, University of Hyogo
Himeji, Japan
maenaka@eng.u-hyogo.ac.jp

***Abstract*— Micro Eelectro Mechanical Systems (MEMS) technology has developed considerably in recent years and many sensors utilizing this technology are available in the market. MEMS technology enables miniaturization, mass production, and cost reduction of many sensors. In particular, MEMS inertial sensors that include an acceleration sensor and an angular velocity sensor (gyroscope, or simply "gyro") are the most popular devices. Applications of inertial sensors have now extended into the field of networked sensing systems. In this presentation, we will describe current MEMS inertial sensors and their applications.**

Keywords—Sensors; Transducers; MEMS; Acceleration Sensor; Gyroscope; Sensor Integration.

I. INTRODUCTION

An inertial sensor includes an acceleration sensor and a gyro[1]. Almost all MEMS acceleration sensors have a seismic mass and support spring made of silicon[2]. The structure of MEMS gyros is somewhat similar to that of acceleration sensors—a mass supported by a spring is continuously vibrated in the device, and the Coriolis force generated by the applied angular velocity affects the movement of the mass (vibrating gyroscope)[3]. The mass in an MEMS device is very small, and therefore, the inertial forces acting on the mass, especially the Coriolis force, are also extremely small. Thus, the design of the circuit that measures the movement in mass due to the force is important in addition to the design of the mechanical structure. Recently MEMS inertial sensors have been built with an integrated circuit, with sensor structure on a single device chip. Examples of MEMS inertial sensors available in the market are shown in Fig. 1. All of them provide an output of the order of several volts; some even provide digital output and only require a power source.

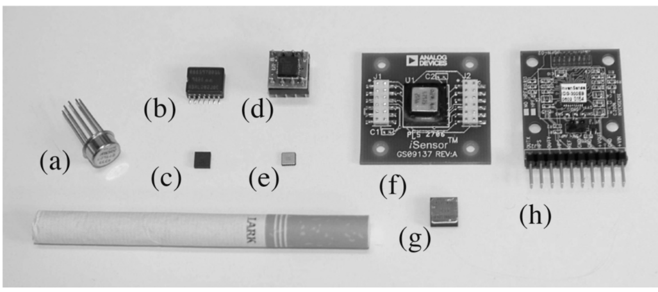


Fig. 1. Examples of MEMS inertial sensors.
(a)–(e): MEMS acceleration sensors, (a) first type of integrated acceleration sensor (1-axis); (b), (c) 2-axes; and (d), (e) 3-axes sensors.
(f)–(h): MEMS gyros (f), (g): 1-axis, (h): 2-axes.
Part numbers: (a) ADXL50, (b) ADXL202, (c) ADXL320, (d) KXM52, (e) H34C, (f) ADIS16250, (g) ADXL300, (h) IDG300. (a)–(c), (f), (g): Analog Devices Inc., (d) Kinonix Inc., (e) Hitachi Material, (h) InvenSense Inc.

II. MEMS ACCELERATION SENSORS

MEMS acceleration sensors are currently in the limelight. Of utmost concern in this field is further miniaturization, decrease in cost, three-dimensional detection, and on-chip digital signal processing. Several MEMS acceleration sensors are available in the market, and they have been well incorporated into many types of mass-produced goods, such as automobiles, pedometers or exercise meters, cell phones, PDAs, gaming consoles, etc. These products require low-cost and small-sized sensors rather than those providing optimum performance, and most sensors are being developed to fulfill this demand. The field of MEMS acceleration sensors thus seems to be competing over price reduction. To reduce the price, the size of the sensor chip should be minimum and the structure and fabrication process should be simple. A typical structure of an MEMS acceleration sensor is shown in Fig. 2, where a silicon mass is supported by silicon springs and the displacement of the mass due to acceleration is measured by capacitance change between the mass and fixed electrodes.

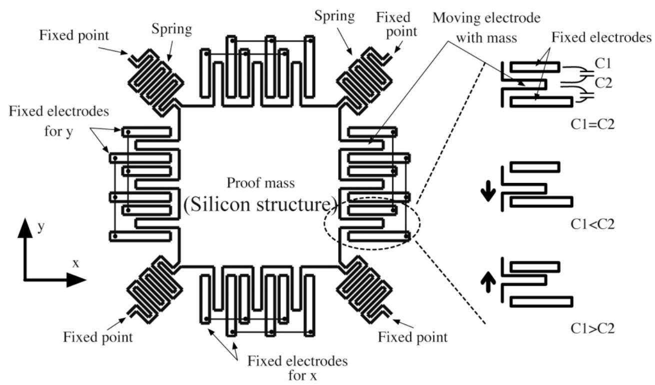
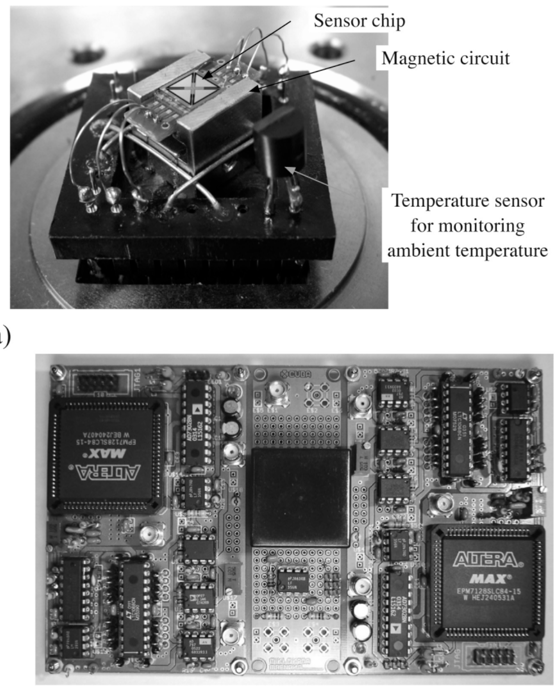


Fig. 2. Structure of MEMS acceleration sensor (2-axis). Figure only shows conceptual operation. Designs of actual devices involve much more detail.

Since the mass is very small and the displacement is also small, the resolution of the device is generally limited to around 0.1 mg $Hz^{-1/2}$.

On the other hand, there are some applications that require high resolution and stability in acceleration measurement, e.g., earthquake detection, inertial navigation systems, and seismic reflection profiling. To meet these requirements, different approaches have been employed[4,5]. One of them is the vibrating accelerometer; the force causing acceleration is measured by a change in stress in the beam supporting the mass, which results in a change in the beam's resonance frequency. The frequency change can be measured accurately and is essentially digital, and thereby, high-performance sensing systems can be realized. An example is shown in Fig. 3[5]. This particular device is composed of a proof mass, frame, and two sets of suspension beams and vibrating beams. An external magnetic circuit applies a magnetic field to all beams. The beams are wired in order to vibrate them and detect the movement of the beams caused by electromotive force. With AC currents applied through the driving wires and electromotive force detected from the sensing wires, we can obtain the resonance frequencies of the beams using self-oscillation circuitry. The vibrating beams have their own initial resonance frequencies depending on the length and thickness of the beams. When acceleration is applied along the *x* direction (parallel to the set of vibrating beams), one of the vibrating beams receives compressive stress and the other receives tensile stress, resulting in the decrease and increase of resonance frequencies for individual beams. These resonance frequency changes constitute the output of the device.



(a)

(b)

Fig. 3. Example of vibratory beam accelerometer: (a) sensor part (10 × 10 × 10 mm^3, including magnetic circuit) and (b) digital interface circuit. Currently, both components are somewhat large, but system size may be reduced drastically using a different excitation method and full-CMOS circuit design.

Although this device is currently somewhat large, it has the ability to detect very small accelerations with high stability.

III. MEMS GYROSCOPES

In the past several years, some silicon MEMS gyroscopes have been developed and marketed. A typical structure of the device is shown in Fig. 4[6]. The basic structure is similar to acceleration sensors, i.e., a mass is supported by springs. The main difference in operation is that the angular velocity is obtained by measuring the Coriolis force on the vibrating mass. Thus, the movement of the mass should have at least two degrees of freedom. The device shown in Fig. 4 has two perpendicular sets of springs, Kx and Ky, where spring Kx allows movement of the whole structure in the *x* direction and spring Ky permits constant vibration of the inner part of the structure in the *y* direction. The comb-type actuators at the center of the device vibrate the inner mass in the *y* direction. The applied angular velocity shown in Fig. 4 exerts an *x*-direction Coriolis force over the inner mass, resulting in the *x*-movement of the whole structure including the outer section. The outer section of the structure has several combs that act as the movement detector using the capacitance change between the combs. This capacitance change constitutes the output of the device. The absolute value of the Coriolis force is extremely small in typical MEMS devices and it is difficult to precisely measure the movement of the structure using Coriolis forces. Several corporate and educational/research institutions are attempting to improve gyroscope characteristics by designing optimized structures and effective interface circuitry. Currently, MEMS gyroscopes have a resolution of 0.01–0.1 deg s^{-1} $Hz^{-1/2}$. A major drawback of MEMS gyros is zero-point stability. This is due to the difficulty in measurement of the small displacement generated by Coriolis force. It often reaches hundreds of deg/s. Therefore, their application to inertial navigation systems, in

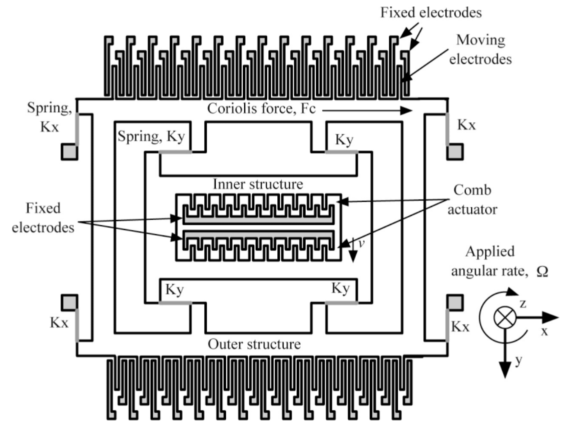


Fig. 4. Conceptual structure of an MEM gyroscope. In order to generate Coriolis force, electrostatic actuators are placed at the center of the device and the inner structure is vertically vibrated continuously. The Coriolis force for the applied angular rate about the *z* axis is generated in the *y* direction and the outer structure moves in the *y* direction. The comb electrode around the outer structure measures this displacement.

which zero-point offset induces a large error, is difficult. Techniques such as Kalman filtering are being used at present for correcting this error in navigation systems.

Some researchers are developing a different type of gyros, e.g., ring laser gyros, which use the Sagnac effect on rotating laser rays[7,8]. These gyros will have extremely stable zero-point stability. The concept of such a device is shown in Fig. 5. In this device, four silicon mirrors form a rotational light path resulting in the resonator of the laser. In this rotational path, both CW and CCW waves will be generated and these waves interfere according to the applied angular velocity. These devices have not been commercialized so far, but future studies are anticipated for the development of next-generation MEMS gyros.

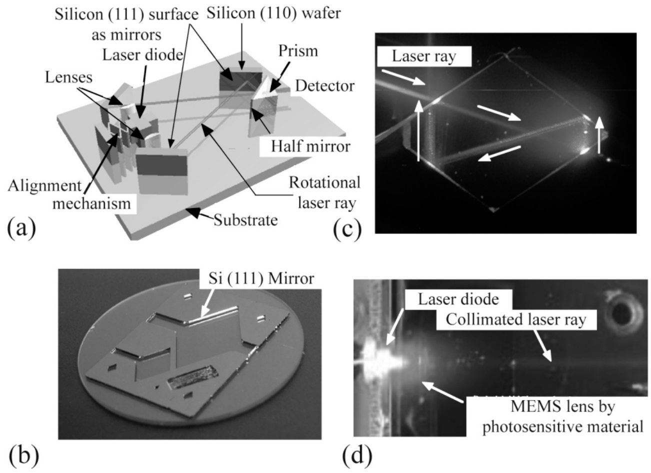


Fig. 5. Demonstration of MEMS ring laser gyro: (a) structure, (b) silicon wafer with (111) surface mirrors, (c) rotating laser ray, and (d) demonstration of MEMS lens.

IV. Applications of Inertial Sensors

Inertial sensors have numerous applications. One successful application is Nintendo's Wii remote controller, in which player movement is measured using a three-dimensional acceleration sensor and an infrared transmitter detects controller direction. Data is transmitted to the base station via a Bluetooth interface. The base station has Wi-Fi network capability and one can play against other players located at a distance. This system may possibly be one of the perfect networked sensing systems.

Movement detection is also useful for human activity and health monitoring; a pedometer is one such application. We are now studying an MEMS-based human activity monitoring system that includes an acceleration sensor as well as of other types. Figure 6 shows the prototype system (wristband type) of the activity monitor[9]. It has a three-dimensional acceleration sensor, pressure sensor, temperature sensor, humidity sensor, memory, CPU, real-time clock, and wireless network capability. A gyroscope is not included because current MEMS gyroscopes consume considerably more power than other sensors. Although this system has a limited variety and number of sensors, many parameters of human activity can be measured. For example, the data roughly show the activity being performed by the user and the user's current position. We are now trying to integrate more sensors of different types into a single chip, to miniaturize the system, to increase operational lifetime, and to realize data analysis and a networked system.

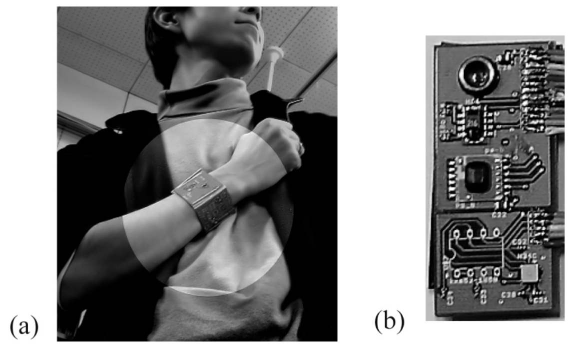


Fig. 6. Prototype model of human activity monitoring system (a) and sensor part of the system (b).

V. Conclusion

The current status of MEMS inertial sensors and some of their applications were described. Inertial sensors are useful for sensor networking, for example, monitoring of human motion, distribution of earthquakes, vibration of buildings, etc. Presently, the resolution and stability of MEMS inertial sensors are not adequate, but it is only a matter of time before they become more suitable for networked sensor systems.

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