Overview of Micro-Mechanical Accelerometer Research Based on ΣΔ Modulation Technology

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Manuscript received November 25, 2023; revised December 15, 2023; accepted December 29, 2023

***Abstract*—This paper provides an overview of the current development status of acceleration sensors from three aspects: development methods, working principles, and sigma-delta (ΣΔ) modulation technology. The performance characteristics of the most representative EM-ΣΔM inertial sensor system are introduced. The optimized methodology for improving the performance and accuracy of capacitive Micro-Electro-Mechanical Systems (MEMS) accelerometers while reducing mechanical and electronic noise is given. Finally, by comparing with advanced foreign technologies, the challenges and development directions faced by domestic MEMS accelerometer research have been identified.**

***Keywords*—Micro-Electro-Mechanical Systems (MEMS), micro-capacitive accelerometer, EM-ΣΔM, force feedback, optimized methodology**

I. Introduction

Accelerometers, as important mechanical sensors, have been widely applied in various fields such as industrial automation, automotive industry, vibration and seismic testing, scientific measurements, military, and space systems. Micro-mechanical accelerometers designed based on the principle of force balance have made significant progress over the past few decades. They are indispensable components of inertial systems, largely determining the measurement accuracy of motion carriers or the precision of motion control.

In the field of industrial automation, accelerometers are often used to control the orientation of cameras to ensure the stability of captured images. They are also utilized to detect the vibration of conveyor belts, ensuring the safe operation of the feedback circuit during material transport. Additionally, accelerometers are commonly employed to ensure the precise positioning of industrial robot movements.

In the automotive industry, accelerometers play a crucial role in safety systems, including vehicle tilt detection, collision detection, and airbag triggering, contributing to enhanced driving safety.

In seismic detection, accelerometers are used to create seismometers embedded in relevant geological layers. By measuring the vibration acceleration at various measurement points, the properties and structure of different depth layers can be analyzed. This aids in preliminary assessments of whether conditions for oil production and storage are present, determining drilling locations.

In military and aerospace applications, accelerometers find extensive use in missile arming safety, missile navigation and guidance, as well as applications in inertial measurement systems and stabilization platforms.

Currently, both smartphones and tablets are equipped with 3-axis accelerometers to detect the motion trajectories of devices and identify impacts before falling. Accelerometers are also integrated into wristbands worn by the elderly in home care environments to trigger alarms promptly in the event of a fall.

To sum up, low-cost, compact accelerometers have a strong demand in both military and civilian sectors. Products from countries like Japan have dominated certain domestic application markets. Therefore, it is essential to research and develop accelerometers with independent intellectual property rights.

II. Current Development Status of Accelerometer Sensors

A. Several Development Approaches for Accelerometers

An accelerometer is an instrument that measures the acceleration of a motion unit. According to its design principles, it can be classified into the following five types:

1) Piezoresistive accelerometer

The core of a piezoresistive accelerometer is a piezoresistor located at the most stress-sensitive part of a cantilever beam. When the sensitive mass block undergoes displacement, it causes the expansion and contraction of the cantilever beam, changing the stress distribution on the beam and thereby altering the resistance of the piezoresistor. Acceleration is obtained by sensing the change in resistance. Its advantages include a simple structure, manufacturing process, and detection circuit. However, its disadvantages include poor operational stability and low sensitivity.

2) Resonant accelerometer

A resonant accelerometer measures acceleration by inducing frequency changes caused by acceleration variations. The working principle involves the acceleration-induced inertial force on a sensitive mass block, transmitted through hinges to two pairs of resonators, resulting in tension and compression stresses on them, thereby increasing and decreasing their respective frequencies. Comparing the frequencies of the two resonators allows for the determination of acceleration.

3) Tunnel current-type accelerometer

The tunnel current-type accelerometer is a high-precision micro-mechanical accelerometer that combines micro-silicon mechanical structures with measurement technology based on the electronic tunnel effect. The basic principle involves using the tunnel effect of electrons in a narrow vacuum potential barrier. The change in tunnel current between the atomic-scale needle tip and the electrode is used to detect

DOI: 10.7763/IJET.2024.V16.1246

acceleration. However, it requires closed-loop control circuits and long-term drift of voltage. This type of accelerometer cannot detect static acceleration inputs.

4) *Microthermal convection accelerometer*

The microthermal convection accelerometer utilizes free thermal convection inside a sealed air chamber to measure acceleration sensitivity. Two temperature sensors symmetrically distributed on both sides of a closed cavity containing gas, with a heat source in the middle. In the absence of acceleration input, the gas moves symmetrically around the heat source. When acceleration is applied, the distribution of gas in the cavity changes, causing a temperature difference between the two sensors. The acceleration can be derived from the temperature difference detected by the two sensors. This type of accelerometer, without a large mass block, has strong shock resistance and high accuracy.

5) *Micro-capacitive accelerometer*

The micro-capacitive accelerometer utilizes the capacitance variation caused by the relative motion between the sensitive mass block and the detection electrode to measure acceleration. It is primarily composed of a sensitive mass block, a cantilever beam, and two fixed electrodes and can detect acceleration parallel to the silicon plane. The cantilever beam and the two fixed electrodes constitute a pair of parallel plate differential capacitor structures, and measuring the change in differential capacitance allows for the determination of acceleration values. This type of accelerometer is currently the most researched and offers advantages such as high accuracy, good noise characteristics, low drift, low temperature sensitivity, low power consumption, and a relatively simple structure. Micro-capacitive accelerometers with structural configurations can be divided into two categories: bulk micro-machined accelerometers and surface micro-machined accelerometers. Bulk micro-machined accelerometers have the advantages of a large measurement range and high accuracy but come with high production costs, complex processing techniques, and incompatibility with certain manufacturing processes. On the other hand, surface micro-machined accelerometers have the benefits of simple processing and easy integration with circuits but produce weak output signals. Therefore, they must be combined with integrated circuits to achieve more accurate results. Micro-capacitive accelerometers can also be classified into open-loop and closed-loop control modes based on different control methods. Compared to open-loop control, closed-loop control has advantages such as good dynamic performance, high linearity, and low requirements for micro-machining processes.

The paper adopts a micro-capacitive design approach and uses the ΣΔ closed-loop force feedback working mode. This approach is relatively easy to control micro-mechanical sensitive components to keep them working in the middle position. It effectively avoids the drawbacks of open-loop and analog closed-loop micro-accelerometers and can directly perform signal analog-to-digital conversion, thereby outputting pulse density modulation digital signals.

B. *Basic Principles of Micro-Capacitive Accelerometer*

The basic principle of a micro-capacitive accelerometer is based on Micro-Electro-Mechanical Systems (MEMS). It involves measuring the acceleration of a carrier by capturing the capacitance changes caused by the relative motion between the sensitive mass block and the detection electrode.

The principal structure of a capacitive accelerometer is illustrated in the following diagram:

As seen in Fig. 1, it is essentially a variable reluctance capacitive displacement sensor. The sensitive mass block, placed inside the housing by a spring, is connected to the variable reluctance on the left side. The movement of the mass block drives the motion of the variable reluctance, thereby altering the dielectric constant.

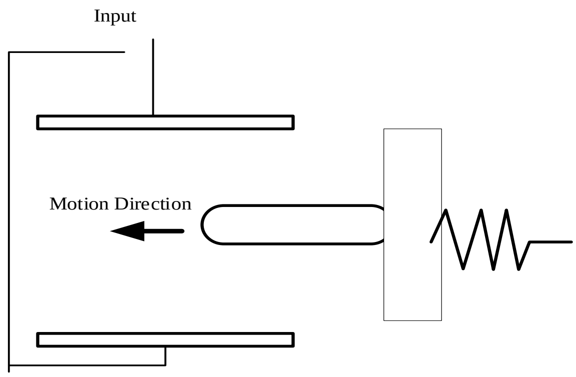

Fig. 1. Schematic diagram of the principle of capacitive accelerometer.

The header's mechanical spring can provide feedback force, ensuring the movement of the mass block within the equilibrium zone. This device establishes an equivalent relationship between acceleration and capacitance values. The subsequent circuitry only needs to convert the changes in capacitance into voltage changes, obtaining the corresponding values of acceleration through analog-to-digital conversion.

However, such a device requires a relatively high-precision analog-to-digital converter to support data acquisition. High-precision analog-to-digital converters often come with higher costs. This paper proposes a ΣΔ modulation-based sampling model sacrificing a certain sampling speed in order to obtain a cost-effective solution.

C. *Capacitive Acceleration Sensor Based on ΣΔ*

In recent years, ΣΔ modulation technology has been widely used in areas where the rate of change of the measured object is not too high, benefiting from its high resolution and low cost. This paper applies ΣΔ modulation technology to the structural design of a micro-mechanical accelerometer, achieving the acquisition of acceleration signals and high-precision digital output. Based on ΣΔ analog-to-digital converters, analog signals are digitized with very low sampling resolution and a high sampling rate. The paper improves resolution through oversampling, noise shaping, and digital filtering techniques. Additionally, a corresponding sampling extraction algorithm is employed to reduce the effective sampling rate.

III. Related Work

With the widespread adoption of Micro-Electro-Mechanical Systems (MEMS) technology, MEMS accelerometers with lower sensitivity requirements have been commercialized in various fields. However, certain applications such as inertial navigation systems, oil and gas exploration, space systems, and seismic detection demand accelerometers with high sensitivity and stability. To achieve high performance and maximize accuracy from capacitive MEMS accelerometers, it is crucial to minimize both mechanical and electronic noise as much as possible. Therefore, research on capacitive MEMS accelerometers is mainly focused on the following three aspects. Scholars both domestically and internationally are conducting research on the stability and cost-effectiveness of micro-accelerometers.

A. Research on the Mechanical Component of the Accelerometer Header

One optimization study focuses on the origin of the sensor (the mechanical part) because the higher the sensing capacitance, the higher the sensitivity, and the lower the gain required for the complementary acquisition circuit, resulting in lower electronic noise. Furthermore, higher driving capacitance leads to higher electrostatic force generation, requiring lower feedback voltage to reduce the required power.

To achieve higher sensing capacitance and driving capacitance, the electrodes must be designed with a larger overlapping area and minimal gap. Many design schemes set the gap between the sensitive mass and electrodes to around 2 micrometers. Another design approach is to increase the sensitive mass area, leading to a larger capacitance for unit mass displacement. Both requirements are constrained by microfabrication processes. Currently, batch microfabrication or Silicon on Insulator (SOI) technology can provide a larger overlap area, depending on the entire wafer thickness.

Chae *et al.* [1] pointed out that increasing the sensitive mass can improve sensitivity and reduce the impact of Brownian noise. They designed an accelerometer using a groove-filling process. The accelerometer header incorporates a sensitive mass block with dimensions of 0.5 mm thickness and 2.4×1.0 mm^2, and high aspect ratio polycrystalline silicon sensing electrodes. The electrodes are separated from the detection object by a 1.1 μm sensing gap formed using a sacrificial oxide layer. The device achieves a sensitivity of 5.6 pF/g.

Yazdi *et al.* [2] from Arizona State University utilized surface micromachining to prepare a fully symmetric axis micro-accelerometer header on a single silicon chip. Microfabrication uses the entire chip thickness to generate the sensitive mass and a thinner sacrificial layer to produce a large sensing capacitance. Sensing and feedback electrodes are formed by deposited 2-3 μm polycrystalline silicon film embedded with 25–35 μm thick vertical reinforcing ribs. Embedded thick reinforcing ribs can support force rebalancing.

The capacitive accelerometer header uses the entire chip thickness to increase the sensitive mass. However, the increase in sensitive mass size comes at the cost of mechanical design complexity, where unnecessary vibration modes can easily affect measurement accuracy within the frequency band. To prevent such issues, vacuum packaging is a preferable solution, which also reduces the Brownian noise effect but objectively increases sensor production costs [3].

Japanese company Shoji Kanno and others designed an accelerometer sensor involving a movable rotor. When the accelerometer moves with an acceleration component perpendicular to the substrate plane, the movable rotor can rotate away from the substrate plane. The capacitive MEMS accelerometer includes additional damping springs to reduce unwanted movement of the rotor in the substrate plane, thereby reducing parasitic capacitance caused by the rotor's motion in the substrate plane. The damping springs are vertically recessed relative to other components of the accelerometer to minimize their impact on the rotor's movement away from the substrate plane [4].

Research on MEMS in China began in the early 1990s and received support from government agencies during the "Eighth Five-Year Plan" and "Ninth Five-Year Plan" periods. In 1997, Chongqing University successfully developed a silicon microarray accelerometer and completed the development of a silicon force balance accelerometer in 1998. Tsinghua University successfully developed a fork-shaped capacitive silicon microaccelerometer in 1999. In 2000, the Shanghai Institute of Metallurgy of the Chinese Academy of Sciences proposed a variable area structure micro-mechanical capacitive accelerometer. He Hongtao and others from the Hebei Semiconductor Research Institute published a comb-shaped silicon capacitive accelerometer in 2002. The Sensor Research Center of the Institute of Electronic Engineering of the China Academy of Engineering Physics developed the "fork-type electrostatic servo micro-accelerometer" with a maximum range of 60g. Huazhong University of Science and Technology explored the processing technology of the comb-type micro-mechanical accelerometer and successfully achieved the suspension of the sensitive mass block and the active comb teeth using a dry release method. The capacitive accelerometer of Tsinghua University adopts a fixed-tooth-bias fork-type closed-loop measurement scheme. The header is manufactured using a bulk silicon wafer dissolution process [5]. The circuit uses a differential capacitor bridge measurement, electrostatic force feedback thin film integrated circuit, and the header is hybrid assembled with the circuit. The header is co-processed with the 13th Institute of the Ministry of Information Industry [6].

B. Optimization of the Front-End Readout Circuit

The second area of focus in the development of MEMS accelerometers is the front-end electronic circuitry. Its main task is to convert capacitance values into voltage values. The key to circuit design is to eliminate the impact of noise on measurements as much as possible.

In most capacitive MEMS accelerometers, electronic noise generally has a significant impact on the output voltage signal. Additionally, the amplification circuit of the front-end electronic devices can also contribute to electronic noise. Therefore, it is necessary to control electronic noise below mechanical noise. The front-end readout circuits of capacitive MEMS can be roughly divided into three categories [7]: AC bridge circuits with voltage amplifiers, transimpedance amplifiers, and switch capacitor circuits [8]. It is important to note that the choice of an appropriate circuit also depends on the sensor manufacturing technology and packaging.

The Michigan University accelerometer developed by Yazdi et al. in 1999 uses a readout structure based on a switch capacitor. It employs two fixed reference capacitors and a sensitive capacitor to form a balanced full-bridge circuit. The interface circuit uses a correlated double-sampling circuit to eliminate 1/f noise, amplifier offset, and compensate for the finite gain of the amplifier. Aezinia *et al.* [9] designed a readout circuit for differential capacitive sensing applications. This design can be referenced to develop a universal framework for interface circuits suitable for various sensing applications. This design scheme features a high dynamic range, low power consumption, and adjustable sensing range. Wei-Jun Lin from Zhejiang University designed a single-carrier modulation detection circuit for variable-area capacitive MEMS accelerometers and analyzed the impact of environmental factors such as temperature on the detection circuit and its impact on the system MEMS [10].

C. Overall System Structure Optimization

Another aspect that researchers are paying attention to involves the entire control loop strategy, which can be an open-loop system or a closed-loop system. Most commercial accelerometers with low to medium sensitivity use an open-loop approach. High-performance accelerometers are usually designed as closed-loop structures. Compared to open-loop structures, the latter can achieve higher bandwidth, better linearity, and a larger dynamic range. However, these advantages come at the cost of increased circuit complexity.

Currently, capacitive MEMS accelerometers use two closed-loop strategies: analog feedback and digital feedback. Analog closed-loop involves converting the CV to analog voltage feedback to the top and bottom electrode plates to generate an electrostatic force, controlling the sensitive mass close to its reference position. Digital feedback static force is generated based on the ΣΔ M architecture, controlled by a unit comparator to output the feedback force. However, it is essential to ensure that the electrostatic force and the direction of sensitive mass movement are opposite. Digital closed-loop methods eliminate the pull-in problem that occurs in analog closed-loop methods. As one electrode near the proof mass is grounded and the other electrode is powered, even under shock acceleration, the proof electrode always moves toward the powered electrode.

Henrion *et al.* [11] first used a second-order ΣΔ to control capacitive MEMS accelerometers in 1990 at the Fourth International Solid-State Sensor Conference, noting that the microfabricated sensor operates in a vacuum, eliminating nonlinear viscous damping and equivalent to a high-q second-order mechanical resonant circuit. Kraft *et al.* [12] provided a mathematical model of this two-order ΣΔ circuit, demonstrating through simulation that this oversampling conversion-based digital device has superior stability compared to analog accelerometers. Turkish scholars provided a four-order design in 2011, achieving a significant dynamic range in the accelerometer system without significantly increasing the process and circuit integration complexity [13].

Berkeley and the University of Michigan in the United States are researching the application of Σ-Δ modulation technology to the design of closed-loop capacitive MEMS accelerometers and have developed prototypes. In China, Tsinghua University and other units have preliminarily developed capacitive MEMS accelerometers using bulk silicon processing technology. Northwestern Polytechnical University [14], Tianjin University [15], and Harbin Institute of Technology have also conducted relevant theoretical research on Σ-Δ MEMS accelerometers. Du Wenhe of Qiqihar University designed a high-order structure with a high-Q closed-loop ΣΔ accelerometer interface circuit, significantly reducing quantization noise within the digital interface circuit baseband. To ensure the stability of this high-order system, a front-end compensator circuit was designed to improve electrical damping. Test results show that the high-Q high-order structure system is stable, and its ability to suppress quantization noise is significantly higher than that of a second-order structure [16].

IV. The Conclusion of the Review

In recent years, the Chinese government has placed great emphasis on research, and with government funding, some progress has been made in the research on MEMS accelerometers in China. However, there is still a considerable gap between device research in China and developed countries. Compared to MEMS accelerometers using microfabrication technology, there are differences in both performance and engineering level compared to foreign counterparts, as outlined below:

There is a significant gap in theoretical research on sensor design compared to foreign countries.

There is a substantial difference in MEMS process conditions compared to foreign counterparts.

There is a considerable gap in the level of signal detection, design circuits, and integration compared to foreign counterparts.

To suppress noise in the bandwidth of the accelerometer signal, this paper designs a closed-loop system for a MEMS accelerometer based on a fifth-order ΣΔ modulator. The modulator is modeled, optimized, and its stability is discussed through behavioral-level simulation in MATLAB/Simulink. The accuracy and stability of the circuit are validated at the PCB level, and the acceleration values are displayed on a host computer through a digital filtering algorithm implemented on an FPGA. This provides a comprehensive testing and calibration environment, laying the foundation for the localization of accelerometer sensors.

Conflict of Interest

The author declares no conflict of interest.

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