In-Plane Bulk-Micromachining Fabrication of High Dynamic Range Tactical Grade Open Loop and Closed Loop MEMS Accelerometers

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Abstract — in this paper we describe open loop and closed loop capacitive MEMS accelerometers fabricated using In-Plane Bulk-Micromachining technology. Our robust process assures high yield and high reliability of both product types. The MAXL-OL-2000 open loop accelerometers series shows temperature sensitivity of 20 – 200µg/°C with typical hysteresis of 1mg, typical TOTO repeatability of 70µg and typical overall repeatability of 1mg.

We demonstrate first test results of our MAXL-CL-3030 closed loop ΔΣ accelerometer. Typical Vibration Rectification Error of 100µg/g²rms and scale factor linearity less than 0.1% of full 30g dynamic range are presented.

Keywords—MEMS accelerometer, open loop, closed loop, tactical grade, dynamic range

I. INTRODUCTION

Over the past decades, Micro-Electro-Mechanical Systems (MEMS) accelerometer has made tremendous advancements in airbag deployment and automotive pressure sensing. Additionally, it has found opportunities in many other areas of motion sensing which require the measurement of acceleration, vibration, shock, tilt, rotation etc. For example, in low-g applications micro-accelerometers can be found in pace makers [1] and robot-assisted surgeries [2]; in high-g applications they are commonly used in Inertial Measurement Units (IMUs) for Inertial Navigation Systems (INS) [3]. The mechanism of a micro-accelerometer, based on capacitive sensing principle, has advantages of low cost manufacturing and easy integration with microelectronics. On the other hand the high impedance readout node for capacitive sensing is one of the key challenges in the design of the interface circuit. The readout node is highly susceptible to parasitic, leakage current and electromagnetic interference. Therefore, the design of the interface circuit cannot be done without consideration on the sensor and the packaging specifications. Differently from the widely used out-of-plane fabrication technique in bulk micromachining for capacitive accelerometers, the in-plane approach allows utilization of full bridge capacitive sensing configuration for parasitic rejection and improved noise performance. Additionally, in plane design enables improved linearity due to utilizing capacitor area changing concept. [4]. A large proof mass, which is realized in SOI wafer handle layer, contributes to enhanced sensitivity.

We first present the MAXL-OL-2000 open loop series, enclosed in LCC20 package with a proprietary ASIC. This 18 bit resolution accelerometers' series is offered with dynamic ranges from 2g to 40g.

Although the open loop MEMS accelerometers meet the classification of tactical grade, a concept change was needed to overcome inherent non-linearity and further improve bias stability performance.

We secondly present our closed loop MAXL-CL-3030 ΔΣ MEMS accelerometer which provides improved performance, such as scale factor linearity, bias stability and vibration rectification. The MAXL-CL-3030, with 30g dynamic range and 20bit resolution, is a fully integrated sensor enclosed in a specially designed and manufactured LCC44 package.

Physical Logic initiated 2 parallel projects on the development of both open loop and closed loop capacitive MEMS accelerometers. The objective was to achieve tactical grade performance with the open loop accelerometer and inertial navigation grade performance with the closed loop accelerometer. A unique design which enables identical MEMS device fabrication process flow for both products contributed to fast and efficient progress of both projects. A robust process ensures high yield and high reliability. Fig. 1 shows a photo of both open loop and closed loop accelerometers prior to cover sealing.

Fig. 1: Photos of closed loop and open loop accelerometer before cover sealing.
II. HIGH DYNAMIC RANGE OPEN LOOP MEMS ACCELEROMETER

A. In Plane Bulk micromachining

Physical Logic's accelerometers are uniquely designed using In-plane Bulk Micromachining Technology to achieve higher performance than out of plane designed sensors:

- Improved reliability and process simplicity – no need for vacuum packaging. (Out-of-plane sensors need vacuum packaging since squeeze film damping of large parallel plate electrodes is very severe in out-of-plane configuration)
- Improved linearity performance due to capacitance area-changing architecture. (Out-of-plane sensors use the gap-changing principle)
- Improved performance during vibrations
- Full bridge capacitance sensing architecture for parasitic rejection and improved noise performance (For out-of-plane devices this is very challenging)

A scheme of In-plane bulk micromachining is presented in Fig. 2. Both open loop and closed loop structures include an array of capacitive electrode plates, mechanically coupled to a common proof mass (the rotor shown in picture A) and an array of the same electrode plates attached to the fixed silicon frame (the stator). A careful design of the supporting springs constrains the proof mass to linearly move in the plane parallel to the plane of the fixed electrode plates. The capacitance between the two arrays of plates is variable and dependent on the proof mass displacement.

![Fig. 2: Scheme of in-plane bulk micromachining](image)

B. Performance - Temperature sensitivity

Our MAXL-OL-2000 MEMS accelerometers go through acceptance test procedure (ATP), performed on 100% of the assembled accelerometers. Prior to the ATP all accelerometers pass Environmental Stress Screening (ESS) which includes multiple temperature cycles & Z direction random vibration, perpendicular to the sensing direction. The ATP includes both static and dynamic tests at room temperature and under temperature cycles. Temperature hysteresis is measured at a certain point where the largest measurement difference between heating and cooling cycles occurs.

Statistical analysis shows that 90% of accelerometers results with 1st order dependency of bias to temperature. 10% of accelerometers results with 2nd order bias to temperature dependence. While typical temperature sensitivity of 200µg/°C features MAXL-OL-2040 accelerometers (40g dynamic range), an order of magnitude lower sensitivity is achieved in MAXL-OL-2020 accelerometers (20g dynamic range), as is shown in Fig. 4. Fig. 4 shows also the excellent bias stability over 10 continuous temperature cycles between -40°C to 85°C @ dT/dt of 1°C/min. On both accelerometers types typical hysteresis results are between 0.5 – 1.5 mg.

![Fig. 3: MAXL-OL-2040 open loop accelerometer temperature sensitivity and hysteresis plot under 3 temperature cycles between -40°C to 85°C @ dT/dt of 1°C/min.](image)

![Fig. 4: MAXL-OL-2020 open loop accelerometer temperature sensitivity and hysteresis plot under 10 temperature cycles between -40°C to 85°C @ dT/dt of 1°C/min.](image)

C. Bias Repeatability

Acceptance test procedure includes two repeatability tests. One tests the repeatability ten Turn On to Turn Off (TOTO) cycles. The other tests the repeatability during the whole acceptance test procedure.

Fig. 5 and Fig. 6 are copies of statistical data monitoring, collected from ATP of MAXL-OL-2020 accelerometers.
The figures show typical TOTO repeatability of 70µg and typical overall repeatability of 1mg for the last 2 production batches (Batch B and Batch C).

III. HIGH DYNAMIC RANGE CLOSED LOOP MEMS ACCELEROMETER

A. architecture

Fig. 7 shows the system block diagram of the MAXL-CL-3030 high-order ΔΣ MEMS accelerometer. The key blocks on the diagram are: an analog front-end (AFE) block to perform capacitance-to-voltage conversion, an N-bit analog-to-digital converter (ADC), a digital electronic filter block to perform ΔΣ modulation and phase compensation, and a feedback driver block to generate the rebalance force on the proof mass.

From Fig. 7, the capacitive MEMS sensor is displaced from its equilibrium position when it experiences an external acceleration. This results in a corresponding capacitance change in the sensor which is converted and amplified into a voltage signal via the AFE block. The amplified analog signal is oversampled and converted into digital signal by the ADC block, and then passed to the digital electronic filter block for further signal processing. After the digital ΔΣ modulation and phase compensation, a single-bit bit-stream is generated and applied as a feedback to the sensor through the driver blocks. The feedback control signal restores the MEMS sensor back to its equilibrium position, minimizing the mechanical displacement of the proof mass. The described concept makes possible a significant improvement in the linearity and vibration rectification of the sensor.

To ensure an effective shaping of the quantization noise created by the single-bit comparator, 4-th order ΔΣ modulation was implemented. However, it increased susceptibility to stability issues as additional poles and zeros were introduced into the control system. A careful system design was performed prior fabrication to ensure stable closed loop. The concept of mixed signal ASIC was adopted to enable more flexibility in the choice of control parameters and improve their preciseness [5].

B. Dynamic range

Fig. 8 shows 30g dynamic range design confirmation on MAXL-CL-3030 closed loop accelerometer. Accelerometers were mounted on vibration table and a sine acceleration of 100Hz constant frequency was applied. The acceleration amplitude was increased by 5g every 30 seconds from 5g to 30g. The figure shows bias during the vibration, marked in blue and the vibration amplitude, marked in red.
C. Vibration Retrification and Scale Factor Linearity

The main reason for choosing the close loop concept is to get improved performance under vibration and scale factor linearity. Fig. 7 shows vibration rectification during applying 5g sine sweep acceleration on 10 MAXL-CL-3030 closed loop accelerometer.

The plot demonstrates the average of 100µg/g²rms Vibration Rectification Error (VRE) over 20 – 2000Hz frequency range.

![RE vs Frequency during 5g sine sweep (10 devices)](image)

Fig. 9: Rectification error versus frequency of ten MAXL-CL-3030 closed loop accelerometers.

Fig. 7 shows scale factor linearity performance of MAXL-CL-3030 accelerometer, tested on precise centrifuge with increasing acceleration steps up to 30g. A linear approximation based on 0g and 1g points was applied. The figure shows that in both directions the acceleration error is way under 0.1% of the applied acceleration (marked in red lines) at each of the monitored points.

![Centrifuge acceleration vs. Acceleration error (g)](image)

Fig. 10: Centrifuge test on MAXL-CL-3030 closed loop accelerometer: acceleration on both clockwise and counterclockwise directions from 0 to 30g.

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