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Data Analyses of Structural Parameters Impacting the Sensing Characteristics of Single-axis Accelerometers

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In this study, we utilized COMSOL Multiphysics® (version 6.0) finite element software to conduct simulations on accelerometers with varying structural parameters. The data analyses of structural parameters considered included accelerations of 25, 50, and 75 g, and variations in the thicknesses of the mass block, electrodes (both movable and external fixed comb electrodes), and spring elements, ranging from 0.5 to 10 μm. Our analysis focused on evaluating the impacts of these parameter changes on several key metrics: sense voltages, displacements, and maximum von Mises stresses within the accelerometer structure. By systematically altering acceleration levels and the geometrical dimensions of the accelerometer components, we aimed to discern how these variations affect the device performance characteristics. This approach enabled us to gain insights into the structural behavior of the accelerometers under different operational conditions and provided valuable data for optimizing their design and functionality in practical applications. The results obtained from these simulations contribute to advancing the understanding and development of high-performance accelerometer technologies.

1. Introduction

An accelerometer is a device used to measure acceleration. Accelerometers detect changes in the acceleration of objects, which can be used to infer motion states and changes in position. They find extensive applications across various fields including smartphones, sports tracking devices, automobiles, aircraft, and industrial machinery. Accelerometers function by measuring the acceleration experienced by an object along a specific axis or multiple axes. They typically consist of movable components such as movable comb electrodes and fixed components like external fixed comb electrodes. These electrodes form capacitive sensing elements that change capacitance with acceleration-induced movement, allowing the precise measurement of acceleration. The key functionalities and applications of accelerometers include the following:

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1. Motion detection: Accelerometers detect changes in the direction and speed of motion, crucial for applications like motion tracking devices and smartphones. For instance, they capture rotations or movements during physical activities or when the device is repositioned.(1)
2. Stabilization and navigation: In aircraft and vehicles, accelerometers provide stability and navigation information. For example, in autonomous vehicles, they detect changes in road conditions and adjust accordingly.(2)
3. Safety applications: In automobiles, accelerometers detect collision events and trigger safety mechanisms like the deployment of airbags. Additionally, in smartphones, they detect falls to protect internal components.(3)
4. Health and medical applications: Accelerometers in wearable devices monitor users' activity levels, sleep quality, and other health metrics, providing valuable data for healthcare and medical applications.(4)

The design and selection of accelerometer components, including movable comb and fixed electrodes, directly impact their sensitivity, accuracy, and durability. Accelerometers can be categorized into several main types on the basis of their operational principles, including capacitive, piezoelectric, and piezoresistive types. Each type of accelerometer has distinct characteristics and applications. Capacitive single-axis accelerometers are devices that measure acceleration on the basis of changes in capacitance. Their operation involves several key components:

1. Proof mass: Inside capacitive accelerometers, there is a freely moving mass known as the proof mass. When acceleration acts on the accelerometer, the proof mass moves according to the direction and magnitude of the acceleration.(5)
2. Fixed and movable electrodes: The proof mass forms a capacitor with electrodes fixed on the substrate. As the proof mass moves, the capacitance of the capacitor changes. These electrodes typically appear in pairs to measure the displacement of the proof mass along a single axis.(6)
3. Components for the measurement of capacitance changes: Greater acceleration results in a larger displacement of the proof mass and greater changes in capacitance. The variation in capacitance is converted into a voltage signal, which is further processed into a digital signal.(7)
4. Signal processing circuitry: Signals resulting from capacitance changes are amplified and converted by a signal processing circuitry for data reading and analysis. Such a circuitry typically includes oscillators, amplifiers, and analog-to-digital converters (ADCs).(8)

Capacitive single-axis accelerometers are utilized in various applications where the precise measurement of acceleration along a single axis is required. Their design and performance are critical in applications such as motion sensing in consumer electronics, inertial navigation systems in aerospace, and vibration monitoring in industrial machinery. Understanding the operational principles and components of these accelerometers is essential for optimizing their performance in specific use cases. The operational process of a capacitive single-axis accelerometer when acceleration occurs is as follows. The mass block shifts in the direction of acceleration, altering the distance between the mass block and the fixed electrode, thereby changing the capacitance. Capacitance changes are measured and converted into corresponding voltage signals. Subsequently, the voltage signals undergo amplification and conversion processes, ultimately generating digital signals proportional to the acceleration. Capacitive single-axis accelerometers offer several advantages: they are highly sensitive and capable of accurately measuring small displacements and accelerations; they operate at low power compared with other accelerometer types; and they exhibit high stability and reliability over extended periods.

Capacitive single-axis accelerometers find widespread use in applications requiring the precise measurement of acceleration in a single direction, such as in smartphones, gaming controllers, automotive safety systems, medical devices, and industrial control systems. In capacitive single-axis accelerometers, adjustments of the thicknesses of the mass block and sensing electrodes (movable comb electrodes) or fixed electrodes can significantly impact their sensing performance. The effect of varying the thicknesses of the mass block and sensing electrode in sensor design can be described as follows. Increasing the thickness of the mass block results in greater mass, thereby increasing the displacement of the mass block under the same acceleration, which can enhance the sensitivity of the designed accelerometer.

Moreover, increasing the thickness of the sensing electrode enlarges the surface area between electrodes, thereby improving structural strength and enhancing sensitivity to changes in capacitance. This means that changes in capacitance due to mass block movement become more pronounced.

However, thicker sensing electrodes also increase the initial capacitance, which may affect the measurement range and linearity. When considering the combined effects of varying the mass block thickness while keeping the electrode thickness constant, increasing the mass block thickness enhances sensor sensitivity and structural strength but increases system inertia, affecting high-frequency responses.(9,10) Conversely, increasing the thicknesses of fixed electrodes increases the surface area between electrodes, improving sensitivity to capacitance changes and signal strength. Additionally, thicker fixed electrodes contribute to measurement stability by reducing the impact of external interference and noise. Previous studies have rarely addressed the simultaneous effects of varying the thicknesses of the mass block and electrode on the characteristics of capacitive single-axis accelerometers. Therefore, in this study, we used Comsol (version 6.0) software as a simulation tool to simultaneously vary the thicknesses of the mass block and electrodes, including the sensing electrodes (movable comb electrodes) and fixed electrodes (external fixed comb electrodes), to investigate how these data analyses impact the effects of structural parameters on the induction characteristics.

2. Simulation Parameters

This type of accelerometer can be further classified into two main types: accelerometers that measure the lateral displacement and those that measure the vertical displacement. In this study, the ADXL150 single-axis differential capacitive bridge accelerometer served as the prototype, utilizing electrode displacement detection for sensing purposes.(11) Figures 1 and 2 illustrate the structure of the simulated model proposed in this study. This model incorporates variations in the thicknesses of both the mass block and the electrode, consisting of movable comb electrodes

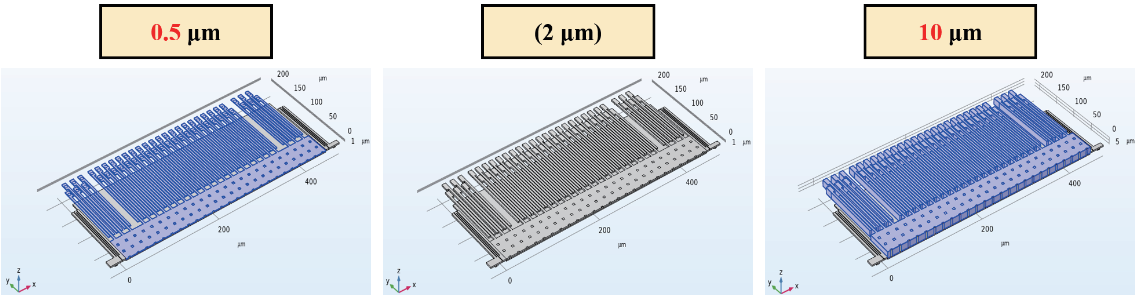

Fig. 1. (Color online) Schematic diagrams of simulated model with thicknesses of the movable and external fixed comb electrodes changing from 1 to 10 µm.

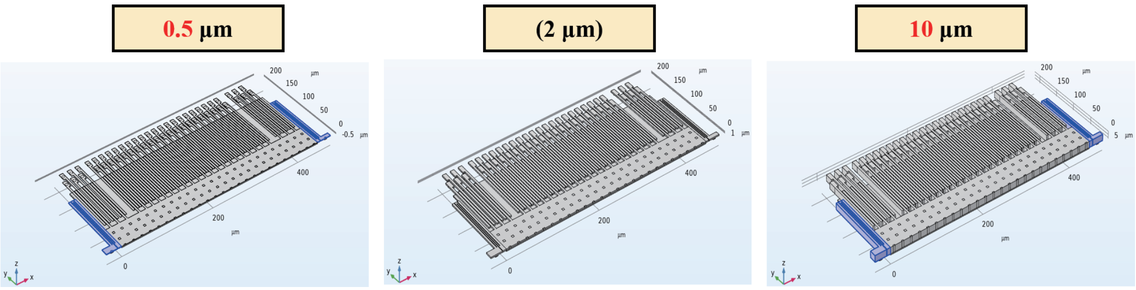

Fig. 2. (Color online) Schematic diagrams of the simulated model with spring thickness changing from 1 to 10 µm.

for sensing and external fixed comb electrodes. Because of the accelerometer's symmetric structure, computational efficiency is enhanced by analyzing only half of the model. Figure 1 illustrates the simultaneous alteration of the thicknesses of the mass block and electrodes, focusing on two critical components: the movable and external fixed comb electrodes. The thicknesses of the mass block and electrode of the standard-structure ADXL150 single-axis differential capacitive bridge accelerometer are both 2 µm. In this study, the thicknesses of these structural components are varied from 1 to 10 µm. These modifications could impact various aspects of the device, including its sensitivity, response speed, and overall performance. Investigating the effects of these thickness variations is essential for optimizing the design, thereby enhancing the device's functionality and reliability.

The precise control and measurement of thickness variations are necessary to ensure the accuracy and consistency of results. Furthermore, such variations may affect the mechanical and electrical properties of the device. Therefore, meticulous data recording and analysis during the experimental process are crucial to drawing reliable conclusions. This thorough examination helps in understanding the interplay between the structural modifications and the device performance, paving the way for improved and robust designs. The spring thickness of the standard-structure ADXL150 single-axis differential capacitive bridge accelerometer is also 2 µm. Figure 2 also shows the structural parameters for changing the spring thickness ranging from 1 to 10 µm. Once the parameters to be changed were confirmed, we used Comsol (version 6.0) directly for modeling. Subsequently, we used this finite element method (FEM) software to simulate the data analyses of different structural parameters. The simulations included sense voltage (mV), displacement (μm), and maximum von Mises stress (10^6 N/m²) at different thicknesses of the movable and external fixed comb electrodes, and the spring.

3. Workshop Production Planning Simulation Modeling

As shown in Fig. 3(a) and Table 1, when specific accelerations are applied, increasing the thicknesses of electrodes and mass blocks results in a corresponding increase in the range of sensed voltages and significantly expands the sensing range. At an acceleration of 25 g, for instance, increasing the electrode thickness from 0.5 to 10 μm increases the sensed voltage from 10.842 to 214.98 mV. Similarly, at 75 *g* acceleration, increasing the electrode thickness from 0.5 to 10 μm increases the sensed voltage from 18.941 to 697.66 mV. As shown in Fig. 3(a) and Table 1, increasing the thickness of the intermediate sensing electrodes leads to a substantial increase in maximum stress on both sides of the spring, thereby necessitating an increase in spring thickness for testing the sensing results. As depicted in Fig. 3(b) and Table 2, when specific accelerations are applied, increasing the thickness of the spring results in a corresponding increase in the range of sensed voltages, although the magnitude of the increase is not substantial. For instance, at 25 *g* acceleration, increasing the spring thickness from 0.5 to 10 μm increases the sensed voltage from 4.6963 to 40.539 mV. Similarly, at 75 *g* acceleration, increasing the spring thickness from 0.5 to 10 μm increases the sensed voltage from 36.615 to 130.32 mV. As shown in Fig. 3(b) and Table 2, after the spring thickness exceeds 3.5 μm, the upward trend in sensing voltage gradually levels off.

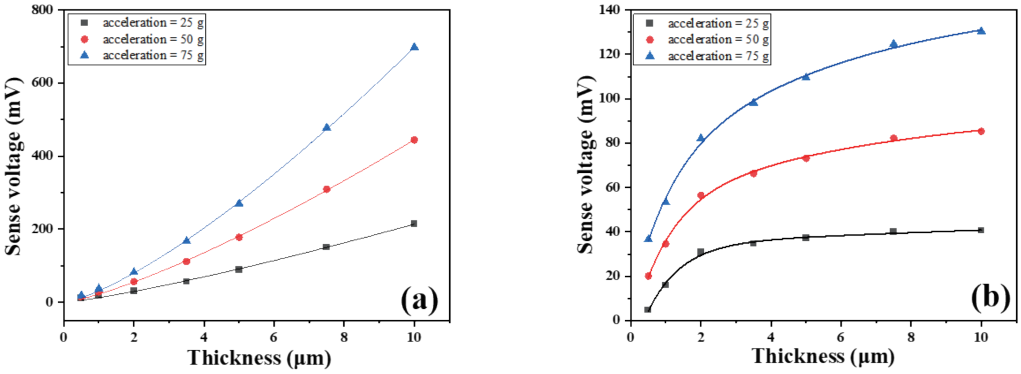

Fig. 3. (Color online) Effects of (a) thicknesses of electrodes and mass block and (b) thickness of spring on sensing voltages.

Table 1
Effect of thicknesses of movable comb electrodes (as well as fixed electrodes) on sense voltage.

Acceleration (g)	Sense voltages (mV) at different electrode thicknesses		
	0.5 μm	2 μm	10 μm
25	10.842	30.922	214.98
50	14.89	56.456	444.44
75	18.941	82.159	697.66
Sense voltage range	8.099	51.237	482.68

Table 2
Effect of thickness of spring on sense voltage.

Acceleration (*g*)	Sense voltages (mV) at different spring thicknesses		
	0.5 μm	2 μm	10 μm
25	4.6963	30.922	40.539
50	20.067	56.456	85.335
75	36.615	82.159	130.32
Sense voltage range	31.9187	51.237	89.781

Thus, while electrode thickness significantly affects the performance of capacitive accelerometers, the thickness of the spring does not have a substantial impact. These observations can assist engineers in making informed choices and adjustments during the design and application phases. These results also highlight several significant observations:

1. Relationship between sensed voltage and electrode thickness: Increasing electrode thickness leads to higher sensed voltages. This is because the larger electrode area increases capacitance, thereby affecting the magnitude of the sensed voltage.
2. Considerations of accuracy and sensitivity: With increased electrode thickness, the sensed voltage range of the accelerometer also expands. This enhances the accelerometer sensitivity, enabling a more precise detection and measurement of acceleration changes.
3. Engineering applications and design choices: When designing and selecting accelerometers, engineers need to consider the impact of electrode thickness on sensing performance. Choosing an appropriate electrode thickness enables the adjustment of sensing range and sensitivity according to application requirements, optimizing overall performance. Thus, electrode thickness significantly affects the performance of capacitive accelerometers.

As depicted in Fig. 4(a) and summarized in Table 3, the application of specific accelerations shows that increasing the thicknesses of electrodes and mass blocks correlates with greater displacements. For instance, at an acceleration of 25 *g*, increasing the electrode thickness from 0.5 to 2 and 10 μm results in displacements from 0.0098 to 0.0342 and 0.1643 μm, respectively. Similarly, at 75 *g* acceleration, increasing the electrode thickness from 0.5 to 10 μm increases displacement from 0.0294 to 0.4929 μm. These findings illustrate that thicker electrodes lead to a higher overall structural mass, which consequently increases the displacement under acceleration. Furthermore, from the results presented in Fig. 4(b) and detailed in Table 4, when considering the thickness of the spring, it was observed that thicker springs correspond to a reduced displacement. This reduction in displacement is a significant factor contributing to the decrease in sensing voltage.

Increasing the thickness of the spring in a capacitive single-axis accelerometer results in a slight reduction in displacement and significantly decreases the sensing voltage primarily owing to the increased stiffness of the spring. In such accelerometers, the spring plays a crucial role in supporting mass and reflecting acceleration. When the spring becomes thicker or stiffer, its elastic modulus increases, thereby reducing the displacement generated under the same acceleration conditions. Specifically, the increased stiffness of the spring diminishes its responsiveness to external forces. Consequently, when acceleration acts upon the accelerometer, the spring no longer produces the same extent of displacement as softer or thinner springs

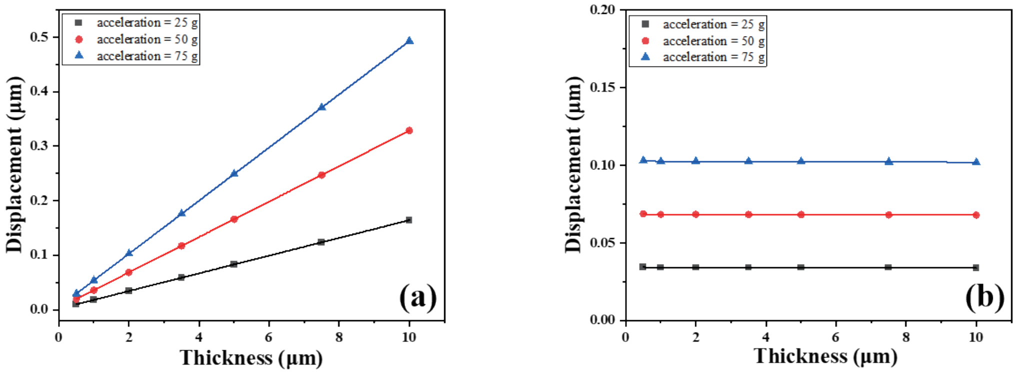

Fig. 4. (Color online) Effects of (a) thicknesses of electrodes and mass block and (b) thickness of spring on displacement.

Table 3
Effect of thicknesses of movable comb electrodes (as well as fixed electrodes) on displacement.

Acceleration (*g*)	Displacements (μm) at different thicknesses		
	0.5 μm	2 μm	10 μm
25	0.0098	0.0342	0.1643
50	0.0196	0.0684	0.3286
75	0.0294	0.1026	0.4929
Displacement range	0.0196	0.0684	0.3286
Weight (10^{-7} g)	1.046	3.483	16.175

Table 4
Effect of thickness of spring on displacement.

Acceleration (*g*)	Displacements (μm) at different thicknesses		
	0.5 μm	2 μm	10 μm
25	0.0344	0.0342	0.0339
50	0.0688	0.0684	0.0679
75	0.1031	0.1026	0.1018
Displacement range	0.0687	0.0684	0.0679
Weight (10^{-7} g)	0.914	3.483	17.185

would. As a result, the mechanical displacement of the sensor decreases, leading to a marked reduction in sensing voltage. The main reason for the decreases in displacement and sensing voltage when increasing the spring thickness is the higher stiffness of the spring, which limits its deflection in response to applied acceleration in the accelerometer.

Figure 5(a) and Table 5 show the effect of different thicknesses of electrodes on the maximum von Mises stress. Accelerations of 25, 50, and 75 *g* were applied with the thicknesses of the mass block and electrodes ranging from 0.5 to 10 μm. As shown in Fig. 5(a) and Table 5, increasing the thicknesses of electrodes and mass block results in a proportional increase in maximum von Mises stress. For instance, at an acceleration of 25 *g*, increasing the thickness from 0.5 to 10 μm led to the maximum von Mises stress increasing from 0.0264×10^6 to 4.745×10^6 N/m^2.

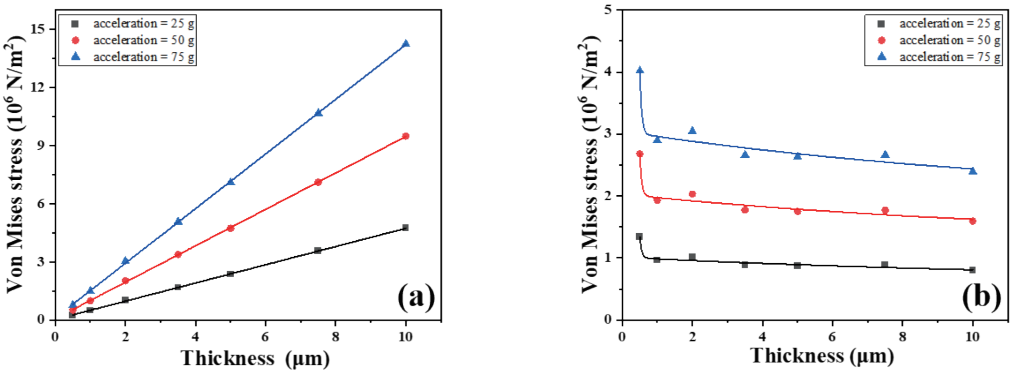

Fig. 5. (Color online) Effects of (a) thicknesses of electrodes and mass block and (b) thickness of spring on maximum von Mises stress.

Table 5
Effect of thicknesses of movable comb electrodes (as well as fixed electrodes) on maximum von Mises stress.

Acceleration (*g*)	Maximum von Mises stresses (10^6 N/m^2) at different thicknesses		
	0.5 μm	2 μm	10 μm
25	0.2604	1.016	4.745
50	0.5207	2.032	9.49
75	0.781	3.047	14.24
Maximum von Mises stress range	0.5206	2.031	9.495

Table 6
Effect of thicknesses of spring on maximum von Mises stress.

Acceleration (*g*)	Maximum von Mises stresses (10^6 N/m^2) at different thicknesses		
	0.5 μm	2 μm	10 μm
25	1.34	1.016	0.7978
50	2.679	2.032	1.596
75	4.019	3.047	2.393
Maximum von Mises stress range	2.679	2.031	1.5952

Similarly, at 50 and 75 *g* accelerations, increasing electrode thicknesses from 0.5 to 10 μm linearly increased the maximum von Mises stress. This is primarily because thicker electrodes and mass blocks increase the overall structure mass, resulting in a greater displacement and consequently more stress on the spring. Similarly, Fig. 5(b) and Table 6 show the impact of different thicknesses of springs on the maximum von Mises stress. Regardless of the acceleration, increasing the thickness of a spring from 0.5 to 1 μm rapidly reduced the maximum von Mises stress. However, as the thickness increases from 1 to 10 μm, the reduction in maximum von Mises stress slowed down linearly. Thicker springs increase the mass of the overall structure but reduce displacement, resulting in less stress on the spring.

4. Conclusions

In a capacitive single-axis accelerometer, we discovered that the electrode thickness significantly affected the performance of capacitive accelerometers. Increasing the electrode thickness resulted in larger electrode area and capacitance, leading to higher sensed voltage. This expansion in electrode thickness also broadened the sensed voltage range of the accelerometer, enhancing its sensitivity for a more accurate detection and measurement of acceleration changes. Increasing the thickness of the spring led to decreases in displacement and sensing voltage. Such decreases can be attributed to the higher stiffness of the spring, which limits its deflection in response to applied acceleration within the accelerometer. The increased spring thickness resulted in a slight decrease in displacement and a significant reduction in sensing voltage, primarily due to the heightened stiffness of the spring. Increasing the thicknesses of electrodes and mass blocks led to a proportional increase in maximum von Mises stress. Specifically, increasing the spring thickness from 0.5 to 1 μm resulted in a rapid reduction in maximum von Mises stress. However, as the thickness continued to increase from 1 to 10 μm, the reduction in maximum von Mises stress slowed down linearly. By selecting the right electrode thickness, adjustments to the sensing range and sensitivity could be made to meet specific application needs.

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