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Using COMSOL to Simulate the Effects of Different Parameters on the Sense Characteristics of Capacitive Single-axis Accelerometers

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In this study, we employed the finite element software COMSOL Multiphysics® (version 6.0) as a simulation tool to analyze the characteristics of accelerometers with different structures. The initial investigation centered around the 114 μm movable comb electrodes of the ADXL150 accelerometer, known for its single-axis differential capacitive bridge design. These electrodes were chosen as the baseline for our study. Our main goal was to examine how alterations in both the length of the movable comb electrodes and the acceleration rates affect the sensing voltage and displacement of the accelerometers. In this investigation, we aimed to provide a comprehensive understanding of the interplay between electrode length variations and acceleration rates on accelerometer performance. At the outset, our aim was to investigate how varying the length of the electrodes would affect the performance of the accelerometer. We methodically decreased the length of the movable comb electrodes from 114 to 20 μm and increased them from 114 to 129 μm. This range of electrode lengths allowed us to observe and analyze the corresponding variations in sensing voltages across different acceleration rates, namely, 25*g*, 50*g*, and 75*g*. Also, the displacements and von Mises stresses under these different acceleration rates and with lengths of the moveable comb electrodes were also investigated in this study.

1. Introduction

As technology advances, the scope of “manufacturing” expands beyond automated production alone. Whether it is detecting anomalies in equipment, predicting component lifespan, or integrating machine tool networking, sensors have become increasingly indispensable. For instance, to understand why there are abnormal vibrations during machining processes, accelerometer measurements are essential for analyzing vibration signals. Similarly,

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to comprehend the impact of temperature changes on machine tool thermal deformation, data from displacement and temperature sensors are crucial for constructing thermal displacement error models. Indeed, accelerometers are highly practical and versatile sensors, making them well suited to meet these requirements.[1–3] A plethora of accelerometer sensors exist, each tailored primarily to the vibration characteristics of the object under test, resulting in varied specifications. However, it is important to note that simply opting for high-quality sensors does not automatically ensure excellent signal quality in measurement data. Selecting the appropriate sensor for measuring vibrations depends on whether the user has sufficient understanding of the signal characteristics generated by the object under test and whether they can effectively assess the potential impact of the measurement environment in advance.

Accelerometer are of three distinct types: piezoresistive, thermal bubble, and capacitive. Piezoresistive accelerometers operate on the basis of the principle of the piezoresistive effect, where the material's resistance changes in response to pressure variations.[4,5] Piezoelectric accelerometers are made from ceramic materials that exhibit piezoelectric effects. They offer superior characteristics such as low sensing noise, wide effective bandwidth, and high linearity, making them suitable for precise vibration measurements. The manufacturing technology for commercial piezoelectric accelerometers is highly developed, with well-known manufacturers such as PCB, Kistler, and Endevco offering extensive product lines.[6] For instance, sensors with a broad measurable range and high effective bandwidth are well suited for monitoring rotating machinery, while accelerometers featuring low bandwidth yet high resolution are optimal for monitoring ground vibrations or bridge oscillations.[7]

Conversely, hot-wire accelerometers operate mainly on the principle of the thermal expansion effect. The main principle behind a hot-wire accelerometer involves utilizing this effect. In a hot -wire accelerometer, a thin wire is heated to a constant temperature.[8] When subjected to acceleration, the mass block attached to the wire moves, causing a change in the wire's tension and consequently altering its resistance. This change in resistance is then measured and correlated with the applied acceleration. A capacitive accelerometer operates on the principle of capacitive variation. As acceleration changes, so does the capacitance within the sensor. Capacitive accelerometers primarily utilize silicon chips as their main material. Through microelectromechanical system (MEMS) processes, these chips are etched into gate or comblike structures. The variation in capacitance resulting from the movement within the gaps serves as the basis for vibration measurement sensors. In recent years, with the proliferation of IoT, commercially available capacitive accelerometers have become more accessible and affordable. However, compared with piezoelectric accelerometers, most of them exhibit slightly inferior vibration performance.

Therefore, they are more suitable for applications with less stringent accuracy requirements. Examples include gravity sensors (G sensors) for flipping smartphone screens[9] and collision sensors for vehicle safety airbags.[10] A capacitive accelerometer utilizes changes in capacitance to detect acceleration. Its basic structure consists of a fixed stationary plate electrode and a movable plate electrode connected by an elastic support structure. Hence, the structure of a capacitive accelerometer considerably affects its characteristics, with several key factors affecting its performance as follows:

1. Design of the elastic support structure: The design of the elastic support structure directly affects the sensitivity and frequency response of the capacitive accelerometer to acceleration. The support structure should possess sufficient flexibility and strength to generate adequate displacement under acceleration while maintaining sufficient rigidity to prevent excessive vibrations.
2. Electrode spacing and area: The design of electrode spacing and area directly affects capacitance variation, thereby affecting sensor sensitivity. Generally, a small electrode spacing and a large electrode spacing result in a large capacitance variation, thereby enhancing sensor sensitivity.
3. Material selection: The materials used in the sensor affect its mechanical and conductive properties, thereby affecting the sensitivity and stability of the capacitive accelerometer. For instance, selecting lightweight and highly elastic materials for electrodes and support structures can enhance the sensor's ability to detect small accelerations.
4. Packaging and protection: Packaging and protection designs safeguard the capacitive accelerometer from external environmental effects such as vibrations, temperature variations, and humidity, ensuring the stability and reliability of its performance.

Capacitive accelerometers are widely used in various applications such as mobile phones, motion tracking devices, and vehicle stability systems owing to their compact size and high sensitivity. Two common features for capacitive accelerometer sensing are the MEMS(11) and differential capacitive bridge.(12) When acceleration is applied to the device, the movable electrode undergoes displacement due to the effect of acceleration, thereby altering the capacitance. In this study, we primarily focused on investigating how structural variations affect the characteristics of a differential capacitive bridge accelerometer. The main structure of a differential capacitive bridge accelerometer consists of one or more movable electrodes and fixed electrodes, and acceleration causes changes in the distance or area between the electrodes.(13) Therefore, in this study, we employed simulation methods to investigate the impact of the electrode structure on the characteristics of a differential capacitive bridge accelerometer. The main focus was to explore the effects of varying electrode length, displacement (acceleration), and electrode thickness on sensing voltage (mV), displacement (μm), and von Mises stress (10^6/m^2).

2. Simulation Parameters

The differential capacitive bridge accelerometer detects changes in acceleration by measuring small changes in capacitance and converting them into voltage signals for processing and analysis, facilitating acceleration measurement. This type of accelerometer can be further categorized into two types: one can detect vertical displacements and the other lateral displacements. In this study, the ADXL150 single-axis differential capacitive bridge accelerometer was used as a prototype, which relied on the detection of displacements in the electrodes for sensing.(14) Figure 1 depict the structures of the simulation model. Owing to the symmetrical nature of the accelerometer structure, analysis can be performed on half of the

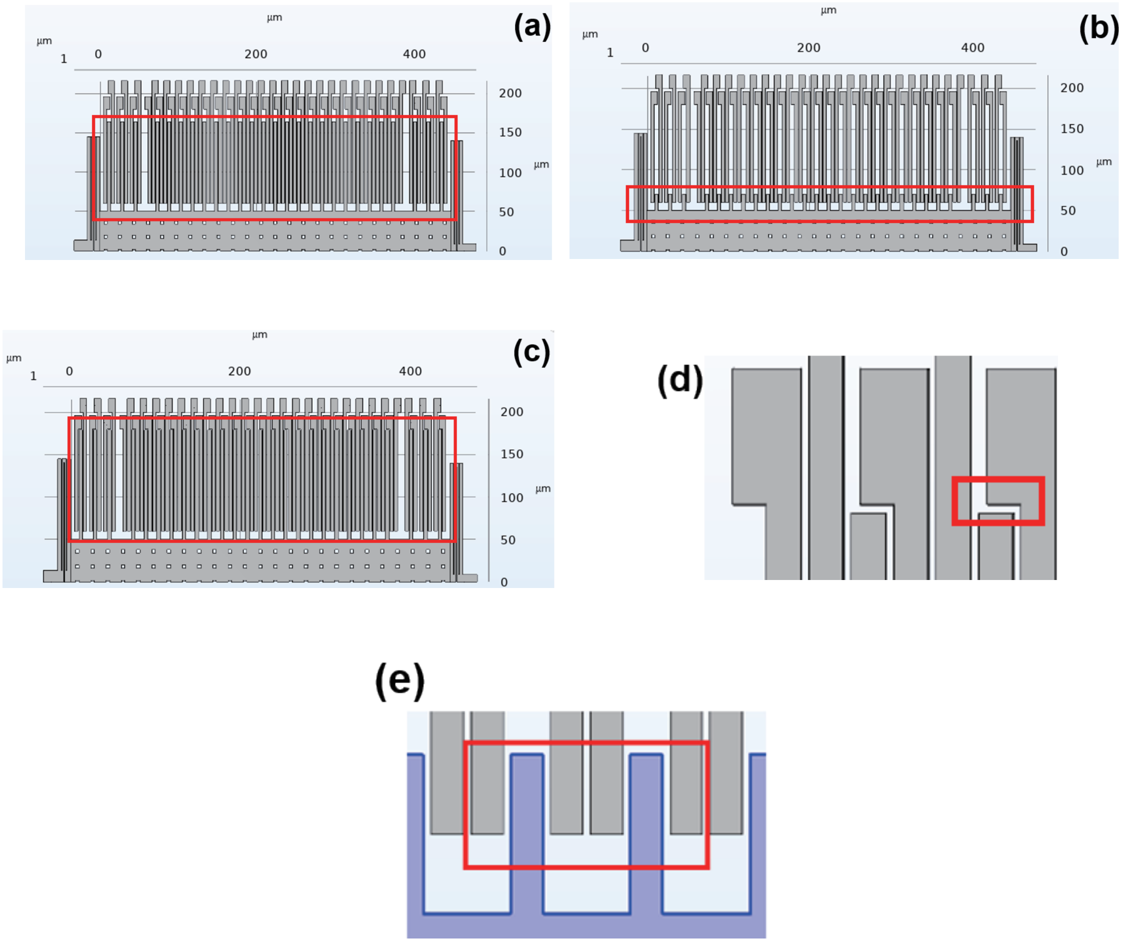

Fig. 1. (Color online) Lengths of the moveable comb electrodes of ADXL150 accelerometer: (a) 114, (b) 20, and (c) 129 µm. (d) Gap between the 129 µm moveable comb electrodes and external fixed comb electrodes and (e) moveable comb electrodes with 20 µm length.

model to save computation time. The initial length of the external fixed comb electrodes of the ADXL150 accelerometer was 114 µm, as depicted in Fig. 1(a). However, in the simulation process, they were either reduced to 20 µm, as shown in Fig. 1(b), or increased to 129 µm, as illustrated in Fig. 1(c). These two variations were not combined primarily owing to the differing rates of change for each. The originally external fixed comb electrode lengths could only be extended up to 129 µm at maximum, primarily owing to the risk of interference or contact with the internal comb array electrodes beyond that point, as Fig. 1(d) shows. This interference could potentially affect the test results. The moveable comb electrodes can only be reduced to a minimum length of 20 µm. If they are shorter than 20 µm, it becomes difficult to establish coupling characteristics with the internal comb array electrodes, as illustrated in Fig. 1(e).

3. Workshop Production Planning Simulation Modeling

As depicted in Fig. 2, it is evident that the sensing voltage exhibited a notable increase corresponding to the acceleration rate in the ADXL150 accelerometer, with the moveable comb electrode length set at 114 µm. Moreover, as the length of the moveable comb electrodes decreased from 114 to 20 µm, the sensing voltages decreased in a nearly linear fashion across three different acceleration levels. The sensing voltage decreased from 74.2, 49.8, and 25.5 mV to 20.1, 15.4, and 9.68 mV at the accelerations of 75*g*, 50*g*, and 25*g*, respectively. This decrease maintained consistency with the electrode length set at the 114 µm, demonstrating a nearly proportional relationship with the reduction in electrode length. However, when the length of the moveable comb electrodes was increased from 114 to 129 µm, the relationship was no longer linear once the electrode length exceeded 120 µm. The sensing voltages increased from 74.2, 49.8, and 25.5 mV to 97.5, 70.3, and 43.3 mV at the accelerations of 75*g*, 50*g*, and 25*g*, respectively. As observed, some of the sensing voltages exhibit an approximately exponential rise with acceleration in the ADXL150 accelerometer at the standard moveable comb electrode length of 114 µm. Figure 2 also demonstrates how the length of the moveable comb electrodes can affect the voltage generation and performance of a differential capacitive bridge accelerometer. The main factor at play is capacitance, as electrode length directly determines the sensing capacitance.

In general, capacitance is proportional to electrode area, and electrode length plays a crucial role in determining this area. Therefore, modifying the length of the electrodes could potentially alter the sensing capacitance, thereby affecting the generated voltage. Another important factor to consider is sensitivity; variations in length may impact the accelerometer's sensitivity. Longer electrodes may enhance the sensor's capability to perceive acceleration, as they can capture more variations. However, excessively long electrodes may also introduce noise interference, thereby reducing the sensor's accuracy. Moreover, Fig. 2 also clearly demonstrates that an increase in acceleration leads to a noticeable rise in the generated voltage of the differential capacitive bridge accelerometer. The primary reason for this phenomenon is that acceleration

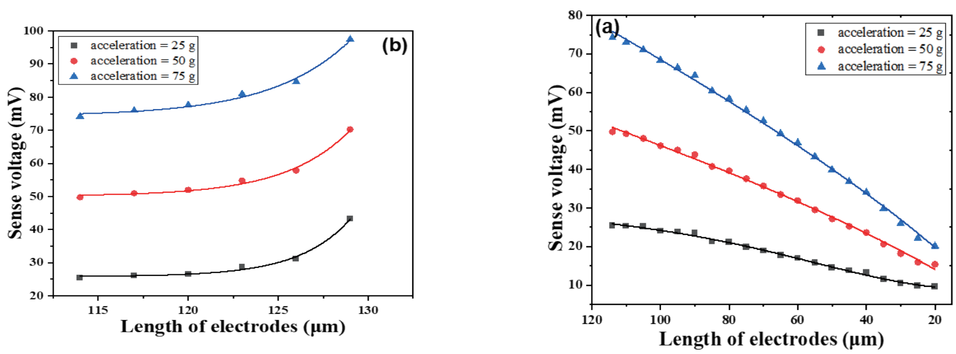

Fig. 2. (Color online) Variations of the sensing voltage at different acceleration rates as the length of the moveable comb electrodes is changed from 114 µm to (a) 20 µm and (b) 129 µm.

induces the movement of the mass block within the sensor, consequently altering the capacitance. As sensors are typically engineered to be sensitive to capacitance changes, this variation is directly reflected in the generated voltage. Therefore, when a greater acceleration is applied to the sensor, the strain leads to a larger and more rapid variation in capacitance over a short time.

To compute the displacement of a differential capacitive bridge accelerometer, the measurement primarily centers on a point at the bottom of the mass block of the moveable comb electrodes, as depicted in Fig. 3. Figure 4 illustrates that when the moveable comb electrodes are fixed, displacement proportionally increases with acceleration rate. Additionally, regardless of whether the moveable comb electrode length is reduced to 20 µm or increased to 129 µm, the displacement linearly increases with the length of the moveable comb electrodes. As the moveable comb electrode length decreased from 129 to 20 µm, the displacements decreased from 0.106, 0.0707, and 0.0354 µm to 0.0724, 0.0483, and 0.0241 µm at the accelerations of 75*g*, 50*g*, and 25*g*, respectively. This phenomenon can be explained through the operational principle of the sensor. When acceleration is applied to the sensor, the mass block experiences a force, resulting in its displacement. This displacement causes deformation in the internal structure of

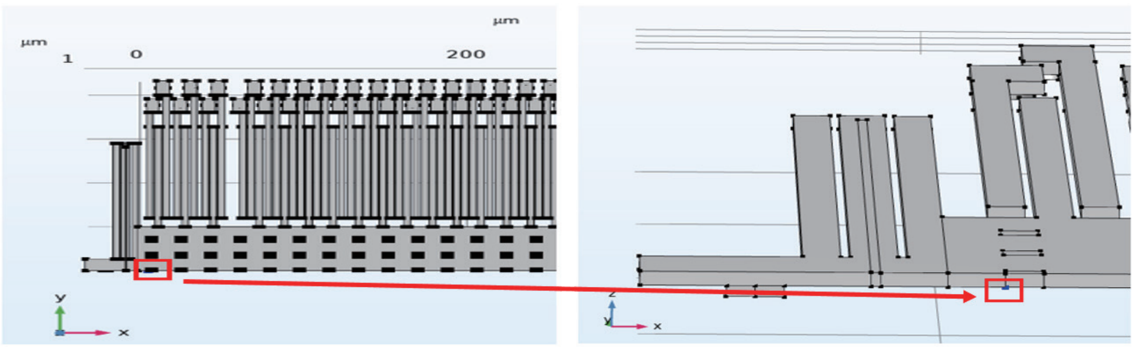

Fig. 3. (Color online) Structure shown to measure the displacement of a differential capacitive bridge accelerometer.

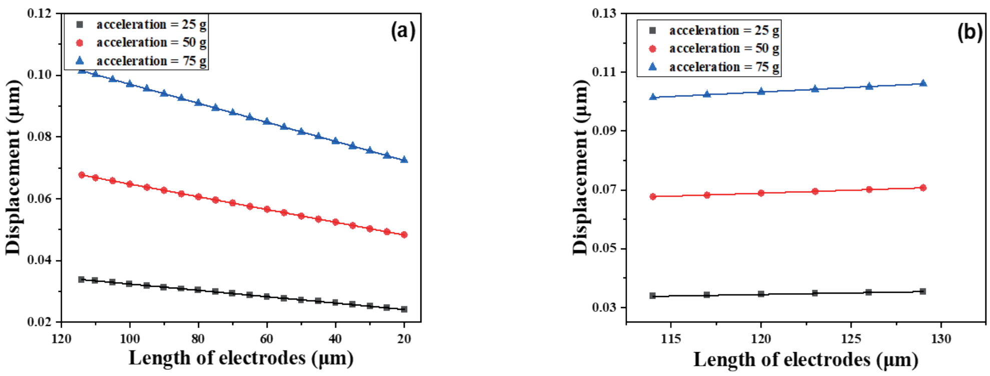

Fig. 4. (Color online) Variations of displacements at different acceleration rates as the length of the mass block is changed from 114 µm to (a) 20 µm and (b) 129 µm.

the sensor, leading to changes in the capacitance between sensing electrodes. With the increase in the length of the moveable comb electrodes, the range of displacement variations that can be captured also increases, thereby resulting in an increase in displacement measurement data. Specifically, longer electrvodes can effectively capture the displacement of the mass block. Moreover, as acceleration increases, a greater force acts on the mass block, resulting in a larger displacement. Consequently, the acceleration increase corresponds to higher displacement measurement data.

The von Mises stress method is widely used to evaluate stress levels in materials under multiaxial loading conditions. Figure 5 illustrates the location for presenting the maximum stress values, aiding engineers in assessing whether structures are susceptible to failure. In contrast, the differential capacitive bridge accelerometer is an instrument used for measuring acceleration, typically utilized to monitor structural vibrations and dynamic characteristics. Hence, when designing and employing a differential capacitive bridge accelerometer, it is essential to consider the distribution of von Mises stress in the structure to ensure that the performance and accuracy of the accelerometer are not compromised by stress concentration. This may involve optimizing the structural design, altering materials, or implementing additional support structures to mitigate the effects of stress concentration. This consideration is crucial because stress concentration near the accelerometer can lead to structural deformations, affecting the calibration and accuracy of the accelerometer, especially in applications requiring high precision and sensitivity. By assessing and addressing von Mises stress in the design and installation of differential capacitive bridge accelerometers, engineers can enhance their reliability and effectiveness in monitoring structural dynamics.

Figure 6 clearly illustrates why von Mises stress decreases with the decreases in the length of the moveable comb electrodes and the reduction of acceleration in the accelerometer. The main reasons for this phenomenon are as follows:

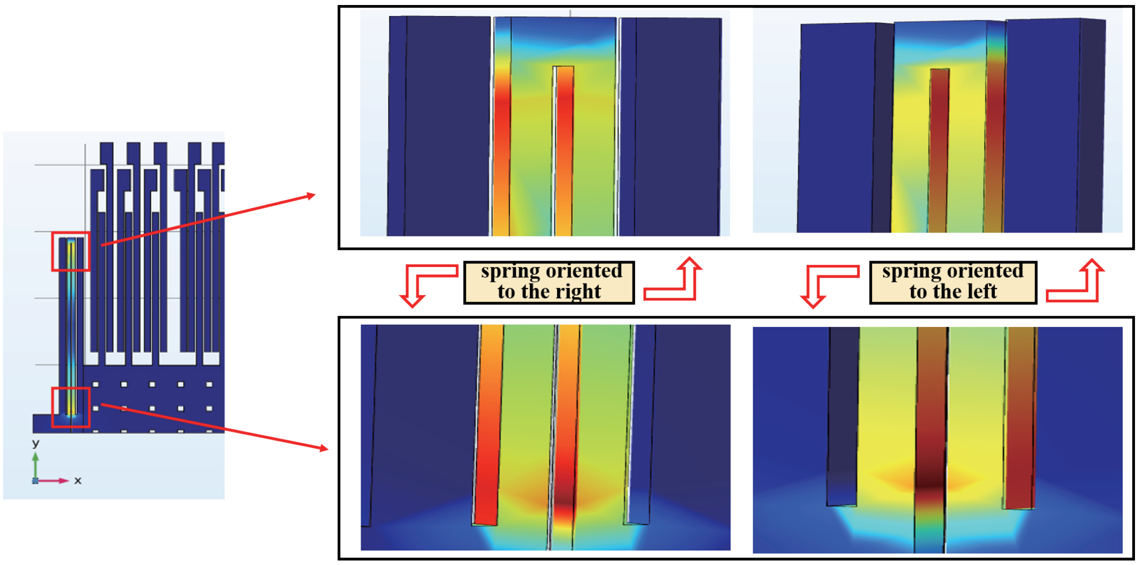

Fig. 5. (Color online) Location for presenting the maximum von Mises stress values.

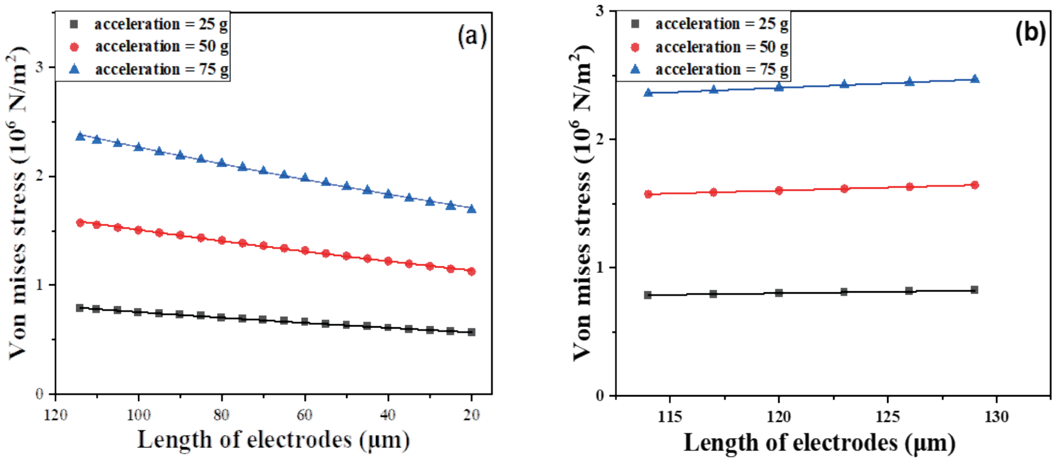

Fig. 6. (Color online) Variations of von Mises stress of the structure shown in Fig. 5. with the length of electrodes changed from 114 μm to (a) 20 μm and (b) 129 μm.

1. When the moveable comb electrodes are shortened, the overall size of the accelerometer component decreases, leading to a reduction in the force exerted under acceleration.
2. A smaller size implies a relatively smaller force area under the same force, thereby reducing the stress generated within the structure.

Therefore, reducing the length of the moveable comb electrodes helps alleviate the stress concentration within the structure. Additionally, a decrease in acceleration means that less force is exerted on the accelerometer component. Since von Mises stress is calculated on the basis of the stress state within the material, a decrease in force also decreases stress. Consequently, when the acceleration decreases, the von Mises stress within the accelerometer component also decreases. Hence, when the length of the moveable comb electrodes is decreased or the acceleration decreases, the force exerted on the accelerometer component decreases, resulting in a reduction in the von Mises stress. This helps mitigate the stress concentration within the structure and contributes to improving the stability and reliability of the accelerometer.

The relationship between the stress experienced by an accelerometer and factors such as electrode length and acceleration rate depends on various factors. One primary reason is that the electrode length of the accelerometer can affect its sensitivity. Longer electrodes may enhance the accelerometer's sensitivity to subtle changes because a larger electrode length implies a larger surface area for detecting motion. However, increasing the electrode length may also increase its inertial mass, thereby reducing its speed of response to rapid movements. In addition, the stress experienced by the accelerometer is also affected by the acceleration rate it encounters, which refers to the rate of change in acceleration within a unit of time. Typically, higher acceleration rates indicate faster motion or larger inertial loads. Accelerometers need to respond quickly to such changes and maintain accuracy without being compromised or damaged by higher acceleration rates. Other factors such as material properties, design considerations, and environmental conditions also play significant roles in determining the stress experienced by an accelerometer. Indeed, the relationship among stress, electrode length, and acceleration rate in accelerometers is intricate and multifaceted. Factors such as material selection and structural design can affect the accelerometer's resilience to stress, whereas environmental conditions such as temperature, humidity, and vibration levels can affect its performance and stability. In summary, optimizing the accelerometer's performance and durability across various applications necessitates a comprehensive consideration of design parameters, material characteristics, and environmental conditions. By carefully addressing these factors, engineers can enhance the reliability and effectiveness of accelerometers in diverse operating environments.

4. Conclusions

The length of moveable comb electrodes impacted the sensing area, leading to variations in the size of the sensing electrode area, which in turn affected the magnitude of the sensing voltage. As the length of the moveable comb electrodes was increased beyond 120 μm, there was a noticeable upward trend in the sensing voltage, with the increase becoming more pronounced with rising acceleration. Conversely, the decrease in the length of the moveable comb electrodes had a relatively smaller effect on the sensing voltage. For instance, at an acceleration of 25*g*, for every 5 μm reduction in length, the range of decrease in sensing voltage was only between 0.16 and 1.2 mV. It was observed that regardless of the acceleration (i.e., 75*g*, 50*g*, and 25*g*), once the length of the moveable comb electrodes decreased beyond 25 μm, the decrease in sensing voltage became gradual. However, with increasing acceleration, the decrease in sensing voltage became more apparent. Moreover, as the length of the moveable comb electrodes increased, the overall structural mass increased, leading to an increase in the displacement of the accelerometer, thereby subjecting the spring to greater stress. Conversely, smaller lengths of moveable comb electrodes reduced the overall structural mass, resulting in decreased accelerometer displacements and consequently less stress on the spring.

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