Biasing Voltage Optimization in MEMS Wireless Sensors for Enhanced Multiple Sclerosis Tremor Detection

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Abstract: - The objective of this work is to present the complete design and simulation of a microelectromechanical system (MEMS) based differential capacitive accelerometer developed to detect tremor signals in patients with Multiple Sclerosis (MS). The primary challenge is to address the difficulties of sensing at low frequencies (below 10 Hz) associated with tremors in multiple sclerosis (MS). The design mainly focuses on the 3.5 to 7.5 Hz band of frequencies. The methods used in the design of the accelerometer consider these multiple attributes to provide optimization with regard to resonance frequency, mechanical stability, and sensitivity. The design is validated by performing finite element analysis (FEA) in COMSOL Multiphysics software. The mechanical properties of the accelerometer are characterized by the development of analytical models to compute resonance frequency and effective spring constant. The FEA results show that the system has a resonance frequency of 5.5 Hz, and the maximum displacement is around 1.77 μm under an acceleration of 0.04 g taking into account bias voltage at operation 10 V in air as external condition for this study; hence mechanical sensitivity was found to be about 44.25 μm. The accelerometer exhibits a considerable dynamic range: from static forces up to near resonant frequencies with very high level sensitivities; linearity also outperforms previous research studies. The feasibility of using a MEMS differential capacitive accelerometer in the effective and accurate evaluation/quantification of tremor signals from MS patients is demonstrated as an emerging technology. Specific documentation and analyzed tremors could have a dramatic impact on many areas of disease identification/management especially in the area of multiple sclerosis.

Key-Words: - Accelerometer, Diagnosis, Biasing, Multiple Sclerosis, Tremor Detection, Differential capacitive sensing, Proof mass dynamics, Analytical validation, Dynamic range assessment.

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1 Introduction

Wireless Sensors are devices that measure accelerations in three dimensions, [1]. They were first developed in the late 1920s with the introduction of the earliest resistance bridge-type accelerometer. With the fast progress of science, technology, and application requirements during past decades, many kinds of Wireless Sensors emerge piezoelectric sensors, [1], laser-based sensors, [2], surface acoustic wave, optical actuation, and magnetic induction, [3], [4]. The advent of Microelectromechanical Systems (MEMS) technology has played a crucial role in advancing Wireless Sensors, [5], enabling miniaturization and enhancing performance, [6], [7], [8]. MEMS Wireless Sensors have been utilized in applications such as inertial navigation with ultra-high sensitivity & specificity, and as biaxial silicon resonant wireless sensors, offering low cross-sensitivity, energy efficiency, and high sensitivity, [4], [9], [10]. Among the most effective methods for providing reliable acceleration readings is the capacitive spring mass base system, [11], [12]. The miniaturization made possible by MEMS technology allows for precise measurements in a wide range of machines and systems, including medical applications for detecting and monitoring tremors in individuals with multiple sclerosis (MS). Wireless Sensors are extensively used in various fields, such as navigation systems, airbag deployment, biomedical equipment, robotics, and MS tremor analysis, [13]. The progress in MEMS technology has made Wireless Sensors more accessible, offering advantages like low power consumption, high sensitivity, compact size, and design flexibility. These sensors convert acceleration into measurable signals using various transduction mechanisms, including piezo-resistive, piezoelectric, capacitive, and thermal, [14]. Among various techniques, Capacitive Wireless Sensors emerge as a preferred choice due to their minimal temperature sensitivity, strong DC response, reduced noise levels, and efficient power consumption. These sensors detect variations in capacitance resulting from the displacement of a proof mass triggered by external acceleration. This research concentrates on developing and simulating a MEMS-based differential capacitive accelerometer. The study examines the device's cross-axis response, sensitivity, linearity, and functional frequency range. The paper primarily addresses sensing challenges at extremely low frequencies (under 10 Hz) associated with MS tremors. The accuracy of the design technique has been demonstrated by the fact that the results of the simulation are very similar to the findings of the analytical calculations. The purpose of this study is to construct monolithic Wireless Sensors and then examine their architectures as well as the main design decisions that were made in order to handle the sensing issues that are present in MS tremor detection. This work makes a contribution to the creation of Wireless Sensors that are more dependable and cost-effective, which in turn facilitates breakthroughs in the medical diagnosis and monitoring of multiple sclerosis. This is accomplished by offering a detailed analysis of these elements.

The following outline is the body of this paper: Modeling and analysis carried out on the suggested design for MS tremor detection are presented in Section 2, along with a brief summary of those processes. In the following section, "Section 3," we will provide the results of the simulation and provide an in-depth discussion of the findings. In the final section of this article, which is titled "Concluding Remarks," we provided a summary of the most important insights and contributions that this work has made to the field of multiple sclerosis.

2 Materials and Methods

This section provides a detailed overview of the design and analysis process of the proposed proof mass, which incorporates capacitive fingers and four serpentine meanders. We have designed this to detect low-frequency tremor signals, such as those wavering from patients who suffer the effects of Multiple Sclerosis (MS). As MS tremors usually lie between (3.5 – 7.5) Hz, hence the accelerometer must have a resonance frequency of up to about 10Hz in order to well embed these signals, [15], [16]. The proposed design manages a resonance frequency of 5 Hz and linear dynamic performance for ±5g, suggesting potential benefits in targeting MS tremor frequencies. Advances in the technology of wireless sensors have been applied to measuring and monitoring tremor severity, [17], which is an area where much more can be learned about the characteristics of MS tremors. This approach increases the sensitivity of inertial measurements to tremor frequency as experienced by individuals with MS, and addresses specific issues associated with MS tremors; hence this design will be valuable for diagnostics and monitoring in complex neurological disorders like multiple sclerosis.

The authors used the following design inputs during the development of the Capacitive Sensing Proof mass.

a →Acceleratrion
E →Young's modulus of the material
l_t →Total length of the meander
n_b →No of turns in the meander.
w_{cb} →Width of a connector beam
l_{cb} → Length of Connector beam
t_b-> Thickness of spring beam
w_l-> Width of the Span beam
l → Length of the Span beam
d_0 →Distance between Stator and Rotor fingers
D_0 → Distance between adjacent sense fingers
t_f →Thickness of Comb fingers
W_f →Width of Sense fingers
L_f →Length of Sense fingers
t_{pm} →Thickness of the proof mass
W_{pm} →Width of the proof mass
L_{pm} →Length of the proof mass

The proof mass is a multi-part component which is interconnected with each other. The capacitive fingers, proof mass, connector beam, and span beam are the components. The configuration and dimension have been chosen based on parameters that affect the resonant frequency. Parameters include sensitivity, mechanical stability, as well as mass, and effective spring constant. Schematic diagrams are illustrated by the visual representation in Figure 1 and Figure 2.

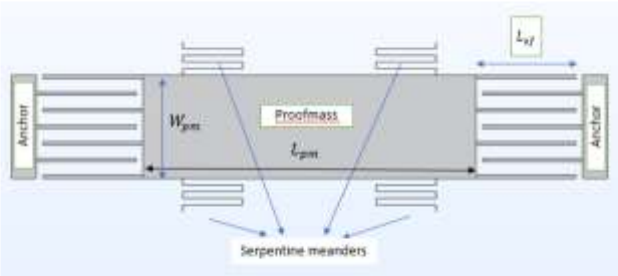

Fig. 1: Design of Proof Mass Housing Capacitive Fingers and Four Serpentine Meanders for Tremor Detection in MS Patients

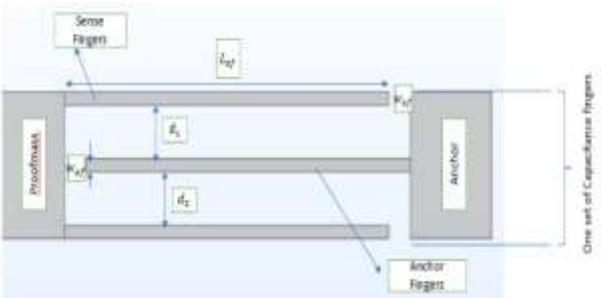

Fig. 2: Anchor Fingers and Sense Fingers Combined as a Differential Capacitive Pair for Improved Sensing Applications

Finite element analysis (FEA) available within COMSOL Multiphysics is used to examine the dynamics of the proof mass, [18], [19]. Upon detecting the boundary conditions, material properties, and complicated geometries, the finite element method (FEM) is employed for precise simulation, [20]. The serpentine meander is configured in such a manner that one end of each individual serpentine meander can be linked to the proof mass and independent to move with respect thereto in response to applied acceleration while another end (opposite charge collection plate) stays stationary. To achieve a resonance frequency of less than 10 Hz, the parametric study consists of finding an optimal setting for the geometric parameters describing serpentine meander and proof mass. The modeling of serpentine meanders was used to achieve the resonant frequencies sought. Serpentine Meanders — Feature of the proof mass which may include interconnecting, curved structures that allow for flexure and compliance. The whole length of the serpentine is computed by initially arising a quadrate-proof mass together with four-supports. This is the serpentine length total. Because of how the proof mass had been constructed, this time around it resonated at its intended frequency—the desired acceleration sensitivity improved as a result.

The spring plays a crucial role in detecting and responding to external forces, enabling the accelerometer to measure between -5g and +5g. While this range is sufficient for capturing various types of acceleration, it's particularly suited for measuring tremors associated with conditions like multiple sclerosis, which typically occur at much lower g-forces (around 0.04g) than those experienced in everyday activities 1. This specific application may necessitate different requirements compared to commercial Wireless in multiple sclerosis applications, accurately measuring low-amplitude, and low-frequency accelerations especially in the 0.04g range, is vital. Commercial Wireless Sensors, on the other hand, are designed to monitor different ranges of accelerations in the high-frequency domain. Consequently, the accelerometer must be exceptionally sensitive mechanically.

To achieve high sensitivity, the proof mass must be light and responsive to minor accelerations. One approach is to optimize the proof mass design parameters, such as its geometry, size, mass, and material properties, [21]. However, for low-frequency operation, the mass needs to be relatively large compared to the spring constant. This creates an inevitable trade-off between design parameters, as the perfect counteraction of the spring force requires an extremely low mass, which affects accuracy and limits sensitivity. Increasing the proof-mass size while maintaining a constant mass can enhance sensitivity without significantly impacting performance in low-frequency applications. Additionally, carefully selecting materials with appropriate density and stiffness properties can help balance sensitivity and performance to meet user expectations, as these properties influence a metal's resistance to deformation.

Polysilicon (PS) was selected as the actuator material due to its high mechanical strength, [21], compatibility with semiconductor processes, electrical conductivity, [22], thermomechanical stability, [23], low stress, and suitability for microfabrication.

The simulation results are presented in the Figures below. Figure 3 shows the frequency response characteristics of the simulated serpentine support, featuring a maximum stroke of 16 µm at the resonant frequency of 5.5 Hz. Certain statements in this press release may be forward-looking; please refer to our investor information for cautionary advice on Forward-Looking Statements.

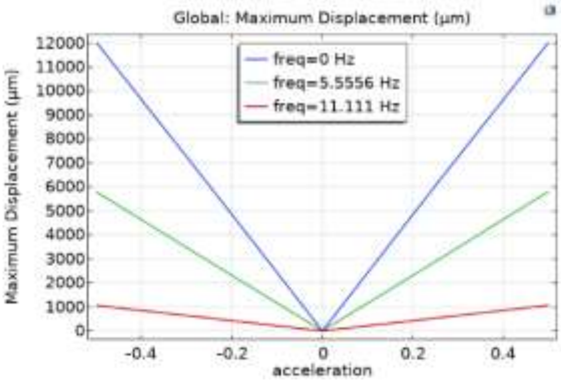

Fig. 3: Frequency Impression of Serpentine Support Created for Tremor Detection in Multiple Sclerosis Patients.

Figure 4 illustrates the mechanical linearity of the proof mass for an acceleration range of -0.5g to +0.5g, demonstrating a linear response even at accelerations as low as 0.04 g (high sensitivity within the specified excitation mode angle). These characteristics make the design suitable for detecting and monitoring tremors in individuals with multiple sclerosis (MS).

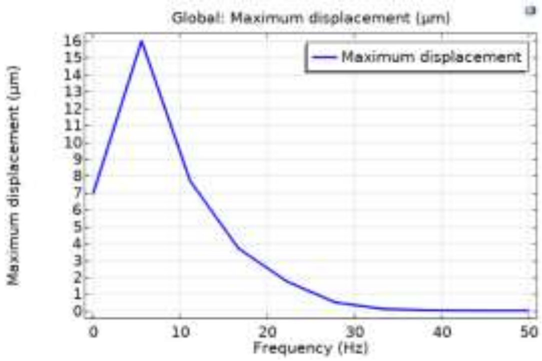

Fig. 4: The sensitivity examination of the proof mass with its mechanical linearity over an acceleration range from -0.5g to +0.5g for multiple sclerosis applications

Figure 5 depicts the frequency-displacement relationship, specifically designed to identify tremor signals associated with multiple sclerosis (MS). The graph shows the maximum displacements along the Y and X axes within the operational range. Notably, a significant maximum displacement of 70,000 µm occurs at 5g acceleration, relevant to MS tremor characteristics.

Figure 6 illustrates the frequency-displacement properties in the 3 axes (X. Y & Z), crucial for understanding complex tremor patterns in MS patients. Interestingly, minimal cross-sensitivity was observed in the X and Z axes during Y-direction acceleration experiments.

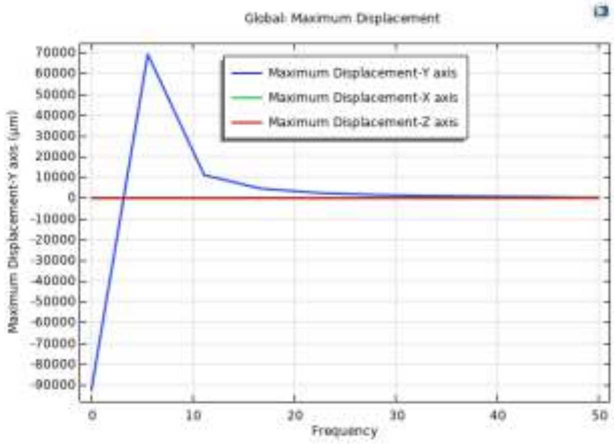

Fig. 5: Maximal Displacement in the X and Y axes within the Operating Range for Tremor Analysis of Multiple Sclerosis Patients

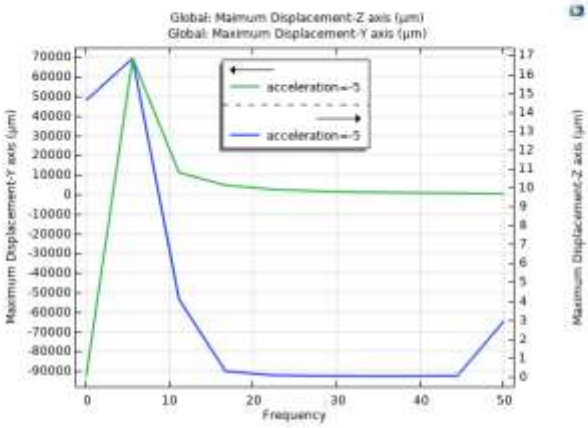

Fig. 6: Cross Sensitivity for Acceleration in Y Direction with Respect to Z and X Axes is Negligible, as Required from the Perspective of High-Accuracy Multiple Sclerosis Tremor Analysis

When acceleration is applied in the Y direction, only the Y axis experiences substantial displacement (6000 µm), while the other axes show minimal displacement. The authors show that the accelerometer is indeed capable of measuring and responding to different accelerations within a reasonable range in which linear properties remain essentially constant with minimal cross-sensitivity from axis-to-axis. This feature makes it potentially useful for the accurate detection and quantification of tremor signals in MS patients.

For the detection of MS tremor signals, equation 1 represents the calculation of the resonant frequency (f) in the proposed design of accelerometer. Based on the material and geometric properties of this device, its resonant frequency is found to be 3.62 Hz. The proof mass with the serpentine meander system oscillates at an optimum frequency to measure and analyze low-frequency MS tremors and that can be calculated as follows:

$$f = \frac{1}{2\pi}\sqrt{\frac{4Etw_l^3}{n_b \rho t_{pm} w_{pm} L_{pm} l^3}} \quad (1)$$

$$= \frac{1}{2\pi}\sqrt{\frac{4 * 1.69 * 10^{11} * 0.0025 * (8.4147 *}{4 * 2320 * 0.0025 * 0.0587 * 0.1174 *}}$$
$$= 3.62Hz$$

An empirical Serpentine Spring model was used for the detection and analysis of tremor signals in MS patients. Effective spring constant (K_{eff}) of the serpentine meander is calculated using equation 2. Given the need to detect low-frequency MS tremors, this equation directly follow an analytical model of the spring structure associated with meanders. Replacing appropriate values and making calculations, it gives a spring constant 5.1725 N/m. This parameter is basic in determining the rigidity of meander-patterns and their restoring forces to applied accelerations. It would be ideal in the case of tremor signals for subjects with MS, but it is not intended to replace commonly used screening tools or diagnostic tests. The calculated resonant frequency and spring constant are of key importance in the assessment of the working effects of an accelerometer design and its sensitivity to measure MS tremors.

$$K_{eff} = \frac{4Et}{n_b}\left(\frac{w_l}{l}\right)^3$$
$$= \frac{4 * 1.69 * 10^{11} * 0.0025 * (8.4147 * 10^{-5})^3}{4 * 0.023^3}$$
$$= 5.1725\frac{N}{m} \quad (2)$$

The device is shown to operate in the intended frequency span, respond sensitively to imposed varying accelerations and be particularly well calibrated for low-frequency tremor frequencies typically seen in MS-sufferers. The spring model simplifies determination of the responsiveness of this system to applied accelerations, which has been characterized by an extremely low value-5.17 N/m, enabling accurate recording and detection of low-amplitude vibrations. This is important for identifying medical diagnosis and monitoring tremor signals in MS sufferers, what leads to a better care and treatment of people with this disease. The accelerometer proof-mass, which is also used to sense tremor signals in MS patients, acts as a voltage divider. As per the mathematical model shown in the pictures below, which means 'x.' is actually indicative of displacement produces a linear voltage out across proof-mass. This allows highly accurate acceleration measurements, especially at the low frequencies that hallmark MS tremors. To obtain a higher output voltage, the differential capacitance (C) value should be increased or more input voltage is required. Applying high voltage to the accelerometer can create risk of causing pull-in, therefore is applied with a certain value only. This can have a huge effect on the performance of the accelerometer and may lead to destroy it physically. Consequently, there is a need to treacherously weigh the voltage output among MS diagnosis and monitoring applications using accelerometers due to the operational performance of an accelerometer. Figure 7 shows a schematic of the optimized differential capacitive accelerometer for MS tremor detection. Figure 8 schematically represents the accelerometer as a voltage divider-biased circuit.

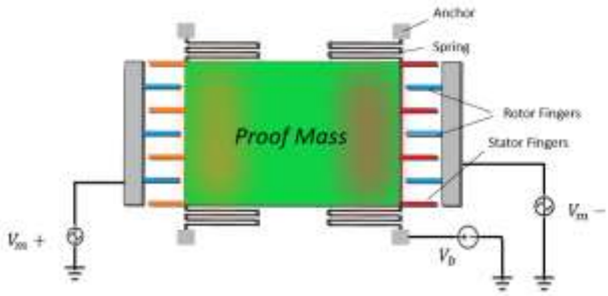

Fig. 7: Proposed Differential Capacitive Accelerometer for Multiple Sclerosis Tremor Detection

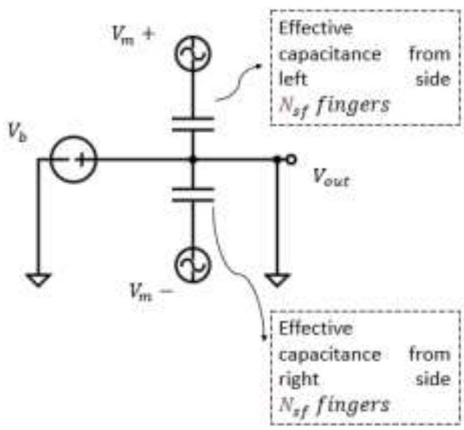

Fig. 8: Equivalent Circuit of the Accelerometer (Proposed) working as a Voltage Divider for Multiple Sclerosis Tremor Detection

If performed properly, changing the bias of the proof mass can modify its resonance frequency and allow for a concurrent change in spring constant.

This connection between resonance and biasing frequency is particularly relevant when detecting tremors associated with multiple sclerosis (MS).

By adjusting the biasing voltage, it becomes possible to modify the spring constant, thereby influencing the accelerometer's overall effectiveness and characteristics in detecting MS tremors. The ability to adjust the spring constant allows for fine-tuning the MS tremor detector's sensitivity to a specific frequency range. The total spring constant can be expressed as follows:

$$K_{em} = K_{mech} - K_{elec} \quad (3)$$

$$K_{em} = K_{mech} - \left[\frac{\varepsilon_0 A V_0^2}{d_0^3}\right] 2 * N_{sf} \quad (4)$$

K_{elec} = Equivalent Spring Constant caused by electrostatic force.
K_{mech}= Mechanical Spring Constant.
V_0 = is the dc voltage across the capacitor.

d_0= Initial gap between stator and fingers.
A = Total area of electrodes.
ε_0= dielectric constant in air.

$$f_{em} = \frac{1}{2\pi}\sqrt{\frac{K_{mech}-K_{elec}}{M}} = f_{em} = \frac{1}{2\pi}\sqrt{\frac{K_{mech}}{M}}\sqrt{1-\frac{K_{elec}}{K_{mech}}} \quad (5)$$

$$f_{em} = \frac{1}{2\pi}\sqrt{\frac{K_{eff}}{M}}\sqrt{1-\frac{K_{elec}}{K_{mech}}} = f_0\sqrt{1-\frac{K_{elec}}{K_{mech}}} \quad (6)$$

$$f_{em} = f_0\sqrt{1-\frac{[\varepsilon_0 A V_0^2]2*N_{sf}}{K_{mech} d_0^3}} \quad (7)$$

$$K_{mech} = K_{eff} = \frac{4Et}{n_b}\left(\frac{w_l}{l}\right)^3 \quad (8)$$

$$f_{em} = f_0\sqrt{1-\frac{[\varepsilon_0 A V_0^2]2*N_{sf}*n_b*l^3}{4Et(w_l)^3 d_0^3}} \quad (9)$$

3 Results and Discussions

In MEMS accelerometers designed to detect MS tremors, the proof mass plays a crucial role in acceleration sensing and measurement. When no external acceleration (0 g) is present, such as during the absence of MS tremors, the device is expected to remain stationary. However, a displacement factor may be observed on the proof mass due to various factors, including the electric field potential difference between the capacitive fingers on either side. This displacement is obtained from the offset voltage generated on proof mass. In Figure 9, a 0.004 µm displacement factor at 0 V biasing voltage and 0 g acceleration is shown. That is, a small displacement can still be detected due to electric field effects even in the absence of acceleration, as in patients with MS tremors presumably not active. This is crucial information for the development of accurate accelerometers to detect and track MS-related tremors as shown in Figure 10.

Figure 11 and Figure 12 show the surface stress and displacement of proposed proof mass for MS tremor detection at a biasing voltage of 10 V under an acceleration of 0.04 g. This analysis is important for understanding how the accelerometer behaves and performs under MS tremor-relevant circumstances. This electric field is used to operate the accelerometer, and it is created by a biasing voltage. The measured surface stress for the given acceleration depicted in Figure 11 is 7.4×10^{-7} N/m. The surface stress (force per unit area on the proof mass surface), was evaluated to demonstrate that the accelerometer can withstand the applied force with sufficient mechanical integrity and structural stability, making it suitable for MS-related applications. Figure 13, Figure 14 and Figure 15 point outs the key aspects of tremor detection, all focusing on optimizing sensor performance in MS patients, with Figure 13 demonstrating the influence of bias voltage on linearity for 60 fingers, Figure 14 depicting the maximum and minimum surface stress at a 0.04 g and 20 Volt bias, and Figure 15 provides peak displacement against resonance frequency for 0.25g and 0.5g.

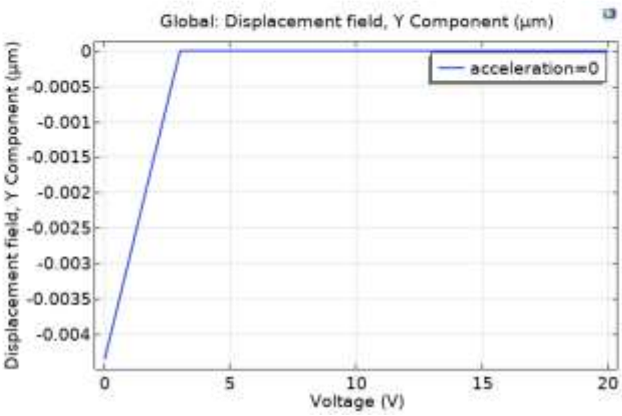

Fig. 9: Impact of voltage bias on the proof mass at zero g acceleration, specifically for MS tremor detection

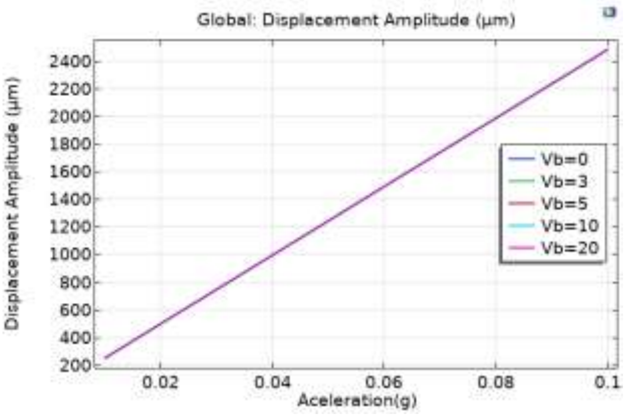

Fig. 10: The proof mass design for MS tremor monitoring exhibits ideal linearity across various bias voltages, ensuring precise measurements

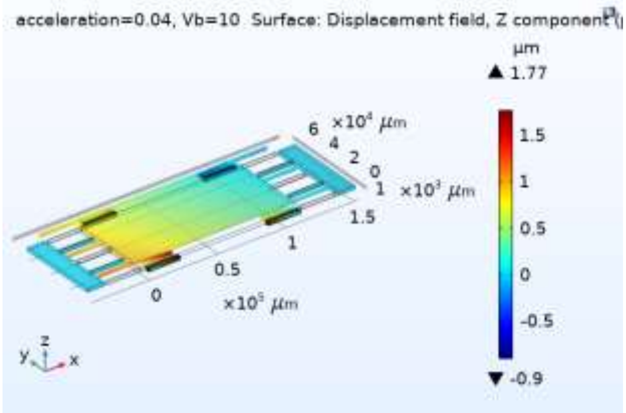

Fig. 12: Surface displacement under 10 Volt bias & 0.04g acceleration, customized for MS tremor monitoring

In the context of monitoring tremors in Multiple Sclerosis (MS) patients, Figure 12 illustrates that a 0.04 g external acceleration at the specified biasing voltage results in a 1.77 µm deformation or movement of the proof mass. The accelerometer's mechanical sensitivity was calculated to be 44.25 µm/g, representing the surface displacement per gravity. This level of sensitivity is achieved with minimal cross-sensitivity due to the carefully designed geometric features and the connection method of the meanders to the proof mass. The significant movement of the proof mass allows for precise measurement and calculation of displacement sensitivity. Such sensitivity is crucial for detecting the subtle tremors characteristic of MS. The spring softening phenomenon observed, compared to the static displacement study in Figure 16, can be attributed to the 10 V voltage bias applied to the spring. This design ensures accurate measurement and characterization of low-amplitude vibrations, making it suitable for MS tremor investigation.

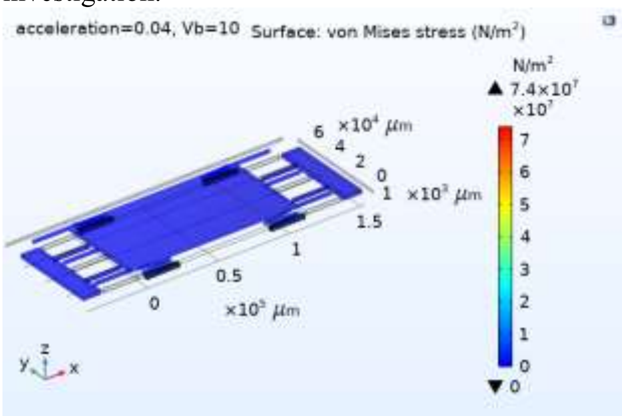

Fig. 11: Surface stress under 10 Volt bias & 0.04g acceleration, particularly engineered for MS tremor detection

Figure 17 showcases the surface electric field generated using capacitive fingers and four serpentine meanders, specifically designed for MS tremor detection. It displays the distribution and intensity of the electric field, both essential for accurate measurement. Figure 18 demonstrates the strain experienced by the proof mass across an acceleration span of (-0.5 to +0.5) g, highlighting the device's ability to detect minute movements associated with MS. Figure 19 depicts the proof mass's electric potential contours, emphasizing the electrical properties necessary for MS tremor characterization. Figure 20 provides the capacitance generated by the sensing fingers for a differential capacitive pair, a crucial feature for achieving the sensitivity required in MS applications. The graph illustrates the capacitance change as a function of applied acceleration. The accelerometer's responsiveness and electrical sensitivity was determined to be 1.428 nF/g.

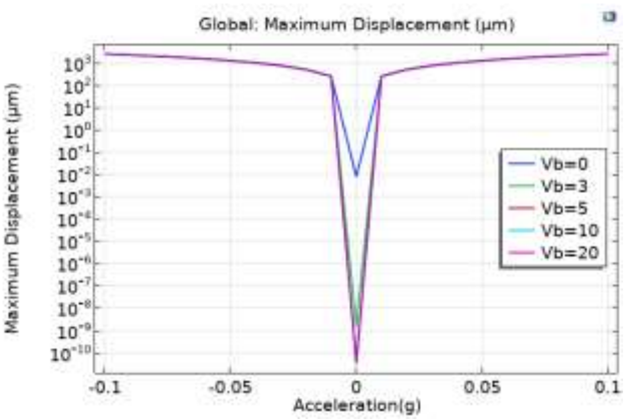

Fig. 13: Influence of bias voltage on linearity across different voltages for 60 fingers, optimized for MS tremor detection

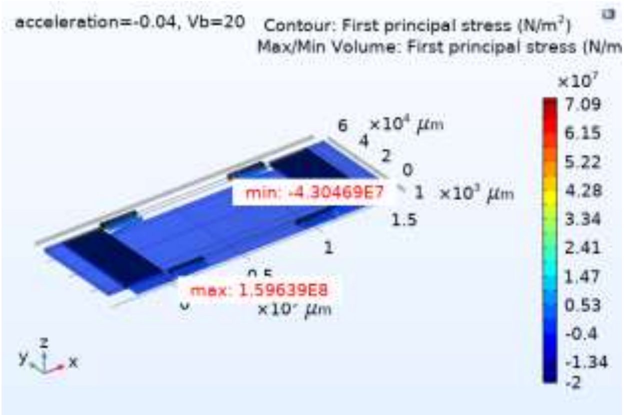

Fig. 14: Maximum and minimum surface stress at 20 Volt bias and 0.04 g, engineered for analyzing tremors in MS patients

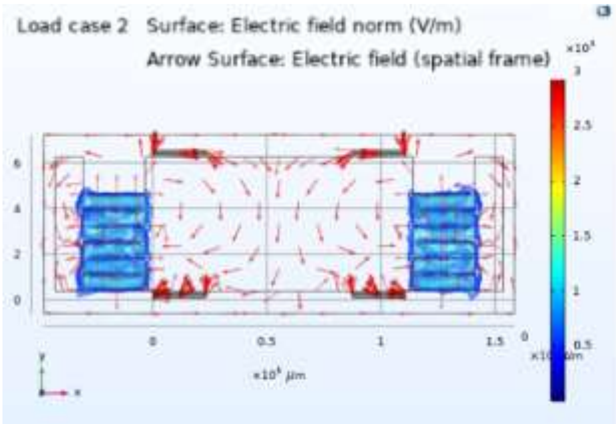

Fig.17: Electric field distribution on the surface, generated using capacitive fingers and four serpentine meanders, aimed at improving MS tremor detection sensitivity

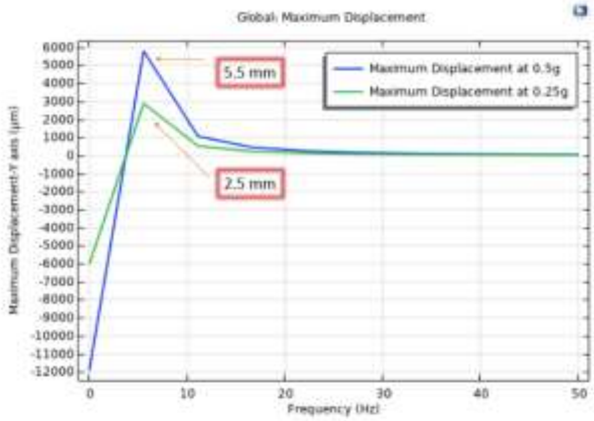

Fig. 15: Peak displacement plotted against resonance frequency for 0.25g and 0.5g, focusing on the MS tremor frequency range

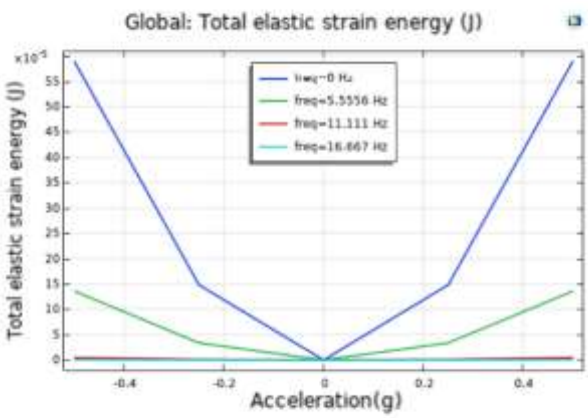

Fig. 18: Proof mass strain across an acceleration span of (-0.5 to +0.5)g, addressing specific requirements for MS tremor monitoring

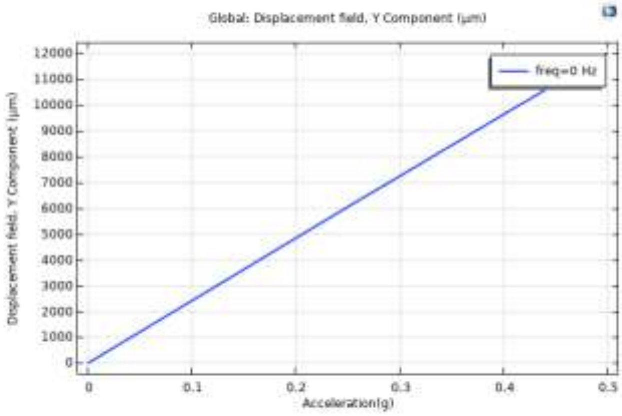

Fig. 16: Static analysis showing displacement changes with rising acceleration, designed for precise MS tremor measurements

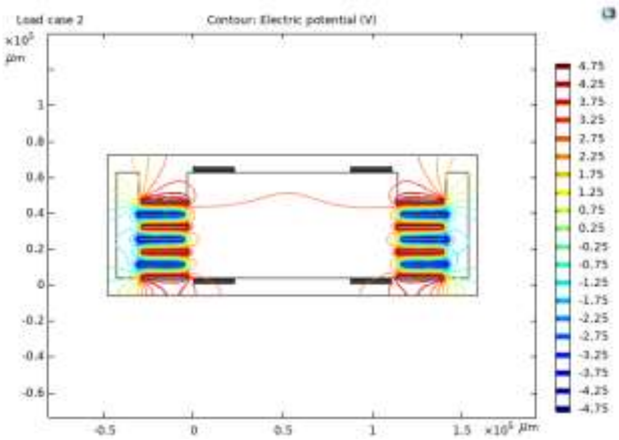

Fig. 19: Electric potential distribution on the proof mass, incorporating capacitive fingers and four serpentine meanders, customized for MS tremor analysis.

Table 1 provides valuable data on the electrical and mechanical sensitivity of the accelerometer at different acceleration levels. Table 2 offers a comprehensive comparison of the accelerometer's dynamic range and sensitivity with some reported in the literature, primarily for MS tremor detection. This table enables a quantitative assessment of our proposed accelerometer design's performance relative to other options for MS diagnosis and monitoring.

Table 1. Accelerometer's Electrical and Mechanical Sensitivity at Various Acceleration Levels for Multiple Sclerosis Tremor Evaluation

Acceleration (g)	**Electrical Sensitivity (nF/g)**	**Mechanical sensitivity (mm/g)**	**Capacitance (F)**	**Displacement (mm)**	**Freq (Hz)**
0.25	1.428	22.4	$3.570*10^{-10}$	5.6	5.5
0.5	0.714	23.6	$3.570*10^{-10}$	11.8	5.5

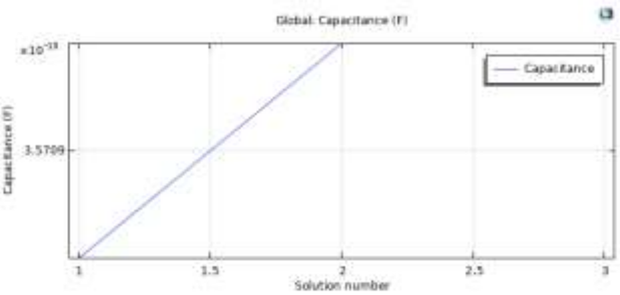

Fig. 20: Differential Capacitive Pair's Sense Fingers Capacitance, Optimized for Detecting Tremors in Patients with Multiple Sclerosis (MS).

Table 2. Accelerometer's Dynamic Range and Sensitivity Compared to Published Data for Multiple Sclerosis Applications

Reference	**Resonant Frequency (Hz)**	**Electrical Sensitivity (V/g) or (F/g)**	**Mechanical Sensitivity (m/g)**	**Dynamic range of operation (g)**
[24] (2016)	13.2	112 V/g	-	-
[25] (2016)	4255	80 fF/g	0.0136 μm/g	10
[26] (2017)	3000	35 fF/g	0.0136 μm/g	10
[27] (2021)	10209	6.41 fF/g	2.64 nm/g	-
[11] (2022)	400	2.01 mV/g	41 nm/g	0.26
This Work	5.5 Hz	1.428 nF/g	44.25 μm/g	5

4 Conclusion

This research aimed to showcase the creation, simulation, and evaluation of a MEMS differential capacitive accelerometer tailored for medical diagnostic purposes, particularly for Multiple Sclerosis (MS). The device exhibited minimal cross-axis sensitivity, high sensitivity, and excellent linearity within the target frequency domain, making it suitable for detecting and monitoring subtle tremors and movement abnormalities associated with MS.

As tremors related to MS present differential frequency and intensity, careful choice of design parameters was needed for an appropriate symptom evaluation. In all cases studied, the resonance frequency of the sensor was found to be 5.5 Hz, which is within a range consistent with MS tremor characteristics. Consistent results between simulation and analytical calculations justified the precision of this design methodology for its potential uses in MS diagnosis.

The design parameters such as component length, width, and thickness optimization were important for obtaining the resonance frequency and sensitivity of the sensor. The serpentine meanders helped to increase the proof mass flexibility and compliance, thus providing a sensitivity of 44.26 m/g for low-frequency accelerations. Importantly, this is also a crucial feature for patients with multiple sclerosis, because in some cases detecting the most subtle of hand tremors can be important to an early diagnosis and treatment.

The authors also tested the frequency-displacement relationships of the design and its mechanical linearity, as well as approximating the corresponding frequency response. A study of biasing on the accelerometer is also given here which establishes manipulating factors in both mechanical nature and frequency response characteristics for a design. This control is critical in order to optimize treatment for the particular needs of each individual with MS.

The study also investigated the surface stress, displacement, and electric field effect on the proof mass to understand how the accelerometer behaves mechanically and electrically with different levels of conditions. These analyses lead to a comprehensive understanding of the role this device plays in the complex landscape of MS symptoms.

In summary, the proposed MEMS differential capacitive accelerometer shows great potential in MS diagnosis and monitoring. These characteristics make it useful for the medical staff and researchers in the study for diagnosis or treatment of MS. This innovative design has been tested highly sensitively with good specificity. It will be a large support to carry out further studies on multiple sclerosis as well future operation development may change entirely the life standard of many people suffering from this disease so far that no other similar device have had reached yet.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work the authors used Consensus: AI-powered Academic Search Engine in order to survey of literature. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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The authors have no conflicts of interest to declare.