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INVESTIGATION OF OPTIMUM GEOMETRY FOR ROBOTICS TORQUE SENSOR

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ABSTRACT

Purpose: This study aims to optimise the geometry of joint torque sensors to enhance sensitivity and precision while minimising stress.

Design/Methodology/Approach: The research involves designing and evaluating three-ring geometries (Ring A, Ring B, and Ring C) under varying rib angles (30°, 45°, 60°, and 90°) using Finite Element Analysis (FEA) in ANSYS. Experimental validation was performed on the geometry with the highest stress (Ring C, 60° rib angle), utilising strain gauges for stress measurement.

Findings: FEA revealed that Ring A and B geometries exhibited lower stress levels, with Ring A being the most favourable. While showing higher stress, Ring C demonstrated suitability for applications requiring precise strain measurements.

Research Limitation: The study focuses on aluminum alloys 6061 and 7075-T6.

Practical Implication: Optimised torque sensors can enhance robotic applications requiring precise force measurement and control, improving operational safety and precision.

Social Implication: Enhanced torque sensor design supports safer and more efficient robotics and benefits society by enabling technological advancements.

Originality/Value: This work comprehensively evaluates torque sensor geometries, combining FEA and experimental validation to identify designs that balance stress minimisation and measurement precision, contributing to advancements in robotic sensor technology.

Keywords: *Ring geometry. robotics. strain measurement. stress analysis. torque sensor*

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INTRODUCTION

Torque sensors play a crucial role in robotics, where precise force measurement and control are vital for various applications. These sensors measure the rotational force or torque applied to an object, providing essential data that enhances the robot's functionality in several key areas, including force control, safety, and precision.

In robotics, force control is critical for tasks requiring delicate handling or precise object interaction. Torque sensors enable robots to measure the amount of force being applied in real time, allowing for precise adjustments to ensure optimal force application. This capability is vital in tasks such as assembly, machining, and handling fragile objects, where excessive force could cause damage or compromise the quality of the work (Dai-Dong, 2021).

For instance, in robotic assembly lines, torque sensors can help ensure that bolts and screws are tightened to the correct specifications, preventing over-tightening or under-tightening, which can lead to product defects or failures (Hernandez-Salinas et al., 2024).

In medical robotics, these sensors allow for the delicate handling of tissues and organs, providing the necessary sensitivity to avoid injury during surgical procedures. Safety is paramount in robotics, mainly when robots operate close to humans.

Savino et al. (2020) revealed that torque sensors contribute significantly to safety by providing feedback that helps prevent accidents and injuries. They can detect abnormal force levels that may indicate a collision or malfunction, prompting the robot to stop or adjust its actions to avoid harm. For example, in collaborative robotics (cobots), torque sensors can detect unexpected resistance or force, such as when a human inadvertently enters the robot's workspace.

The sensor data can trigger an emergency stop or a change in the robot's behaviour, preventing potential accidents. This capability is essential in environments where robots and humans work together, such as automotive manufacturing or healthcare (Lai et al., 2021). Precision is another critical aspect of robotic applications, particularly in aerospace, electronics, and pharmaceuticals, where exact specifications and high-quality standards are required.

Torque sensors enhance precision by accurately measuring the forces applied during various processes, ensuring consistency and repeatability (Noh et al., 2016). In robotic machining, torque sensors help maintain consistent cutting forces, leading to high-quality surface finishes and precise dimensions.

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This precision is crucial in producing components with tight tolerances, where even slight deviations can lead to performance issues or failures. In electronics assembly, torque sensors ensure that delicate components are handled with the appropriate force, preventing damage and ensuring the reliability of the final product (Muhammad et al., 2021).

Optimising torque sensors involves addressing several specific challenges, notably sensitivity, accuracy, and response time. Sensitivity refers to the sensor's ability to detect small changes in torque. High sensitivity is crucial for applications requiring precise force control, but achieving it can be challenging due to noise and signal interference, which can mask subtle variations. Accuracy, or the sensor's ability to accurately represent the applied torque, is another critical challenge.

Temperature variations, material inconsistencies, and calibration drift can degrade accuracy. Consistent and reliable readings require meticulous design, calibration, advanced materials, and manufacturing techniques (Yunjiang et al., 2019). Response time, the speed at which the sensor can react to changes in torque, is vital in dynamic applications, such as robotic arms or automotive systems. Slow response times can lead to delayed or inaccurate feedback, compromising the performance and safety of the system. Balancing these three factors, sensitivity, accuracy, and response time, requires careful consideration of the sensor's design, materials, and electronics, often involving trade-offs to achieve the best overall performance for specific applications (Suslu et al., 2023; Farhad et al., 2001).

The primary objective of optimising torque sensor geometry for greater sensitivity is to enhance the sensor's ability to detect minute variations in applied torque (Cao et al., 2021). By refining the geometric design, such as the shape, size, and placement of strain gauges, engineers aim to maximise the sensor's strain response to torque inputs. This optimisation allows for precise force measurement, which is critical in applications requiring delicate manipulation or precise control, like surgical robots or precision assembly lines. Increased sensitivity can lead to more accurate and reliable data, improving robotic systems' overall performance and safety.

Additionally, it can enable the detection of subtle force changes, enhancing the sensor's functionality in detecting potential issues or anomalies, such as unexpected resistance or component wear. Ultimately, the goal is to create a highly sensitive torque sensor that can operate effectively in various environments and applications (Han et al., 2020).

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LITERATURE REVIEW

Current technologies for torque sensors include strain gauge-based, piezoelectric, magneto-elastic, and optical sensors, each offering strengths like high accuracy, sensitivity, and non-contact measurement. However, they also face limitations such as temperature sensitivity, cost, and complexity. Understanding these factors is essential for choosing the right technology for specific applications. Finite Element Analysis (FEA) is a valuable tool in sensor design, allowing for detailed stress, strain, and thermal effects analysis. It helps optimise sensor geometry and materials, improving sensitivity and accuracy and predicting sensor behaviour under various conditions (Mahadik et al., 2022).

Existing Methods

Current technologies and methods used in designing and optimising torque sensors encompass various approaches, each with distinct strengths and limitations. The most prevalent technologies include strain gauge-based, piezoelectric, magnetoelastic, and optical sensors (Mahadik et al., 2019).

Strain Gauge-Based Sensors

Strain gauge-based sensors are the most common torque sensors in use today. They measure the deformation (strain) in a material due to applied torque, with the strain gauges converting this deformation into an electrical signal. The strengths of this technology include high accuracy, reliability, and a well-established manufacturing process. Strain gauges can be designed to handle a wide range of torque levels, making them versatile for different applications. However, they are sensitive to temperature changes, affecting their accuracy. Additionally, the adhesive used to attach strain gauges to the substrate can deteriorate over time, impacting the sensor's longevity (Chen et al., 2023)

Piezoelectric Sensors

Piezoelectric sensors leverage the piezoelectric effect, where certain materials generate an electrical charge in response to mechanical stress. These sensors are known for their high sensitivity and ability to measure dynamic changes in torque. They are particularly useful in applications where rapid torque variations occur, such as in automotive and aerospace systems. The main limitation of piezoelectric sensors is that they are less effective for measuring static or slowly varying torques. They also tend to be more

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expensive and complex to manufacture than strain gauge-based sensors (Devshete et al., 2019).

Magneto elastic Sensors

Magneto elastic torque sensors detect changes in the magnetic properties of a material caused by mechanical stress. This technology offers non-contact measurement capabilities, making it ideal for applications where physical contact with the sensor is impractical or undesirable. Magneto elastic sensors are robust and can operate in harsh environments with high temperatures or chemical exposure. However, they are sensitive to external magnetic fields, which can interfere with measurements. The technology is also less mature than strain gauge or piezoelectric sensors, limiting its widespread adoption and availability (Chavan et al., 2011)

Optical Sensors

Optical torque sensors use changes in light properties, such as intensity or phase, to measure torque. These sensors are highly sensitive and immune to electromagnetic interference, making them suitable for environments with high electrical noise. They can also provide high-resolution measurements and can measure static and dynamic torque. However, optical sensors can be sensitive to environmental conditions, such as dust and temperature changes, which may affect their performance. The complexity of the optical components and the need for precise alignment can also increase manufacturing costs and maintenance requirements (Mahadik et al., 2019)

Emerging Technologies and Methods

Recent advancements in materials science and sensor technologies are driving innovations in torque sensor design. For example, using micro electromechanical systems (MEMS) technology enables the creation of miniature torque sensors with low power consumption and high sensitivity. Additionally, advancements in wireless sensor technology enable the development of torque sensors that can transmit data wirelessly, reducing the need for physical connections and improving system integration (Mahadik et al., 2020). Each torque sensor technology offers unique strengths and faces specific limitations. Strain gauge-based sensors are versatile and accurate but sensitive to temperature changes.

Piezoelectric sensors excel in dynamic applications but struggle with static measurements.

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Magneto elastic sensors offer non-contact measurements but are affected by external magnetic fields. Optical sensors provide high sensitivity and are immune to electromagnetic interference but can be costly and sensitive to environmental factors. As technology advances, developing more robust, sensitive and cost-effective torque sensors will expand their application in various industries (Siradjuddin et al., 2018; Pu et al., 2022).

FEA in Sensor Design

Finite Element Analysis (FEA) has been extensively used in designing and optimising robotic torque sensors, offering significant advantages in understanding and enhancing sensor performance. FEA allows engineers to create detailed simulations of sensor components under various conditions, such as mechanical stress, thermal effects, and dynamic loads. This simulation capability is critical for optimising the sensor's geometry, material selection, and placement of strain gauges or other sensing elements.

One key advantage of using FEA in torque sensor design is its ability to predict how design parameters influence the sensor's sensitivity and accuracy (Al-Mai et al., 2018). For instance, FEA can help identify the optimal locations for strain gauges to maximise their response to torque while minimising the effects of unwanted stresses or thermal expansions. This leads to more accurate and reliable torque measurements. FEA also enables the analysis of complex, non-linear behaviours that are difficult to assess through traditional analytical methods. This is particularly useful in designing sensors operating under varying environmental conditions, such as temperature fluctuations or exposure to vibrations and shocks (Yasin et al., 2023). By simulating these conditions, FEA helps engineers design sensors that maintain high performance and durability in real-world applications.

Furthermore, FEA can assist in the iterative design process, allowing for rapid testing and refinement of sensor designs without needing costly and time-consuming physical prototypes. This accelerates development and reduces costs, making it feasible to explore a broader range of design options (Kim et al., 2012; Kim et al., 2005).

In summary, FEA offers significant advantages in designing robotic torque sensors by providing detailed insights into the effects of different design choices on sensor performance. Its ability to simulate complex behaviours and optimise sensor design

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parameters makes it a powerful tool for developing highly sensitive, accurate, and reliable torque sensors for various robotic applications.

METHODS

Finite Element Analysis Model

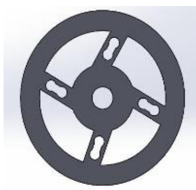
For optimising geometry, sensors with three types of geometry are taken for experimentation: Ring A (without holes on the inner and outer ring of sensors with a cut section on ribs), Ring B (with holes on the inner and outer ring of sensors with a cut section on ribs), and Ring C (with holes on the inner and outer ring of sensors without a cut section on ribs). For ring geometry, the following constraints are considered.

Table 1: Ring Geometry Specifications.

Parameter	Values
The outside diameters	78 mm
The inner diameters	10 mm
Thickness of joint sensor	5 mm
Torque range	20 Nm
Factor of safety	3

The lightweight robot required a joint torque sensor. As a result, the widely used aluminium alloys 6061 and 7075-T6 were considered sensor materials.


Ring A 90◦ geometry.


Ring A 60◦ geometry.


Ring A 45◦ geometry.


Ring A 30◦ geometry.

Figure 1: Ring A Geometry Configurations

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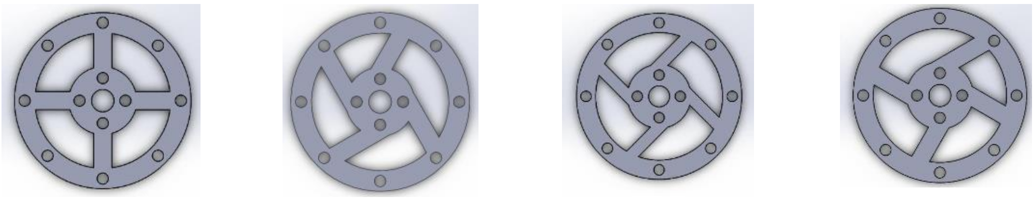
Ring B 90° geometry. Ring B 60° geometry. Ring B 45° geometry. Ring B 30° geometry.

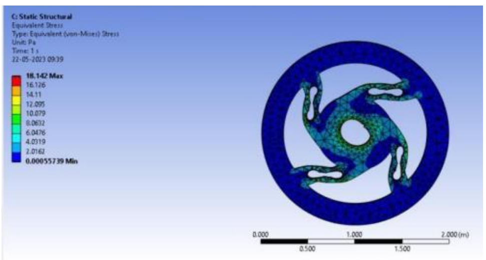
Figure 2: Ring B Geometry Configurations



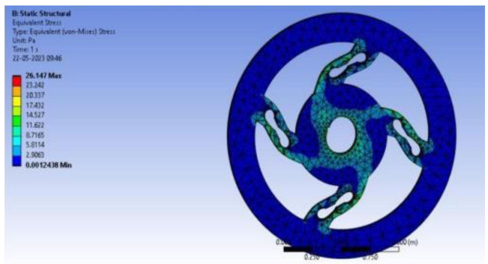
Ring C 90° geometry. Ring C 60° geometry. Ring C 45° geometry. Ring C 30° geometry.

Figure 3: Ring C Geometry Configurations

The FEA is performed using an ANSYS workbench by applying torque at an internal hub and keeping the external hub fixed on aluminium alloys 6061. It is observed that the Ring C geometry has high stresses compared to the Ring A and Ring B geometry.



a) FEA of Ring A 30° geometry.



b) FEA of Ring A 45° geometry.

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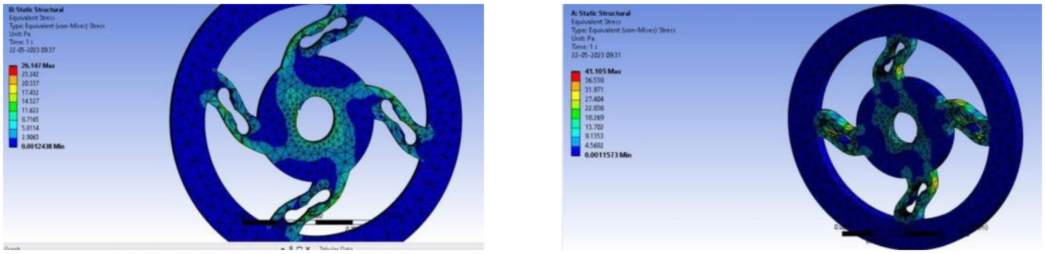
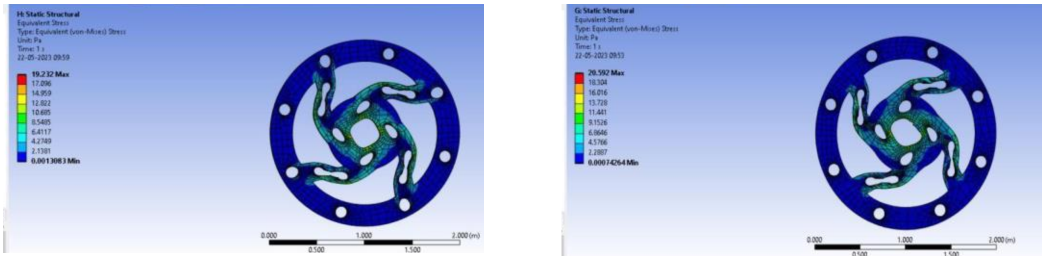
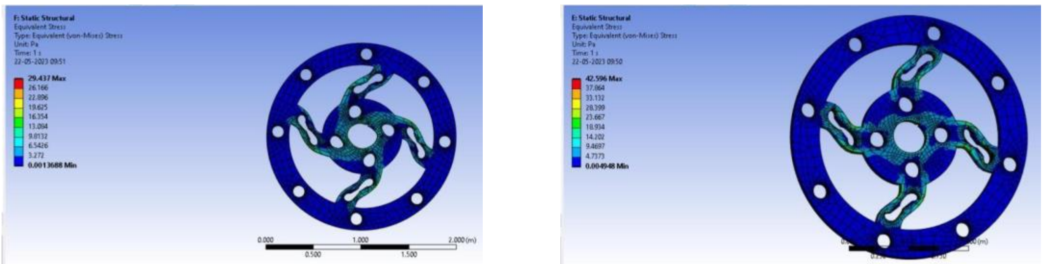


c) FEA of Ring A 60° geometry. d) FEA of Ring A 90° geometry.

Figure 4: Stress analysis of Ring A geometry joint torque sensor



a) FEA of Ring B 30° geometry. b) FEA of Ring B 45° geometry.



c) FEA of Ring B 60° geometry. d) FEA of Ring B 90° geometry.

Figure 5: Stress analysis of Ring B geometry joint torque sensor

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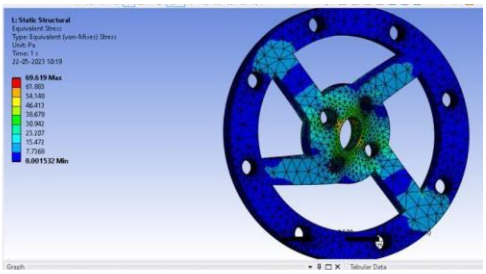
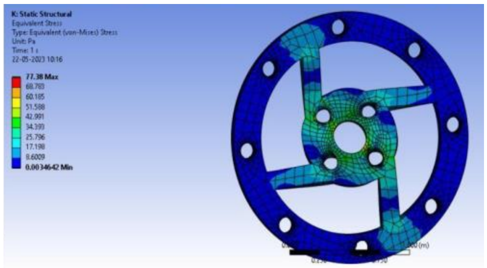
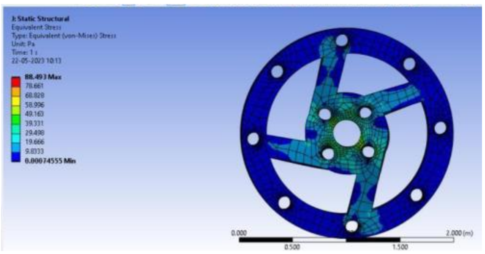


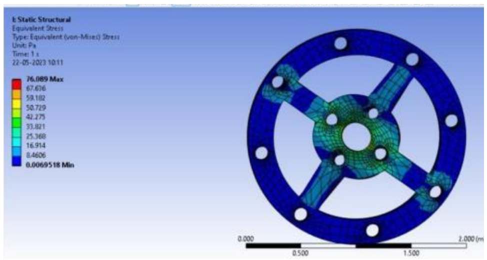
a) FEA of Ring C 30° geometry.



b) FEA of Ring C 45° geometry.



c) FEA of Ring C 60° geometry.



d) FEA of Ring C 90° geometry.

Figure 6: Stress analysis of Ring C geometry joint torque sensor

The following table shows the maximum stress values in Pa for a combination of different geometry and rib angle. The table shows that for geometry, Ring C has a maximum stress value of 88.49 Pa at a 60° rib angle.

Table 2: Maximum stress values (Pa) for different geometry and rib angle.

		Rib Angle (°)			
		30	**45**	**60**	**90**
Geometry	**A**	18.14	26.14	26.14	41.01
	B	19.23	20.59	29.43	42.95
	C	69.61	77.38	88.49	76.09

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Experimentation

The experimentation was conducted to determine the strain and stress in a specimen with Geometry C, characterised by a rib angle of 60°. To ensure accurate strain measurement, the setup involved mounting strain gauges at highly localised stress areas identified through finite element analysis (FEA).

A torque application mechanism was designed, where one end of a beam was fixed in the inner hub of a torque sensor, and a controlled load was applied at the other end to induce torque on the specimen. This arrangement allowed for precise replication of real-world torque conditions. The strain gauges recorded deformation data during the loading process, while the torque sensor measured the applied torque.

The data acquisition system facilitated real-time collection and analysis of strain and stress values. The derived experimental stress value of 81.49 Pa validated the setup's effectiveness, with the results closely aligning with FEA predictions. This methodical approach accurately characterised the specimen’s stress-strain behaviour under an applied torque.

Experimentation is carried out to determine the exact strain and stress value in a specimen for Geometry C with a rib angle of 60°.

Figure 8: Experimental Setup.

Strain gauges are mounted on a highly localised stress area identified from FEA to measure strain. A load is applied to the beam at one end to apply torque to the specimen,

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and the other end of the beam is fixed in the inner hub of the torque sensor. The experimental stress value is *81.49Pa.*

RESULTS AND DISCUSSION

Stress Analysis Using Finite Element Analysis (FEA)

The FEA of various ring geometries with rib angles of 30°, 45°, 60°, and 90° was performed using ANSYS Workbench on Aluminium Alloy 6061. The stress distribution results provided insights into the mechanical behaviour of each configuration under an applied torque of 20 Nm.

Ring A geometry exhibited relatively low stress values across all rib angles, with a maximum stress of 41.01 Pa at a 90° rib angle. The stress distribution indicates this design's robustness and suitability for moderate torque applications. Ring B geometry showed moderate stress levels, peaking at 42.95 Pa for the 90° rib angle. Introducing holes on the inner and outer rings contributed to a slightly higher stress concentration than Ring A. Ring C geometry registered significantly higher stress values, particularly at a rib angle of 60°, where the maximum stress reached 88.49 Pa. The absence of cut sections on the ribs increased stiffness, leading to elevated stress concentrations.

Figure 7 graphically depicts these variations, showing stress values for different geometries and rib angles. The graph shows that stress levels increase progressively from Ring A to Ring C, with the highest stresses observed for Ring C at a 60° rib angle.

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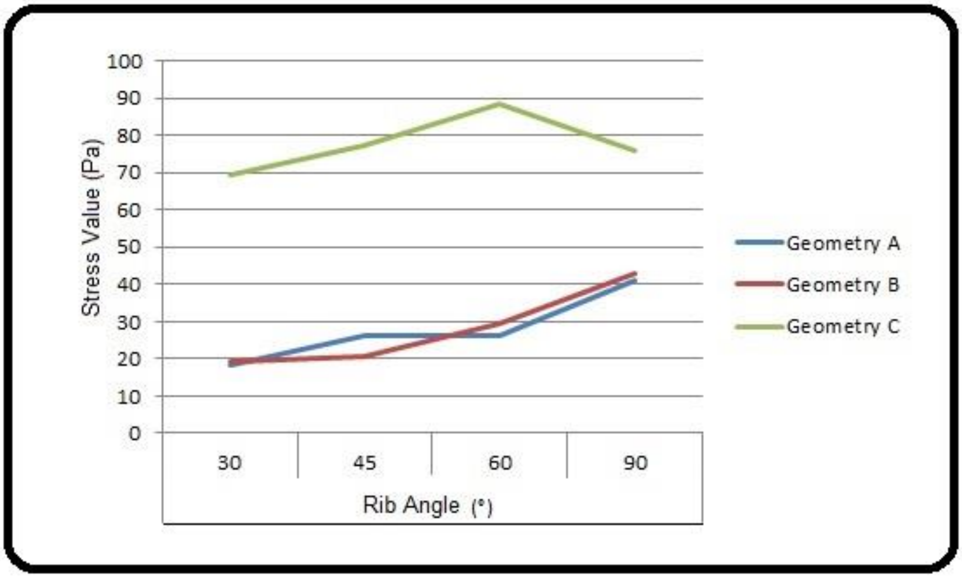

Figure 7: Variation of stress value vs. Rib angle for different geometry.

Experimental Validation

Experimentation was conducted for the Ring C geometry at a 60° rib angle. Strain gauges were mounted on areas of high stress identified from the FEA results. The applied torque induced measured stress of 81.49 Pa, consistent with the FEA prediction of 88.49 Pa, with a deviation of approximately 7.9%. The experimental data validated the computational findings and confirmed the accuracy of the FEA predictions.

Comparison with Previous Studies

The results of this study were compared with existing literature. Siradjuddin et al. (2018) highlighted the viability of low-cost materials and additive manufacturing for joint torque sensors, and our study utilising Aluminium Alloy 6061 aligns with the principles of cost-effectiveness and functionality. Kim et al. (2012) focused on minimising crosstalk and torque ripple in robot arm sensors, and our Ring A and B geometries demonstrated minimal stress concentrations, indicating potential for reduced crosstalk in practical applications.

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Kim et al. (2005) emphasised the integration of torque sensors with actuators, and our findings support the integration of Ring A geometry due to its low stress and structural simplicity. Pu et al. (2022) addressed elastomer displacement analysis for multi-axis sensors. While our study focuses on single-axis torque, the methodology can extend to multi-axis designs, particularly for configurations like Ring C with complex stress patterns.

CONCLUSION

Based on the FEA and experimental results, Ring A and Ring B geometries are more favourable for minimising stress in the joint torque sensor. Ring A geometry stands out due to its lowest stress values across most rib angles. In contrast, Ring C geometry shows higher stress levels and is less suitable for applications where minimising stress is crucial. On the other hand, it concludes that Ring C geometry at a 60° rib angle is suitable for precise strain measurement.

Design Implication

The study suggests that Ring A geometry is optimal for lightweight applications with moderate torque requirements. In contrast, Ring B geometry suits applications demanding a balance between weight and structural rigidity. Ring C geometry, though exhibiting high-stress levels, has potential applications in high-stiffness scenarios with further design optimisation.

The findings of this study contribute to the evolving field of joint torque sensor design, emphasising the interplay of geometry, material selection, and application-specific requirements.

Future Work

Future work will explore advanced materials such as Aluminium Alloy 7075-T6 for improved performance, conduct fatigue testing to evaluate long-term durability and investigate crosstalk and torque ripple for integration into robotic systems. Developing multi-axis torque sensors leveraging insights from Ring C geometry stress patterns will also be considered.

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