



Kent Academic Repository

Liu, Xuanda, Yan, Yong, Hu, Yonghui and Wang, Lijuan (2025) *Rotational Speed Measurement of a Metallic Rotor through Electret-assisted Electrostatic Sensing*. IEEE Transactions on Instrumentation and Measurement . ISSN 0018-9456.

Downloaded from

<https://kar.kent.ac.uk/108636/> The University of Kent's Academic Repository KAR

The version of record is available from

<https://doi.org/10.1109/tim.2025.3545525>

This document version

Author's Accepted Manuscript

DOI for this version

Licence for this version

UNSPECIFIED

Additional information

Versions of research works

Versions of Record

If this version is the version of record, it is the same as the published version available on the publisher's web site. Cite as the published version.

Author Accepted Manuscripts

If this document is identified as the Author Accepted Manuscript it is the version after peer review but before type setting, copy editing or publisher branding. Cite as Surname, Initial. (Year) 'Title of article'. To be published in **Title of Journal** , Volume and issue numbers [peer-reviewed accepted version]. Available at: DOI or URL (Accessed: date).

Enquiries

If you have questions about this document contact ResearchSupport@kent.ac.uk. Please include the URL of the record in KAR. If you believe that your, or a third party's rights have been compromised through this document please see our [Take Down policy](https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies) (available from <https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies>).

Rotational Speed Measurement of a Metallic Rotor through Electret-assisted Electrostatic Sensing

Xuanda Liu, Yong Yan, *Fellow, IEEE*, Yonghui Hu, *Senior Member, IEEE*,
and Lijuan Wang, *Senior Member, IEEE*

Abstract—The rotational speed monitoring of rotating machinery is required in many industrial processes. Electret marker tracking provides a new approach to improving the performance of electrostatic sensors in rotational speed measurement of metallic rotors. This paper proposes a technique for monitoring the rotational speed of a metallic rotor using an electrostatic sensing system with electret markers on the rotor. The impact of the geometric shape, size, number, and arrangement of electret markers on the sensing characteristics of the sensor are analysed through numerical simulation, leading to the optimisation of the design of the markers. Experimental tests were conducted with a metallic rotor with attached markers made from five types of material, including fluorinated ethylene propylene (FEP), polytetrafluoroethylene (PTFE), polyimide (PI), polyethylene terephthalate (PET), and polyvinyl chloride (PVC). The performance of the measurement system is assessed in terms of accuracy, reliability, and rangeability. Experimental results indicate that, FEP electret exhibits superior charge affinity as markers than the other materials. The lower end of the measurement range is as low as 1 rpm (revolution per minute). The measurement system yields a relative error within $\pm 3\%$ over the range of 1 to 3000 rpm with a repeatability of 4.8%. While ensuring the minimum measurable speed (1 rpm), the upper limit of the distance between the rotor surface and the electrodes is 4 mm.

Index Terms—Rotor, rotational speed, electrostatic sensors, tachometer, electret.

I. INTRODUCTION

ROTATIONAL machinery is a common component in mechanical systems, often used in various industrial sectors. Rotational speed is an important indicator of its operational status, which is crucial for system control, adjustment, and potential fault detection [1], [2], [3].

Traditional techniques for rotational speed measurement often pose challenges such as limited accuracy, susceptibility to environmental factors, and the need for physical contact with the rotating elements. Electrostatic sensing-based speed measurement technique offers a simpler structure, lower cost, easier installation and maintenance compared to other

techniques [4]. Moreover, since the correlation signal processing technique focuses solely on the similarity between signals rather than their amplitudes, environmental factors, such as temperature, humidity, dust around the rotor, and mechanical vibration have little impact on the operation of the electrostatic measurement system coupled with correlation algorithms [5]. Therefore, the electrostatic sensing technique holds vast potential for industrial applications.

A series of theoretical and experimental studies have been conducted on electrostatic sensors for rotational speed measurement in recent years [5], [6], [7], [8]. Wang et al. [5], [9], [10] investigated the impact of electrode number and sensor arrangement on the performance of rotational speed measurement. In view of the complexity of the mechanical structure required for the installation of multiple electrostatic sensors, a combination of separate electrostatic sensors [5] with a single electrode is not suitable for monitoring large-scale rotors. Dual-electrode sensors, due to their simple structure, ease of installation, and wider rangeability compared to single-electrode sensors, are more suitable for practical applications [9]. To address the challenge posed by the conductivity of metallic rotors in the application of electrostatic sensors, a method of marker tracking has been proposed. By attaching small dielectric markers to the rotor surface, effective outputs are generated from the electrostatic sensor, making it possible to measure rotational speed [11] and vibration displacement of a metallic rotor [12]. However, the effects of material type, charge quantity, and geometric parameters (size, number, and arrangement) of the markers on sensing characteristics remain unknown. Therefore, it is essential to optimise the marker design and assess the performance of electrostatic sensors in conjunction with the markers. Finite element modeling has been proven to be an effective approach for optimising the geometric parameters of electrodes, and it can similarly be applied to markers. Furthermore, due to the extremely low charge level on the surface of common dielectric markers at very low speeds, which are insufficient to generate effective output signals from the sensor, as reported in previous studies [11], electrostatic sensors can only measure speeds above 30 rpm (revolutions per minute). Materials carrying quasi-permanent charges

Manuscript received Month xx, 20xx; revised Month xx, 20xx; accepted Month xx, 20xx. The Associate Editor coordinating the review process was xx. (Corresponding author: Lijuan Wang)

Xuanda Liu and Yonghui Hu are with the School of Control and Computer Engineering, North China Electric Power University, Beijing 102206, China (e-

mail: liuxd@ncepu.edu.cn; huyhui@gmail.com).

Yong Yan is with Hangzhou International Innovation Institute, Beihang University, Hangzhou 311115, China (e-mail: yongyan@buaa.edu.cn).

Lijuan Wang is with the School of Engineering, University of Kent, Canterbury, Kent CT2 7NT, UK (e-mail: l.wang@kent.ac.uk).

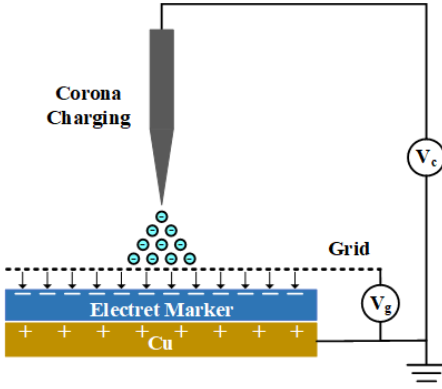


Fig. 1. Schematic of the corona discharge device.

(Electrets), are known for their ability to retain charges stably over time and across a range of environmental conditions [13], have been widely used in energy harvesters [14] and MEMS devices [15], offer the potential for further improving the rangeability, accuracy, and repeatability of electrostatic sensors for rotational speed measurement. The novelty of this paper lies in the combination of electret marker tracking with electrostatic sensing technique for the rotational speed measurement of metallic rotors. Through the optimised design of the markers, the accuracy, repeatability, rangeability, and sensing distance of electrostatic sensors are improved significantly. In this work, an electret-assisted electrostatic sensing system is designed and constructed. The geometric parameters, number, and arrangement of electret markers are optimized through theoretical analysis and computational modeling. Markers made of several electret materials are tested on a rotor rig. The performance of the electret-assisted electrostatic sensing system is assessed.

II. MEASUREMENT PRINCIPLE AND SYSTEM DESIGN

A. Electrification mechanism of electret markers

Due to the low levels of triboelectric charge on the surface of dielectric markers on a rotor at low speeds, the magnitude of signals from electrostatic sensors are low, thereby affecting the accuracy and repeatability of speed measurement. Therefore, to improve the charge levels on the marker surface and hence maintain reasonable accuracy of rotational speed measurement and extend the lower limit of speed measurement, dielectric materials with good charge affinity and stability are pre-treated through charge injection. The charged materials, i.e. electrets, are then used as markers. Electrets are able to maintain electrostatic charges on their surface through time and can keep an electric field for years due to the charge trapping phenomenon. The dissipation process of the injected charge under different environmental conditions is also prolonged [13]. The charge carried by the electrets is mainly acquired through the following two forms of charging mechanism:

1) Charge injection

Grid-controlled corona charging is a stable and effective method for charge injection [16], which is capable of preparing electrets with uniformly distributed charges. Fig. 1 shows a schematic of the corona charging setup. The charging device

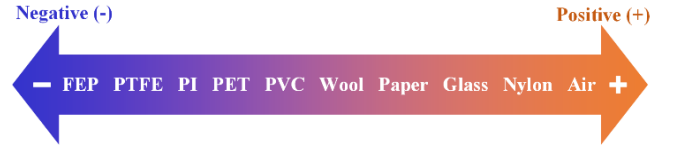


Fig. 2. Triboelectric series [17], [18].

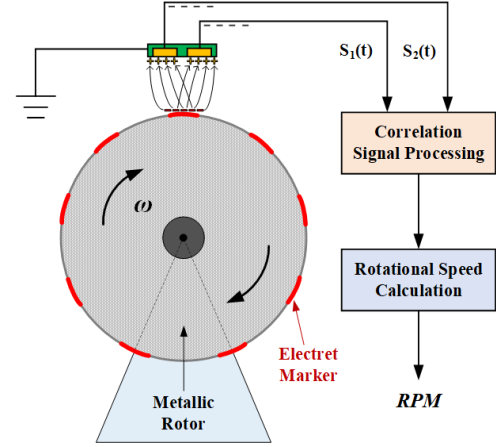


Fig. 3. Principle of electret-assisted electrostatic sensors for speed measurement.

consists of a needle-grid-plane structure, where the needle electrode is subjected to a negative high voltage (V_c), and ionizes the air to generate plasma. Then ions are injected into the near-surface of the dielectric material. The grid with voltage V_g is used to limit the surface potential of the electret and improve the uniformity of charge distribution on its surface.

2) Triboelectric effect

After charge injection, the surface charge of the electret is uniformly distributed and remains stable for an extended period of time. Due to the triboelectric effect of the rotor, the surface of the electret marker on the rotor comes into contact with air, causing secondary charging. The level of triboelectric charge depends mainly on the material type of the marker, rotational speed, and environmental factors such as humidity. Materials with higher charge affinity typically act as charge receptors, while those prone to lose charge act as charge donors. Fig. 2 lists the triboelectric series of some common non-metallic materials [17, 18]. The charge on the surface of the electret marker originates from both charge injection and triboelectric charging effect.

B. Measurement principle

The principle of the rotational speed measurement system for metallic rotors is shown in Fig. 3. The details of the principle have been introduced in earlier work [11]. The rotational speed obtained using the autocorrelation and cross-correlation algorithms are expressed as follows

$$\begin{cases} RPM_{auto} = \frac{60}{T} \\ RPM_{cross} = \frac{30\alpha}{\pi\tau} \end{cases} \quad (1)$$

where T represents the rotation period of the marker, τ is the transit time of the marker passing through the upstream and downstream electrodes, and α is the central angle between the

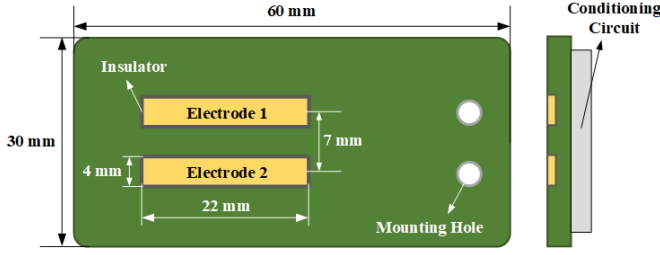


Fig. 4. Structure of dual-electrode electrostatic sensor.

two electrodes. For a given data length l for correlation signal processing, the threshold speed for algorithm switching is determined from

$$RPM_{threshold} = \frac{120}{l} \quad (2)$$

where the threshold is the minimum speed obtained from the autocorrelation algorithm [11]. When the rotational speed is below the threshold, only the cross-correlation algorithm is used for speed calculation. The minimum measurable speed of the cross-correlation algorithm is the lower limit of the speed measurement. On the contrary, if the rotational speed is the same or greater than the threshold, the measured speeds from both autocorrelation and cross-correlation are fused with their correlation coefficients as the weighting factors [8].

C. Sensor design

The optimal design of the dual-electrode electrostatic sensor has been reported in previous papers [11], [19]. The diameter (D) of the rotor used in this study is 60 mm. The electrodes are part of a printed circuit board, hence the electrodes are flat. Based on the optimisation results, as shown in Fig. 4, the electrodes are all strip-shaped. The width (W_e) and length (L_e) of the electrode are set to $(1/15)D = 4$ mm and $(11/30)D = 22$ mm respectively. The spacing (d) between the two electrodes is $(7/60)D = 7$ mm. The signal conditioning circuit is mounted on the other side of the printed circuit board (Fig. 4).

III. OPTIMISED DESIGN OF ELECTRET MARKERS

A. FEM modeling

The geometric properties of electret markers have a significant impact on the sensing characteristics of the electrostatic sensor. Unlike previous studies focused on electrode optimization [11], this paper applies finite element modeling to optimise the marker design. The charge distribution on the marker surface is assumed to be uniform after both corona charging and triboelectric charging. As shown in Fig. 5, the physical model of the sensing system consists of a metallic rotor with a diameter of D , several thin electret markers attached to the surface of the rotor, and two strip-shaped electrodes.

As shown in Fig. 6, the surfaces of the electret marker and electrodes are divided into n and m grids, respectively. On the basis of the modeling of a single-point charge [11], the marker is considered as a collection of n point charges uniformly distributed on the marker. Finite element method is used to obtain the spatial position information of each grid in the

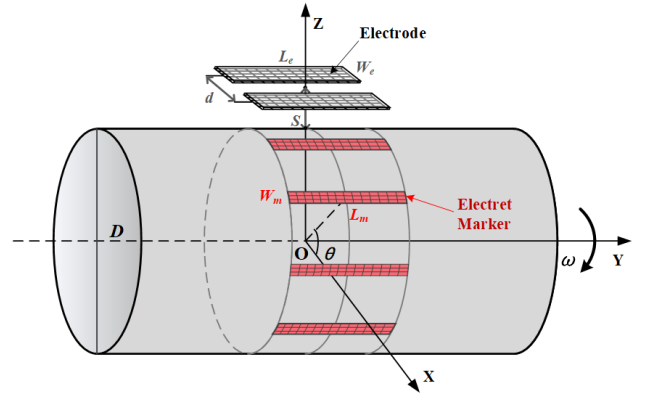


Fig. 5. Physical schematic of the sensing model.

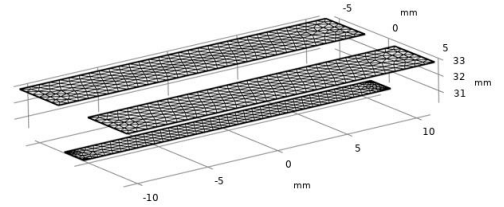


Fig. 6. FEM model of the electrostatic sensor and the marker.

electrode and marker. The area of the i^{th} electrode grid is denoted as A_i . Based on the principle of electrostatic induction and Gauss's law, the potential (φ_j) within the j^{th} grid of the electrode is given by

$$\varphi_j = \frac{1}{4\pi\epsilon_0} \left(\sum_{k=1}^n \frac{q_k}{r_{kj}} + \sum_{i=1}^m (\sigma_s)_i \int_{A_i} \frac{1}{r_{ij}} dA \right) = 0 \quad (3)$$

where q_k is the charge quantity within the k^{th} grid of the marker, r_{kj} is the center-to-center distance from the k^{th} marker grid to j^{th} electrode grid, and r_{ij} is the center-to-center distance from grid i to j of the electrode. By solving (3), the charge density matrix σ_s on the electrode surface is obtained. The total induced charge on the electrode surface $Q(t)$ and the output response $I(t)$ are determined from [11]

$$Q(t) = \sum_{i=1}^m [(\sigma_s)_i \times A_i] \quad (4)$$

$$I(t) = \frac{dQ(t)}{dt} \quad (5)$$

The spatial sensitivity $S_s(t)$ of the sensor is defined by [19]

$$S_s(t) = \left| \frac{Q(t)}{q} \right| \quad (6)$$

where q is the inducing charge on the surface of electret markers. Then, the frequency response of the sensor is represented by the power spectrum of the output response

$$S_I(f) = \int_{-\infty}^{+\infty} R_I(\tau) e^{-j2\pi f\tau} d\tau \quad (7)$$

$$R_I(\tau) = \int_{-\infty}^{+\infty} I(t) I(t+\tau) dt \quad (8)$$

where $S_I(f)$ is the power spectrum density (PSD) and $R_I(\tau)$ is the autocorrelation function of sensor output response $I(t)$. Finally, the sensing characteristics are quantified through these metrics

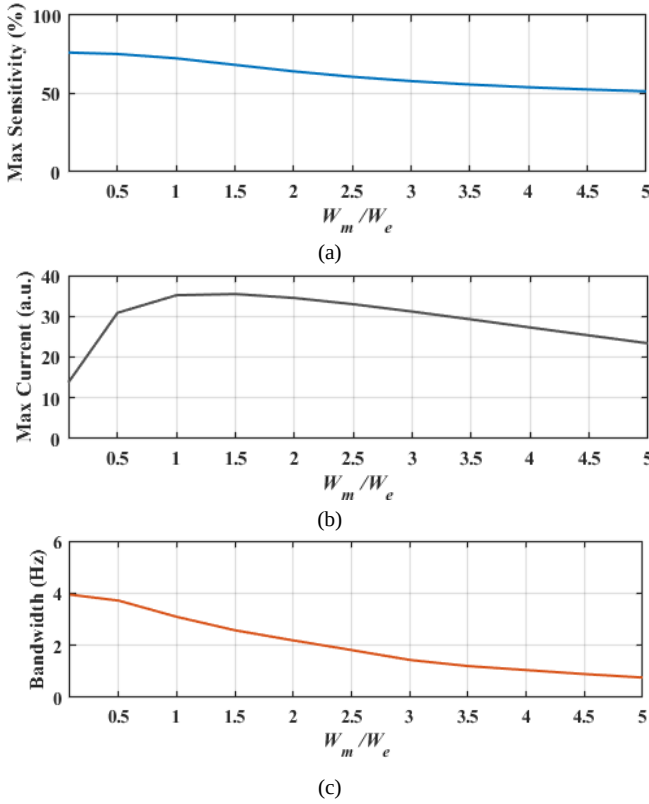


Fig. 7. Influence of marker width on sensing characteristics. (a) Maximum spatial sensitivity. (b) Maximum output response. (c) Signal bandwidth.

of the electrostatic sensor.

B. Optimisation of electret markers

1) Size of markers

As a simple, easy-to-prepare shape, the strip-shaped marker helps to homogenize its surface charge distribution and the spatial sensing volume of the electrostatic sensor [19], [20]. Therefore, this study focuses on optimizing the structural parameters of strip-shaped markers.

The number of finite element grids (n) for the marker and the distance between marker grids and electrode grids (r_{kj}) depends on the size of the electret marker. Based on the control variable method, the normalized length of the strip-shaped marker is initially set as a constant ($L_m/L_e = 1$, Fig. 5), then the sensing characteristics are analyzed while varying the normalized width (W_m/W_e , Fig. 5) from 0.1 to 5. The effects of the marker width on the spatial sensitivity, output response, and bandwidth are shown in Fig. 7.

The results in Fig. 7 imply that spatial sensitivity and signal bandwidth decrease with the marker width. This is because the cross-section of the marker attached to the rotor surface is arc-shaped. Although the quantity of charge on the marker increases with its width (W_m), the maximum region F_V (field of view) where the electrode can detect charge changes is fixed, and the sensor is highly sensitive to sensing distance (r_{kj}). Changes in marker charge outside the F_V do not significantly affect the induced charge on the electrode surface. The amount of charge on the electrode surface first increases and then remains almost unchanged. Consequently, it can be explained from (6) that spatial sensitivity decreases gradually (Fig. 7(a)).

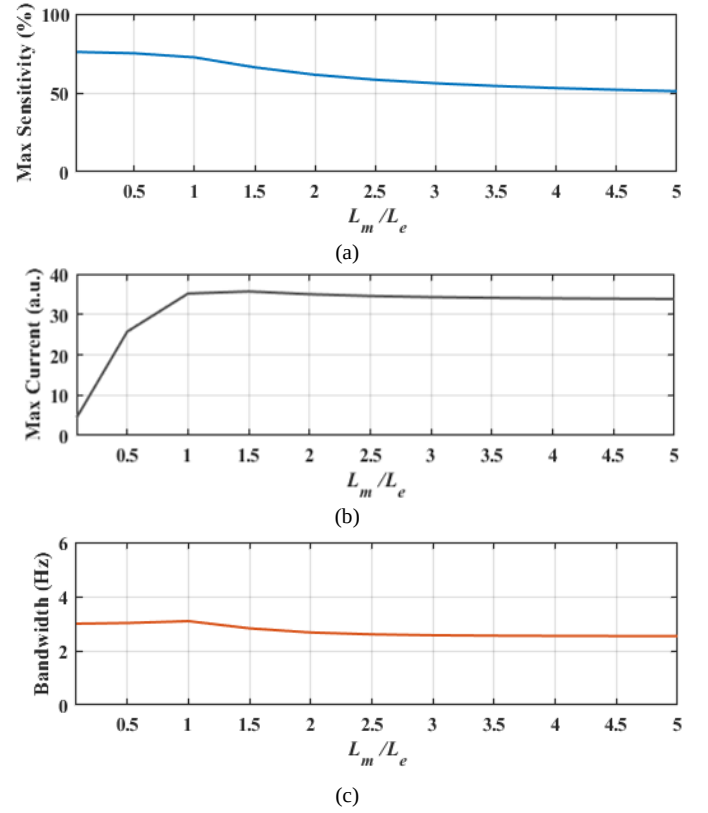


Fig. 8. Influence of marker length on sensing characteristics. (a) Maximum spatial sensitivity. (b) Maximum output response. (c) Signal bandwidth.

This is also why the maximum output response (gradient of induced charge quantity) initially increases and then decreases (Fig. 7(b)). In addition, the increase in width causes the transition of the marker from entering to exiting the F_V happens more slowly, resulting in a lower output signal frequency. Therefore, the signal bandwidth decreases with the marker width (Fig. 7(c)). When the marker width exceeds the electrode width, the change in the induced charge as the marker passes is more gradual because, at any given time, only a portion of the marker influences the electrode. According to (5) and (6), the maximum spatial sensitivity and output response decrease significantly. Therefore, to ensure optimal sensing characteristics, the marker width is chosen to be within the range of $(1/2)W_e - W_e$.

Similarly, assuming the normalized width is constant ($W_m/W_e = 1$), the variation in sensing characteristics is obtained as the length (L_m/L_e) changes from 0.1 to 5, as shown in Fig. 8.

As the marker length increases, the amount of surface charge increases. When the length of the marker continues to increase beyond the F_V of the sensor, the change in the induced charge on the electrode surface slows down until it stabilizes, resulting in a decrease in spatial sensitivity (Fig. 8(a)). When the length of the marker exceeds the electrode length, the output response remains almost constant (Fig. 8(b)). Additionally, the increase in length does not change the transition of the marker passing through the electrode, hence the marker length has a minimal impact on the signal bandwidth (Fig. 8(c)). Therefore, the optimal marker length is equal to the electrode length.

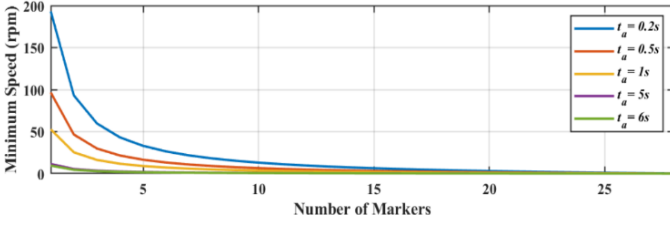


Fig. 9. Relationship between the number of markers, data length, and speed limit.

2) Number and arrangement of markers

For a metallic rotor, the sensor only generates valid signals when the marker on its surface passes through the electrode region (field of view F_v). Therefore, the number and arrangement of markers affects the response time of the sensor significantly. Assuming the number of markers on the rotor surface is N_m , the sensor signal within one revolution consists of N_m pulses. Clearly, for a given sampling frequency, different numbers and arrangements of markers have no effect on the autocorrelation algorithm but will alter the number and intervals of pulses in the output signal, thereby affecting the data length (l_{cross}) required for the cross-correlation algorithm and the theoretical lower limit of speed measurement ($RPM_{crossmin}$). Based on the theoretical analysis results when a single marker is attached [11], it is essential to ensure that the upstream and downstream signals exhibit clear similarity within the data length. The relationship between the data length required for the cross-correlation algorithm and the speed limit with N_m markers attached are expressed as

$$l_{cross} \geq \frac{T_{max}}{N_m} - \tau_{max} = \frac{60\pi - 30\alpha N_m}{N_m \pi RPM_{crossmin}}. \quad (9)$$

The relationship among the three is shown in Fig. 9. It can be seen that as the number increases, both the required data length and the speed limit decrease. For steady-speed measurement, a longer data length is required to fully capture the signal within the range of delay time, lower speeds can be measured by increasing the data length (l_{cross}). However, dynamic speed measurement requires a shorter response time, thus the data length should be kept as small as possible. Therefore, there is a trade-off between the number of markers and the data length.

The arrangement of markers needs further consideration. Firstly, to ensure the maximum sensitivity of the sensor, the rotational trajectory of markers should be aligned with the center of the electrodes. Furthermore, for a given data length (l_{cross}), when the markers are unevenly distributed on the rotor surface, the spacing between adjacent pulses in the output signal varies. This inevitably reduces the reliability of cross-correlation operations, resulting in discontinuous or erroneous measurement results. Therefore, markers should be arranged as evenly as possible on the rotor surface.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Marker design

Based on the optimisation results of the marker, the strip shape is considered as the optimal marker shape, with the

TABLE I. PROPERTIES OF DIFFERENT ELECTRET MATERIALS

Material	Surface roughness
FEP	Ra-0.43
PTFE	Ra-0.47
PI	Ra-0.40
PET	Ra-0.40
PVC	Ra-0.51

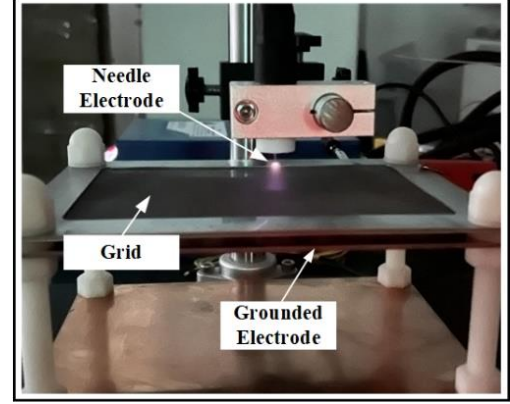


Fig. 10. Corona charging device.

optimal width between 0.5 and 1 of electrode width, and the optimal length being equal to the length of the electrode. Therefore, in the experiment section, the width and length of the marker are set to $(1/2)W_e = 2$ mm and $L_e = 22$ mm, respectively. Moreover, since the focus of this study is on the measurement of steady-state rotational speed, and the number of markers mainly affects the dynamic measurement performance of the sensor, there are no specific requirements for the number of markers in this study. A total of nine markers are used for experiments.

To evaluate the speed measurement performance of electrostatic sensor using different electret materials as markers, five common low-cost electret film materials (FEP, PTFE, PI, PET, PVC) with a thickness of 80 μ m listed in Table I, are selected for experimental analysis. The surface roughness of the materials has a significant impact on their charge storage capacity. Due to the varying manufacturing processes of different film materials, it is challenging to ensure strictly identical roughness. Therefore, materials with similar roughness are chosen for analysis in this study.

These markers were pre-charged on a corona discharge device as shown in Fig. 10. Before charging, the marker surface was wiped with ethanol and dried to remove surface electrostatic charges. The needle electrode voltage is set as $V_c = -15$ kV, while the copper plate electrode is connected to the ground, the grid electrode voltage is $V_g = -0.8$ kV, and the charging duration is 15 minutes. After charging, the surface voltage of the electret marker is approximately equal to the voltage of the grid electrode. The charge distribution on the surface of markers is approximately uniform. Electret markers were then fixed evenly on an aluminium foil tape and attached to the rotor surface.

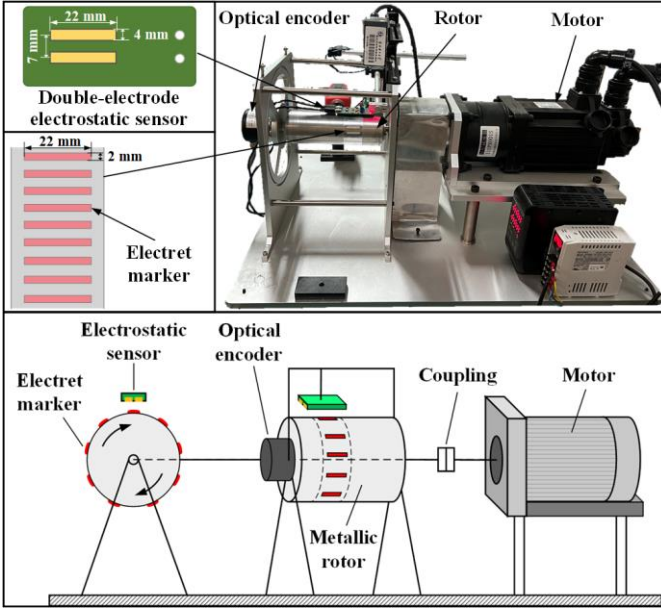


Fig. 11. Motor test rig.

B. Experimental setup

Experimental tests were conducted on a purpose-built test rig as shown in Fig. 11. The metallic rotor is driven by a servo motor, and the rotational speed is adjusted within the range from 0 to 3000 rpm with a minimum increment of 1 rpm. The electrostatic sensor was placed 2 mm away from the rotor surface. For an electrode spacing $d = 7$ mm, central angle $\alpha = 0.218$ rad, and a relative error tolerance $\delta = \pm 1.5\%$ in correlation algorithms, a sampling frequency of 50 kHz is deemed sufficient to meet the measurement requirements [11]. A commercial optical rotary encoder (Atonics, model E40H12) with a resolution of 2500 pulses per revolution (ppr) was used as the reference tachometer. According to early research, temperature and humidity can affect the output magnitude of the sensor [20], [21]. Therefore, all the tests were conducted under controlled ambient conditions with a temperature of $20 \pm 2^\circ\text{C}$ and a relative humidity of $42 \pm 3\%$.

C. Measurement results

1) Sensor signals

Fig. 12 illustrates typical output signals from the electrostatic sensor at extremely low rotational speeds (10 rpm) when electret markers (charged) and triboelectric markers (uncharged) are attached to the rotor surface. It can be observed that, due to the weak triboelectric effect at low speeds, the charge level on ordinary triboelectric markers is extremely low, leading to almost no fluctuation of signal as markers pass through the electrode. In contrast, the introduction of electret material significantly enhances the pulse intensity and signal-to-noise ratio, as the injected charge enhances sensor output signals.

To observe the impact of different electret materials on signal strength and correlation function, output signals and cross-correlation functions are obtained at low speeds (10 rpm), as shown in Fig. 13. It can be seen that, even at extremely low speeds, the electret marker ensures the signal quality. The FEP

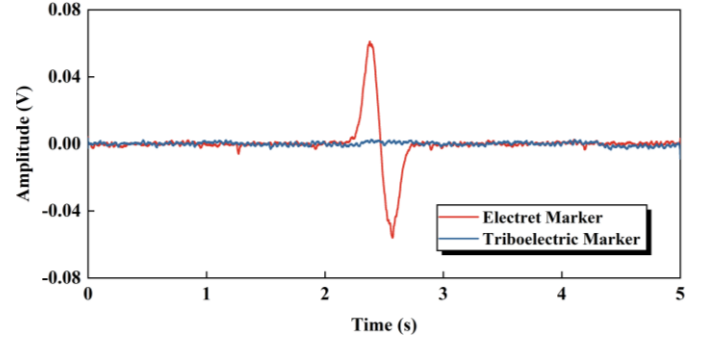
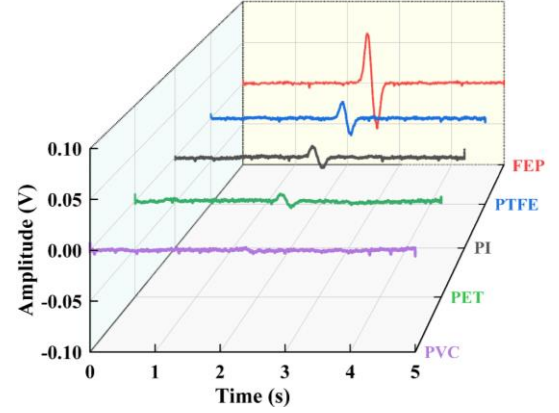
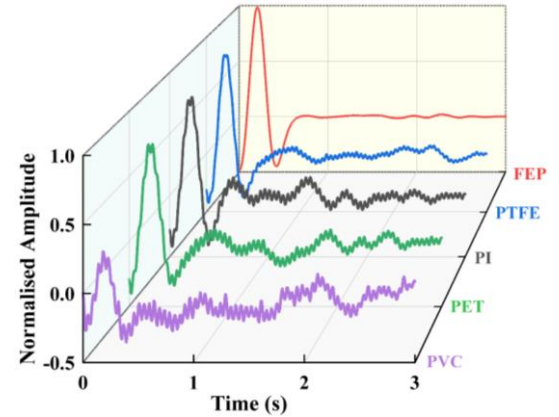


Fig. 12. Typical signal waveforms for electret and triboelectric markers (10 rpm).



(a)



(b)

Fig. 13. Typical sensor signals and resulting cross-correlation functions (10 rpm). (a) Signal waveforms. (b) Resulting cross-correlation functions

electret shows significant advantages in both signal amplitude and correlation coefficient, with smaller fluctuations and stable peak values in the cross-correlation function, which is important to maintain the accuracy of low-speed measurement.

2) Signal amplitude

In addition to environmental factors (temperature and humidity), the amplitude of the sensor signal depends also on the material type of the marker, surface roughness, and rotational speed. The impact of the rotational speed on the signal strength under given environmental conditions and surface roughness is shown in Fig. 14. It can be seen that, as the speed increases, the surface of charged electret markers

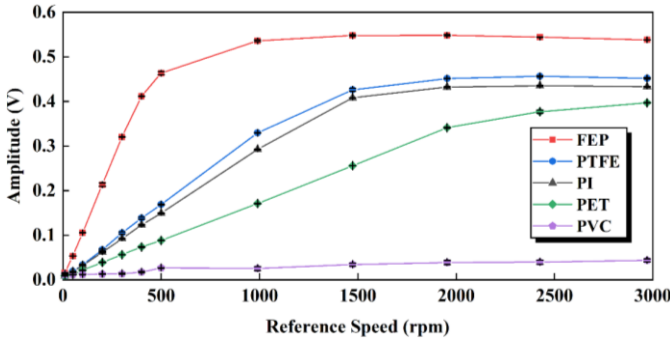


Fig. 14. Signal amplitude as a function of rotational speed for different electret materials.

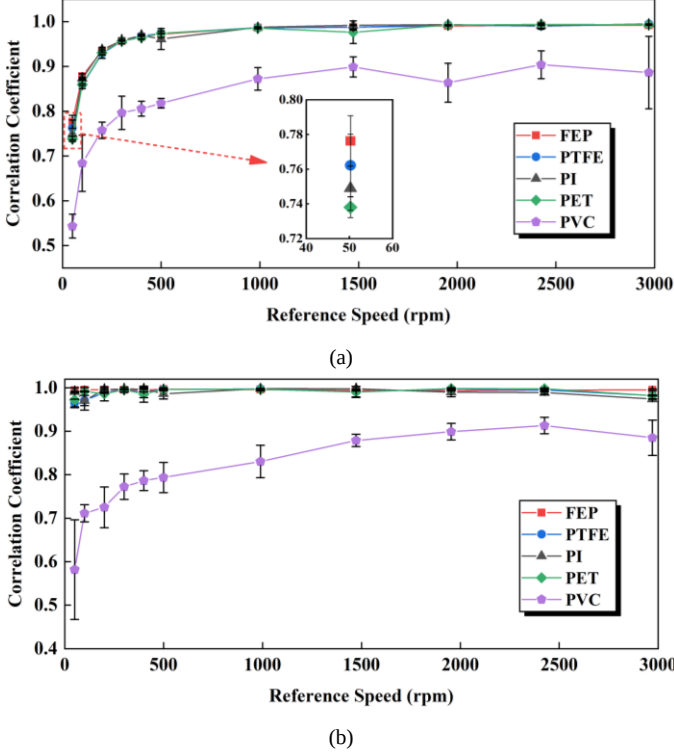


Fig. 15. Correlation coefficients of different electret materials. (a) Autocorrelation coefficients. (b) Cross-correlation coefficients.

accumulates more triboelectric charge, resulting in a higher signal amplitude. When the FEP electret marker is attached, the amplitude of the signal remains higher than that from the other electret materials of the same size and reaches saturation (0.54 V) around 1500 rpm, indicating that the FEP marker surface accumulates the highest electrostatic charge during rotation. On the contrary, due to the relatively weak charge affinity of PVC, the quantity of injected charge and triboelectric charge on the PVC marker is significantly lower than other materials. These results are consistent with the triboelectric series shown in Fig. 2.

3) Correlation coefficient

The relationship between the correlation coefficient and the rotational speed is shown in Fig. 15. It can be observed that both the autocorrelation and cross-correlation coefficients increase with speed and then stabilize. This is also attributed to the accumulation and saturation of charges during the rotation process. Since the transit time (τ) of the marker passing through

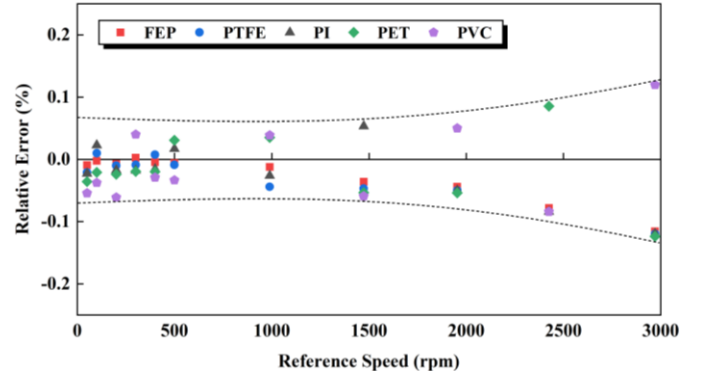


Fig. 16. Accuracy of the measured speed with different electret materials attached (50 – 3000 rpm).

adjacent electrodes is much smaller than the rotation period (T), and the charge variation of the marker is not significant, the cross-correlation coefficients for the same material type are consistently higher than the autocorrelation coefficients. Except for the PVC material, the correlation coefficients for the other four electret materials are very close, the autocorrelation coefficients are all above 0.7, and the cross-correlation coefficients are above 0.95. However, there are still significant differences at extremely low speeds (Fig. 15(a)). Due to the strong charge affinity of the FEP electret marker (Fig. 2), it exhibits the highest correlation coefficients in the speed range below 200 rpm. In contrast, correlation coefficients corresponding to PVC electret markers in both cases are significantly lower than those of other materials and fluctuate more.

4) Accuracy

The accuracy of the speed measurement system is quantified in terms of relative error. The measured speed is an average of 30 repeated measurements. The relative errors of speed measurement for different types of electret markers are plotted in Fig. 16. The dashed lines represent the error range. It can be seen that all five types of markers achieve speed measurements above 50 rpm. When the FEP marker is used, the accuracy is consistently higher than that with other materials with relative errors within $\pm 0.11\%$. At lower speeds, the triboelectric charge on the surface of the markers is insufficient, the quality of the output signal depends on the quantity of injected charge. The different capabilities of the electret materials in retaining the injected charge result in the differences in the relative error. As the speed goes up, the increasing triboelectric charging effect leads to more charge accumulated on the surface of the markers and hence improved signal quality. At one point, the influence of material type diminishes so that the resulting relative errors for different materials are closer to each other. For a given sampling frequency, a higher speed results in a larger error in determining T and τ , ultimately leading to a reduced accuracy of the measured speed. This outcome is consistent with previous findings [11].

5) Repeatability

The normalized standard deviation is used to assess the repeatability of the measurement system. Due to the outstanding charge affinity and retention capability of the FEP

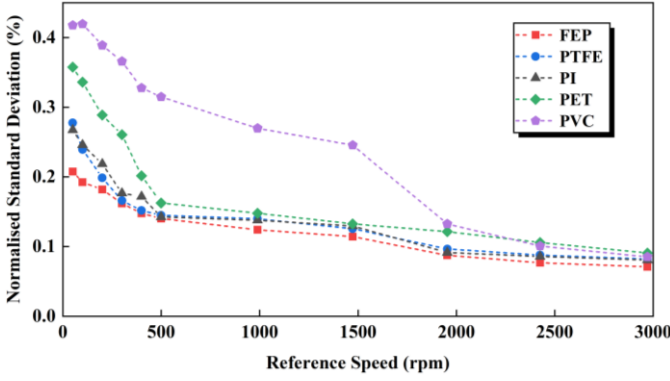


Fig. 17. Repeatability as a function of the rotational speed for different electret materials.

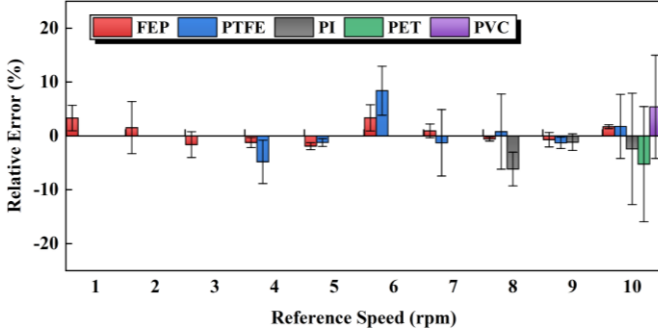


Fig. 18. Relative error of the measured speed with different electret materials attached (0 – 10 rpm).

marker, the normalized standard deviation of the measurement results is consistently the lowest ($<0.2\%$), as shown in Fig. 17. Moreover, as the rotational speed increases, the charge on the surface of each marker continues to accumulate, the location of the dominant peaks in correlation functions tend to stabilize, leading to improved repeatability.

6) Rangeability

At very high speeds, the data fusion algorithm is used to obtain the measured speed. At this point, the amplitude of the pulsed signal is very stable, and measurement error mainly stems from the uncertainty in T and τ determination. At the maximum speed of the rotor used in this study (3000 rpm), the measurement accuracy completely meets the requirements of the relative error tolerance (δ) (Fig. 16).

To assess the performance of the measurement system under extremely low-speed conditions with different electret markers and explore the lower limit of the measurable speed, another set of experiments was conducted over the range from 0 to 10 rpm with a step size of 1 rpm. The cross-correlation algorithm is used for speed calculation in this case. The relative error and repeatability of speed measurement are plotted in Fig. 18. The results indicate that the quality of the sensor signals at low speeds significantly improves after using the charged electret as a marker, thereby the rangeability of the system is effectively extended. It can be observed from Fig. 18 that, when FEP is used as a marker, the system is capable of measuring rotational speeds as low as 1 rpm with a relative error within $\pm 3\%$ and repeatability $<4.8\%$. The minimum measurable speed for PTFE, PI, PET, and PVC markers are 4, 8, 10, and 10 rpm, respectively.

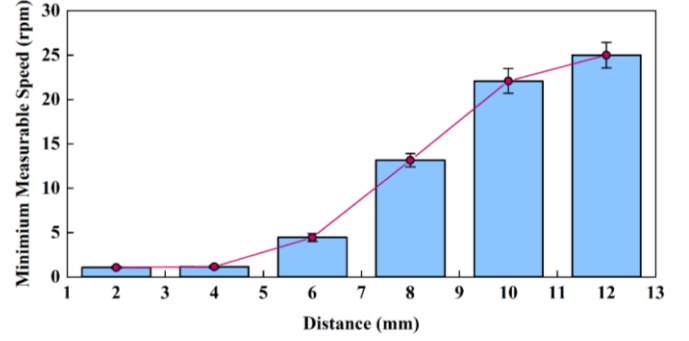


Fig. 19. Minimum measurable speed at different distances.

In summary, the FEP marker has outperformed all other markers in terms of signal amplitude, correlation coefficients, accuracy, repeatability, and rangeability. Therefore, FEP electret should be considered as the ideal marker material. The rangeability of the electret-assisted electrostatic sensing system is further extended (1 – 3000 rpm). The resolution of the speed measurement represents the resolution of the transit time, which depends on the sampling frequency (f_s) of the measurement system. With reference to the findings from previous studies [11], there has been an improvement in the performance of the measurement system as a result of the use of the electret markers. To minimize potential interference of the markers with the rotor operation and ensure an adequate safety clearance, the thickness of the marker should not be too large. Furthermore, since the conductive nature of metallic rotors ensures that the electrostatic interaction between the markers and the rotor surface is consistent, electret-assisted electrostatic sensors are effective for various metallic rotors.

7) Upper limit of the distance between the rotor and the electrode

The distance between the rotor surface and the electrodes is a critical factor affecting the signal amplitude and the accuracy of the measured speed. Therefore, it is essential to further determine the lower limit of the measurable speed for different sensor distances. When the FEP markers are attached to the rotor surface, and the upper limit distance is determined by gradually increasing the distance of the sensor from the rotor surface until the measured speed becomes erroneous or unstable. As shown in Fig. 19, speed measurements as low as 1 rpm are achieved when the distance between the rotor and the electrodes is within 4 mm. Additionally, the repeatability of the lowest speed measurement deteriorates with increasing distance.

V. CONCLUSIONS

A technique for measuring the rotational speed of a metallic rotor using electret-assisted electrostatic sensors has been proposed. The shape, size, number, and arrangement of electret markers have been optimised through finite element modeling. It can be concluded that the strip shape is the optimal marker shape, with the optimal width falling within the range of $(1/2)W_e - W_e$ and the optimal length equal to the electrode length (L_e). The number of markers depends on the requirements for the dynamic characteristics of the measurement system, and the markers should be evenly spaced along the rotational trajectory of the rotor. The performance of

the electret-assisted electrostatic sensor for speed measurement of a metallic rotor has been assessed using different electret materials as markers. Results obtained have indicated that the system performs best when FEP electret is used as the marker, and achieving speed measurements as low as 1 rpm. Over the range of 1 – 3000 rpm, the maximum relative error is less than $\pm 3\%$, and the repeatability is better than 4.8%. Under conditions allowing for the minimum measurable speed (1 rpm), the upper limit of the distance between the rotor and the electrode plane is 4 mm. In future research, further investigation will be conducted into the dynamic response characteristics of the measurement system. Meanwhile, the influence of environmental factors such as ambient temperature, relative humidity, dust level etc.) on the performance of the measurement system will also be evaluated.

REFERENCES

- [1] Y. Yan, Y. Hu, L. Wang, X. Qian, W. Zhang, K. Reda, J. Wu and G. Zheng, "Electrostatic sensors—Their principles and applications," *Measurement*, vol. 169, Feb. 2021, Art. no. 108506.
- [2] S. Lee, G. Stone, J. Daviu, K. Gyftakis, E. Strangas, P. Maussion and C. Platero, "Condition monitoring of industrial electric machines: State of the art and future challenges," *IEEE Ind. Electron. M.*, vol. 14, no. 4, pp. 158-167, Dec. 2020.
- [3] H. Mao, H. Zuo and H. Wang, "Electrostatic sensor application for on-line monitoring of wind turbine gearboxes," *Sensors*, vol. 18, no. 10, pp. 3574, Oct. 2018.
- [4] L. Li, X. Wang, H. Hu and X. Liu, "Use of double correlation techniques for the improvement of rotation speed measurement based on electrostatic sensors," *Meas. Sci. Technol.*, vol. 27, no. 2, Dec. 2015, Art. no. 025004.
- [5] L. Wang, Y. Yan, Y. Hu and X. Qian, "Rotational speed measurement through electrostatic sensing and correlation signal processing," *IEEE Trans. Instrum. Meas.*, vol. 63, no. 5, pp. 1190-1199, May 2014.
- [6] L. Li, X. Wang and H. Hu, "Speed condition monitoring of rotating machinery using electrostatic method," in *2015 9th Int. Conf. Sens. Technol. (ICST)*, Auckland, New Zealand, Dec. 2015, pp. 345-350.
- [7] L. Li, H. Hu and K. Tang, "A specially-designed electrostatic sensor for the condition monitoring of rolling bearings," *Meas. Sci. Technol.*, vol. 32, no. 3, Dec. 2020, Art. no. 035110.
- [8] L. Wang, Y. Yan and K. Reda, "Enhancing the performance of a rotational speed measurement system through data fusion," in *J. Phys.: Conf. Ser.*, Belfast, UK, September 3-6, 2018, Art. no. 072024.
- [9] L. Wang, Y. Yan, Y. Hu and X. Qian, "Rotational speed measurement using single and double electrostatic sensors," *IEEE Sens. J.*, vol. 15, no. 3, pp. 1784-1793, Mar. 2015.
- [10] L. Wang, Y. Yan and K. Reda, "Comparison of single and double electrostatic sensors for rotational speed measurement," *Sens. Actuators, A*, vol. 266, pp. 46-55, Oct. 2017.
- [11] X. Liu, Y. Yan, Y. Hu and L. Wang, "Optimization of Electrostatic Sensors for Rotational Speed Measurement of a Metallic Rotor," *IEEE Trans. Instrum. Meas.*, vol. 73, Dec. 2023, Art. no. 9501811.
- [12] K. Reda and Y. Yan, "Vibration measurement of an unbalanced metallic shaft using electrostatic sensors," *IEEE Trans. Instrum. Meas.*, vol. 68, no. 5, pp. 1467-1476, May 2019.
- [13] G. M. Sessler, "Physical principles of electrets," *Electrets*, pp. 13-80, 2005.
- [14] J. Zhu, Y. Yang, H. Zhang, Z. Zhao, T. Hu and L. Liu, "More Than Energy Harvesting in Electret Electronics - Moving toward Next - Generation Functional System," *Adv. Funct. Mater.*, vol. 33, Feb. 2023, Art. no. 2214859.
- [15] C. Sano, M. Ataka, G. Hashiguchi and H. Toshiyoshi, "An electret-augmented low-voltage MEMS electrostatic out-of-plane actuator for acoustic transducer applications," *Micromachines*, vol. 11, no. 3, pp. 267, Mar. 2020.
- [16] X. Zhang, J. Zhao, P. Xie and S. Wang, "Biomedical applications of electrets: recent advance and future perspectives," *J. Funct. Biomater.*, vol. 14, no. 6, pp. 320, Jun. 2023.
- [17] H. Zou, Y. Zhang, L. Guo, P. Wang, X. He, X., G. Dai, H. Zheng, C. Chen, A. Wang, X. Cheng and Z. Wang, "Quantifying the triboelectric series," *Nat. Commun.*, vol. 10, Mar. 2019, Art. no. 1427.
- [18] R. Zhang and H. Olin, "Material choices for triboelectric nanogenerators: A critical review," *EcoMat.*, vol. 2, no. 4, Oct. 2020, Art. no. e12062.
- [19] Y. Yan and L. Wang, "Mathematical modelling and experimental validation of electrostatic sensors for rotational speed measurement," *Meas. Sci. Technol.*, vol. 25, no. 11, Sept. 2014, Art. no. 115101.
- [20] Y. Hu, Y. Yan, L. Yang, L. Wang, X. Qian, "Online continuous measurement of the operating deflection shape of power transmission belts through electrostatic charge sensing," *IEEE Trans. Instrum. Meas.*, vol. 66, no. 3, 2017, pp. 492-501.
- [21] V. Nguyen, R. Yang, "Effect of humidity and pressure on the triboelectric nanogenerator," *Nano Energy*, vol. 2, no.5, pp. 604–608, 2013.