

Modeling and Simulation of a Gear Electrostatic Monitoring Sensor Using Ansys Maxwell 3D

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I. Introduction

Gears are critical components in mechanical transmission systems and are susceptible to failures such as tooth-surface wear and breakage under harsh operating conditions. Conventional condition-monitoring techniques often struggle to provide early warnings. Electrostatic monitoring technology has garnered significant attention due to its non-contact nature and its ability to detect charged particles generated by wear.

Existing studies have made progress in this field. In modeling, Xue Haiwei et al. clarified the relationship between probe diameter and sensitivity [1]; Deng Fangfang optimized the parameters of a ring-type sensor [2]; and Zhang Jin et al. proposed an innovative coupled simulation method [3]. Liu Ruochen et al. proposed the MWLOF algorithm to improve monitoring performance [4], while Xu Cheng et al. verified the sensor model [5]. However, existing studies still face bottlenecks in multiphysics coupling. Simulations neglect coupling effects, and parameter design lacks theoretical support. This study focuses on the coupling characteristics between the sensor and gear and on parameter optimization. A finite element model was established using Ansys Maxwell 3D to provide a new technical approach for improving sensor performance.

II. Design and Modeling of the Electrostatic Sensor

2.1 Electrostatic Sensor Design

This study used a non-contact, AC-coupled sensing method. A wear-site sensor (WSS) was designed to monitor the electrostatic signal in the wear region and capture irregularly varying AC signals in real time. The WSS has a rod-shaped structure and offers significant sensitivity advantages. Figure 1(a) shows its structural schematic.

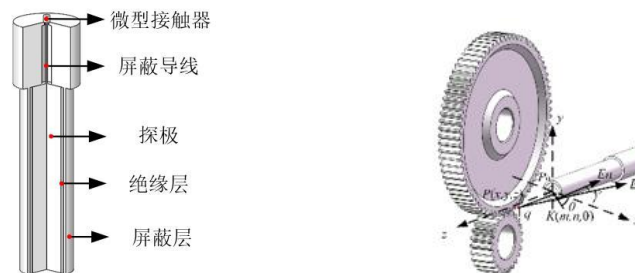


Figure 1. Schematic of the electrostatic sensor design and model: (a) Structure of the WSS; (b) Mathematical-physical model for gear electrostatic induction.

2.2 Construction of the Mathematical and Physical Models

To clarify the coupling mechanism between charged particles in the gear wear region and the sensing probe, we established a mathematical model based on electrostatic induction theory, as shown in Figure 1(b). The model focuses on the core coupling relationship among the "gear-sensor-charged particle" system. The key processes were reasonably simplified, quantitative parameters were defined, and the relationship between induced charge and electric field was derived to provide a theoretical basis for evaluating the electrostatic sensor's performance.

In Figure 1(b), a Cartesian coordinate system was established with the center of the WSS probe sensing surface as the origin. The axial direction was defined as the z-axis, the radial direction as the x-axis, and the normal direction as the y-axis. A charged particle P in the lubricating oil was considered. According to the principle of electrostatic induction and Gauss's law, the simplified relationship for the total induced charge on the probe can be expressed as:

$$|Q| \propto \frac{q \cdot R^2}{x^2 + z^2} \quad (1)$$

(Here, $|Q|$ is the total induced charge on the probe, q denotes the charge of the particle ($q = -1$ C in this study), R is the probe radius ($R = 6$ mm in this study), x is the radial distance between the particle and the probe axis, and z is the axial distance between the particle and the probe sensing surface.)

According to the equation, the charge magnitude $|Q|$ is mainly related to the particle position (x, z) and the probe radius R . To clarify further the relationship between the induced charge and these parameters, the variation in the induced charge on the WSS was investigated in detail, as shown in Figure 2.

The results show that $|Q|$ increases with the probe radius R ($R = 6$ mm and particle charge $q = -1$ C are taken as an example). $|Q|$ exhibits a symmetric distribution about the y -axis. Under a fixed axial position, $|Q|$ exhibits a hyperbolic attenuation trend with increasing x : when $x \leq 6$ mm, the attenuation is relatively gradual; at $x = 6$ mm, $|Q|$ decreases to one-half of its maximum value; when $x > 6$ mm, it gradually approaches zero.

When the radial position is fixed, $|Q|$ decreases with increasing z when $x \leq 6$ mm, whereas when $x > 6$ mm, it first increases and then decreases in a parabolic trend, indicating an optimal monitoring height.

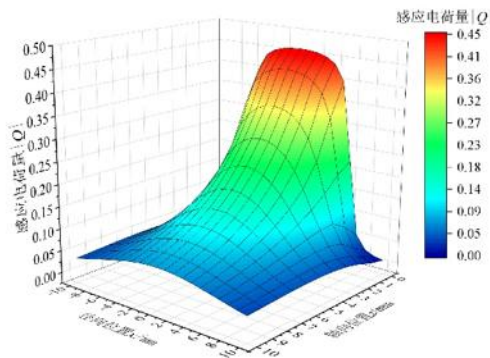


Figure 2. Variation in the induced charge on the WSS

In addition, the maximum total induced charge on the probe is always less than 0.5. This is because fewer than half of the electric field lines generated by the charged particle act on the probe, resulting in an inherent sensitivity threshold of the sensor.

Based on the mathematical model established above, a physical model of the gear electrostatic monitoring sensor was constructed using the 3D Electrostatic module in Ansys Maxwell 3D. The model was then refined through mesh generation and subjected to finite element analysis, followed by data processing and calculation. The simulation results were analyzed to verify the model's effectiveness and the validity of its parameters. Figure 3 shows the WSS simulation process.

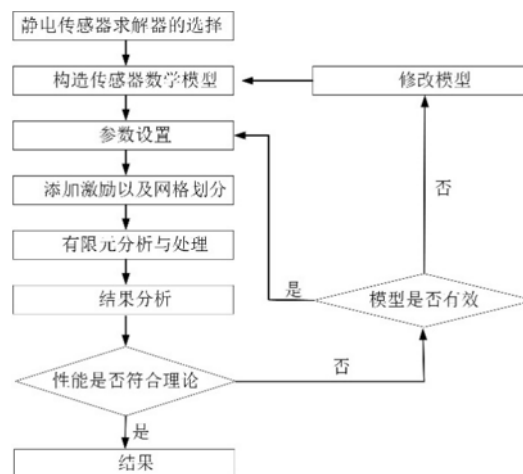


Figure 3. WSS simulation flowchart

III. Simulation Results and Analysis

3.1 Electric-Field Variation on the Probe Sensing Surface

After establishing the monitoring model, finite element simulations were performed to investigate the gear's effect on the electric-field distribution.

A charged particle at a specific spatial position is located in an electrostatic field formed by the interaction between the gear pair and the sensor structure. The resulting electric-field-line distribution exhibits distinct spatial characteristics, as shown in Figure 4.

As shown in the figure, the electric-field lines are symmetrically distributed about the WSS axis. However, due to the presence of the gear, the electric-field distribution changes and is no longer completely symmetrical. Therefore, the gear changes the electric-field-line distribution and affects the induced charge on the WSS.

Outside the circular region of the probe sensing surface, the electric-field strength tends to zero. On the probe sensing surface, the electric-field strength is higher closer to the projection point of the charged particle. This is because the induced charge in the probe concentrates toward the charged particle, forming a dense distribution of opposite charges on the side closer to it.

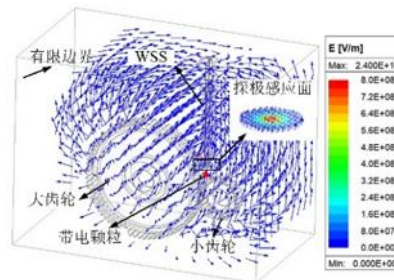


Figure 4. Electric-field-line distribution for gear electrostatic monitoring

3.2 Simulation Analysis of Spatial Sensitivity

Electric-field-strength variation and magnitude cannot directly characterize the physical characteristics of the charge-induction process. The core function of the gear electrostatic sensor is to convert the probe charge signal into an output voltage signal. Therefore, this study uses spatial sensitivity s , which directly reflects the sensor's ability to detect charged particles, as the core evaluation index and focuses on investigating and quantifying its intrinsic coupling relationship with the probe's structural parameters.

The shielding layer can effectively reduce the influence of external interference on the probe and is a key component of the WSS. Therefore, subsequent simulation analyses were conducted around the WSS. Because the gear's irregular geometry makes it difficult to accurately determine the influence of its metal body on the WSS's spatial sensitivity, a rectangular specimen made of the same material and 20 mm wide was used to replace the actual gear. This simplification was adopted to investigate the influence of the relative positions among the gear, WSS, and charged particle on spatial sensitivity while ensuring the reasonableness of the analysis.

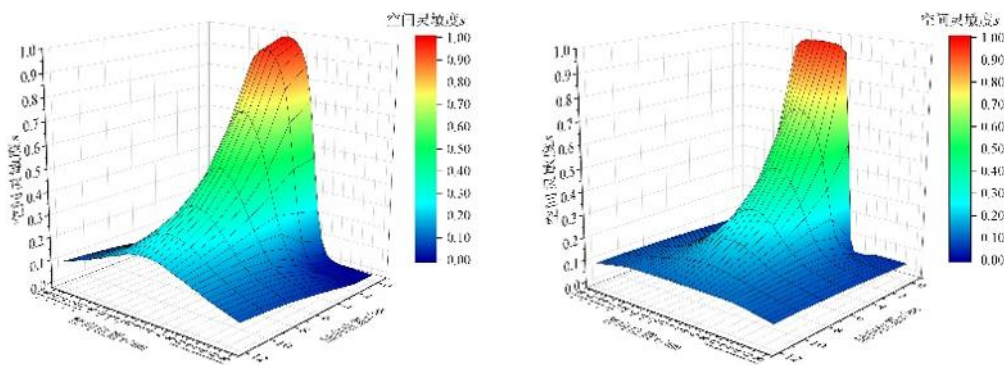


Figure 5. Influence of relative distance d on spatial sensitivity s . (a) $R = 6$ mm, $d = +\infty$ mm. (b) $R = 6$ mm, $d = 12$ mm.

The WSS probe radius was $R = 6$ mm. Figure 5 shows the influence of the relative distance d between the gear and WSS on the spatial sensitivity s .

As shown in Figure 5(a), under a constant axial position, the spatial sensitivity s continuously decreases with increasing x and gradually approaches zero. Its maximum value occurs at $x = 0$. This value lies between one-half of the theoretical induced charge of a single particle and the charge carried by the particle itself. This characteristic indicates that the probe conductor can cause the electric-field lines generated by the charged particle to converge toward its surface, thereby enhancing the local electric-field strength.

In Figure 5(b), when $x = 0$, s at $z = 2$ mm decreases by 28.9% compared with that at $z = 0$, which is much greater than the 3.8% decrease in Figure 5(a). This indicates that the closer the gear is to the probe, the stronger the suppression of s . At $z = 0$ and $x = 5$, $s(b) > s(a)$, indicating that the gear mainly suppresses s , with enhancement occurring only at specific positions.

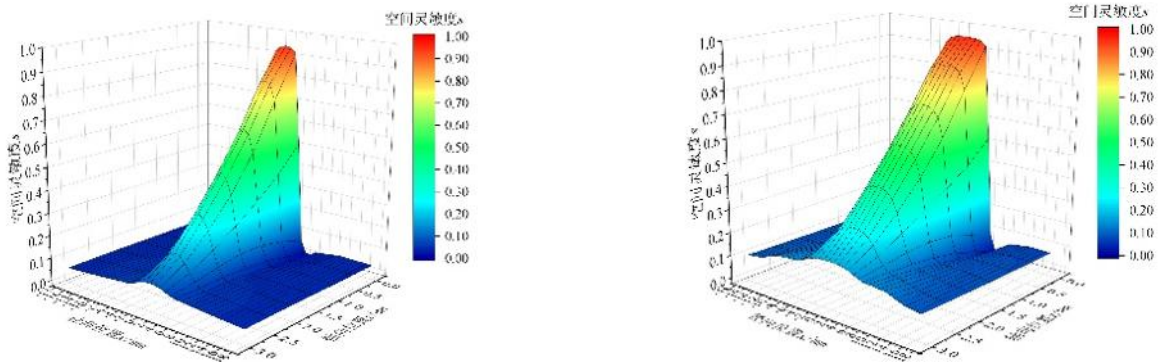


Figure 6. Influence of probe radius R on spatial sensitivity s . (a) $R = 3$ mm, $d = 3$ mm. (b) $R = 5$ mm, $d = 3$ mm.

The probe radius is also an important factor affecting s and can further disturb the electric-field distribution. Therefore, we investigated the influence of different probe radii on s at $d = 3$ mm, as shown in Figure 6.

When $z = 0$ and $x = R$, the reduction in s relative to that at $x = 0$ is close to 50%. As the particle approaches the shielding layer, s decreases sharply and approaches zero, then increases again as the particle moves away. This indicates that the shielding layer produces an edge effect. It was also found that increasing the probe radius improves overall sensitivity, thereby expanding both the radial and axial monitoring ranges of the sensor.

IV. Conclusion

A three-dimensional coupled simulation model was built in Ansys Maxwell 3D to analyze the gear's influence on electrostatic-induction characteristics under multiphysics conditions. Systematic spatial-sensitivity analysis showed that increasing the probe radius expanded the sensor monitoring range, whereas decreasing the gear-to-sensor distance suppressed spatial sensitivity. The edge-edge effect originating from the shielding layer was also illustrated. The multidimensional performance assessment presented in this work offered references for sensor-structure optimization and practical installation-parameter selection.

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