



Minimizing Position Errors in Helical Motion Resolvers Through Optimal Turn Function Design

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Abstract

As the demand for Two-Degree-of-Freedom (2-DoF) electrical machines continues to grow, the need for advanced sensors capable of detecting positions in multiple directions becomes increasingly critical. Compared to employing two separate sensors, using a single 2-DoF sensor offers significant advantages by reducing weight, volume, and complexity in control systems. This paper investigates a 2-DoF position sensor designed for helical motion detection. Given the significant impact of winding arrangements on resolver performance, determining the optimal winding configuration for helical motion is essential. To address the computational challenges associated with 3D Finite Element Analysis (3D-FEA), an analytical model based on the Winding Function (WF) method is developed to facilitate the optimization process. Subsequently, the Particle Swarm Optimization (PSO) algorithm is applied to refine the winding arrangement further and achieve greater accuracy. The results demonstrate that the resolver equipped with the optimized winding configuration significantly outperforms the one with the initial winding arrangement in terms of accuracy.

Keywords: Wound rotor resolver – 2DoF resolver - Winding Arrangement - Winding Function – PSO.

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1. INTRODUCTION

A wide variety of position sensors are employed in closed-loop control systems to accurately monitor and regulate the position of moving components. These sensors play a critical role in providing real-time feedback to the control unit, ensuring precise adjustments, and maintaining system stability. Depending on the application, position sensors can vary in design, operating principle, and accuracy, ranging from simple encoders to more complex resolvers. Although encoders are generally more accurate, resolvers are widely used in industry due to their ability to function in high temperatures, maintain accuracy in noisy environments, and operate reliably in harsh conditions [1].

The rotor's structural design categorizes resolvers into two primary types: wound rotor resolvers, where both the rotor and stator contain windings, and variable reluctance resolvers, which feature a rotor without windings but rely on variations in magnetic reluctance to detect position [2]-[5]. In a wound rotor resolver, both the rotor and stator contain windings embedded in their slots. The number of turns in each coil is carefully determined to ensure that the output signals vary proportionally to the sin and cos of the rotor's position. This design enables accurate position detection by producing output signals that represent angular

or linear displacement in a continuous and precise manner [6]-[7]. In a variable reluctance resolver, the rotor is a non-wound ferromagnetic component. However, the rotor is designed so that the mutual inductance varies as a sinusoidal function. In this type of resolver, all the windings are located in the stator slots [8]. In addition to rotational resolvers, linear resolvers are employed to detect position in linear motion [9]-[12].

Most of the introduced resolvers have one degree of freedom in motion, allowing them to detect position in only one direction [13]-[19]. However, multi-degree-of-freedom position sensors can reduce volume, weight, and cost [20]-[21]. Furthermore, they can be designed to be as accurate as one-directional sensors. [20], demonstrates the need for 2-DoF position sensors. [21], proposed the first 2-DoF resolvers, resulting from the authors' innovative winding arrangement that enables the resolvers to detect positions, making it a notable advancement for multi-directional sensing. However, this design lacks sufficient accuracy for application in control systems. Therefore, proposing a new configuration for a 2-DoF resolver that achieves high accuracy while maintaining a compact size remains a challenge.

In addition to introducing a new configuration for resolvers, many researchers have focused on optimizing

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existing resolvers to enhance their accuracy [22]-[28]. [22] optimizes the linear resolver with the objective of increasing accuracy while decreasing the size of the resolver. [23] optimizes the winding of a wound rotor rotational resolver to enhance accuracy. [24] designs a slotless disk-type resolver to enhance accuracy in multi-speed rotational applications. [25] proposes a novel structure for a multi-speed resolver. In this innovative design, two structures are combined to introduce a double-sided resolver as a multi-turn resolver. In [29], winding optimization is studied for multi-turn resolvers. [30] employs the winding function to optimize the dimensions of a linear variable reluctance resolver. [31] studies the performance of a rotational variable reactance resolver with distributed winding and demonstrates that this method can enhance the resolver's accuracy.

A two-degree-of-freedom (2-DoF) resolver is initially introduced in this paper designed to sense positions in rotational, linear, and helical displacement. The proposed resolver is based on the wound rotor design for all types of motion. Its performance is analyzed through 3D finite element analysis (3D-FEA) to assess its accuracy and effectiveness in various motion scenarios. Given the significant computational demands of the finite element method, a winding function-based analytical model is introduced to minimize simulation time [32]. The analytical model results are validated through comparison with the FEA results. Afterward, the optimization of the rotor and stator teeth is performed using the proposed method. In this regard, PSO optimization is employed to minimize the MPE as the objective function. Employing optimal winding significantly increases the accuracy of the resolver in both rotational and linear motion. The optimized number of slots minimize both AAPE and MPE at a same time.

2. Proposed Resolver

Fig.1 illustrates the structure of the proposed resolver. As shown in this figure, two different excitation windings are placed on the rotor, oriented perpendicularly to each other. The number of coil turns in each vertical/horizontal rotor slots can be computed as below:

$$Turn_{exc}(i) = [N_{M,E,H}(N_{M,E,V}) \times \cos(P_{r,H}(P_{r,V}) \left(\frac{2\pi}{Z_{r,H}(Z_{r,V})} (i - 1) \right))] \quad (1)$$

In this equation, $N_{E,M,H}$, $N_{E,M,V}$ represents the upper limit of turns in the excitation coils in horizontal and vertical slots respectively, $P_{r,H}$ and $P_{r,V}$, represents the number of rotor pole pairs in linear and rotational motion, $Z_{r,H}$ and $Z_{r,V}$ represent the number of rotor horizontal and vertical slots and i is given the slot number.

As shown in Fig. 1(b), four distinct windings are placed on the stator. There are two cos (sin) winding which are

physically perpendicular. Furthermore, cos and sin windings in each axis are electrically perpendicular. The number of coil turns in each stator slots can be calculated as below:

$$Turn_{sin}(i) = [N_{M,S,H}(N_{M,S,V}) \times \sin(P_{s,H}(P_{s,V}) \left(\frac{2\pi}{Z_{s,H}(Z_{s,V})} (i - 1) \right))] \quad (2)$$

$$Turn_{cos}(i) = [N_{M,C,H}(N_{M,C,V}) \times \cos(P_{s,H}(P_{s,V}) \left(\frac{2\pi}{Z_{s,H}(Z_{s,V})} (i - 1) \right))] \quad (3)$$

In the equation above, $N_{S,M,H}$, $N_{S,M,V}$ represents the upper limit of turns in horizontal and vertical stator slots respectively, $P_{s,H}$ and $P_{s,V}$ represents the number of stator pole pairs in linear and rotational motion, $Z_{s,H}$ and $Z_{s,V}$ represents the number of horizontal and vertical stator slots, and i denotes the tooth number.

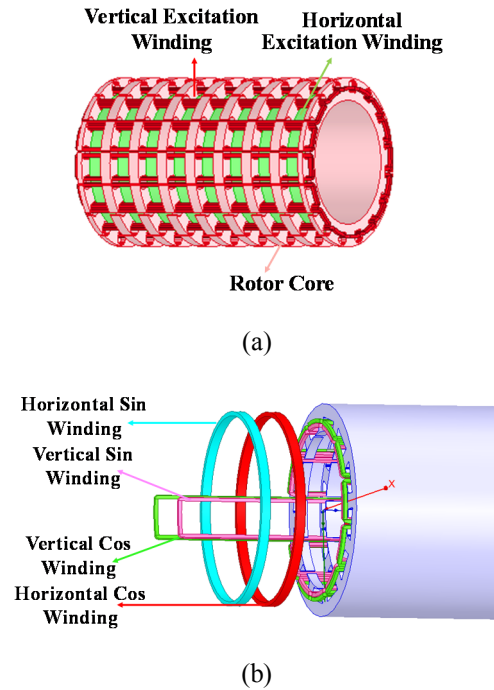


Fig.1: proposed wound rotor proposed 2-DoF resolver a) rotor b) stator

3. Finite Element Analysis

The proposed resolver is designed with 12 horizontal and 12 vertical stator slots, as well as 16 vertical and 8 horizontal rotor slots. Notably, to allow adequate space for linear motion, the stator length along the axial axis is designed to be at least twice the length of the rotor.

Given the orthogonality of the windings, it is expected that in rotational motion, the induced voltages in the vertical sin and cos windings will be high-frequency amplitude-modulated signals, with amplitudes that correspond to the sin and cos of the rotational position, respectively. Additionally, the output voltages in the horizontal signal windings will be high-frequency, constant amplitude signals. Thus, during linear displacement, the induced voltages in the horizontal sin and cos windings are expected to be high-frequency amplitude-modulated signals, with amplitudes that correspond to the sin and cos of the linear position, respectively. Due to orthogonality, the induced voltages in the vertical sin and cos windings will be high-frequency, constant amplitude signals.

Fig.3 (a) displays the output voltages in horizontal signal winding during rotational displacement. Given that the mutual inductance between the horizontal excitation and signal windings remains constant during rotational motion, the induced voltages behave as expected. Figure 3(b) illustrates the output voltages of the vertical sin and cos windings during rotational displacement. This figure illustrates that the vertical signal windings detect the rotor position during rotational motion.

Fig.4 gives the position error of rotational motion. To assess this figure, the real position and resolver detected position are calculated and performed. Figure 4 reveals that the maximum absolute position error is 0.19° , while the average absolute position error is 0.09° . As demonstrated, the accuracy of the proposed resolver is highly satisfactory considering rotational motion.

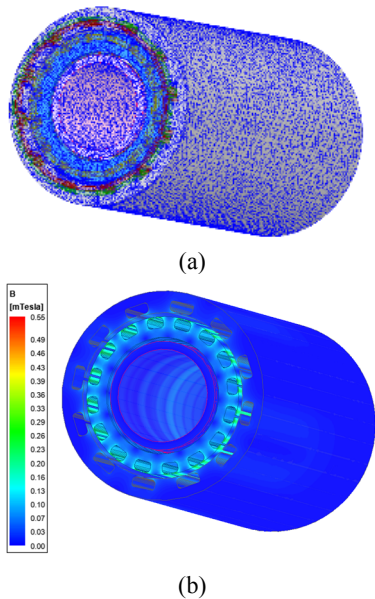


Fig.2: Simulation of proposed resolver with FE a) mesh b) distribution of magnetic flux density

Figures 5(a) and 5(b) illustrate the output voltages of the signal windings during linear displacement. As shown in Fig.5, during linear motion, the output voltages of the signal

windings are consistent with expectations. Fig.6 presents the position error of the 2-DoF resolver during linear displacement. As shown in the figure, the maximum absolute position error is 0.35 mm, while the average error is 0.14 mm. Therefore, the proposed resolver demonstrates high accuracy in linear motion, just as it does in rotational motion.

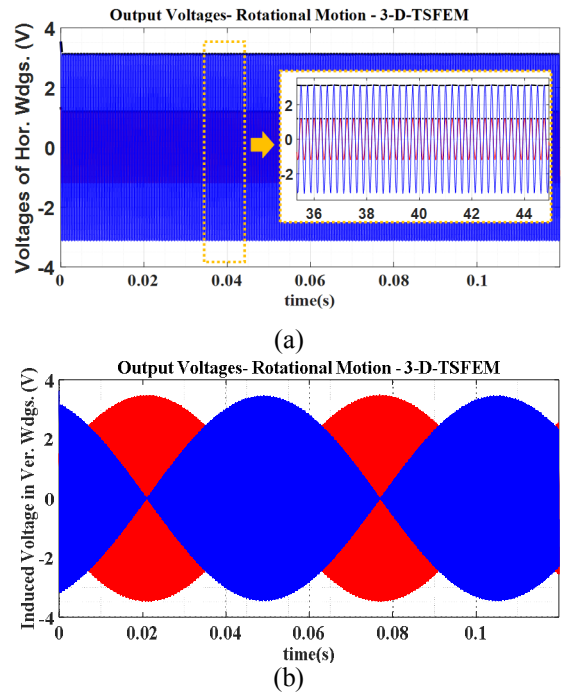


Fig.3: The output voltages of signal winding in rotational motion, a) horizontal signal windings, b) vertical signal windings

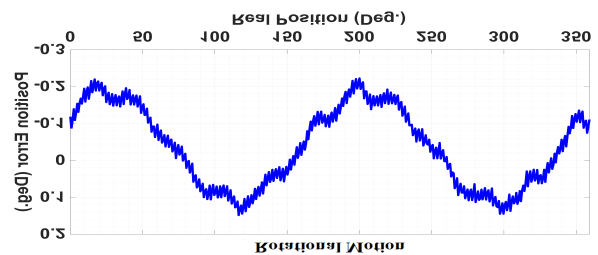


Fig.4: 2-DoF resolver position error in rotational motion

4. Winding Function – Based on Analytical Model

Although the FEA is highly precise for analyzing the performance of the 2-DoF resolver, it can be computationally expensive and time-consuming. Due to the design of the proposed resolver, finite element simulations are restricted to a 3D environment. As a result, the simulation requires a considerable amount of time. On the other hand, despite its high accuracy, it is not well-suited for optimization studies. Therefore, to optimize the functionality of the 2-DoF resolver, an analytical model based on the winding function method is introduced in this

section. This model allows for studying the resolver’s performance with both high accuracy and speed. A comparison between the proposed model and FE is then conducted.

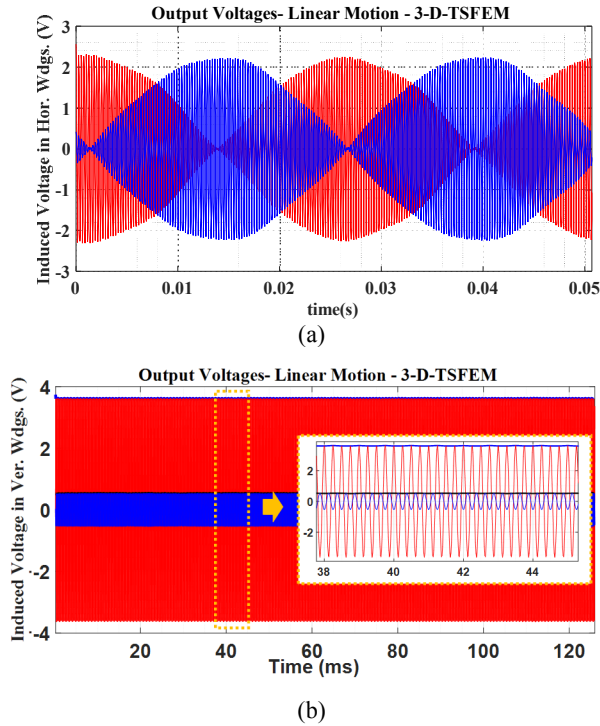


Fig.5: The output voltages of signal winding in linear motion, a) horizontal signal windings, b) vertical signal windings

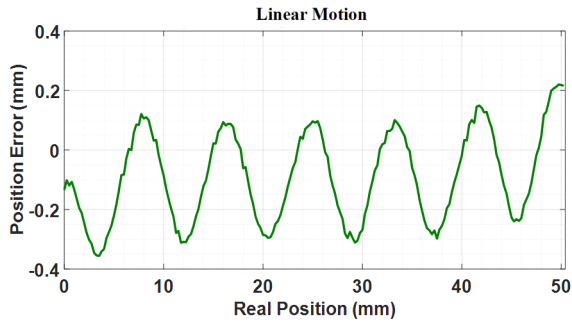


Fig.6: 2-DoF resolver position error in linear motion

Considering Ampere’s law:

$$\oint H \cdot dl = n(\theta/x) \cdot i \quad (4)$$

In this equation, $n(\theta)/n(x)$ represents the turn functions. Given the two separate paths for the rotational and linear resolver shown in Fig. 7, and assuming the core permeability is significantly higher than that of air, eq.5 can be derived.

$$\int_{2-3} \vec{H} \cdot \vec{dl} + \int_{6-7} \vec{H} \cdot \vec{dl} = n(\theta) \cdot i \quad (5)$$

$$\int_{2-3} \vec{H} \cdot \vec{dl} + \int_{3'-4'} \vec{H} \cdot \vec{dl} = n(x) \cdot i \quad (6)$$

Therefore:

$$F_{2-3}(\theta) + F_{6-7}(\theta) = n(\theta) \cdot i \quad (7)$$

$$F_{2-3}(\theta) + F_{3'-4'}(\theta) = n(x) \cdot i \quad (8)$$

Taking into account the Gaussian path that includes the air gap,

$$\int_{c_s} \vec{B} \cdot \vec{ds} = 0 \quad (9)$$

So:

$$\int_0^\varphi \int_{-\frac{z}{2}}^{\frac{z}{2}} \mu_0 H(\theta, x) r(\theta, x) dr d\theta dx = 0 \quad (10)$$

For rotational motion, and for linear motion:

$$\int_{r_{min}}^{r_{max}} \int_0^{z_\tau} \mu_0 H(\theta, x) dr dx = 0 \quad (11)$$

Therefore, in each desired angle:

$$H(\theta/x)g(\theta/x) + H(0)g(0) = n(\theta/x) \cdot i \quad (12)$$

Thus $H(\theta/x)$ can be determined using the following equation:

$$H(\theta/x) = \frac{n(\theta/x) \cdot i - H(0)g(0)}{g(\theta/x)} \quad (13)$$

That in this equation, $\langle n \rangle$ and $\langle g \rangle$ can be describe as below:

$$\langle n \rangle = \frac{\int_0^{2\pi/l} \frac{n(\theta/x)}{g(\theta/x)} d\theta/dx}{\langle g \rangle} \quad (14)$$

$$\langle g \rangle = \int_0^{2\pi/l} \frac{1}{g(\theta/x)} d\theta/dx \quad (15)$$

Defining the M as eq.16,

$$M = n(\theta/x) - \langle n \rangle \quad (16)$$

And H Parameter in each desired angle can be described below:

$$H(\theta/x) = \frac{M}{g(\theta/x)} \quad (17)$$

Therefore, electromagnetic force can be defined as below:

$$F = H \times I \quad (18)$$

So

$$d\varphi = F\mu_0 l g_{eq}^{-1} \tag{19}$$

The flux that path through each tooth is equal to:

$$\varphi_k = \int_0^{2\pi/l} n_{s,c} F_{exc}(\theta/x) \cdot g^{-1}(\theta/x) d\theta/dx \tag{20}$$

$$\lambda_{exc-s,c} = \sum \varphi_k \tag{21}$$

Fig.8 (a) and (b) are given the output voltages in linear and rotational signal winding respectively employing the proposed method.

The maximum absolute position errors in rotational and linear displacement are 0.17° and 0.12 mm, in that order. Additionally, the average absolute position errors in rotational and linear displacement are 0.09° and 0.08 mm, in that order. The comparison of the induced voltage amplitudes and position errors confirms the validity of the proposed analytical model.

5. Optimization

As previously mentioned, the stator of the proposed resolver contains 12 vertical and 6 horizontal slots per module, while the rotor is designed with 16 vertical and 8 horizontal slots. [24] proposed various combinations of rotor and stator slot configurations. However, due to the significant computational demands of 3D FE, these combinations result in a high computational burden and require substantial time and effort for simulation. As a result, comparing the performance of these different structures is not feasible due to the extensive time required for 3D-FE simulations. Therefore, the proposed analytical model is utilized to optimize the combination of rotor and stator slots. For this purpose, the rotor and stator slots are varied independently, ranging from 6 to 18. To determine the most accurate winding arrangement, PSO optimization is applied. Fig.9 is given the algorithm of design high accurate 2-DoF resolver, employing Winding Function and PSO. The PSO algorithm was configured with the following parameters: 20 particles, 100 iterations, an inertia weight linearly decreasing from 0.8 to 0.4, and cognitive and social learning coefficients set to 2. The search space for the number of rotor and stator slots was defined within the range of 6 to 18. The optimization was executed on a standard desktop computer equipped with an Intel Core i7 processor and 16 GB of RAM. The total computational time for a complete optimization run was less than 5 minutes while computational time for FEA is more than 7 days. During the optimization process, the algorithm demonstrated consistent convergence behavior.

The results of optimization, as given in Figs. 10 and 11, shows that the minimum position error for rotational and linear motion are equal to 0.07° and 0.009 mm respectively, corresponding to the configuration of 11 rotor slots and 16

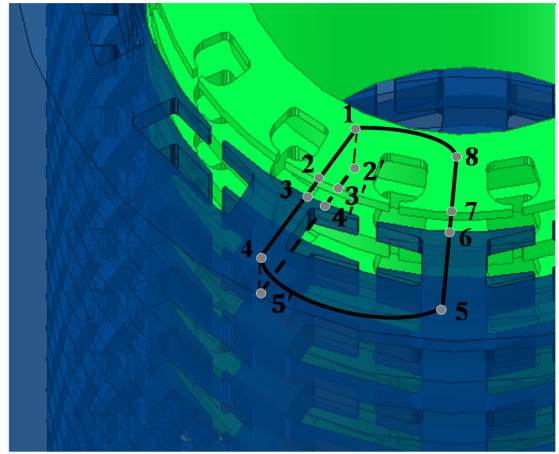


Fig. 7: Amper's law path for proposed resolver

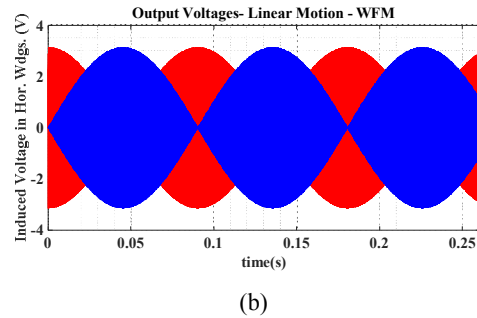
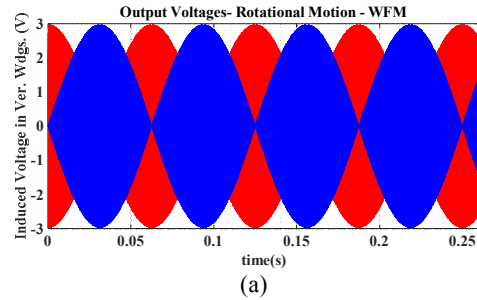


Fig. 8: The output signal voltages employing analytical model a) rotational motion b) linear motion

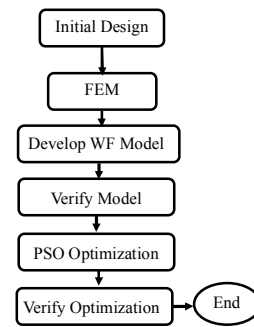


Fig. 9: algorithm of design high accurate 2-DoF resolver, employing Winding Function and PSO

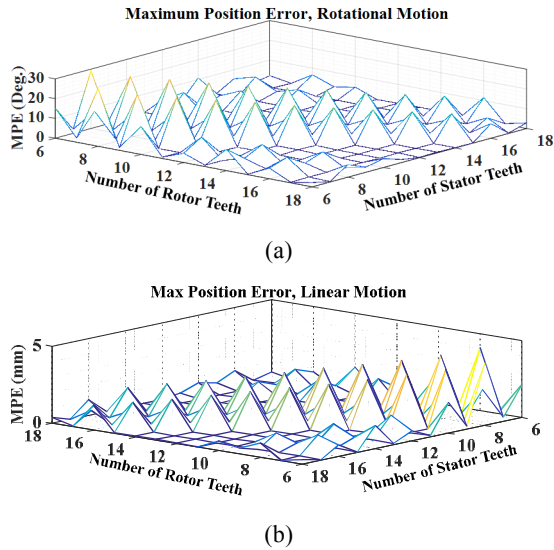


Fig. 10: maximum of absolute position error in different combination of rotor and stator slots a) rotational motion b) linear motion

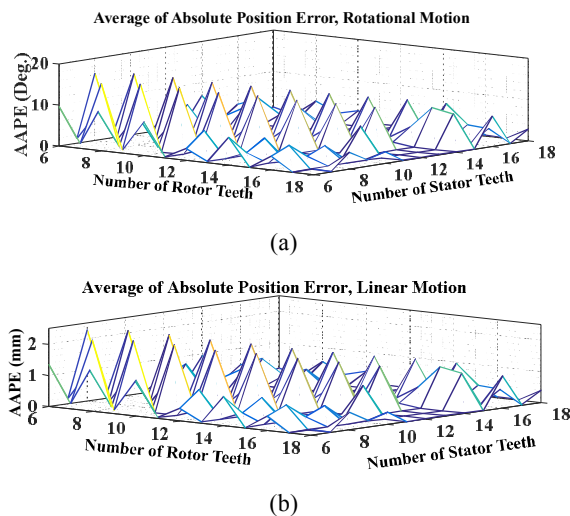


Fig.11: average of absolute position error in different combination of rotor and stator slots a) rotational motion b) linear motion

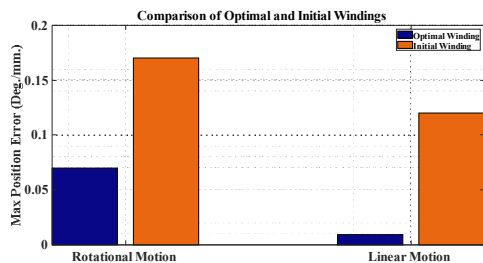


Fig. 12: The comparison of employing optimal winding on MPE

stator slots. It is worth noting that this combination yields the minimum maximum position error.

Figure 12 compares the accuracy of the initial and optimal designs. As shown, in rotational motion, the MPE of the optimal design is less than half that of the initial design. In linear motion, as in rotational motion, employing the optimal design significantly reduces the MPE. Therefore, the optimization method can significantly improve accuracy in helical motion. Table.I compare the initial design and optimized model.

TABLE. 1: Comparison of initial design and optimal design

		MPE
Initial Design	Rotational Motion	0.17
	Linear Motion	0.12
Optimal Design	Rotational Motion	0.07
	Linear Motion	0.009

6. Conclusion

This paper introduces a 2-DoF wound rotor resolver capable of measuring positions in rotational, linear, and helical motions. The performance of the proposed resolver is evaluated using the Winding Function Method (WFM). The close agreement between the results of the finite element (FE) analysis and the analytical model confirms the accuracy of the latter. Consequently, the analytical model, with its high accuracy and computational efficiency, is well-suited for optimization purposes.

The model is utilized to optimize the number of stator and rotor slots, aiming to minimize position error. Optimization is performed using the Particle Swarm Optimization (PSO) algorithm. Results demonstrate that the optimized winding arrangement significantly improves accuracy in both rotational and linear motions.

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