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# A Study on the Detent Torque Reduction of Claw Pole Permanent Magnet Type Motor

Dae-Sung Jung* · Ju Lee · Sang-Taek Lee**

## Abstract

This paper has done a three-dimensional FEM analysis of the PM claw pole stepping motor. As magnetization happens in the z-axis, which does not have a constant value, three-dimensional FEM analysis is necessary for characteristic analysis of PM claw pole stepping motors. Because it is a type of permanent magnet motor, the PM claw pole stepping motor naturally has a detent torque. This torque is known to show negative effects on motor performance. To improve motor performance, reducing the detent torque is very important during the motor design. This paper applied DOE for optimization of stator pole design of the motor. Also, we compared motor performance by applying a different type of rotor shape, dividing the permanent magnet. To verify the simulation results, an experiment was done.

Key Words : PM(Permanent Magnet), Detent Torque, Claw Pole, DOE, Motor

## 1. Introduction

The PM claw pole stepping motor rotates at a constant degree synchronized to the pulse generated by a power source. As the rotating speed is directly proportional to the input frequency, open loop control is possible. Additionally, by adopting permanent magnets to the rotor, the motor has high a holding force to be used for precise position control. Based on these characteristics, it is used for ODD, printers, digital cameras, and mobile devices. In particular, the simple structure, structure robustness, and low manufacturing cost make the motor more popular in the industries[1-2].

The analysis model of this paper is a product applied for ODD drive, which has a smaller size, reduced poles, and low power compared to the general PM type claw pole step motors. Because of its small size, the motor will show high variances to small changes of design parameters. For this reason,

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accurate modeling and analysis is required for this model. Additionally, magnetization along the z-axis causes three-dimensional analysis necessary to analyze the model[3-4].

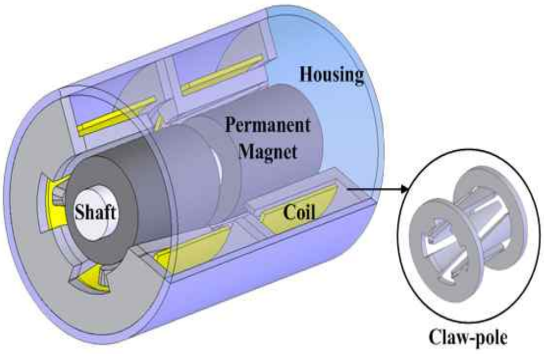


Fig. 1. Structure of Claw Pole Stepping Motor

The PM claw pole stepping motor has detent torque, which is a natural characteristic for permanent magnet type motors. This torque causes vibration and acoustic noises which degrades the control performance of the motor. From previous studies, design methods to reduce this detent torque have been introduced. For example, introducing skews to the motor or notching the motor was proposed.

However, for a motor that has a small size, applying these methods is impossible from an industrial view. Therefore, a new method should be introduced for this specific model, small PM type claw pole stepping motor, to reduce the detent torque. In this study, even though a reduction of holding torque takes place, the detent torque will be reduced to 0.1gfcm.

An optimization of the stator pole shape has been done by using DOE, and a three-dimensional FEM analysis was done for various models by dividing the permanent magnet of the rotor. An improvement was shown by applying less analysis steps compared to conventional analysis papers. The simulation results are also verified by comparing them with experiment results.

## 2. Design Considerations for Simulation & Experiment

### 2.1 Drive & Structure of Claw Pole Motor

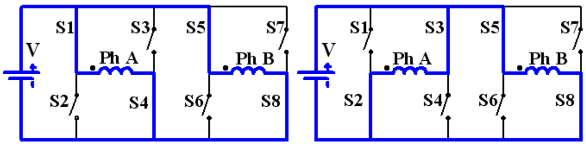
A stepping motor with claw poles has a rotor made with iron and magnetized permanent magnets attached to it. The stator usually has a two-stack structure, composed of claw pole-shaped teeth and a coil. Each phase of the stator is manufactured to have a teeth layout with a shift of 90 degrees, electrically, from other teeth. The pole number of the rotor is identical to the number of teeth per phase. In our case, the two phases—A and B—have eight pairs of teeth poles. Therefore, the step angle of the model is 22.5 degrees (360/2p). The coil has a ring shape, which is coiled between the teeth and housing. The housing of the motor is the outer structure and acts as a magnetic circuit. The structure of the analysis model, PM claw pole stepping motor, is shown in Figure 1.

Figure 2 shows the operating principles of the motor in a bipolar drive, one step rotation for a single pulse. The rotating direction can change depending on the excitation method. Table 1 shows the main specifications of the analysis model of this study. The fundamental equation for the magnetic field with permanent magnets can be written as,

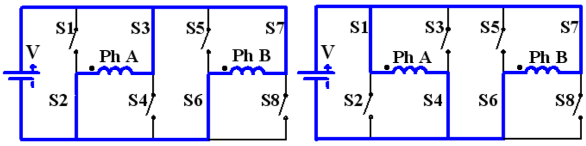
$$rot\ (\upsilon\ rot\mathrm{A}) = J_0 + \upsilon_0 rot\mathrm{M} \tag{1}$$

Where $\upsilon$ is the reluctivity, $\upsilon_0$ is the reluctivity of the vacuum, A is the magnetic vector potential, M is the magnetization of the permanent magnet, and $J_0$

is the current density. The magnetic saturation of iron is taken into account by the Newton Raphson Method.



(a) Step I (b) Step II



(c) Step III (d) Step IV

Fig. 2. Operating Principles of the Motor

Table 1. The Specification of the PM type stepping motor with claw-poles

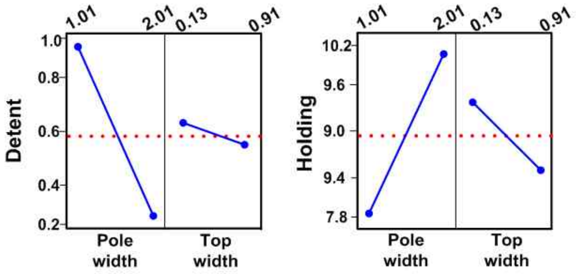
| Section | Specifications | |
|---|---|---|
| | Item | Value |
| Stator | Phase number | 2 |
| | Poles per phase | 8 |
| | Outer diameter | 7.45mm |
| | Length | 12.2mm |
| | Step angle | 22.5deg |
| Rotor | Number of poles | 8 |
| PM(NdFeB) | Residual flux density | 0.43T@20℃ |
| Air gap | Length | 0.195mm |

## 2.2 Design of the Claw Pole Stator

Design of experiments, which means the planning of experiments, is a theory of experiment design in order to investigate what variables affect output including statistical analysis for interpreting obtained data.

In this study, the pole width and the stator top width were selected as the main design parameters, and the level of design parameters was selected at level 2. The width should be selected within constrained boundaries to satisfy the electrical and mechanical characteristics of the motor. If the width is too large, the flux leakage will increase, and with a width that is too small, the output power of the motor will to be too minimal for application.

By changing the values of the design parameters, the performance difference, detent torque, and holding torque, are shown in Figure 3. As it is shown, the detent torque decreases as the pole width increases, while the holding torque increases. Therefore, the pole width can be considered to be an important design variable. Effect analyses of design parameters are shown Figure 3.



(a) Detent Torque (b) Holding Torque

Fig. 3. Effect Analysis of Design Parameters

## 2.3 Design of the Rotor Permanent Magnet

The rotor has a shape that has a permanent magnet divided into parts. In our study, the permanent magnets are divided into a maximum of four parts. As can be seen in Figure 4, even though there was a decrease of holding torque, the detent torque is reduced with models that have permanent magnets divided compared to the original motor that has no division in the permanent magnet. Considering manufacturing cost and process implementation, the rotor that has a bisected permanent magnet (Proposal Rotor I) was selected. The detent torque and holding torque analysis results of the conventional rotor and proposal rotor

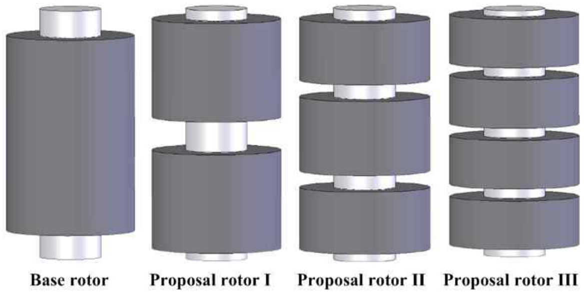


Fig. 4. Base Rotor and Proposal Rotor

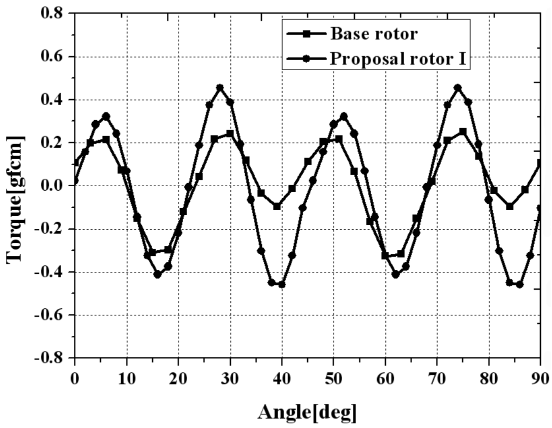


Fig. 5. Detent Torque Wave According to Dividing PM

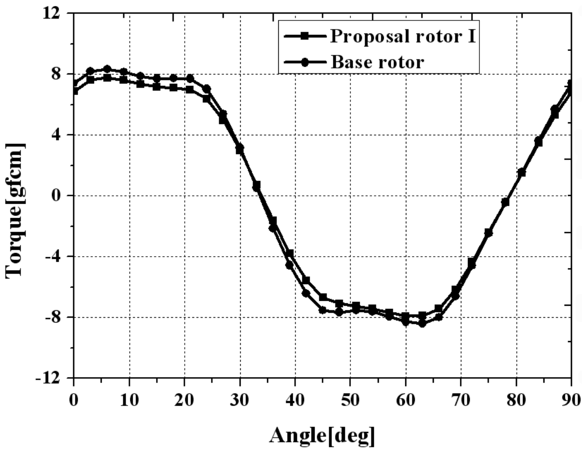


Fig. 6. Holding Torque Wave According to Dividing PM

is shown in Figures 5 and 6. While the holding torque reduced by 6%, the detent torque shows a 44% reduction. This can be explained by the flux leakage made by dividing permanent magnets as shown in Figure 7. Physically, the holding torque reduces proportional to the flux, while the detent torque reduces proportional to the square of the flux. Based on this fact, there is a significant improvement in reducing the detent torque.

## 2.4 Analysis Results of Optimal Model

The proposed model is shown in Figure 10(b). The stator is based on optimization of DOE, and the rotor has a permanent magnet divided into two pieces. The analysis model has 300,000 elements and 80,000 nodes. In the case of 3D analysis, the accuracy of the analysis strongly depends on the number of elements. Therefore, selecting the proper number of elements is important. The vector distribution of the permanent magnet and meshed analysis model are shown in Figure 7.

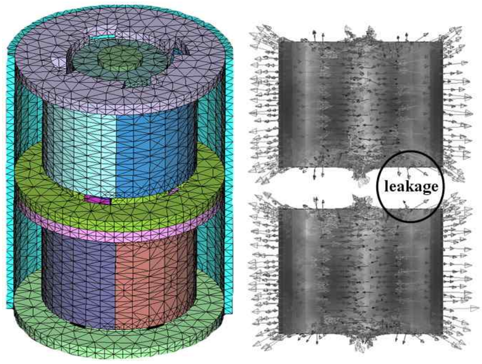


Fig. 7. The Proposed Model

### 2.4.1 Characteristics of Detent Torque

The stator teeth of the PM type claw pole stepping motors introduce varying reluctance to the motors. The Co-Energy of the PM makes the motor rotate. It can be calculated by the partial derivative of magnetic co-energy with respect to the angular displacement as,

$$T_{detent} = \frac{\partial W_f'}{\partial \theta} \tag{2}$$

where is the total co-energy of the field and the rotor position. Numerically, this partial derivative can be calculated approximately as the variation of co-energy against the rotor angular displacement.

$$T_{detent} \approx \frac{\Delta W_f'}{\Delta \theta} = \frac{W_{f2}' - W_{f1}'}{\theta_2 - \theta_1} \tag{3}$$

The detent torque causes vibration and acoustic noises to the PM motors which degrade the control characteristics. Therefore, the detent torque should be minimized during the design process. The analysis model has 90 degrees of holding torque, and the period of the detent torque can be calculated by equation (4).

$$\begin{aligned} &\textit{The cycle of cogging torque} \\ &= \frac{360°}{\textit{the LCM between number of PM pole and claw pole}} \end{aligned} \tag{4}$$

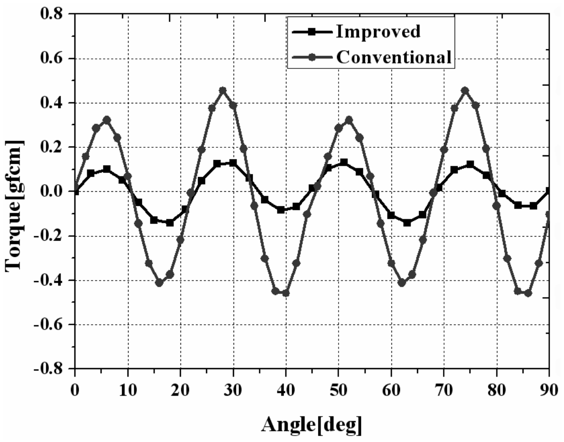


Fig. 8. Detent Torque Wave

So, the period of detent torque is 45 degrees. The detent torque distribution of both the conventional model and improved model is shown in Figure 8. The detent torque of the improved model shows a 71% decrease compared to the conventional model, which also matches the initial design goal with detent torque of 0.1gfcm.

### 2.4.2 Characteristics of Holding Torque

Holding torque is defined as the maximum torque that can be induced to the motor shaft under the condition that the motor shaft can recover its initial position with rated currents flowing to the stator. A motor that shows a higher holding torque shows robust performance to external disturbances. For this advantage, motor designs that result in higher holding torque and sinusoidal wave forms are necessary for industrialization of the product.

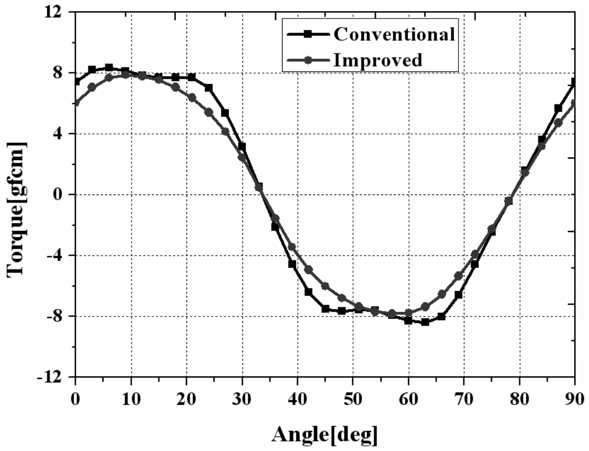
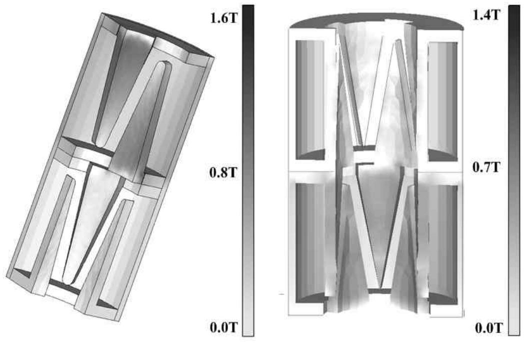


Fig. 9. Holding Torque Wave

The holding torque waveforms of both the conventional and proposed model are shown in Figure 9. A small distortion at the end of the waveform can be observed in the conventional model. This distortion can be explained by two reasons. The detent torque of the motor is the first reason; the high flux density at the teeth is the second reason. As shown in Figure 10(b), the flux density at the teeth is relatively high which causes a magnetic flux path from the axial direction. This can cause magnetic saturation. The flux density of the improved model is shown in Figure 10(b). Compared to the conventional model, the proposed model shows a lower flux density at the teeth region. Therefore, the proposed model of this study has reduced the detent torque while also distributing the flux for a wider region compared to conventional models. Although the holding torque has been reduced, the holding torque does show a sinusoidal distribution. For the analysis, the motor was driven by a two-phase bipolar drive with a rated current of 0.27A for both coil stack A and B. The proposed model showed a 5% holding torque reduction based on analysis results.



(a) Conventional Model (b) Improved Model

Fig. 10. Flux Distribution

## 3. Comparison Between the Analysis Results and Experimental Results

A motor with the improved design factors could not be manufactured because of its cost. However, the validity of the simulation results is verified indirectly by comparing the simulation results and experiment results of the conventional model. Figure 11 shows the conventional motor, and Figure 12 shows the test equipment to measure the characteristics of the holding torque for the stepping motor by using the torque-meter. After the stepping motor is connected with the torque-meter, the torque is measured with the constant supply voltage of 4V. The simulation and experiment results of the conventional model are shown in Figures 13 and 14. The simulation results show a higher value compared to the experiments. This can be explained by excluding various physical considerations, such as friction coefficient of bearings, static friction coefficient, etc., for the simulation. Considering these factors, it can be said that the simulation results follow the real experiment results fairly closely.

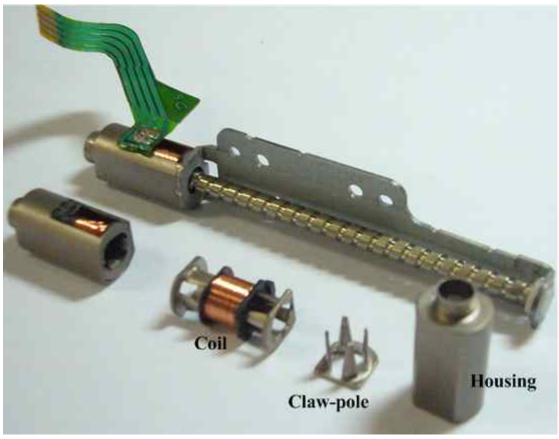


Fig. 11. Conventional Motor

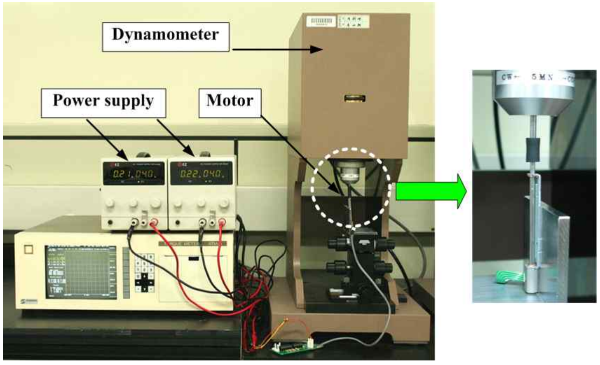


Fig. 12. Test Equipment to Measure the Characteristics of the Holding Torque

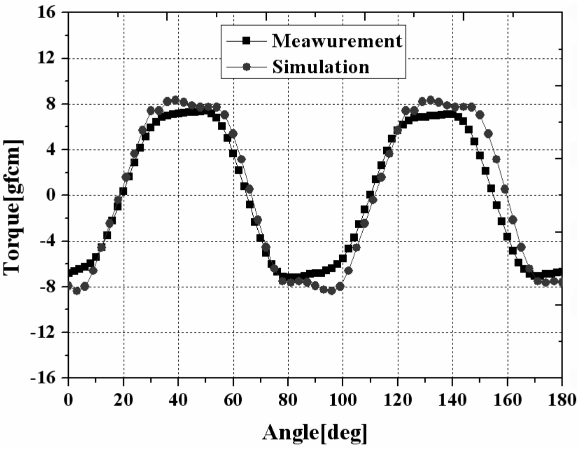
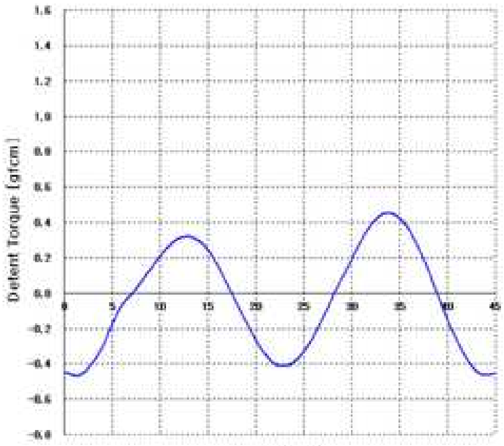
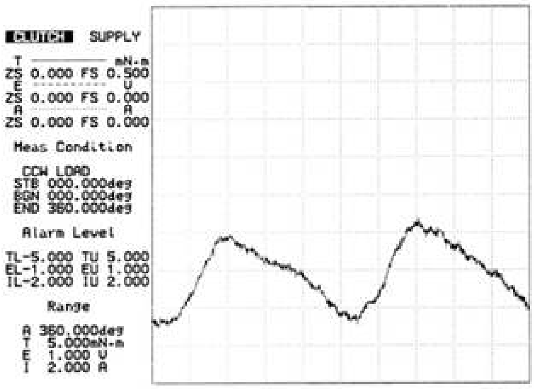


Fig. 13. Experimental and Simulation Results of the Holding Torque



(a) Simulation Results



(b) Experimental Results

Fig. 14. Simulation and Experimental Results of the Detent Torque

## 4. Conclusion

In this paper, a method to reduce the detent torque of a PM claw pole stepping motor used for ODD devices was studied. The stator pole design was done by applying DOE to minimize magnetic saturation for fluent magnetic flux flow. For the rotor design, cutting the PM showed good results for reducing the detent torque. Through a trade-off study, an improved design model is proposed that shows a sinusoidal holding torque waveform with the detent torque reduced. By reducing the detent torque effectively, with sinusoidal holding torque wave forms, the proposed models will show better precise control performance for digital cameras and emerging mobile device markets. The simulation results were also verified by performing an experiment.

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