Torque Characteristic Analysis of Electro-Magnetic Electronic Controller Power Steering by Using Quasi-3D Method

Jae-Ok Jo, Young-Kyoun Kim,J ung-Jong Lee, Jung-Pyo Hong
Department of Electrical Engineering
Changwon National University
Kyungnam, 641-773, Korea

***Abstract* — This paper presents the quasi-3D analysis for rotary actuator using magnetic circuit coupled with 2D-FEM. This method is widely used for electric machine analysis but neither always accurate enough nor sometimes available to easily use. On the other hand 3D-FEM is inherently unsuitable for electric machine performance evaluation due to its poor computational efficiency. In this paper, nonlinear equivalent magnetic circuit in combination with 2D-FEM is proposed to analyze the electric machine having 3D phenomenon, and this method applies to analysis and design for rotary actuator of electro-magnetic electronic controller power steering.**

***Key Words* – Equivalent magnetic circuit method, electro magnetic electronic controller power steering (EM-ECPS), finite element method (FEM), rotary actuator, quasi-3D method**

I. INTRODUCTION

Nowadays, many subcomponents of automobiles tend to employ a large number of electric and electronic systems, due to growing demands of consumers on safety, fuel efficiency, convenience of drive and improving vehicle performance. According to their tendency, several vehicle companies are working on developing of power assisted steering systems. About fifty years ago, the concept of hydraulic power assisted steering was introduced. Since that time a number of different systems have been developed [1].

This paper deals with design and analysis of a rotary actuator, which is repulsion device of Electro-Magnetic Electronic Controller Power Steering (EM-ECPS), and this actuator can develop attractive force in either the left or the right direction of rotation. This high torque actuator performs an electromagnetic spring action by developing electromagnetic torque with limited angular movement to enhance that of the basic hydraulic power assisted steering system [2].

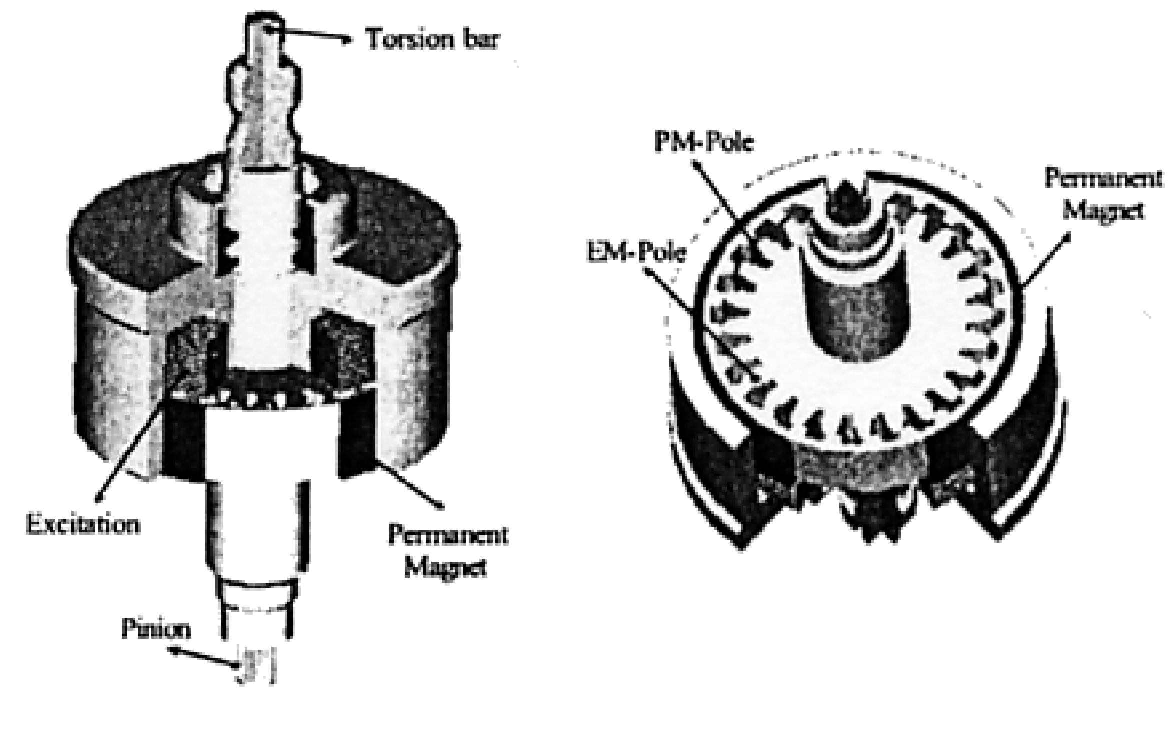
The rotary actuator consists of toothed poles, excitation coil, and unipolar radially oriented permanent magnet ring as shown in Fig. 1. This rotary actuator features high torque output since its many toothed poles provide transverse flux with a high density. Therefore, it is necessary for it to analyze with 3D-FEM.

At this paper, it is proposed that a method of design and an analysis of this rotary actuator using the equivalent magnetic circuit in combination with 2D-FEM in spite of requiring 3D-FEM, which has inherently poor computational efficiency [3]. Although, its defect can be compensated as advance of computer performance, using this method pays a lot of cost such as an expense of high performance computer, difficulty modeling due to complicated analytical model, requiring of much experience and attention to generate 3D-mesh.

II. PROPOSED ANALYSIS METHOD

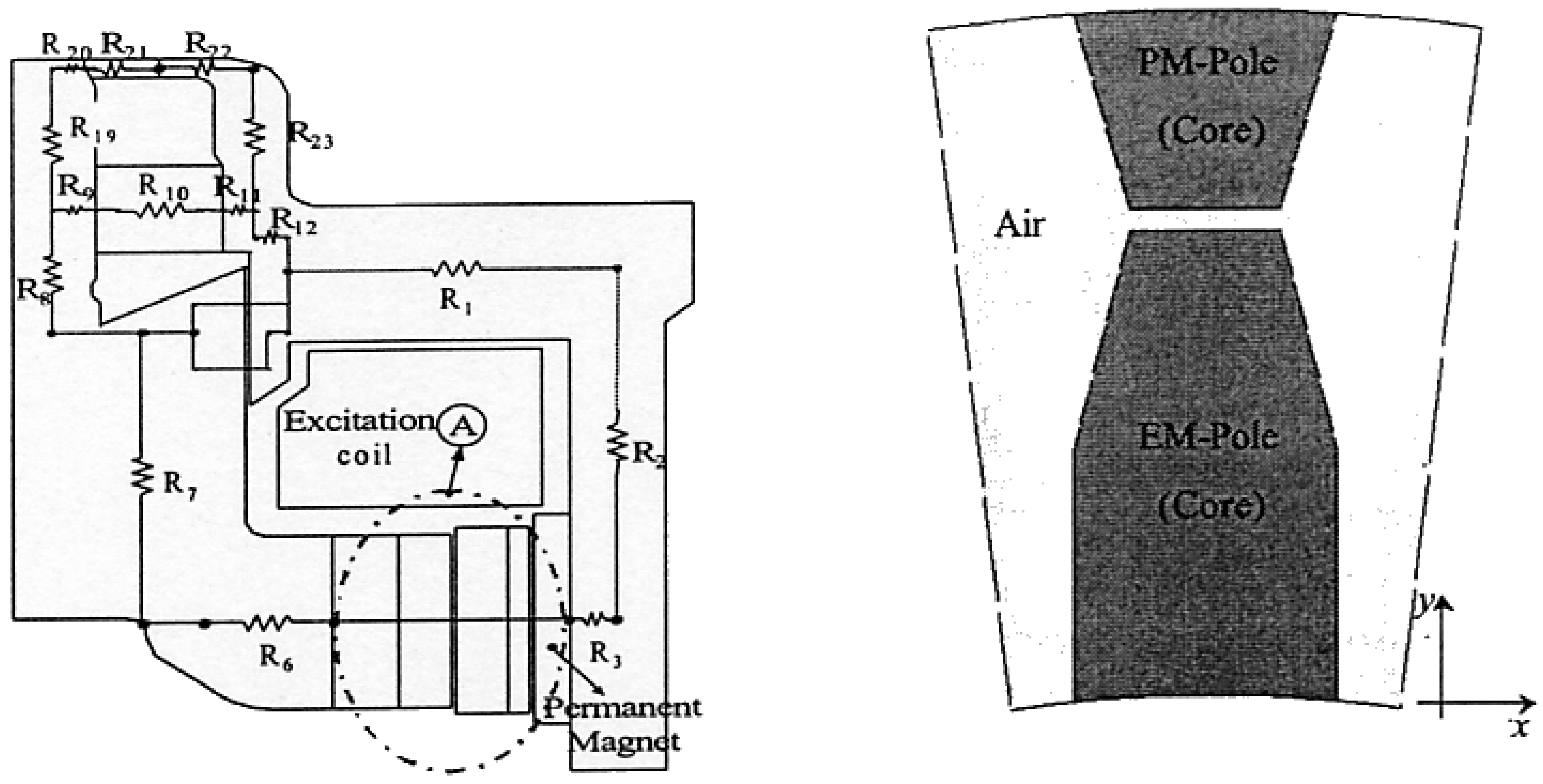
The magneto motive force of this rotary actuator comprises excitation coil and permanent magnet ring. And controlling the magnitude and direction of the excitation coil current can change the torque developed by the permanent magnet. Proper balance of both magnetic flux densities, one due to PM-pole and second due to EM-pole illustrated in Fig. 2, is important task during the actuator's design.

Therefore, to analyze the rotary actuator accurately, magnetic circuit of rotary actuator is analyzed by the suggested method that divided it into two parts. Toothed pole and air-gap employ 2D-FEM and other parts of magnetic circuit are considered by equivalent magnetic circuit method. The flow chart of the proposed method is shown in Fig. 3



(a) Front view (b) Bottom view

Fig. 1 Structure of rotary actuator



(a) Equivalent magnetic circuit model (b) 2D-FEA model

Fig. 2 Equivalent magnetic circuit model and 2D-FEA model

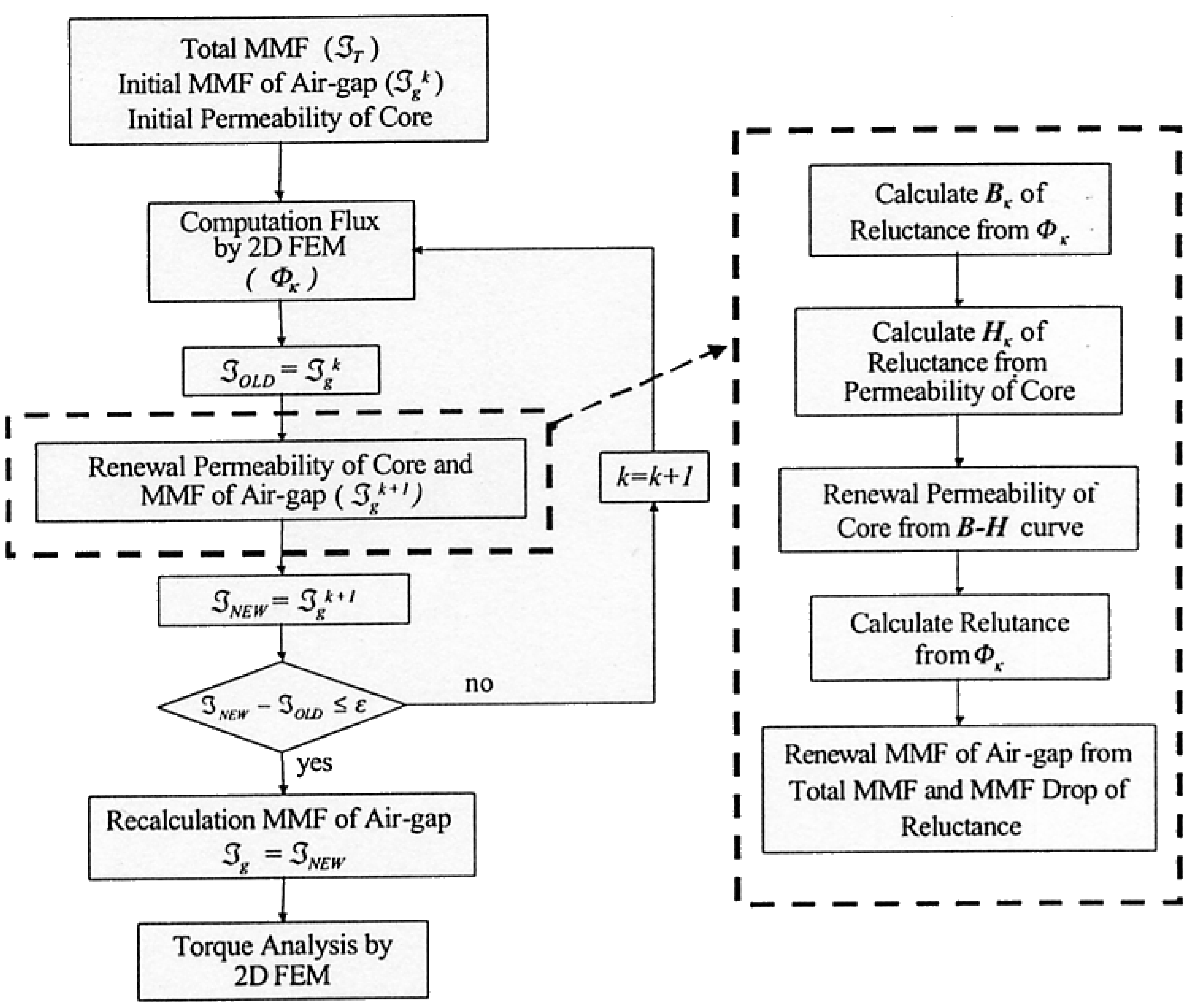


Fig. 3 Flow chart of proposed analysis method

A. Equivalent magnetic circuit model

Flux path of other regions except toothed pole and air-gap is assumed as Fig. 2(a) and other leakage flux is neglected. The lumped parameters are properly apportioned for applying the equivalent magnetic circuit at the each flux path.

The permeance of lumped parameters is calculated by the flux of air-gap, which is obtained by the FEA region (Ⓐ), and its accuracy can be achieved by considering B-H curve of material.

B. 2D-FEM model

2D-FEM is used to analyze toothed poles and air-gap of the EM-ECPS. To analyze phenomena occurring electromagnetic field, the characteristic formulation of electromagnetic field can be used to illustrate their phenomena. However, it is convenient for the finite element analysis to deal with field variables through a scalar potential or a vector potential.

2D-FEM using one toothed pole pitch as shown in Fig. 2(b) can achieve the magnetic force calculation. The governing equation for electromagnetic field problems with magnetic scalar potential Ω is as follows [4]:

$$\nabla \cdot (\mu \nabla \Omega) = 0 \qquad (1)$$

where, μ is the magnetic permeability. (1) obtained from Maxwell equations can be rewritten for 2-D Cartesian coordinate, as described in (2).

$$[\frac{1}{\mu}\frac{\partial^2 \Omega}{\partial x^2} + \frac{1}{\mu}\frac{\partial^2 \Omega}{\partial y^2}] = 0 \qquad (2)$$

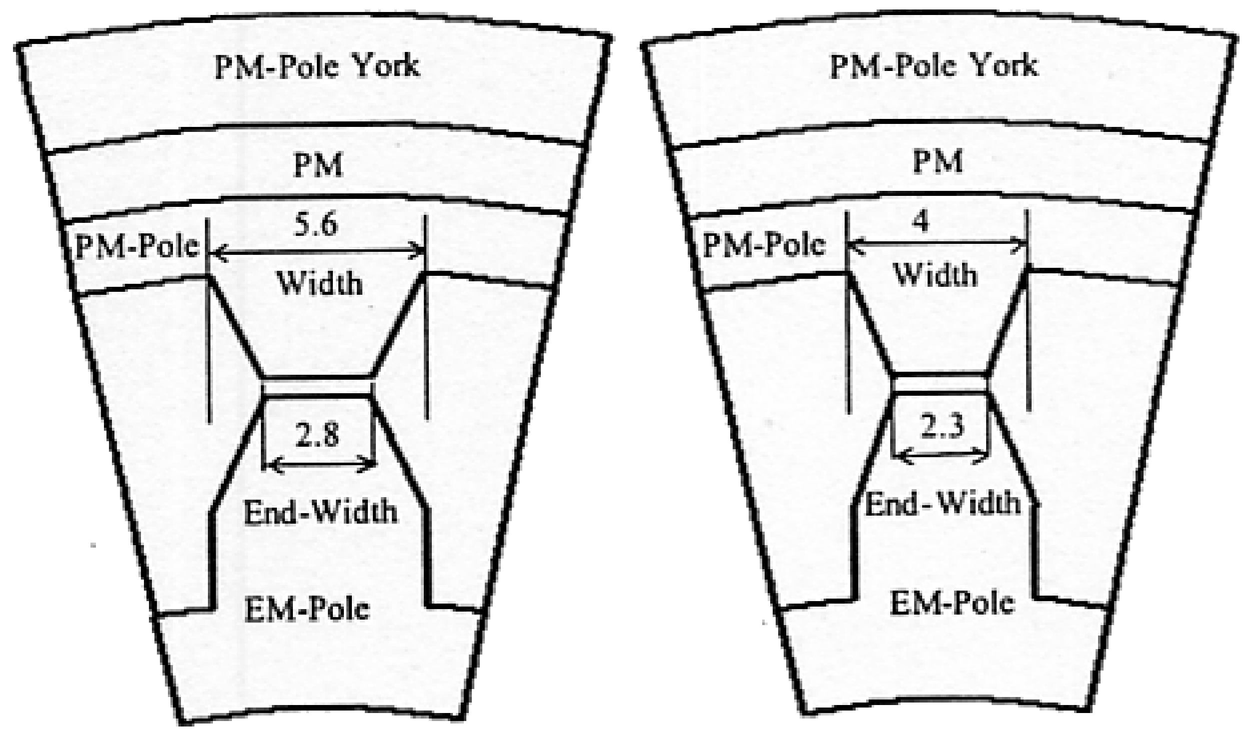
(2) is the characteristic equation to analyze 2-D FEM for field problem with magnetic scalar potential Ω.
The total force developed by the actuator is sum of the forces developed by each pole pitch. These forces per unit length are calculated by using the Maxwell stress tensor, and it is as follows.

$$F_t = \int_s \frac{B_n B_t}{\mu_0} dl \qquad (3)$$

Therefore, the torque of rotary actuator is obtained from the total force multiplied by both the pole' s stack width and integral radius.

III. RESULTS AND DISCUSSION

The EM-ECPS is composed of PM-pole coupled with permanent magnet and EM-pole joined with the exciting coil and axis of the EM-ECPS. The torque characteristics of the EM-ECPS to obtain comfortable steering of a vehicle have to get large amplitude of the torque and operation ranges due to exciting current.
Therefore, to reform the magnetic circuit of initial design for the EM-ECPS, the shape of its poles is determined from changing pole width, pole end-width, pole number, air-gap length and core material for satisfying demand performances. Fig. 4 shows comparison of the initial model and reformed model for the shape the pole on the EM-ECPS and Table. 1 and Table. 2 show comparison of the initial and reformed terms. The torque characteristics due to change the residual flux density are investigated and the results of 1.1 (T) and 0.75 (T) are shown in Fig. 5 and Fig. 6, respectively.
In the former case, the maximum torque is larger than the latter case. On the other side, the control range of torque is very small according to exciting current. It is caused by saturation of the magnetic circuit on the EM-ECPS



(a) Initial model (b) Reformed model

Fig. 4 Shape of the pole on the EM-ECPS

Table. 1 Dimension of initial model for the EM-ECPS

Pole number	15 (ea)	Permanent magnet thickness	2 (mm)
Air-gap length	0.5 (mm)	Core martial	AB430
Current	0, ±3 (A)	Residual flux density	1.1 (T)
Exciting coil	200 (turn)	Permanent magnet material	NdFeB

Table. 2 Dimension of reformed model for the EM-ECPS

Pole number	24 (ea)	Permanent magnet thickness	2 (mm)
Air-gap length	0.3 (mm)	Core martial	S20C
Current	0, ±3 (A)	Residual flux density	0.75 (T)
Exciting coil	200 (turns)	Permanent magnet material	Boned NdFeB

In the latter case, the maximum torque is smaller then the former case. On the other hand, as the operation range of torque is larger than the former case according to exciting current. It could be desirable that the EM-ECPS can obtain the comfortable steering condition.
Therefore, if the difference between maximum torque and minimum torque according to exciting current is large, the EM-ECPS can obtain the large operation range. Fig. 7 shows the difference between maximum torque and minimum torque due to change the residual flux density of permanent magnet.
For the steering application, the motion of rotary actuator is mechanically limited either the left or the right direction of rotation. The torque of the rotary actuator according to control of the magnitude and direction of the exciting current is shown in Fig. 8.
In this paper, the optimum geometry of the rotary actuator

requiring high torque and wide torque region is obtained by the proposed analysis method

IV. CONCLUSIONS

In this paper the design and analysis of the rotary actuator used the steering application are presented. In order to analyze the rotary actuator, the equivalent magnetic circuit coupled with 2D-FEM in spite of requiring 3D analysis is proposed.

The suggested method is conducted to design and reform the actuator geometry and performance. Therefore, it is expected that the proposed Quasi-3D Method can be easily utilized to analysis the complicated 3D model.

ACKNOWLEDGMENT

This work has been supported by Development Project of Industry Foundation Technology, which is funded by Ministry of commerce, Industry and Energy.

REFERENCE

[1] A.C heryl, "Electric steering system challenges traditional steering approaches," *ELECTRONIC DESIGN*, pp. 42-43, JULY 1997.

[2] A. M. Pawlak, "Rotary actuator with multipole ring magnets," *IEEE Transactions on INDUSTRY APPLICATIONS*, vol.31, No. 6, pp. 1306-1314, Nov. 1990.

[3] K. C. Lim et all, "Characteristic analysis of 5-phase hybrid stepping motor considering the saturation of both teeth and poles," *IAS'2000 Conference proceedings*, pp 132-138, Oct. 2000.

[4] S. J. Salon, *Finite Elements Analysis of Electrical Machines*. Kluwer Academic publishers, 1995.

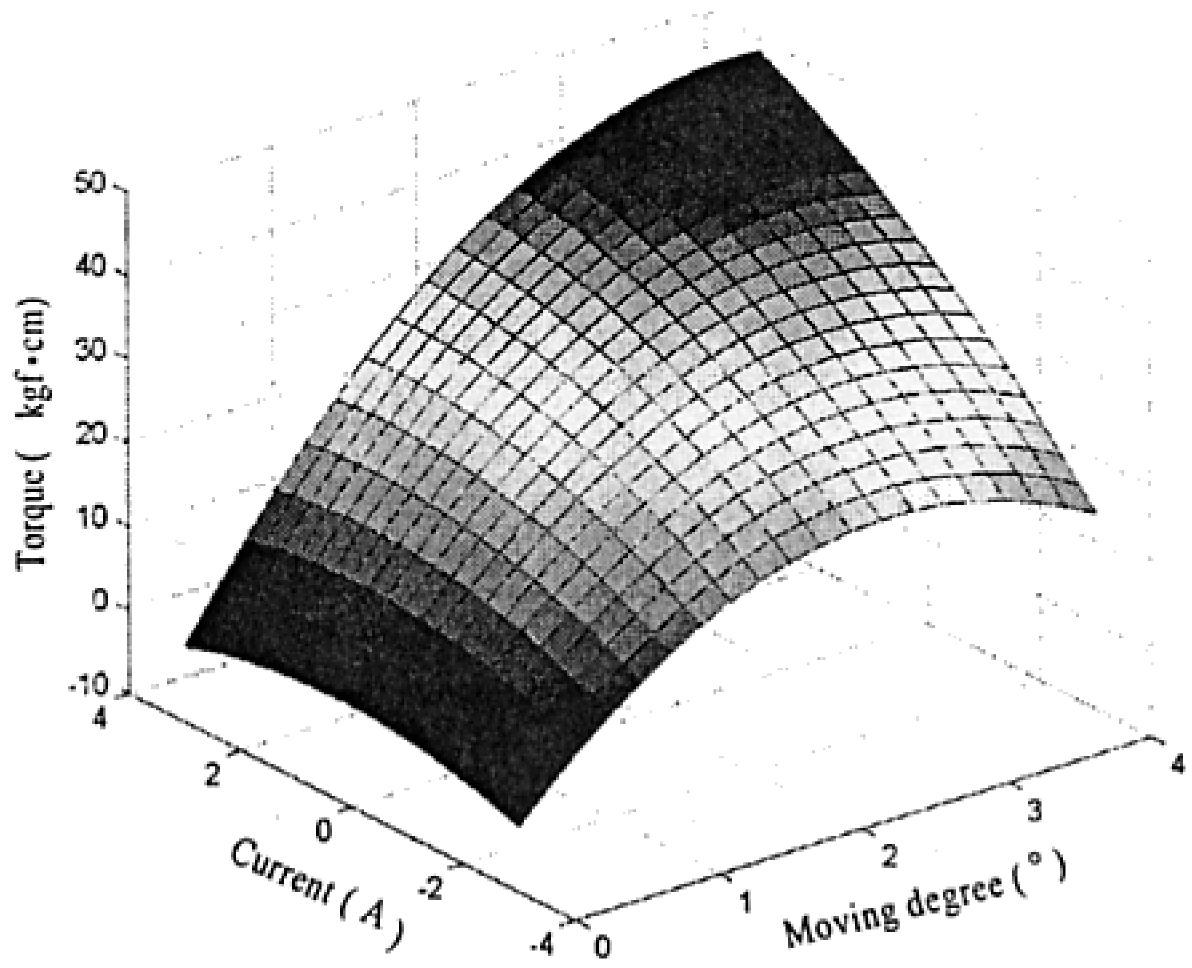


Fig. 5 Operating range of the torque at the residual flux density 1.1 (T)

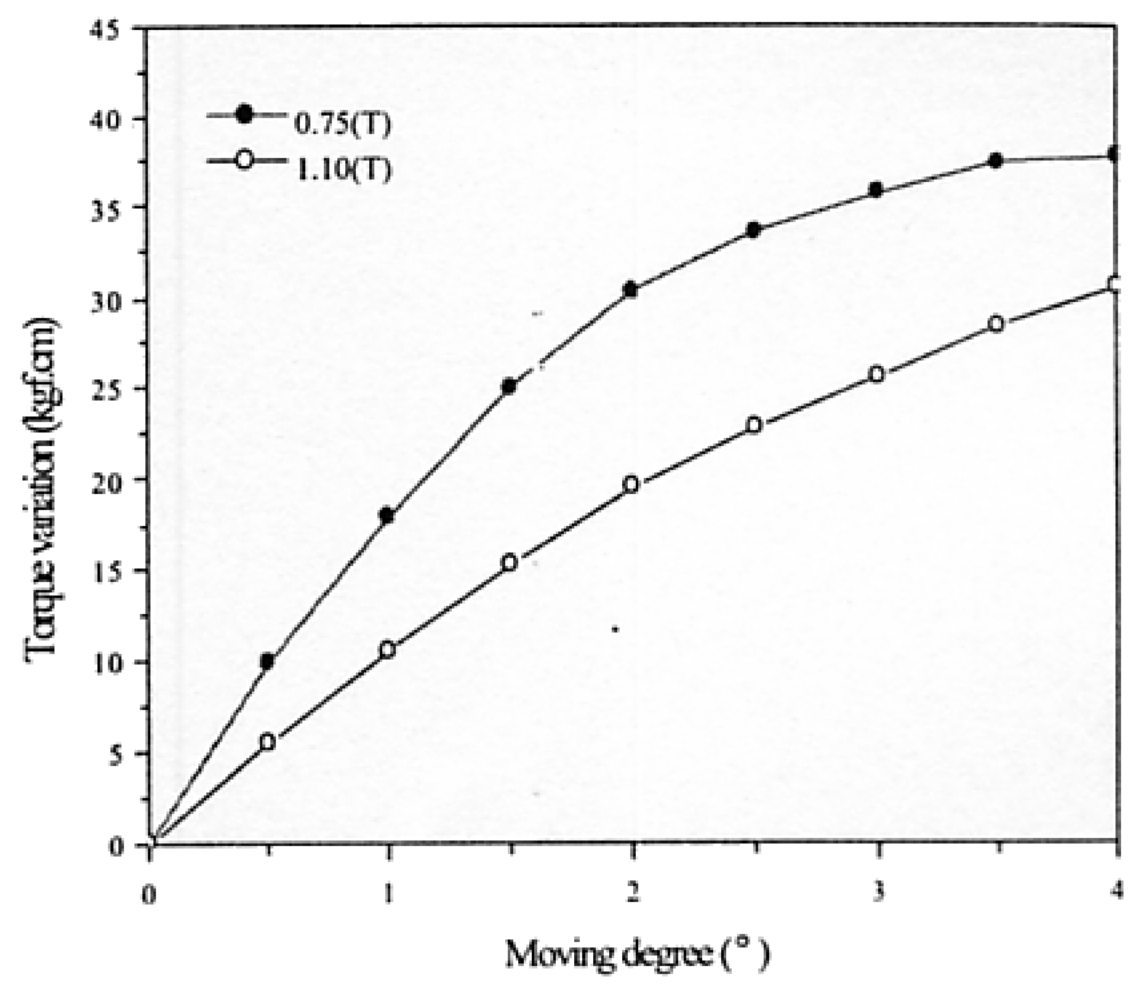


Fig. 7 Difference between maximum torque and minimum torque

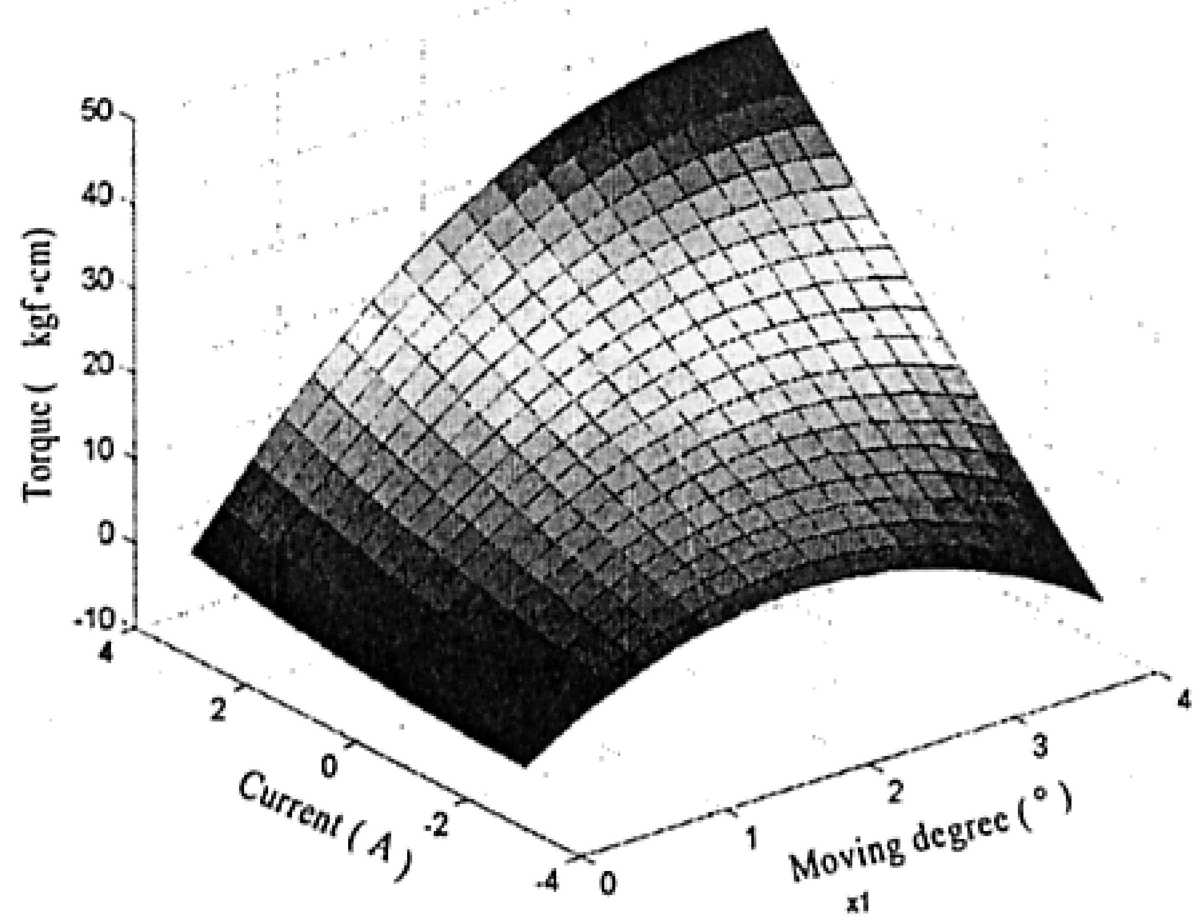


Fig. 6 Operating range of the torque at the residual flux density 0.75 (T)

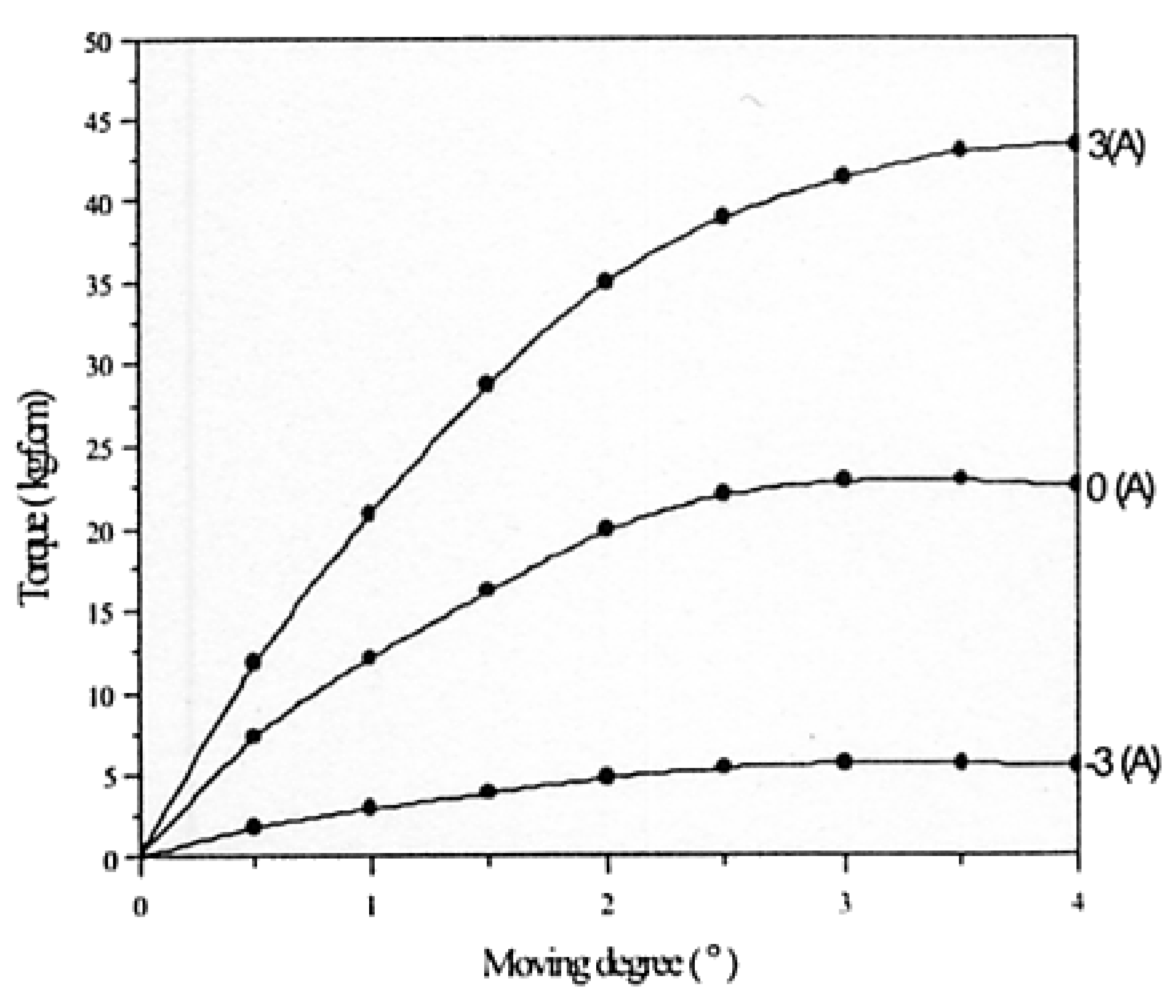


Fig. 8 Torque profile of the reform model

[5] S. J. Salon, *Finite Elements Analysis of Electrical Machines.* Kluwer Academic publishers, 1995.

[6] S. J. Salon, *Finite Elements Analysis of Electrical Machines.* Kluwer Academic publishers, 1995.