

# Experiment and Torque Modeling of Double-Excited, Two-Degree-of-Freedom Motor based on Magnetic Equivalent Circuit Analysis

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**Abstract** – This paper presents the magnetic equivalent circuit analysis of a double-excited, two-degree-of-freedom (DOF) motor. The double-excited, 2-DOF motor is a laminated structure, making it easy to manufacture and giving it simple operating principles. We explain the structure of the 2-DOF motor and analyze the static characteristics using a magnetic equivalent circuit (MEC) to reduce analysis time. The feasibility of MEC analysis was confirmed by experimental results of the tilting, panning motion. We also confirmed the occurrence of holding torque in every motion.

**Keywords:** 3-D finite element method, Magnetic equivalent circuit, Multi degree-of-freedom, Experiment, Security Camera

## 1. Introduction

The conventional multi degree-of-freedom (DOF) motions mechanism is operated by using a single-axis motor connected with a gear and link. This mechanism has increased volume due to the use of several motors, gears, and links, and it is difficult to miniaturize [1-2]. However, the multi-DOF motor can rotate in multiple directions with just one unit. For this problem, the multi-DOF spherical motor was developed due to these advantages [1-14]. The multi-DOF motor has the advantages of a compact structure and reduced volume [10]. This motor can eliminate the combined effects of inertia, backlash, non-linear friction, and elastic deformation of gears.

A few researchers have been concerned with developing a 2-DOF motor. Hirata has proposed a 2-DOF motor that consists of a permanent magnet rotor, and E and C type stator segments for linear and rotational motion, respectively [12]. Yano has proposed a 2-DOF motor that consists of an inner sub-motor and outer sub-motor for horizontal and vertical motion, respectively [13]. However, it is unsuitable for a security camera application with tilt/pan motion.

The Multi-DOF spherical motor has complicated distribution of the electromagnetic field, which leads to difficult magnetic property analysis and complicates torque calculation. At present, an analytical method [14, 15] and 3D finite element method (FEM) are used to calculate the magnetic fields of the multi-DOF spherical motor. However, due to its spherical structure, the analytical method usually neglects the end effects and nonlinear materials in the

motor, and the integral equation method has not yet been used in the torque calculation of the multi-DOF motor. Also, 3D FEM requires a lot of time for analysis due to the large amount of computation [15].

Our previous study (which double excited a 2-DOF motor for a security camera) was proposed by Lee and Kwon [16]. They proposed the structure and analyzed it by 3D FEM. Also, this 2-DOF motor need a lot of time for design and optimization due to 3D FEM.

This paper proposes a torque calculation method of a double-excited, 2-DOF motor based on the magnetic equivalent circuit (MEC). MEC analysis is most commonly used in magnetic field approximation and analyzing motors due to high accuracy and simple analysis. The double-excited, 2-DOF motor is possible to analyze by MEC because it has a pathway of magnetic flux in the laminated direction. The following sections explain the structure of the double-excited, 2-DOF motor, and derive the static torque equation by MEC. Also, the 3D finite element method (FEM) was analyzed. The validity of the proposed structure was shown by a manufactured prototype and by comparing the computer simulation and experiment..

## 2. The Double Excited 2 DOF Motor Structure

Fig. 1 shows the structure of the double-excited, 2-DOF motor. The motor is constructed by laminated structures as shown in Fig. 1(a). Thus, the processing is easy because three-dimensional processing is not needed [16].

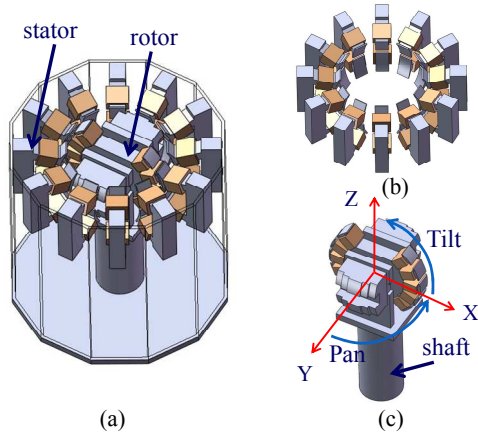
The 2-DOF motor consists of the stator and rotor. In Fig. 1 (b), the stator segments are designed as C type to form the closed flux loop. The stator is placed to 12 stator segments. Also, the stator is placed to a 90° interval by 3-phases, so that it reacts to both the main pole and the auxiliary pole of the rotor. In Fig. 1(c), the rotor is also designed to form a flux closed loop of symmetry via the tilt rotating axis, so that the flux is not overlapped.

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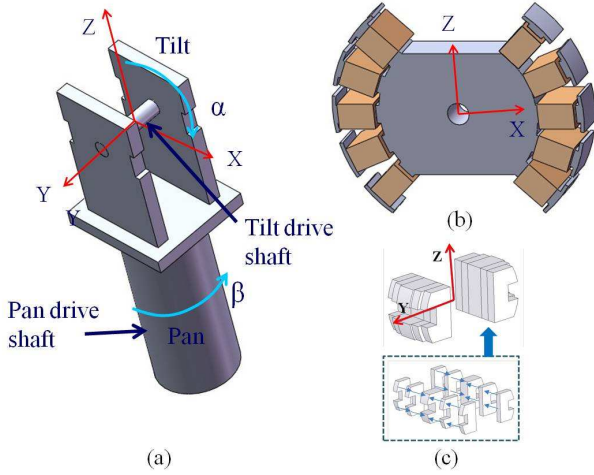
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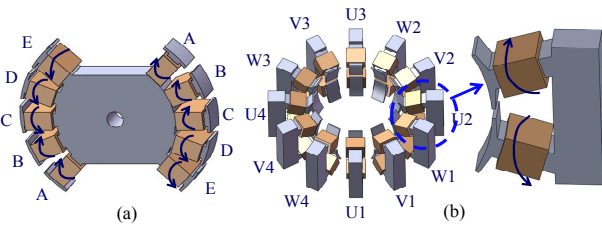
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**Fig. 1.** Structure of proposed 2 DOF motor: (a) Overall structure; (b) Stator structure; (c) Rotor structure.



**Fig. 2.** Rotor structure: (a) Shaft structure; (b) Main pole; (c) Auxiliary pole.



**Fig. 3.** Winding connection: (a) Rotor winding connection and winding direction; (b) Stator winding connection and winding direction.

Fig. 2(a) shows the shaft structure of the rotor. The overall shaft is constructed to form a tilt shaft through the pan shaft, and the rotor coil is a solved slip-ring to prevent coil twist phenomenon in the shaft's end. Fig. 2(b) shows the main pole structure of the rotor, and Fig. 2(c) shows the auxiliary pole structure of the rotor. The rotor is placed at the auxiliary pole to increase panning torque. To maintain the fixed air gap length, the auxiliary pole is attached to a

smaller core.

The structure has coils for rotation inside the rotor. Therefore, the stator has a simple structure. It is possible to extend the range of unhindered motion of the rotor. Fig. 3 shows the winding connection. The stator has 3 phases with 4 sets of winding, and the rotor has 5 phases with 4 sets of winding. The rotor coils are connected in series with the coils that are in opposing positions to the origin.

### 3. Magnetic Equivalent Circuit Analysis of the 2-DOF Motor

In order to use the 2-DOF motor in a robot joint, for example, we need a torque to maintain the rotor in any random place; this torque is called the holding torque. The operating principle of the 2-DOF motor is identical to the motion of the stepping motor, and the stepping motor rotates by one step via electric current switching consequently. The tilting motion rotates to the switching on the phase of the main pole in the excited state of the stator phase facing the main pole. Panning motion rotates depending on the switching on the stator phase coil when the rotor is excited [16]. Fulfilling this analysis condition, the static torques are calculated in each motion, one by one.

The reluctance of each MEC model consists of core reluctance  $\mathfrak{R}_c$  and airgap reluctance  $\mathfrak{R}_g$ . The reluctance is calculated as follows

$$\mathfrak{R}_c = \frac{l_c}{\mu_r \mu_0 A_c} \quad (1)$$

$$\mathfrak{R}_g(\alpha, \beta) = \left( \mu_0 L \left[ \frac{w_t(\alpha, \beta)}{g} + \frac{4}{\pi} \ln \left( 1 + \frac{\pi w_s(\alpha, \beta)}{4g} \right) \right] \right)^{-1} \quad (2)$$

where,  $l_c$ ,  $\mu_0$ ,  $A_c$ ,  $L$ ,  $w_t$ ,  $w_s$ ,  $g$  and  $\theta$  are magnet length, permeability of air, cross-sectional area, stack length, slot width, teeth width and air gap length. Generally,  $\alpha$ ,  $\beta$  are dependent. However proposed 2-DOF motor has a two shaft for each equation as shown Fig. 2(a) and axis of the two rotations are different each other structurally. Therefore, if the rotor operates only one rotation at a time, when the main pole of rotor is aligned stator U phase as shown Fig. 4(a),  $\alpha$  and  $\beta$  are independent each other structurally and electrically. As mentioned above, the analysis conditions meet the independent condition. Thus, (2) can change as follows.

$$\mathfrak{R}_g(\theta) = \left( \mu_0 L \left[ \frac{w_t(\theta)}{g} + \frac{4}{\pi} \ln \left( 1 + \frac{\pi w_s(\theta)}{4g} \right) \right] \right)^{-1} \quad (3)$$

The  $\theta$  become to  $\alpha$  or  $\beta$  according to rotating direction. The  $\mu_r$  is permeability of the core and it is selected by the operating point of the core and is fixed. Thus, each  $\mathfrak{R}_c$  is constant as shown in (1). However  $\mathfrak{R}_g$  is varied by

rotating rotor. The 2-DOF motor can rotate two directions  $\alpha$ ,  $\beta$  as shown in Fig. 2(a).

To calculate the fluxes and inductances in each step, the MEC is created as shown in Fig. 4, 5. The MEC model of tilting consists of 3 steps, as shown in Fig. 4, and panning is shown in Fig. 5. The electromagnetic torque for double excited systems is given by

$$\Phi(\theta) = \frac{Ni}{\mathfrak{R}(\theta)} \quad (4)$$

$$L(\theta) = \frac{\lambda(\theta)}{i} = \frac{N\Phi(\theta)}{i} \quad (5)$$

$$T(\theta, i) = \frac{1}{2} i_s^2 \frac{dL_{ss}(\theta)}{d\theta} + \frac{1}{2} i_r^2 \frac{dL_{rr}(\theta)}{d(\theta)} + i_s i_r \frac{dL_{sr}(\theta)}{d(\theta)} \quad (6)$$

where  $\Phi$ ,  $N$ ,  $T$ ,  $i_s$ ,  $i_r$ ,  $L_{ss}$ ,  $L_{rr}$ ,  $L_{sr}$  and  $\theta$  are the magnetic flux, number of turns, electromagnetic torque, stator current, rotor current, electromagnetic torque, self

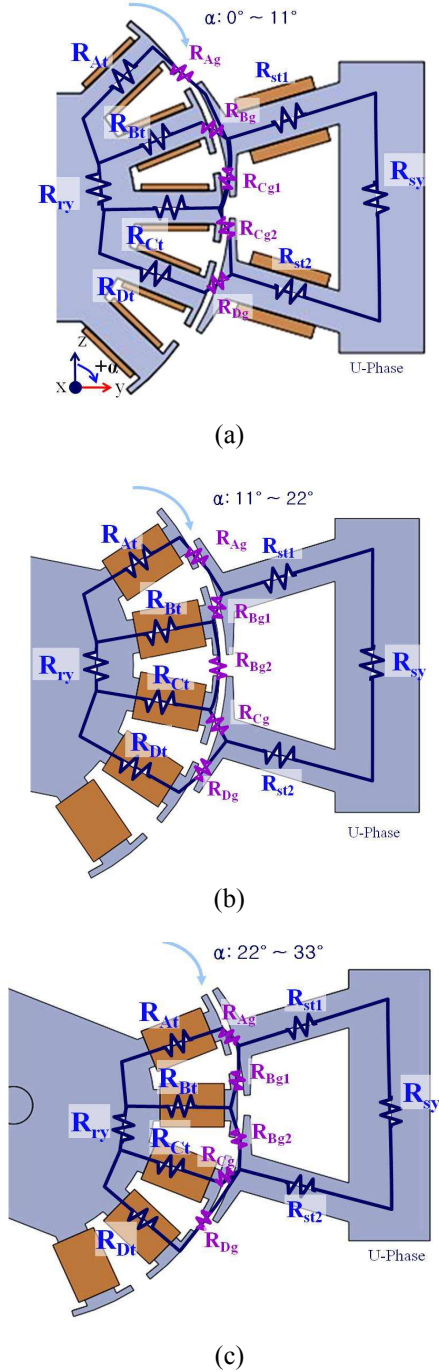


Fig. 4. The MEC modeling of the 2 DOF motor in the tilting motion (a) first step (b) second step (c) third step

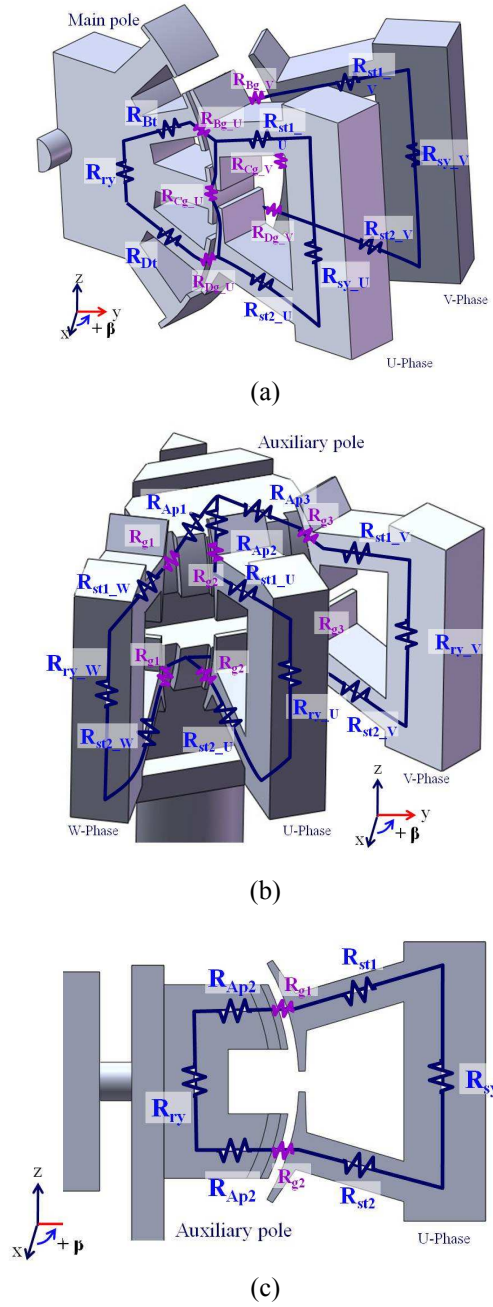


Fig. 5. The MEC modeling of the 2DOF motor in the panning motion (a) main pole (b) auxiliary pole (c) detailed view about auxiliary pole

inductance of stator, self inductance of rotor, mutual inductance and rotor position. The  $\theta$  become to  $\alpha$  or  $\beta$  according to rotating direction

The fluxes are calculated using (4) in each MEC loop. Then the inductances are obtained by using (5). The calculated inductances can be classified into self and mutual inductances according to the flux ingredient. These inductances are changed by varying reluctances, and reluctances are changed by varying the rotor position  $\alpha$  and  $\beta$

The electromagnetic torque is generated by varying the inductance as shown in (5). Thus, it is generated by varying the rotor position and by switching the rotor or stator phase. The first two terms on the right side of (6) represent torques produced in the rotor by the variation of self-inductance. The third term represents torque produced by the variation of the mutual inductance between the stator and rotor windings. The first two components of torque are called the reluctance torque, and the third term is called the magnetic torque. The 2-DOF motor uses both.

The panning motion consists of two kinds of torque: one is magnetic torque by the main pole as shown Fig. 5(a); the other is reluctance torque by the auxiliary pole as shown in Figs. 5(b) and 5(c).

The simulation condition of the tilting is as follows. The tilt motion moves 3 steps, and torque is analyzed at each step. In the first step, after exciting the stator U phases and rotor B and C phases, torque was analyzed by rotating the tilt angle  $\alpha$  from 0 to 22 degrees. In the second step, after exciting the rotor A and C phases, torque was analyzed

by rotating  $\alpha$  from 11 to 33 degrees. In the third and final step, after exciting the rotor A and B phases, torque was analyzed by rotating  $\alpha$  from 22 to 33 degrees. The 2-DOF motor is structurally capable of rotation only from 0 to 33 degrees in the tilting direction. Therefore, the third step is analyzed up to 33 degrees. The input currents of the rotor and stator phases are 2.7 A

The simulation condition of panning is as follows. The rotor is placed as in Fig. 5(a). Phases B and D are excited, and the stator V is on. The torque is then analyzed using MEC and 3D FEM by rotating the pan angle  $\beta$  from 0 to 60 degrees. The input currents of the rotor and stator phases are 2.7 A

#### 4. Prototype and Experiments of 2 DOF Motor

A designed 2-DOF motor was manufactured as shown in Fig. 6, and specifications are listed in Table 1. For the experiment, the shaft was added on the top of the rotor as shown in Fig. 6(a), and a slip ring was added to supply the exiting current in the rotor coil as shown in Fig. 6(c).

The experiment of the 2-DOF motor is different from those of the existing motor because of the need for tilt experiments. Therefore, the testbed that can convert the rotation axis was manufactured as shown in Fig. 7 to

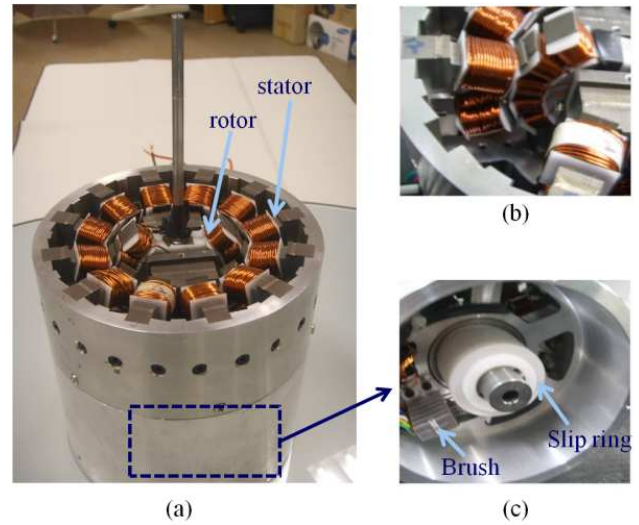


Fig. 6. Prototype of 2 DOF motor. (a) structure of 2 DOF motor (b) detailed rotor and stator structure (c) slip ring

Table 1. Specifications of 2-DOF motor

Stator	
Radius	Øout : 75 [mm], Øin : 36 [mm]
Material	S 30
Stack width	10 [mm]
winding	Number of turns, Ns : 80 [turn] Coil diameter : 0.8 [mm]
Rotor	
Radius	Øout : 75 [mm]
Material	S 30
Stack width	10 [mm]
winding	Number of turns, Nr : 20 [turn] Coil diameter : 0.8 [mm]

measure tilt characteristics. The tilt motions of the 2-DOF motor are transmitted by the testbed to the shaft, which connects the measurement device as shown in Fig. 7(a).

Fig. 8(a) shows the measurement system of tilt torque using the testbed. For measurement, the tilting motions are

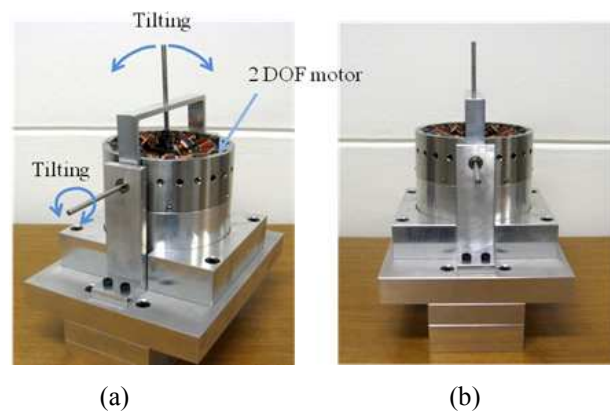
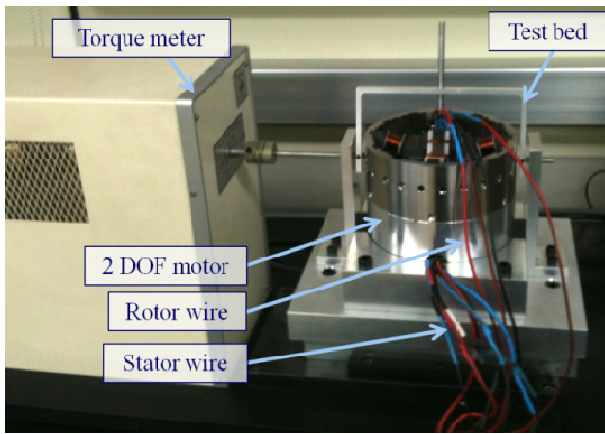
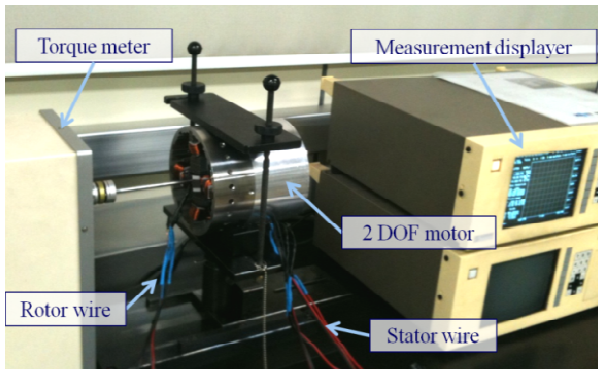


Fig. 7. Testbed for torque measurement of tilting: (a) equal angle view of testbed; (b) a front view of testbed



(a)



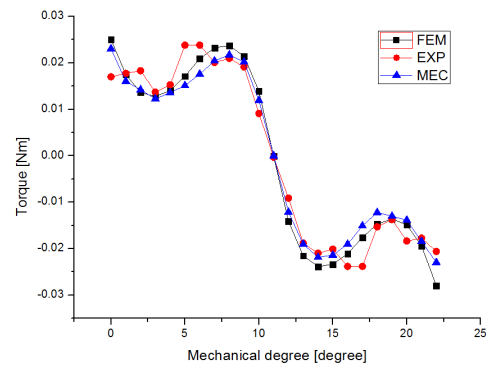
(b)

**Fig. 8** Measurement system of the 2 DOF motor (a) Measurement system of tilting torque Measurement system of pan torque

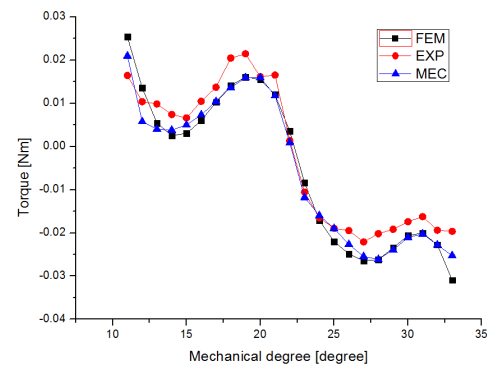
converted into the rotation axis by the testbed. The rotations of the shaft transmitted from the tilt motions are measured by a coupling torque meter. The experiments of tilting motion are measured under the same conditions as in the simulation.

Fig. 8(b) shows the measurement system of pan torque. The pan torque was measured common method of general motor. The experiment of pan motion was also measured under the same condition of the simulation.

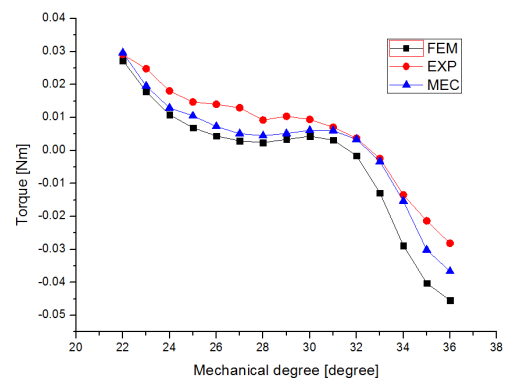
Fig. 9 shows the simulation versus the result of tilt and pan torque. The objective of this experiment is to verify the 2-DOF motor. The 2-DOF motor was measured at each step of tilt. Figs. 9(a-c) show the comparison of the simulation and experimental results for tilt torque, and Fig. 9(d) shows the same comparison for pan torque. The average torque of positive area was about 0.016 Nm in tilt motion, and the average torque of positive area was about 0.051 Nm in pan motion. The tilting consists of three steps, and each torque has a position in which torques become zero. These positions are the holding points of the rotor at each step. The experimental results show that torque becomes zero at the destination.



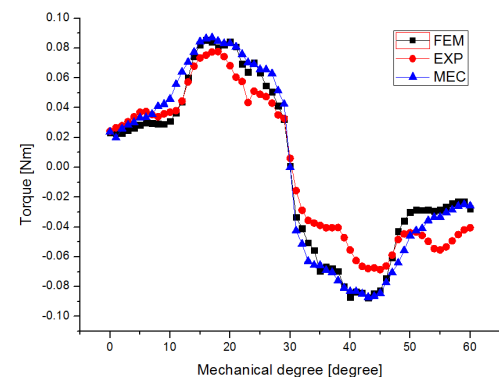
(a)



(b)



(c)



(d)

**Fig. 9.** Simulation and experimental results of 2DOF motor: (a) 1step of tilting; (b) 2step of tilting; (c) 3step of tilting; (d) pan

The comparisons show that the deviations increase after 33 degrees of the third step and pan, as in Figs. 9(c) and 9 (d). Because the torque of the 2-DOF motor needs accurate measurement, the disturbances which like a friction, twisted the coil, testbed affects experiment result.

## 5. Conclusions

This paper proposed a torque calculation method for a double-excited, 2-DOF motor based on MEC analysis. We calculate the static torque using the MEC analysis, and perform 3D FEM. To verify the simulation result, a prototype was manufactured and simulation results were compared with experimental results. As a result, the MEC analysis is matched well and the 2-DOF motor can operate tilt and pan motion. Based on this result, we will apply for the control of 2-DOF motor

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