# Identification and Fuzzy-PI Controller Design for a Novel Claw Pole Eddy Current dynamometer in Wide Speed Range


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*Abstract*— **One of the essential tools in motor tests, especially in high speeds, is access to variable load torque. Eddy current dynamometer (ECD) system, using a variable field, provides different load torque with respect to excitation current. This paper investigates on modeling and controller design for a novel claw pole ECD that is employed to be a variable load torque in DC type counter rotating motor (CRM). DC motors under investigation of this paper consist of inner and outer shaft rotating in different directions that are suitable in under water propulsion applications. To design an accurate controller, achieving to an exact dynamical and parametric model of ECD is necessary. To realize this aim, the state space model of the ECD is identified at low speed range. After that, we use experimental data to determine torque-speed characteristic, which is used in parametric model, in wide speed range. The control strategy of this paper is PI controller adjusted by fuzzy system. Subsequently, using MATLAB simulation results, comparison between PI and fuzzy-PI proves better performance of fuzzy-PI controller.**



***Keywords-component; Eddy Currents Dynamometer; Fuzzy-PI controller; DC Counter Rotating motor***


## I. INTRODUCTION

The extensive application of eddy current system makes it essential to investigate mathematical analysis. Eddy current systems, which are known as electromechanical devices, are generally used in two different applications. The first application is widely in high weight vehicles such as train, trucks and so on as an assistive brake. The second one is to provide a variable load to test motor which is known as eddy current load [1-2].

Because of Newton's third law, variable magnetic field on a moving metal causes swirl like electrical currents in the outer surface called as eddy currents. In fact, variable magnetic field generates eddy currents opposing the movement of the mental. This procedure leads to conversion of kinetic energy to heat.

The performance of the eddy current system extremely depends on accurate mathematical model. Smythe firstly modeled eddy currents in a rotated disk [2]. In [3], the braking torque was calculated by means of eddy-current power as input. Using experimental data and applying the Lorentz's force law, Wiederick formulated the eddy currents with respect to induced voltage and resistance [4]. All of the mentioned works are in the low speed conditions. In [5], a theoretical investigation to survey the effect of high speeds on eddy currents is presented but it extracted different equations to describe each region separately. Some literatures used the introduced model in [5] to design eddy current brakes [6-7].A parametric model for description of eddy currents brake (ECB) is introduced in [8].Literature [9] presents a mathematical model for description of torque-speed characteristic under consideration of armature and skin effect in ECB with cylindrical rotor. In control researches, optimal robust controller using sliding mode controller is proposed to control ECB system in [10]. To reach the optimum braking force in different speeds, literature [11] used a PI controller.

In all of the surveyed works, a unit dynamical model in wide speed range is not reported. In this paper, though having two shafts rotating in different directions, we concentrate on one shaft to model and design controller. At first, with considering experimental data, we depict that analytical characteristic of torque-speed presented in [10] is not usable in high speeds. Next, it reports either mathematical modeling or controlling a claw pole ECD system which has not been presented former. In this paper, in fact, we propose an advanced model to be acceptable in both high speeds and low speeds.

The organization of this paper is as follows: Section 2 present physical structure of claw pole ECD system. Next section gives the mathematical analysis of system. In section 4, using experimental data, torque-speed characteristics is estimated by a polynomial function. Section 5 introduces ECB system nonlinear dynamic using estimated torque. In next section, controller design is presented and simulation results are presented in section7. Finally, section 8 concludes this paper.

## II. MECHANICAL STRUCTURE OF ECD SYSTEM

The theory of basic electromagnetic induction implies on the principle of eddy current brake system. This theory expands

Faraday's induction law, which it explain the procedure of generation of current in a moving conducting element in a constant magnetic field. Due to the inducted current, a reaction force is created to oppose the element motion [1]. In this application, we use the opposite force as a load to test DC motors. The structure of the system consists of claw pole which is presented in [1-2]. Fig. 1 illustrates the schematic of the ECB system. The system's stator consists of just one excitation coil which is mounted between claw pole pairs. Each claw pole generates a magnetic field which together, leads to total magnetic field.

Just one pair of total claw poles is illustrated in fig. 1. If a direct current excites the windings and an external torque, supposed to be applied by a DC motor, rotates the cylinder, a current, named as eddy current, is produced in the iron core mounted on DC motor shaft. As mentioned before, it is concluded form Faraday's induction law. The created torque is a function of applied DC excitation current, rotation speed of cylinder and electromagnetic characteristic of the core. In this paper, we assume that a DC motor rotates the cylinder and created opposite torque is assumed as a load to test high speed DC motors. It makes us possible to determine the torque-speed characteristic of DC motors.

Fig. 2 depicts the whole ECD system structure and Fig. 3 shows the experimental system. The counter motor has two inner and outer shafts rotating opposite directions. In this structure, two eddy current brake systems are used to test motor. Both shafts are connected with a brake. Consequently, two current sources support system. More details of considered system is presented in [1-2].

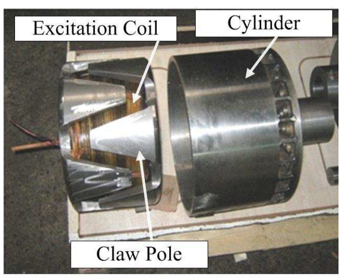


Figure 1. The schematic of the projected eddy current load [1]

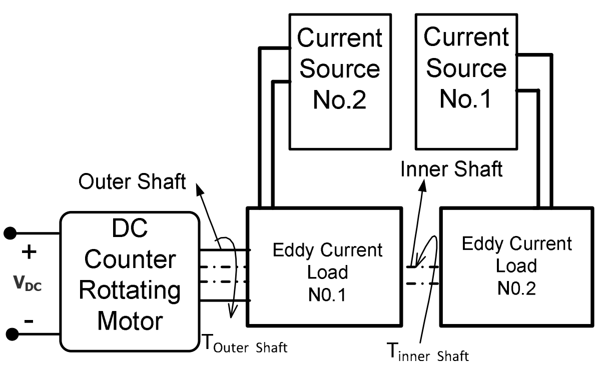


Figure 2. Schematic of experimental system [1]

## III. MODELING ECD AT LOW SPEED

The flux and linear speed vector in ECD is shown in fig.4. As regards, to this fig, these vectors are calculated as follows:

$$\overline{B} = |B|\cos\theta\,\hat{i} + |B|\sin\theta\,\hat{j} \tag{1}$$

$$\overline{V} = |V|\sin\theta\,\hat{i} + |V|\cos\theta\,\hat{j} \tag{2}$$

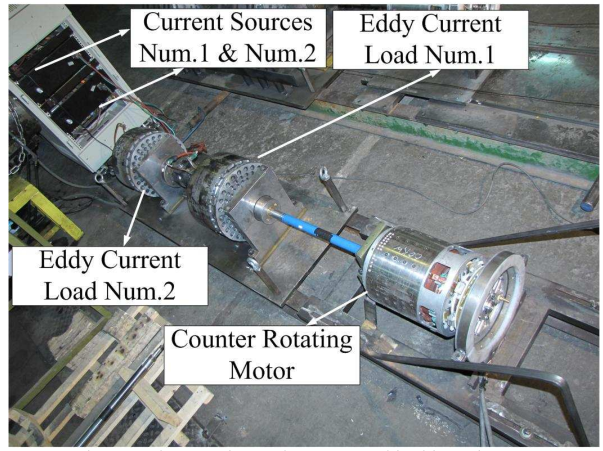


Figure 3. the experimental system used in this project [1]

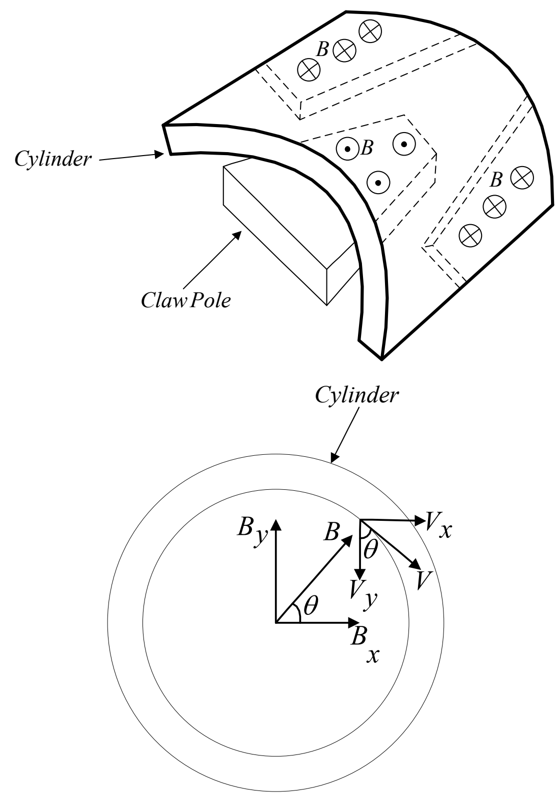


Figure 4. The flux and linear speed vector in ECD, three dimensions (upper), two dimensions (below)

At very low Speed, without considering both skin effect and armature reaction [12], the total power absorbed by the rotor (P) can be found by the following equations:

$$P = \frac{1}{\rho}\int (V \times B)^2 dv \tag{3}$$

$$P = \frac{1}{\rho}\int_0^{h_{cylinder}}\int_0^{2\pi}\int_{R_1}^{R_2}\left[(BV\cos^2\theta) - (BV\sin^2\theta)\right]^2 rdrd\theta dz \tag{4}$$

$$P = \frac{h_{cylinder}}{\rho}\times(B\omega)^2\int_0^{2\pi}\cos^2(2\theta)d\theta\int_{R_1}^{R_2} r^3 dr \tag{5}$$

$$P = \frac{h_{cylinder}}{\rho}\times(B\omega)^2\times\frac{1}{4}(R_2^4 - R_1^4)\times\pi \tag{6}$$

At the above equations $V$ is linear speed and is angular speed of the rotor, $B$ is magnetic intensity of the stator in air gap at zero speed, is cylinder length, $R$ is radius of the cylinder and $\rho$ is resistivity of the rotor. Dividing by $\omega$, the torque speed characteristic of a cylindrical eddy current brake is as follows:

$$T_L = \frac{h_{cylinder}}{\rho}\times(B\omega)\times\frac{1}{4}(R_2^4 - R_1^4)\times\pi \tag{7}$$

Therefore, the dynamical Modeling of Eddy current load and Motor are calculated as follow:

$$\begin{aligned} T_e - T_L &= \\ K\varphi I_a &- \frac{h_{cylinder}}{\rho}\times(B\omega)\times\frac{1}{4}(R_2^4 - R_1^4)\times\pi - Q\dot{\theta} \\ &= K' I_a^2 - \frac{h_{cylinder}}{\rho}\times(B\omega)\times\frac{1}{4}(R_2^4 - R_1^4)\times\pi - Q\dot{\theta} = M\dot{\omega} \end{aligned} \tag{8}$$

$$V_t = RI_a + L\frac{dI_a}{dt} + K' I_a\omega \tag{9}$$

In equation (8), $I_a$ depicts motor winding current. Also, parameters $M, K, Q, L, V_t, R$ and $K'$ are the moment inertia of cylinder, the torque constant of motor, the viscose friction of the motor, motor inductance, motor applied voltage, the winding resistance of motor and constant, correspondingly.

## IV. Modeling of ECD in Wide Speed Range

Using white box identification method presented in equation (8), to extract dynamical behavior of motor tester system which uses eddy current brake as an external load, is just applicable in low speeds. High speeds of disk leads to an unbalanced current distribution in the area of rotated disk which causes a limited area for the existence of current [5]. Experimental results emphasize the contradiction between real and theoretical conclusions in high speeds. Because of curve saturation in torque-speed characteristic in high speeds, we use experimental data in massive range of speed in different -

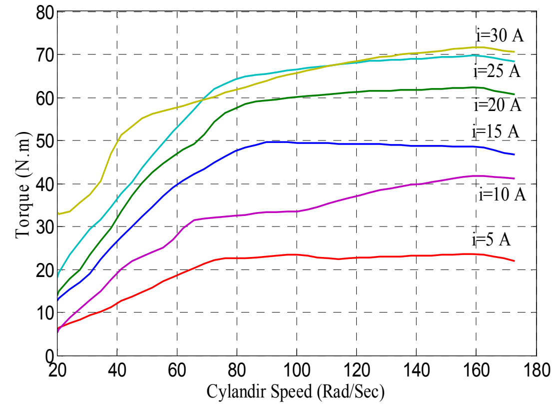


Figure 5. Torque-speed characteristic in different currents using experimental data

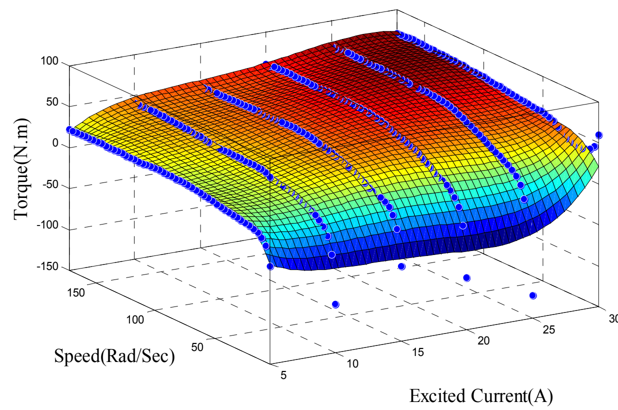


Figure 6. Fitting a polynomial curve to experimental data

currents to extract a function describing torque with respect to current and speed. Fig. 5 shows the torque-speed characteristic of eddy current system in different excitation currents.

Though anticipating curves to be linear in all speeds based on equation 1, referring to fig. 5, torque-speed characteristics saturate in high speeds. Thus, it is the firm reason of this paper to use an estimated characteristic instead of theoretical base. This paper uses curve fitting MATLAB toolbox (cftool), using least square method, to fit a suitable function for extrapolation fig.6. This function is as follows:

$$\begin{aligned} T_{estimate}(\omega, i) &= a_1 + (a_2 i + a_3\omega) \\ &+ (a_4 i^2 + a_5 i\omega + a_6\omega^2) \\ &+ (a_7 i^3 + a_8 i^2\omega + a_9 i\omega^2 + a_{10}\omega^3) \\ &+ (a_{11} i^4 + a_{12} i^3\omega + a_{13} i^2\omega^2 + a_{14} i\omega^3 + a_{15}\omega^4) \\ &+ (a_{16} i^5 + a_{17} i^4\omega + a_{18} i^3\omega^2 \\ &+ a_{19} i^2\omega^3 + a_{20} i\omega^4 + a_{21}\omega^5) \end{aligned} \tag{10}$$

Where $x = (i - 17.5)/8.56$ and $y = (\omega - 95.03)/49.96$ are normalized current and speed values.

## V. PI CONTROLLER DESIGN BASED ON FUZZY SYSTEM

Poor performance of PI controller with constant parameters in different operating point forces controller to be tuned online by supervisor. In this paper, a fuzzy system is used as a supervisor to tune PI controller based on user's knowledge of plant nonlinear behavior. Simulation results prove lower effect of derivative term of PID controller than proportional and integral term, so we neglect derivative term of PID. No initial conditions for PI parameters are considered. The structure of control system is depicted in fig. 7.

Fuzzy system takes $e$ and $\dot{e}$ as inputs and gives $k_p$ and $k_i$ as outputs. Fuzzy member ship functions, based on experiments, are shown in fig. 8.In the fig.8, the linguistic terms are negative big (NB), negative medium (NM), negative small (NS), zero (ZO), positive small (PS), positive medium (PM), positive big (PB), small (S), medium (M) and big (B). Weighted average method is selected for defuzzification, for instance:

$$k_p = \frac{\sum_i b_i \mu_i}{\sum_i \mu_i} \tag{11}$$

where $b_i$ represents the center of output membership functions, and $\mu_i$ is a selected as minimum. Fuzzy if-then rules are given in the tables I to II.

## VI. SIMULATION RESULTS

Constant parameters of under study system are listed in Tab. 3. Figures 9 to 12 illustrate simulation results of proposed controller on dynamical model. Because of the armature effect, we divide figures in two separate figures. In the fig.9, the effect of armature is shown. It is clear that both fuzzy-PI and PI controller have a same performance on transient state. Fig. 10 shows tracking results after crossing of the armature effect. Also, fig. 8 and 9 depict PI parameters tuned by fuzzy system and rotating speed of disk. In all aspects, fuzzy-PI controller has better performance than PI controller.

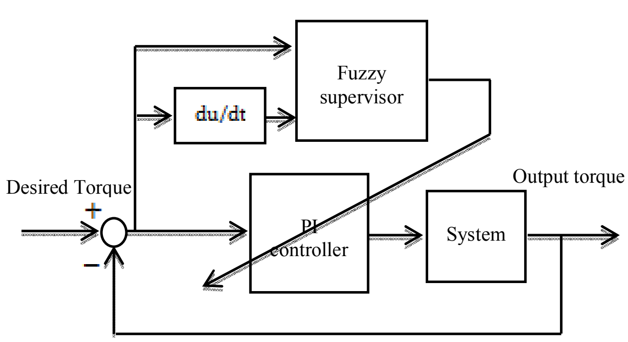


Figure 7. Fuzzy-PI controller structure

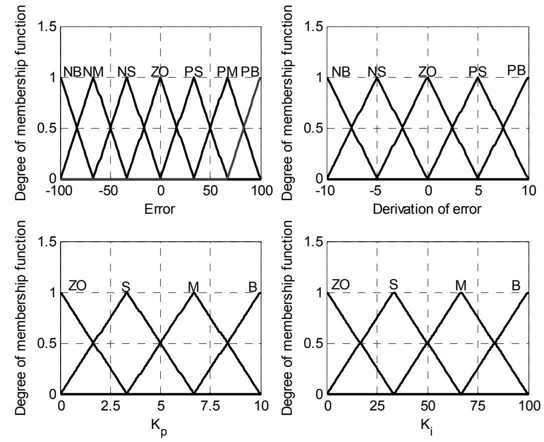


Figure 8. Input-output membership functions of fuzzy system

TABLE I. THE FUZZY RULES FOR $k_p$

| $k_p$ | $\dot{e}$ | NB | NM | NS | ZO | PS | PM | PB |
|---|---|---|---|---|---|---|---|---|
| $e$ | NB | B | B | M | S | M | B | B |
| | NS | B | M | S | ZO | S | M | B |
| | ZO | B | M | S | ZO | S | M | B |
| | PS | B | M | S | ZO | S | M | B |
| | PB | B | B | M | S | M | B | B |

TABLE II. THE FUZZY RULES FOR $k_i$

| $k_i$ | $\dot{e}$ | NB | NM | NS | ZO | PS | PM | PB |
|---|---|---|---|---|---|---|---|---|
| $e$ | NB | ZO | S | B | B | B | S | ZO |
| | NS | ZO | ZO | M | B | M | ZO | ZO |
| | ZO | ZO | ZO | M | B | M | ZO | ZO |
| | PS | ZO | ZO | M | B | M | ZO | ZO |
| | PB | ZO | S | B | B | B | S | ZO |

TABLE III. THE PARAMETERS OF SIMULATION FOR ECB SYSTEM

| Parameters (in SI unit) | Values |
|---|---|
| $M$ | *0.01 kg/m*$^3$ |
| $k$ | *0.00018 N.m/A.Tesla* |
| $k'$ | 0.00018 V/*A*.rad/sec |
| $Q$ | 0.0002 N.m/rad/sec |
| $L$ | 68 micro H |
| $R$ | 0.05 Ohm |

## I. CONCLUSION

Eddy current brake system has a critical role in DC motors tests. Either in low speeds or high speeds, it creates a magnetic load on DC motor shaft. This paper focuses on modeling and controller design for ECB system in wide speed range. Experimental results show low accuracy of analytical model for applied torque in high speeds, so we introduce a polynomial function, based on experimental data, to estimate applied torque in different speeds and excited current. Next, using estimated torque, dynamical model is proposed. Finally, a PI controller, tuned by fuzzy supervisor, is used to control applied torque. Obviously, fuzzy-PI controller has a better performance than PI one.

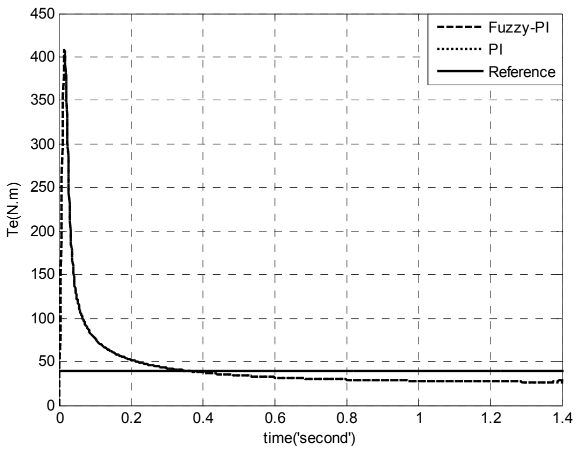


Figure 9. Armature effect in first seconds

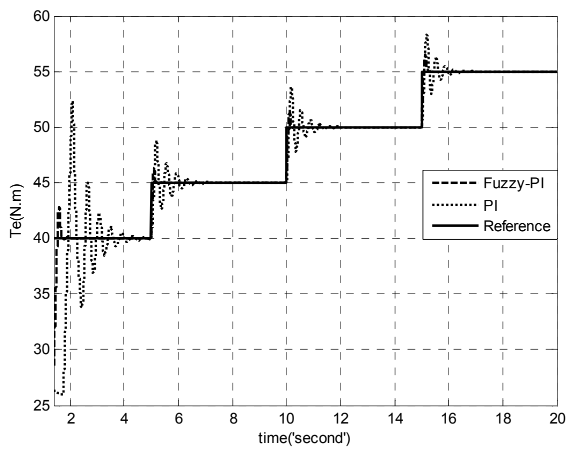


Figure 10. Tracking results using fuzzy-PI controller

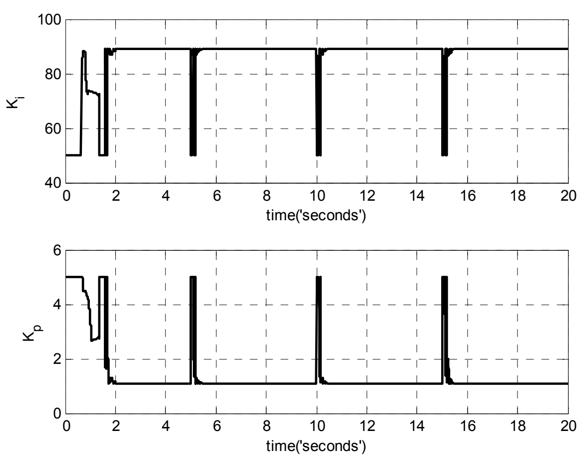


Figure 11. Fuzzy system outputs (PI parameters)

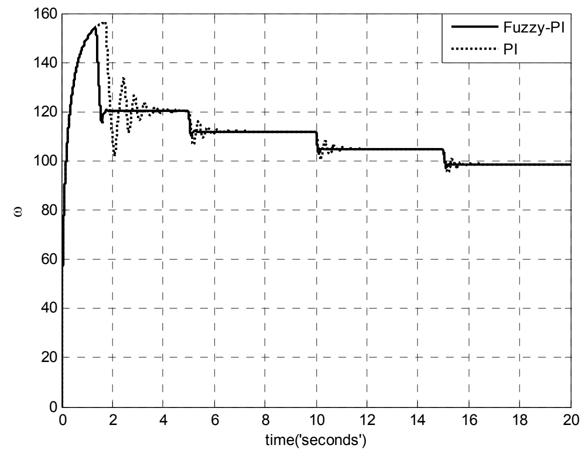


Figure 12. disk rotation speed with fuzzy-PI controller (solid line) and PI controller (dashed line)

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