A Dual-mode Control of a Multi-coil Electromechanical Converter Based on an Improved Bacterial Foraging Algorithm

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Abstract: The objective of this research is to improve the response performance of an electro-mechanical converter (EMC), a new design of EMC provided with the bobbin of triple coils is proposed in this study. A mathematic model and a solution of searching time optimum using an improved Bacterial Foraging Algorithm (BFA) are developed, and a dual-mode controller with Bang-Bang & PI based on the proposed method is designed. Analysis and simulation results show promising effects that the response time of the triple coil EMC driven by dual-mode controller is reduced from 8.5ms to 2.5ms compared to the traditional single coil EMC, and the ringing and overshoot are below 5%. The designed control technology can realize high response performance and display good prospect of development.

Keywords: Electromechanical Converter (EMC), Triple Coil, Bacterial Foraging Algorithm (BFA), Time Optimal Control,
Bang-Bang Control

1. Introduction

An electromechanical converter (EMC) is regarded as the most widely employed linear motion mechanism in various industry driving field**s**, so that electromagnetic energy can be converted to mechanical energy reciprocating linear motion continuously and proportionately. At present, a moving coil type of EMC has been drawing widely attention because of high linearity and small hysteresis. Tanaka [1] pointed out the generated electromagnetic force is about 2.5 times higher than the others with the same size.

Step input is very common in automatic control applications. However, the optimal performance of the EMC is often compromised when driven by a conventional PID controller, since quickness, robustness and overshoot are contradictory in a PID controller [2-4]. K. A [5] built a third-order model that includes the inductance of the motor coil for Bang-Bang control with time optimal performance, and developed universal curves which enable designers to choose appropriate actuator performance parameters to fulfill different design objectives. Khandaker [6] and his group proposed a new control strategy based on applying high and low voltages pulse width modulated (PWM) power for transient and steady period, respectively, and achieved the conflicting requirements of very fast transition time and low contact velocities simultaneously. Mosca [7] applied the Affordable Predictive Control to the position servo control system in HDD, and the performance of good tracking, anti-jamming, robustness is provided.

However, the research above are not sufficient for searching a time optimal solution, some parameters are restricted to keep

the model at overdamping, so that the underdamping state is not taken into consideration, and some models are simplified to avoid cross feedback.

The aim of this study is to improve those deficiencies above, and a dual-mode controller with Bang-Bang & PI based on Bacterial Foraging Algorithm (BFA) is designed to obtain a time optimal control without losing robustness.

2. Structure and Mathematical Model

A schematic of an EMC designed in this study is detailed in Figure 1, which consists of permanent magnetic (PM), coils, bobbin, iron core, covers, output shaft, connector, etc. Several blocks of magnetic are fixed on the inner face of the right cover. An iron core is fixed in the center of the right cover by a screw. The coils are wrapped on the bobbin. The Bobbin which can move axially in the air gap formed between the PM and the iron core is connected to a guide pin and an output shaft. Input voltage signal is provided to coils after being amplified. Thus, the bobbin and the output shaft connected to the carrying currents coils and will move under the effect of Ampere force.
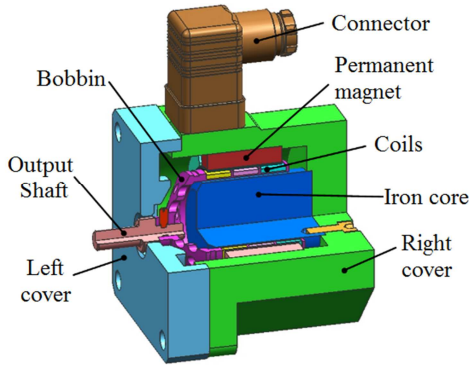

Fig. 1. Schematic of the proposed EMC.

Figure 2 reveals the control principle of EMC. The feedback signal is generated by a position sensor on the output shaft. The controller receives input signal and feedback signal. After comparing the difference between them, the controller output driving signal to eliminate the error. Obviously, a closed-loop control system is proposed and displays high accuracy.
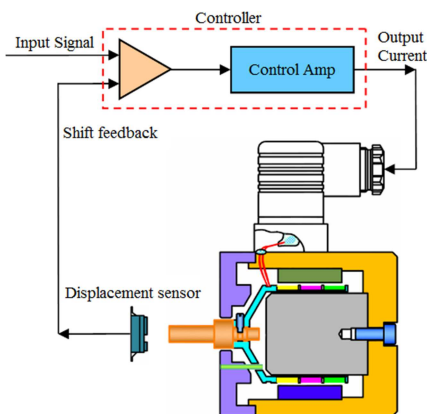

Fig. 2. Control principle of EMC.

Figure 3(a) and 3(b) compare two different bobbins of EMC with single coil and triple coils, respectively, which both provides with the same basic dimensions but the outer face of the triple coil type is divided into three independent sections for wrapping wire. Each of the three coils exhibits lower impendence than the single one, which will generate lager current under the same supply voltage. In addition, the triple coils are energized independent, which allows more flexible control strategy and different current between them.
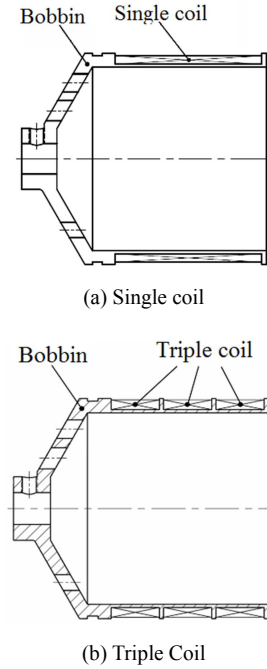

(a) Single coil

(b) Triple Coil

Fig. 3. Two different bobbins of EMC.

The output force of the EMC proposed above is given by Ampere force equation [8]:

$$F = IB\pi DN \tag{1}$$

Where I is coil current, B is magnetic strength, D is average diameter of the coils, N is turns of the coils.

For a certain EMC with known dimension and material, the factor $B\pi DN$ is a constant which can be defined as the transducer constant K_e.

Considering the load connected to the EMC, equations can be given out. The equations of the single coil EMC is:

$$U = RI + L\dot{I} + K_e\dot{x} \tag{2}$$

$$F = K_eI = M\ddot{x} + B_c\dot{x} + K_cx \tag{3}$$

Where U is supply voltage, R is resistance of the coil, L is inductance of the coil, K_e is transducer constant, M is total mass of EMC and load, B_c is damping coefficient, Kc is elastic constant, x is output displacement.

The equations of the triple coil EMC is:

$$U_1 = (R/3)I_1 + (L/3)\dot{I}_1 + (K_e/3)\dot{x} \tag{4}$$

$$U_2 = (R/3)I_2 + (L/3)\dot{I}_2 + (K_e/3)\dot{x} \qquad (5)$$

$$U_3 = (R/3)I_3 + (L/3)\dot{I}_3 + (K_e/3)\dot{x} \qquad (6)$$

$$F = (K_e/3)(I_1 + I_2 + I_3) = M\ddot{x} + B_c\dot{x} + K_c x \qquad (7)$$

Where U_i (i=1, 2, 3) is voltage applied to each coil, respectively, I_i (i=1, 2, 3) is current of each coil, respectively

It can be considered briefly that the impedance and transducer constant of each coil in triple coils are one third of the single coil, and will work at maximum power while paralleled [9], and the equations (4) ~ (7) can be simplified as:

$$U = U_{1,2,3} = (R/3)I + (L/3)\dot{I} + (K_e/3)\dot{x} \qquad (8)$$

$$F = K_e I = M\ddot{x} + B_c\dot{x} + K_c x \qquad (9)$$

where $I = I_1 = I_2 = I_3$

Comparing equation (2) and (8), it is obvious that an EMC with three paralleled coils is equal to a single coil EMC with one third impedance and the same transducer constant, and the goal of lowing impedance is achieved according. Let mechanical quantities to be as follows: $x_1 = x$ (displacement), $x_2 = x'$ (velocity), $x_3 = x''$ (acceleration). Combining (8) and (9), the system can be expressed as:

$$\dot{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = A \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + BU \qquad (10)$$

where

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -\dfrac{K_c R}{K_e L m} & -\dfrac{K_e^2 + K_c L + K_c R}{L m} & -\dfrac{B_c L + B_c R}{L m} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ K_e \end{bmatrix}$$

3. Dual-mode Controller

The equation matrix (10) matches the standard format of a completely controllable single input system. According to the Pontryagin's Minimum Principle, the time-optimal control $U(t)$ is a Bang-Bang type and the solution is unique. The maximum switching times are twice, which is half less than the order of the system [10, 11].

However, the actual EMC system exhibits some uncertain character, such as the error of parameter, the changes in load, the non-differentiable part caused by friction, and some un-modeled dynamics. Bang-Bang control cannot deal with those influence, thus other method is needed to improve stability and robustness [13-15].

To solve the contradiction, we proposed a Dual-mode controller combined PI and time-optimal bang-Bang control together. In the start-up phase, the error is relatively large, the Bang-Bang control is applied, and three coils are paralleled for a fastest speed. While in the ending phase, the error is much smaller, thus, the closed-loop PI control is employed, and only one coil is working to guarantee the convergence of the desired final state. Figure 4 details a dual-mode control flow chart of EMC, the decision-making logic select either bang-bang mode or PI mode, the output signal is amplified by H-Bridge for driving the EMC, and the feedback signal is necessary as well.
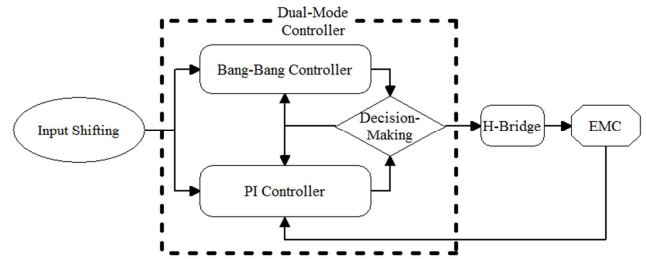

Fig. 4. *A dual-mode control flow chart of EMC.*

3.1. Improved BFA for Time-Optimal Solution

According the analysis above, the problem is to search switching times to keep final time shortest under the constraining of displacement, velocity and acceleration. A Bacterial Foraging Algorithm (BFA) is introduced to search the solution. BFA is a bionic random search intelligent algorithm proposed by Passino [12] in 2002 provided with the advantages of parallel searching, easily escaping a local minimum.

Instead of optimizing the switching time directly, we define the duration of each input to be optimized as: t_1, t_2, t_3, which means:

$$U(t) = \begin{cases} U_{max} & for & 0 \le t < t_1 \\ -U_{max} & for & t_1 \le t < t_1 + t_2 \\ U_{max} & for & t_1 + t_2 \le t < t_1 + t_2 + t_3 \end{cases}$$

The processes of BFA is briefly described as follows:
1) Chemotaxis: Suppose P_i (j, k, l) represent the ith bacterium at jth chemotactic, kth reproductive and lth elimination-dispersal step. $C(i)$ represents the step length and $V(j)$ represents the random direction vector. Thus, in each chemotactic step, the movement of the ith bacterium can be represented as: $P_i(i+1, j, k) = P_i(i, j, k) + C(i)V(j)$.
2) Reproduction: After N_c times of chemotaxis process, bacteria will reproduce. All bacteria are sorted in a reverse order according to their health value. In this step, only the healthiest half of the population survive and splits into two identical ones, which are then placed in the same locations. Thus, the population of bacteria keeps constant.

Elimination-Dispersion: This process improves the diversity of bacteria to prevent being trapped into the local optima. This will move some bacteria to another position according to a preset probability *p*.

Through the description, the fixed step length would result in a contradictory between speed and accuracy. According to the research before, the difference between t_1, t_2, t_3 can be as large as dozens of times [5, 13]. In this way, the step length will be shorten for every finished reproduction process.

As the duration is either too short or too long compared to an optimal solution, we let the bacterium whose health value is decreasing turn to the opposite direction to prevent premature convergence. The improved chemotaxis process is presented in Figure 5.

In this case, since the optimizing is under the constraint of displacement(x_1), velocity(x_2) and acceleration(x_3), penalty function method is easy-to-use to deal with the constraint [16]. The health value in BFA can be expressed as:

$$LiveFun = t_1 + t_2 + t_3 + \sigma_1(x_1 - x_0) + \sigma_2 x_2 + \sigma_3 x_3 \quad (11)$$

where $t_1+t_2+t_3$ is the performance index to be optimized, x_0 is input displacement, σ_i (i=1, 2, 3) is penalty factor.

When penalty factor $\sigma_i \rightarrow \infty$ (i=1, 2, 3), the performance index converge to the optimum. Specifying σ_i require experiences and times of attempt, since if σ_i is too small, the constraint is too weak for convergence, if σ_i is too large, the solution will converge to a local optima. In this situation, x_1 is the most important index, x_2 is less important and x_3 is the least. We therefore apply σ_1=10, σ_2=0.1, σ_3=1×10^{-5} in this study.

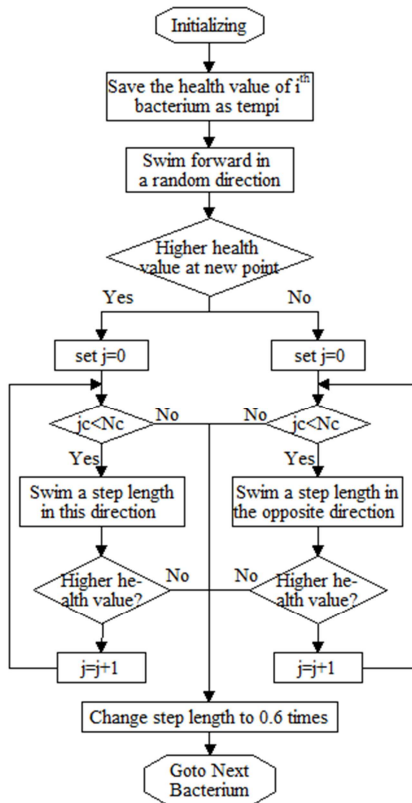**Fig. 5.** *Improved Chemotaxis process of BFA.*

3.2. Closed-Loop PI Controller

The PI controller is most widely control method in various applications, which includes a closed-loop PI displacement controller and a hysteresis comparator to regulate coil current. As this PI displacement controller is proposed to eliminate small displacement error, more aggressive parameters are acceptable, especially the "*I*" can be very large. In this study, we set: P=3×10^4, I=2×10^6.

4. Simulation and Discussion

Using software Matlab 2015 (MathWorks, Inc. USA) for control analysis to search the optimal solution. The analysis conditions are as follows: supply voltage Umax = 12V, start status x_1=0, x_2=0, x_3=0, end status x_1=1(mm), x_2=0, x_3=0, and other parameters are compared in Table 1. The calculation results are: t_1=1.640ms, t_2=0.341ms, t_3=0.123ms, which can be also expressed as:

$$U(t) = \begin{cases} 12V & for & 0ms \leq t < 1.640ms \\ -12V & for & 1.640ms \leq t < 1.981ms \\ 12V & for & 1.981ms \leq t < 2.108ms \end{cases}$$

Figure 6 gives the simulation results of response of triple coil EMC at step input of 1mm, it is obviously that all three mechanical quantities are settled to the required values.

Table 1. *Parameter of EMC.*

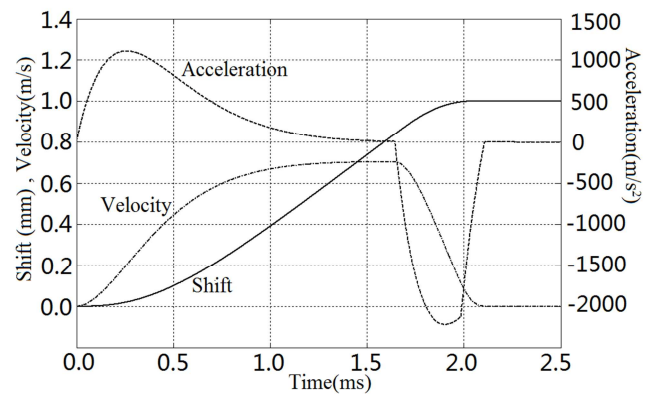| Item	Single coil	Triple coil (for each)
Mass M	0.2kg	0.2kg
Resistance R	3.1Ω	1.03Ω
Inductance L	0.5mH	0.167mH
Supply voltage U	12V	12V
Transducer constant K_e	31.25N·A^{-1}	31.25N·A^{-1}
Damping coefficient B_c	200	200
Elastic constant K_c	1940	1940

Fig. 6. *Response of triple coil EMC at step input of 1mm.*

To illustrate a more detailed character of the triple coil EMC system, step displacement input from 0.2mm to 2.0mm with step length of 0.2mm are calculated, while the velocity and acceleration at the end and start point are 0, which is x_1=0.2mm, 0.3mm…2.0mm, x_2=0, x_3=0. Figure 7 depicts the curves of displacement to excitation, the solid curve shows the

total time cost, and the other three curves with marks indicate the duration of three excitation period, respectively. As detailed in Figure 7, the three-order model of EMC system exhibit saturation characteristics.

The comparison between the triple coil EMC with dual-mode controller and the general single coil EMC with PI controller is proposed in this study. The start status is x_1=0mm, x_2=0, x_3=0 and the end status is x_1=1.0mm, x_2=0, x_3=0. Other parameters are listed in Table 1. In addition, 5N of Coulomb friction is added to make it closer to reality.

Figure 8 represents the curves of response of two different EMCs at step input of 1mm. Curve "1" is the output displacement of triple coil EMC while curve "2" is the output displacement of single coil EMC. The triple coil EMC system settled to 1mm in 2.5ms with slightly overshoot and ringing. However, the single coil EMC system settled to 1mm after 8.5ms with relatively large overshoot and ringing, and the ringing and overshoot are below 5%.

The reason is that during the large error phase, the dual-mode controller is provided with the Bang-Bang type time-optimal solution so that the EMC can transfer to end status quickly, while during the small error phase, the PI part of the dual-mode controller eliminate the error result from Coulomb friction, which results in good robustness and ideal accuracy. The traditional PI controller possesses the contradiction between rapidity and stability so that the response is relatively slow to avoid large overshoot and ringing.
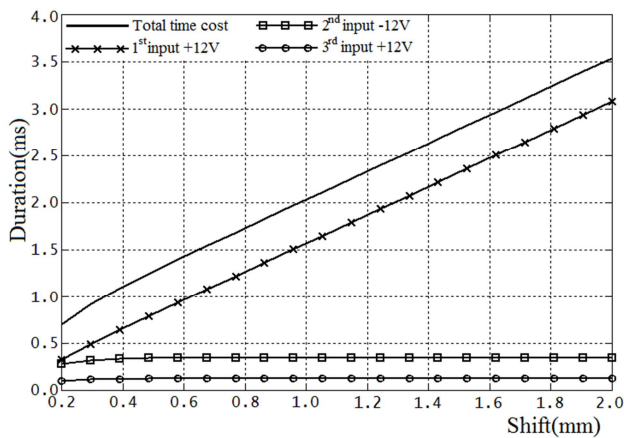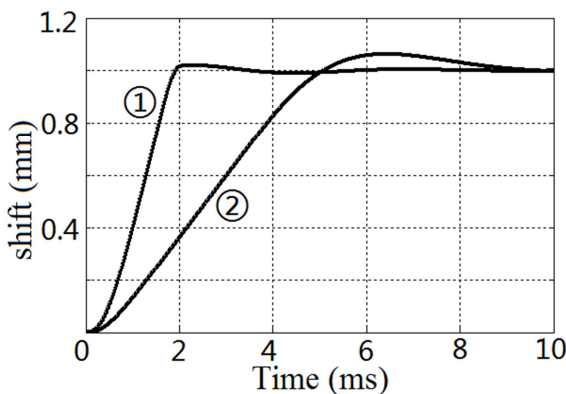

Fig. 7. Curves of displacement to excitation.

Fig. 8. Response of two different EMCs at step input of 1mm.

5. Conclusion

A new design of EMC provided with triple coils is proposed in this study. A model and a solution of searching time optimum using an improved Bacterial Foraging Algorithm (BFA) are developed, and a dual-mode controller with Bang-Bang & PI based on the proposed method is designed. Analysis and simulation results show promising effects that the response time of the triple coil EMC driven by dual-mode controller is 2.5ms, 70% faster than the traditional single coil EMC system, and the ringing and overshoot are below 5%. As evident in this study, the designed control technology can realize high response performance and display good prospect of development.

Acknowledgments

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