Control analysis and experimental investigation of a multi-coil moving coil linear motor based on an improved bacterial foraging algorithm

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ABSTRACT

This study tries to improve the response performance of a moving coil linear motor (MCLM). A newly designed MCLM with a bobbin of triple coils is proposed. 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 put forward. Control analysis and simulation results show the response time of the proposed MCLM driven by the dual-mode controller is reduced from 8.5 to 2.5 ms compared to the traditional single coil MCLM, and the ringing and overshoot are below 5%. The experimental frequency and response time of the proposed MCLM are 300 Hz at 3 dB and 4 ms, respectively. Analysis and experimental results show that the effectiveness of the proposed control technology is verified and the proposed MCLM displays good performance of high frequency and rapid response.

1. Introduction

A linear motor (LM), converting the electromagnetic energy into mechanical energy reciprocating linear motion continuously and proportionally, is regarded as the most widely employed linear motion mechanism in various industry driving fields. Basically, it could be classified into moving iron linear motor (MILM) and moving coil linear motor (MCLM) by the moving part (Goll & Kronmiller, 2000; Takezawa et al., 1998). At present, an MCLM is receiving increased attention for use in applications requiring linear motion at high speed and high accuracy for its smaller hysteresis and higher linearity (George & William, 2000; Ruan, 2013; Zhao & Tan, 2005). The generated electromagnetic force is about 1.5 times higher than the others with the same size (Tanaka, 2000; Zhang, Yu, & Ke, 2007).

In most cases, dynamic characteristics are closely related to the properties of the associated components of the system (Ismagilov et al., 2013; Ryashentsev et al., 1978). An input of step signal is very common in automatic control applications. However, the optimal performance of the MCLM is often compromised when driven by a conventional PID controller, since quickness, robustness and overshoot are contradictory in a PID controller (Zhang et al., 2015; Zhao & Tan, 2005). Ananthanarayanan (1982) 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 enabled designers to choose appropriate actuator performance parameters to fulfill different design objectives. Khandaker, Hong, & Rodrigues (2005) and his group proposed a new control strategy based on applying high and low voltages pulse width modulated (PWM) power for a transient and steady period, respectively, and achieved the conflicting requirements of very fast transition time and low contact velocities simultaneously. Mosca, Baldini, and Tesi (2007) 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 is not sufficient for searching a time-optimal solution, some parameters are restricted to keep the model at over damping, so that the under-damping state is not taken into consideration, and some models are simplified to avoid cross feedback.

To address these shortcomings, this study tries 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 MCLM designed in this study is detailed in Figure 1, which consists of permanent magnets (PMs), coils, bobbin, iron core, covers, output shaft, connector, etc. Several blocks of magnetic are fixed on the inner face of the right cover. The iron core is fixed in the centre of the right cover by a screw. Different coils are wrapped on the bobbin. The Bobbin which can move axially in the air gap formed between the PMs and the iron core is connected to a guide pin and the output shaft.

A DC voltage signal is provided to coils through the connector, so that the output shaft together with the bobbin connected to the carrying currents coils will realize the reciprocating linear motion due to the effect of the Ampere force of the permanent magnetic field.

Figures 2 and 3 compare 2D drawings and prototypes of two different bobbins of the proposed MCLM with single coil and triple coils, respectively, which both provide 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 impedance than the single one, which will generate larger 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.

The output force of the MCLM proposed above is given by Ampere force equation (Guo, Wang, & Xu, 2013):

\[
F = IB\pi DN,
\]

where \( I \) is the coil current, \( B \) is the magnetic strength, \( D \) is the average diameter of the coils, and \( N \) is the turns of the coils.

For a certain MCLM 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 MCLM, equations can be given out. The equations of the single coil MCLM is:

\[
U = RI + LI + K_e x,
\]

\[
F = K_e I = M x + B_c x + K_c x,
\]

where \( U \) is the supply voltage, \( R \) is the resistance of the coil, \( L \) is the inductance of the coil, \( K_e \) is the transducer constant, \( M \) is the total mass of MCLM and load, \( B_c \) is the damping coefficient, \( K_c \) is the elastic constant, \( x \) is the output displacement.

The equations of the triple coil MCLM is

\[
U_1 = (R/3)I_1 + (L/3)I_1 + (K_e/3)x,
\]

\[
U_2 = (R/3)I_2 + (L/3)I_2 + (K_e/3)x,
\]

\[
U_3 = (R/3)I_3 + (L/3)I_3 + (K_e/3)x,
\]

\[
F = (K_e/3)(I_1 + I_2 + I_3) = M x + B_c x + K_c x,
\]

where \( U_i \) (\( i = 1, 2, 3 \)) is the voltage applied to each coil, respectively, \( I_i \) (\( i = 1, 2, 3 \)) is the 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 (Luo, Zhang, Liang, Peng, & Chen, 2015), and the Equations (4)–(7) can be simplified as

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

\[ F = K_e I = M \ddot{x} + B_c \dot{x} + K_c x, \tag{9} \]

where \( I = I_1 = I_2 = I_3 \).

Comparing Equations (2) and (8), it is obvious that an MCLM with three paralleled coils is equal to a single coil MCLM with one-third impedance and the same transducer constant, and the goal of lowering impedance is achieved according. Let mechanical quantities to be as follows: \( x_1 = x \) (means displacement), \( x_2 = \dot{x} \) (means velocity), \( x_3 = \ddot{x} \) (means acceleration). Combining (8) and (9), the system can be expressed as

\[
\dot{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = A \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + BU, \tag{10}
\]

where

\[
A = \begin{bmatrix} 0 & 1 & 0 \\ -K_cR & -K_e^2 + K_cL + K_cR & -B_cL + B_cR \\ K_cLM & Lm & 1 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ K_e \end{bmatrix}.
\]

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 (Shibasaki, Ogawa, Tanaka, & Ishida, 2013).

However, the actual MCLM 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 (Christiansen, Maurer, & Zirn, 2008; Li, Zhou, Wang, & Chen, 2011).

To solve the contradiction, we proposed a Dual-mode controller combining 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 faster 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 the proposed MCLM, the decision-making logic select either bang-bang mode or PI mode, the output signal is amplified by H-Bridge for driving the MCLM, and the feedback signal is necessary as well.

**Figure 4.** A dual-mode control flow chart of the proposed MCLM.

### 2.1. Improved BFA for time-optimal solution

According to 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 (2002) 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:

\[
U(t) = \begin{cases} 
U_{\text{max}} & \text{for } 0 \leq t < t_1, \\
-U_{\text{max}} & \text{for } t_1 \leq t < t_1 + t_2, \\
U_{\text{max}} & \text{for } t_1 + t_2 \leq t < t_1 + t_2 + t_3,
\end{cases}
\]

The processes of BFA is briefly described as follows:

1. **Chemotaxis:** Suppose \( P_i(j, k, l) \) represent the \( i \)th bacterium at \( j \)th chemotactic, \( k \)th reproductive and \( l \)th elimination-dispersal step. \( C(l) \) represents the step length and \( V(j) \) represents the random direction vector. Thus, in each chemotactic step, the movement of the \( i \)th bacterium can be represented as \( P_i(l + l, j, k) = P_i(l, j, k) + C(l)V(j) \).
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 survives and splits into two identical ones, which are then placed in the same locations. Thus, the population of bacteria keeps constant.
(3) 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 (Christiansen et al., 2008; George & William, 2000). In this way, the step length will be shortened 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 ($x_3$), the penalty function method is easy-to-use to deal with the constraint (Coello, 2002). The health value in BFA can be expressed as:

$$\text{LiveFun} = t_1 + t_2 + t_3 + \sigma_1(x_1 - x_0) + \sigma_2 x_2 + \sigma_3 x_3,$$

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

When penalty factor $\sigma_i \to \infty$ ($i = 1, 2, 3$), the performance index converges to the optimum. Specifying $\sigma_i$ require experiences and times of attempt, since if $\sigma_i$ is too small, the constraint is too weak for convergence, if $\sigma_i$ is too large, the solution will converge to 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 $\sigma_1 = 10, \sigma_2 = 0.1, \sigma_3 = 1 \times 10^{-5}$ in this study.

2.2. 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: $P = 3 \times 10^4, I = 2 \times 10^6$.

3. Simulation and discussion

Using MATLAB 9.1 (MathWorks Inc., USA) for control analysis to search the optimal solution. The analysis conditions are as follows: supply voltage $U_{\text{max}} = 12$ V, 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: $t_1 = 1.640$ ms, $t_2 = 0.341$ ms, $t_3 = 0.123$ ms, which can be also expressed as

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

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

To illustrate a more detailed character of the triple coil MCLM system, a step displacement input from 0.2 to 2.0 mm with step length of 0.2 mm are calculated, while the velocity and acceleration at the end and start point
### Table 1. Parameters of MCLM.

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

#### Figure 6. Response of triple coil MCLM at step input of 1 mm.

#### Figure 7. Simulation models of different MCLMs.

are 0, which is $x_1 = 0.2, 0.3 \ldots 2.0$ mm, $x_2 = 0, x_3 = 0$. 8 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 8, the three-order model of MCLM system exhibit saturation characteristics.

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

Figure 7 is the simulation model in MATLAB/Simulink/ and 9 represents the curves of response of different MCLMs at step input of 1 mm. Curve ‘1’ is the output displacement of triple coil MCLM driven by proposed dual-mode controller, curve ‘2’ is the output displacement of single coil MCLM and curve ‘3’ is the output of triple coil MCLM driven by PI controller (tuned by MATLAB® PID Tuner). When the triple coil MCLM is driven by the proposed dual-mode controller, it settled to 1 mm in 2.5 ms with slightly overshoot and ringing, while driven by the PI controller, it settled to 1 mm in 6.5 ms with large overshoot. The single coil MCLM system settled to 1 mm after 8.5 ms with relatively large overshoot and ringing.

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 MCLM can transfer to end status quickly, while during the small error phase, the PI part of the dual-mode controller eliminates 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 (Figure 9).

#### 4. Experimental procedures

Figure 10 reveals the control principle of the proposed MCLM. A digital controller collects the desired position signal and position feedback signal generated by the position sensor on the output shaft. After comparison and compilation, the controller provides a drive current to different coils via a connector, so that the proposed MCLM can keep the reciprocating linear motion.
Experimental analyses had been carried out at a proposed MCLM under actual testing conditions. Figure 11 reveals an image of the prototype of the proposed MCLM. A signal generator provides 10 groups sinusoidal AC voltage with an amplitude of 5 V and a frequency from 1 to 320 Hz to the coils of bobbins, respectively. Both the input signals provided by the signal generator, and the feedback signal generated by the displacement sensor on the output shaft are collected to an oscilloscope, as detailed in Figure 12.

As we can see from figure, when the input signal frequency is 1 Hz, the output voltage amplitude would be 1.26 V. In this case, there is a good linear relationship between input and output, and the phase difference between them is close to 0 (Figure 12(a)). While the input signal frequency is 150 Hz, the output voltage amplitude would be 1.08 V. Likewise, there is also a good linear...
Table 2. The output voltage amplitude with different input signal frequency.

| Input signal frequency (Hz) | 1   | 7   | 20  | 30  | 100 |
|-----------------------------|-----|-----|-----|-----|-----|
| Output voltage amplitude (V) | 1.26| 1.24| 1.24| 1.21| 1.17|

relationship between input and output, and the phase difference between them is small as well (Figure 12(b)).

While the input signal frequency is 260 Hz, the output voltage amplitude would be 0.938 V. There is a good linear relationship between input and output similarly. However, the phase difference between them is larger than before (Figure 12(c)). While the input signal frequency is 320 Hz, at this point, phase difference between input and output is over 90 degrees. However, they still keep a good linear relationship (Figure 12(d)). The phase difference is caused by inertia and damping in the system, which are mass, coil inductance and various frictions.

Table 2 exhibits the output voltage amplitude provided by the displacement sensor on the output shaft with different input signal frequency provided by the signal generator.

According to the tracking characteristics of sinusoidal signal based on the output shaft of the proposed MCLM, a curve of the experimental magnitude-frequency characteristics of the proposed MCLM is presented Figure 13. As evident in figure, the experimental frequency of the proposed MCLM arrives at 300 Hz at 3 dB.

In addition, after a square wave signal with an amplitude of 5 V and a frequency of 25 Hz provided by the signal generator is loaded into the coils of bobbins, the feedback signal generated by the displacement sensor on the output shaft are collected to an oscilloscope, as detailed in Figure 14. As evident in figure, the experimental response time of the proposed MCLM is close to 4 ms.

Experimental procedures show promising results that the proposed MCLM displays high frequency and rapid response, and the designed control technology can realize high performance.

5. Conclusion

A new design of MCLM 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 and PI based on the proposed method is designed. Analysis and simulation results show promising effects that the response time of the triple coil MCLM driven by the dual-mode controller is 2.5 ms, 70% faster than the traditional single coil MCLM system, and the ringing and overshoot are below 5%. The experimental frequency and response time of the proposed MCLM are 300 Hz at 3 dB and 4 ms, respectively.

As evident in this study, analysis and experimental results show that the effectiveness of the proposed control technology is verified and the proposed MCLM can fulfill good performance of high frequency and rapid response.

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