

Incremental Adaptive Fuzzy Control for Sensorless Stroke Control of A Halbach-type Linear Oscillatory Motor

Meizhen Lei¹, Liqiang Wang²

¹Faculty of Mechanical Engineering & Automation, Zhejiang Sci-Tech University, Hangzhou 310018, China

²Faculty of Mechanical & Automotive Engineering, Zhejiang University of Water Resources and Electric Power, Hangzhou 310018, China

*Corresponding author e-mail: Leimeizhen_lmz@163.com

Abstract. The halbach-type linear oscillatory motor (HT-LOM) is multi-variable, highly coupled, nonlinear and uncertain, and difficult to get a satisfied result by conventional PID control. An incremental adaptive fuzzy controller (IAFC) for stroke tracking was presented, which combined the merits of PID control, the fuzzy inference mechanism and the adaptive algorithm. The integral-operation is added to the conventional fuzzy control algorithm. The fuzzy scale factor can be online tuned according to the load force and stroke command. The simulation results indicate that the proposed control scheme can achieve satisfied stroke tracking performance and is robust with respect to parameter variations and external disturbance.

1. Introduction

The use of a LOM instead of a rotary motor connected to a crank-shaft mechanism is becoming ever more popular in short-stroke reciprocating motion systems, such as air-compressors, fluid pumps and vibration control devices due to simple structure, high efficiency and low noise ^[1, 2]. Especially, compared to the conventional LOM, the proposed HT-LOM has the advantage of without moving iron core, compactness, light weight, easy-stacked stator core and good force characteristics.

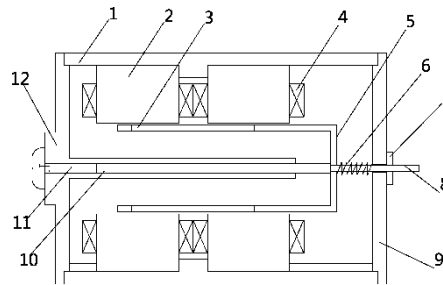
Recently, sliding mode control, adaptive control and robust control, have been proposed considering parameter variations and load disturbances. On the other hand, artificial intelligence control methods have attracted much attention due to their strong robustness against parameter variations and the virtue of requiring little information from the system model. Fuzzy control is a free-model technique ^[3, 4]. As the HT-LOM is described by a set of nonlinear, strong coupling and uncertain differential equations, an incremental adaptive fuzzy controller (IAFC) which combines the merits of PID control, the fuzzy inference mechanism and the adaptive algorithm was proposed. The basic principle of the HT-LOM was illustrated, and the motor dynamic characteristics equations were established. Then the IAFC was designed for stroke tracking control of HT-LOM, and verified by simulation.



2. Motor Model

2.1. Basic Working Principle

Figure. 1 shows the basic structure of HT-LOM. The motor consists of two stators, and is easy to stack the stator iron similar to the rotary motors with centralized windings. Halbach array was introduced in the mover structure, and the mover core is not needed in this motor. Permanent magnet is attached directly to the non-magnetic material made of stainless steel bracket. When the current is injected into the stator coils, the corresponding magnetic polarity of two stators is opposite. One side of the air-gap magnetic field is enhanced, and the other side is weakened, so the electromagnetic thrust is produced in the mover. The amplitude and direction of electromagnetic thrust are reversed in accordance with coil current, and mechanical oscillation frequency is equal to that of the coil current. Then the linear axis moves under the springs force, the electromagnetic thrust, the damping force and load force together, along with fixed reciprocating frequency. The mechanical springs are installed to improve system efficiency when the HT-LOM is driven in a resonant state.



1 shell; 2 stator; 3 permanent magnet; 4 oils; 5 bracket; 6 spring; 7 bearing; 8 linear axis; 9 endcap; 10 piston; 11 compressor chamber; 12 endcap

Figure.1 Basic structure of halbach-type LOM

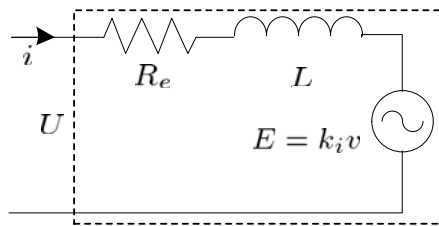


Figure. 2 Equivalent circuit of the H-LOM coil

2.2. Motor Dynamic model

The equivalent circuit of the HT-LOM coil is depicted in Figure.2, and the electromagnetic mathematical model is derived as Eqn. 1, where R and L are stator coil inductance and resistance, k_i and v are Back-EMF coefficient and mover speed, i and U are stator current and voltage. When the HT-LOM works with compressor gas load, the kinetics equation of system can be expressed as Eqn. 2, where m and x are equivalent mass and displacement of the mover, C_m and K_s denote viscous damping coefficient and spring constant, F_g is gas load assuming that the LOM is used to drive the linear air compressor in this paper, the pressure difference and cross-section area of piston are Δp and S_p .

$$U = iR + L \frac{di}{dt} + k_i v \quad (1)$$

$$m \frac{d^2x}{dt^2} + C_m \frac{dx}{dt} + K_s x = k_i i - F_g \quad (2)$$

$$F_g = \Delta p * S_p \quad (3)$$

Since the gas load pressure changes constantly with the piston position, mainly it can be divided into four phases: inspiratory phase, compression phase, exhaust stage and expansion process. Obviously, the gas force is typically nonlinear, and difficult to calculate in the motion process. A simple linear model can be equivalent to the nonlinear force [5], and the simplified mathematical model can be derived as Eqn. 4, where K_g and C_g are equivalent gas spring constant and equivalent damping coefficient. Substitute Eqn. 4 into Eqn. 2, the motor linear dynamic model can be derived as Eqn. 5, where $K = K_g + K_s$, $C = C_g + C_m$.

$$F_g = K_g x + C_g \frac{dx}{dt} \quad (4)$$

$$\begin{cases} m \frac{d^2x}{dt^2} + C \frac{dx}{dt} + Kx = k_i i \\ U = iR + L \frac{di}{dt} + k_i v \end{cases} \quad (5)$$

After the Laplace transformation of (5), it can be written as follows :

$$G(s) = \frac{k_i}{mLs^3 + (mR + CL)s^2 + (CR + k_i^2 + LK)s + RK} \quad (6)$$

$$x(s) = G(s) * U(s) \quad (7)$$

As can be seen from Eqn. 7, the HT-LOM system is a third-order system which can be decomposed into a proportional component, a inertia component, and a second-order oscillating component. And oscillating component mainly influences the system performance in mid-band. When the system damping is small and the frequency of the excitation voltage is close to the resonant frequency, resonant peak of mover displacement will appear in this system.

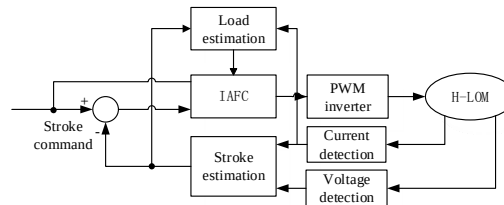


Figure.3 Block diagram for the H-LOM stroke tracking controller

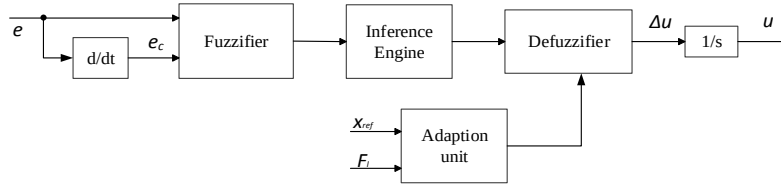


Figure.4 Basic structure of the IAFC

3. IAFC Design

3.1. Basic Design Principle

The block diagram of HT-LOM stroke tracking controller is shown in Figure. 3, and the control system is composed of a HT-LOM fed by a single-phase PWM inverter, a stroke estimation unit, a load estimation unit, an IAFC, voltage and current sensors. Based on the estimated mover stroke, the coil voltage is adjusted by the IAFC, then the real stroke tracks the target command.

The triacs, which control the AC voltage, have been used conventionally to drive the LOM, but it has the disadvantage of high harmonic components, low power factor. As a novel voltage and frequency regulator, the single-phase PWM inverter is introduced to control the stroke by adjusting the voltage as well as the frequency in this system ^[6].

As the stroke of HT-LOM is not limited mechanically, the mover displacement must be detected in the stroke tracking control. The mechanical sensors can obtain the mover displacement accurately, while it increases the system cost and size of the drive systems, also reduces the system operation reliability. Therefore the sensorless algorithms become an interesting alternative to control the HT-LOM. There are two basic techniques to estimate the mover displacement for the sensorless control. The first technique is the free-model technique such as artificial intelligence technique, and the other is based on the motor dynamic model such as several kinds of observers, which is easy to accomplish. By adopting the mover displacement estimation method based on back-EMF observer ^[7], the mover velocity can be calculated according to Eqn. 8 based on measured voltage and current. Then the mover displacement x can be calculated as Eqn.9.

$$v = \frac{1}{k_i} \left(U - iR - L \frac{di}{dt} \right) \quad (8)$$

$$x = \int v dt \quad (9)$$

3.2. IAFC Principle

The basic structure of IAFC is shown in Figure. 4. The IAFC consists of four components: input fuzzification, rule inference, output defuzzification, and adaptive scale factor correction. The input variables are the stroke tracking error e and the derivative of error e_c . The output variable is control voltage increment Δu that determines the increase or decrease of the voltage. $u(k)$ is the control voltage of coil for the stroke control. As shown in Eqn. 10, where $c(k)$ and $x(k)$ are target stroke and actual stroke, t_s is the sampling time.

$$\begin{cases} e(k) = c(k) - x(k) \\ e_c(k) = \frac{e(k) - e(k-1)}{t_s} \\ u(k) = \Delta u(k) + u(k-1) \end{cases} \quad (10)$$

The controller is a Mamdani-type FLC with a typical IF-THEN rule structure. The defuzzification method used in the IAFC is the center of gravity defuzzification method. Figure. 5 shows the membership functions used for the two inputs and the output of the controller. As shown, three triangular membership functions were used for every variable. In the knowledge base, the fuzzy sets of inputs and output are NB, NM, NS, ZE, PS, PM, PB. Input 1 (e) ranges within $[-8, 8]$, and Input 2 (e_c) ranges within $[-1, 1]$. Output Δu ranges within $[-6, 6]$. A scaling factor should be placed before Inputs and outputs to ensure that the signal is mapped correctly into the normalized controller inputs and outputs. By normalizing the inputs and outputs, the IAFC can be used in different LOM and without changing the membership functions of the controller.

Table.1 summarizes the rules used in the IAFC. They have been defined by understanding the behavior of the system. One can find rules maintaining speed error near zero (steady state rules), rules that avoid motor speed overshoot and rules that provide rapid response to large error resulting from command change.

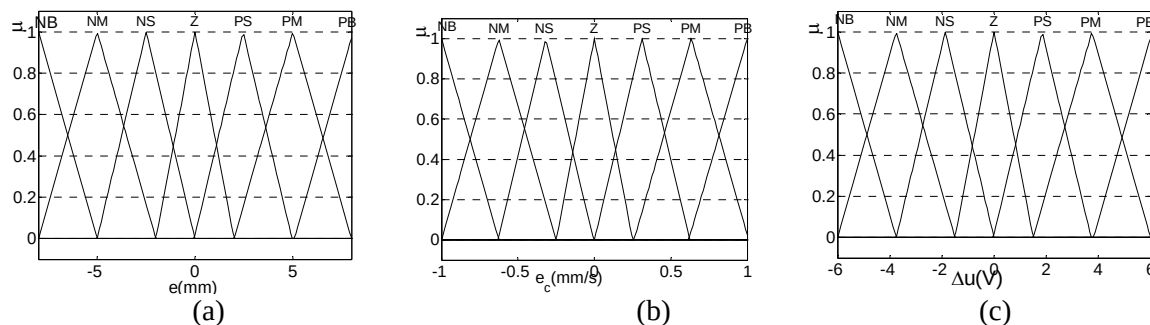


Figure.5 Membership functions of fuzzy sets

Table. 1 The Fuzzy rules used in the IAFC

Δu		e_c						
		NB	NM	NS	ZE	PS	PM	PB
e	NB	NB	NB	NB	NB	NM	ZE	ZE
	NM	NB	NB	NB	NB	NM	ZE	ZE
	NS	NM	NM	NM	NM	ZE	PS	PS
	ZE	NM	NM	NS	ZE	PS	PM	PM
	PS	NS	NS	ZE	PS	PM	PM	PM
	PM	ZE	ZE	PM	PB	PB	PB	PB
	PB	ZE	ZE	PM	PB	PB	PB	PB

As the scaling factor influences dynamic performance of system, too large scaling factor may cause the system oscillation, and too small may increase the dynamic response time of system^[8,9]. When HT-LOM works under different stroke command or load force conditions, a fixed scaling factor is difficult to meet the requirements of the system dynamic and static performance. An adaptive control table was made previously according to the stroke command and load force, then the scaling factor can be tuned online. The load force is estimated by the load estimator based on the phase error between the current and stroke of motor^[10,11].

4. Simulation Results and Analysis

The performance of stroke tracking with different controllers were compared by numerical simulation results via MATLAB/SIMULINK tool, while the nonlinear characteristics of the motor was taken into account. Figure. 6 and Figure. 7 shows the system step response, and the stroke command is 6mm. The

PID controller and IAFC have almost zero stroke error in steady-state. But the stroke of IAFC follows the reference stroke faster compared to PID controller with shorter settling time and smaller undershoot.

Figure. 8 shows the system disturbance response with the grid voltage disturbance. The grid voltage is increased from 220V to 225V that caused the stroke to overshoot for a while. PID controller has a larger overshoot and can follow the reference stroke with longer settling time compared to IAFC.

The HT-LOM system transfer function model is changed with the load conditions. Due to the dependence on the mathematical model, conventional PID controller is difficult to remain robust with respect to parametric variations. The IAFC is based on the linguistic rules obtained from the human experiences, which does not require any mathematical model. Especially, integral-operation was added to this controller, so the steady-state performance of IAFC was improved compared to the conventional system controlled by fuzzy control algorithm. The IAFC has an adaptive scaling factor with the load variations and stroke command. The system step response and disturbance response before and after parameters variation are shown in Figure. 11(a) and Figure. 11(b) respectively. It shows that the IAFC still has good dynamic and static performance in tracking stroke. Therefore, the IAFC is robust with the parametric variations.

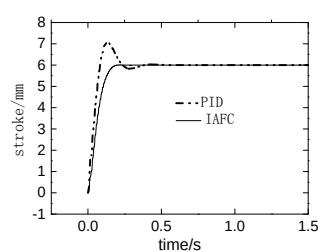


Figure. 6 Step response

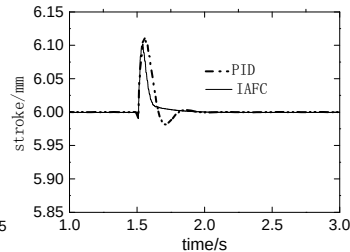
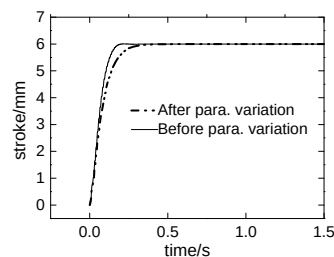
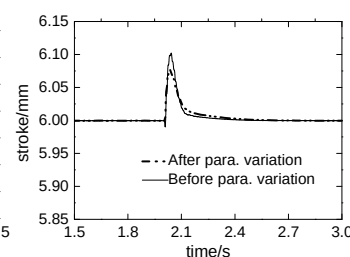


Figure.7 Disturbance Response



(a) Step response curve



(b) Disturbance response

Figure 8 Response curve before and after parameter variation

5. Conclusion

An IAFC and mover displacement estimation method based on back-EMF observer was adopted to stroke tracking control of HT-LOM. The simulation results showed that the IAFC not only tracks accurately the target stroke with good dynamic and static performance, but also has the strong robustness with parametric variations caused by load disturbance.

Acknowledgments

This work was supported by the Zhejiang Science Technology Department Public Service Technology Research Project (2017C33158, 2017C33160) and Science Foundation of Zhejiang Sci-Tech University (ZSTU) under Grant (14022210-Y).

References

- [1] Q.F. Lu, Y.H. Yao, and Y.Y. Ye., "Investigation of an Integrative Transverse-flux Linear Compressor". The International Journal for Computation and Mathematics in Electrical and

- Electronic Engineering, vol. 34, no. 6, pp. 0-8, September. 2015.
- [2] F. Kitayama, K. Hirata, N. Niguchi, and Ma. Kobayashi, "A New Linear Oscillatory Actuator with Variable Characteristics Using Two Sets of Coils," *Sensors*, vol.16, no.3, pp. 377-377, 2016.
 - [3] L.A. Quiroga, J.S. Read, and R.A. Callejas. "Adaptive Fuzzy Control System for a Squirrel Cage Induction Motor," *Latin America Transactions, IEEE*, vol.15, no.5, pp. 795-805, 2017.
 - [4] X. Liu, Y. Wu, B. Liu. "Research of Adaptive Fuzzy Sliding Mode Control for Motor Servo System," *Advanced Science Letters*, Vol.6, no.4, pp. 855-858, 2012.
 - [5] R.V. CADMAN, "A Technique for the Design of Electrodynamic Oscillating Compressors," Indiana: Purdue University, 1967.
 - [6] T.W Chun, J.R Ahn, J.Y YOO, et al.. "Analysis and Control for Linear Compressor System Driven By PWM Inverter," *Proceeding of the 30th Annual Conference of the IEEE Industrial Electronics Society*, Busan: [s.n]2004: 263—267.
 - [7] LG Electronics Co., Ltd. "Devices and methods used to control the of the linear compressor piston position," china, 818510. 7[P]. 2003-06-18.
 - [8] A. Akrad, M. Hilairat, D. Diallo. "Performance enhancement of a sensorless PMSM drive with load torque estimation," *Proc. 36th Annual Conference on IEEE Industrial Electronics Society*, 2010: 945-950.
 - [9] Y.A. Zorgani, Y. Koubaa, and M. Boussak, "MRAS state estimator for speed sensorless ISFOC induction motor drives with Luenberger load torque estimation," vol. 61, no.0, pp. 308-317, 2016.
 - [10] H. Mesloub, M. T. Benchouia, A. Goléa, "A comparative experimental study of direct torque control based on adaptive fuzzy logic controller and particle swarm optimization algorithms of a permanent magnet synchronous motor," *International Journal of Advanced Manufacturing Technology*, vol.90, no. 1-4, pp. 59-72, 2017.
 - [11] O.K. Teresa, D. Mateusz and S. Krzyszt. "Adaptive Sliding-Mode Neuro-Fuzzy Control of the Two-Mass Induction Motor Drive Without Mechanical Sensors," *IEEE Transactions on Industrial Electronics*, Vol. 57, NO. 2, pp: 533-564, Feb. 2010.