Study of Nonlinear Characteristics and Model Based Control for Proportional Electromagnet

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Received 13 April 2018; Revised 14 August 2018; Accepted 26 August 2018; Published 6 September 2018

Academic Editor: Ruben Specogna

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The nonlinear characteristics of proportional electromagnet caused by hysteresis bring great difficulties on its accurate position tracking control by current. In order to enhance the practicability and reliability of long stroke electromagnet in case of position sensor fault and improve the position tracking performance during current closed-loop control, experimental investigations on the electromagnet actuator hysteresis characteristics of diesel engine governor are carried out to analyze the system dynamic features and the effects of hysteresis on actuator position tracking performance. It is clear that hysteresis can significantly hinder the accurate position control of the electromagnet actuator. Consequently, the fuel injection will be delayed, which will lead to hysteresis of engine speed control as well as deterioration of engine performance. In this paper, the hysteresis phenomenon of an actuator and its influence on control performance of engine are investigated. The model of proportional electromagnet actuator (PEA) is established and the hysteresis principle is analyzed. Then the inverse model control strategy based on neural network (NN) is proposed to linearize the transfer behavior of electromagnet and compensate for the magnet hysteresis. Rapid control prototyping (RCP) experiment based on MicroAutoBox is further implemented to validate the real-time performance of the proposed control strategy in D6114 diesel engine. The results show that the speed fluctuation (SF) under steady-state conditions (especially under idle speed condition) and the recovery time as well as the overshoot under transient conditions are significantly improved. This makes it possible to develop redundant electromagnet driving control strategy.

1. Introduction

PEA has been widely applied to position tracking control system of engine automation due to its simple structure and high strength. Diesel engine governor is a typical application of long stroke electromagnet actuator. Position sensor is commonly used to measure the position of the actuator during its position closed-loop control (PCL). It is fatal to the engine once there are some faults causing the position sensor breakdown. So developing sensorless position control technology is of great significance for the proportional electromagnet actuator and further for the engine. And proportional electromagnet actuator is promising in sensorless position control because of its current-force correspondence. However, the idle speed fluctuation (ISF) hinders its development [1]. Since the 1990s, minielectromagnet actuator position tracking based on current closed-loop control (CCL) has been studied in many engineering applications such as valve actuators, fuel injectors, and braking systems [2–4]. In the field of accurate position control research, a typical nonlinear memory shared with most magnetic materials has been frequently proposed. Hysteresis is a phenomenon that the associate output force depends not only on the instantaneous magnetic field strength but also equally on the previous states. The existence of hysteresis may hinder the performance of actuator and consequently increase position tracking error and energy loss. Analyzing and compensating for the hysteresis are a mandatory task for a satisfactory design of a feedback control system [5]. Jiles-Atherton (J-A) hysteresis physical model was firstly proposed in 1983 [6], and the latest J-A model can even describe the hysteresis in
dependence on temperature [7]. Preisach model is currently the most commonly used phenomenological model [8]. And multiple inverse Preisach models have been proposed for the purpose of control [9, 10]. Rosenbaum et al. made a comparison between Jiles-Atherton model and Preisach hysteresis model on their performance and calculation efficiency during inverse feed-forward control [11]. Cao et al. used dynamic recurrent neural network to compensate for the hysteresis of magnetostrictive actuator [12]. A compensating algorithm was proposed to improve the position tracking error and energy loss in a micropositioning task [13]. Pseudo compensator was used to compensate for the Terfenol-D actuator and its effect on feedback control was analyzed [14]. However, the effect of hysteresis on position control of large stroke proportional electromagnet actuator, especially on control performance of the controlled object, was rarely mentioned in the previous researches. In this paper, the effect of hysteresis on the ISF of diesel engine governor, in which a large stroke electromagnet is used as its actuator, is analyzed. An inverse model hysteresis compensator based on neural network is developed to optimize the position tracking and ISF performance of the governor.

2. Experiment Setup

The stroke of the actuator is 20 mm. An electromagnet is used as the armature material. The diesel engine used in this experiment is of four strokes, six cylinders, a mechanical fuel injection pump, and an electronic governor. The cylinder diagram is 114 mm, and the rated power is 90 kW. The engine load is applied directly to the crankshaft through a generator controlled by a PC controlled load system. The diesel engine governor control strategy is undertaken by a RCP system. The instantaneous speed change rate of speed and current state, is designed. From our previous tests [1], it is found that the instantaneous speed change rate of speed and current dual-closed-loop control (SCDCL) is much better than that of speed and position dual-closed-loop control (SPDCL). However, idle speed stability is a major challenge for SCDCL.

As shown in Figure 3, the PEA is generally composed of coil, soft magnetic material armature, and return spring. There are many kinds of ferromagnetic materials. Hysteresis is an irreversible phenomenon which exists during the magnetizing process of magnetic materials. The H (magnetic field strength) and M (magnetization) have a typical hysteresis relationship as plotted in Figure 4. The curve increases rapidly at first and then approaches an asymptote which is called the magnetic saturation. If the magnetic field is reduced monotonically, the M will follow a different curve. At zero field strength, the magnetization is an offset from the origin of the so-called remanence. The hysteresis loop will be formed by plotting the H and M relationship for all magnetic field strengths [15].
Proportional electromagnet is an executive element with strong nonlinearity. The elements of electricity, magnetism, and machine work together to achieve position control. During the working process of the electromagnet, coil inductance is a function of magnetic flux and the armature position, and the energy dissipation, which is caused by the vortex and the magnetic effect in the process of establishing the magnetic field and characterized by the dissipating resistor, is a function of the electric force and the position of the armature. These nonlinear elements result in the hysteresis characteristic of the electromagnet output force and current. In addition, due to the large friction force introduced by the armature of actuator and the dry friction structure of liner, the performance of actuator has obvious dead zone characteristics.

According to Figure 3, the incremental equation of the PEA can be described as

\[ m \frac{d^2 \Delta x}{dt^2} + D \frac{d \Delta x}{dt} + K_s \Delta x = C \cdot \Delta F_m \]  (1)

where \( m \) is the mass of armature pusher, kg; \( D \) is damping coefficient, N/(mm\cdot s\(^{-1}\)); \( K_s \) is stiffness of the spring, N/mm; \( \Delta F_m \) is increment of the electromagnetic force, N; and \( \Delta x \) is increment of displacement, mm.

The character of the PEA control force can be expressed as

\[ C \cdot \Delta F_m = K_I \Delta i - K_x \Delta x \]  (2)

where \( K_I = \frac{\partial F_m}{\partial i} \) is current gain, N/A; \( K_x = \frac{\partial F_m}{\partial x} + K_s \) is the sum of displacement force; and spring stiffness, N/mm.

Laplace transform is used to combine (1) and (2):

\[ m s^2 \Delta x + D s \Delta x + K_s \Delta x = K_I \Delta i - K_x \Delta x \]  (3)

And the incremental equation of coil inductance is given as

\[ \Delta u = L \left( \frac{d \Delta i}{dt} \right) + \left( R_c + r_p \right) \Delta i + K_e s \Delta x \]  (4)

where \( L \) is coil inductance, H; \( R_c \) is coil resistance, \( \Omega \); \( r_p \) is circuit resistance, \( \Omega \); and \( K_e \) is counter electromotive force of the induction coil, V.

If we ignore counter electromotive force (due to it is very small), the Laplace transform of (4) can be expressed as

\[ \Delta u = L s \Delta i + \left( R_c + r_p \right) \Delta i \]  (5)

The system transfer function can be represented by

\[ G_1(s) = \frac{\Delta x}{\Delta u} = \frac{K_I}{(ms^2 + Ds + K_s + K_e) \left( Ls + R_c + r_p \right)} \]  (6)

If hysteresis is ignored, this system is constituted of the one-order element of inductance coil, the two-order element of armature mass, and the spring. By cascading a \( G_2 \) (symbolic transfer function of hysteresis) and feed-forward control, the hysteresis is considered and controlled. The logical relationship of each part of the system is shown in Figure 5.

Hysteresis is caused by irreversible magnetization between magnetic field intensity and electromagnetism as shown above. If we get the hysteresis model and then inverse the model and add it to the control system as a feed-forward controller, the hysteresis effect would be weaken or even offset.
3.2. Hysteresis Test and Analysis. The existing hysteresis may decrease the accuracy of the control system and cause periodic fluctuation. The hysteresis of the PEA is tested in this paper. The testing process consists of two steps.

(1) Rise. The actuator stays at the initial position in the beginning and then increases the duty cycle gradually. The actuator rod keeps still at initial stage because of the spring restoring force and friction force. With the increasing of duty cycle, the actuator rod begins to move. Record the duty cycle, current, and the actuator position until the actuator reaches its maximum position.

(2) Fall. Decrease the duty cycle when the actuator rod reaches its saturation. Because of the existence of hysteresis and the mechanical structure, the actuator stays still till the duty cycle decreases to 40%, AB is the saturation phase, and A is the disaturated point. After that, the actuator rod decreases rapidly.

The same law will be obtained by changing the initial condition. Thus the duty cycle and the position hysteresis loop (including the dead zone and the saturation) are presented in Figure 6. And Figure 8 gives a more detailed illustration of the hysteresis loop presented in Figure 6. Figure 7 shows the hysteresis error which is similar to bell curve and the maximum error occurs in the disaturated point. The testing results are comprehensive results regarding the electronic property, the magnetic property, and the mechanical property. According to the PWM duty cycle and the actuator position correspondence, a clear nonlinear characteristic including hysteresis and dead zone is demonstrated. In addition, all the data in this paper are normalized during the process of analyzing.

3.3. The Effect of Hysteresis on Position Closed-Loop Control. In order to further investigate the working character of the actuator, the PCL experiments are conducted. The closed-loop control experiments include three parts: the PCL tracking experiment, the CCL position tracking experiment, and the PCL static experiment.

The position tracking experiment results are shown in Figure 9. The actuator responds to the set position rapidly, the error of position tracking is acceptable. Attention should be paid to the response time at around 15s in Figure 9 where a direction inverse happens. The actual position tracks the set point with a delay of 0.2s. However, compared with the
CCL experiment results in Figure 11, the set current begins to increase at 4s as the red line shows in Figure 11; the actuator position starts to response at about 7s. And the set current inverses its change direction at 12s, 16s, and 21s. We can find that the maximum position tracking delay is as high as 3s. During 25s to 28s, a fast current change process is presented. However, the position stays still without any slight response, even though the PWM duty follows the set value. The CCL will extend the operating lag in a large scale, which is unacceptable for real-time position tracking control system like diesel engine governor.

The PCL static experiment is conducted as follows. The actuator is stabilized at the set position by PID control. By observing the position fluctuation and the duty cycle change from Figure 10, the following phenomena can be easily understood:

1. Actuator stabilized at the set point; however, there is long periodic, ineffaceable small amplitude fluctuation. Meanwhile the duty cycle fluctuates in a large scale accordingly.

2. The wave amplitude decreases as the increasing of the set position.
3.4. Hysteresis Fluctuation Loop Analysis. Combining Figures 8 and 9, a brief analysis of hysteresis induced fluctuation is presented. With the control of PID, actuator position will approach the set point gradually. However, small overshoot or static error is inevitable. The set point is indicated by the dark line in Figure 8; actuator starts to increase from the initial point alongside the red line. However, the actuator reaches point 1 because of a small overshoot. The control system aims to eliminate this error. The control force starts to decrease alongside the green line from point 1 to point 2. Because of hysteresis loop, the actuator stands still till PWMDUTY reaches point 2. Then the actuator decreases alongside the green line till another overshoot presents at point 3. At point 3 the actual actuator position is smaller than the set point. The control force increases alongside the purple line 3-4-1, then a periodical control output fluctuation is presented. Since the operation of hysteresis loop fluctuation derives from the natural characteristics of magnetic material, the special method should be adopted in order to avoid the system fall into this limit loop.

The impact of hysteresis on the control performance is serious. If the fluctuation character of diesel engine speed is taken into consideration, the situation will be more complicated. This degrades the low speed steady-state performance of the diesel engine governor. Besides, the huge instantaneous speed change rate may derive from the steep duty cycle and position curve during the descent stage. Based on the above conclusions and experiment results, a special control strategy is necessary to improve the stable performance of the diesel engine governor. In this way, the nonlinear integrate circuit causes a large current position hysteresis loop as shown in Figure 8, which can influence the fuel quantity control performance of the SCDCL. Moreover, good fuel quantity control performance is a prerequisite for good speed control performance. Therefore, compensation of the current position hysteresis characteristics is critical to the steady-state speed control performance of the SCDCL.

4. Optimization of PCL

The long periodical small amplitude fluctuation of the PEA cannot be neglected especially when coupling with engine speed. The experiments also found a similar fluctuation at the rated speed. Further analysis should be performed in order to weaken or even eliminate the fluctuation. On the basis of the phenomena, a dead zone module is added during the position error calculation process in order to remove the small error and improve the regulating effect. The optimized experiment results are exhibited in Figure 12. The results prove the existence of hysteresis loop.

4.1. Hysteresis Compensation and Control. Being a strict nonlinearity with memory, hysteresis capturing, modeling and compensation have attracted the attention of researchers. Several physics-based and phenomenological hysteresis models, which are suitable to capture the magnetic hysteresis, are proposed. Inverse model control, which reshapes the given reference value so that the control signal drives a hysteretic plant along such trajectories that provide a linear input-output relationship [16, 17], is an effective method to compensate for the hysteresis. The intelligent neural network identification is proposed in this paper in order to identify the inverse hysteresis nonlinearity of position and current/voltage rather than discussing the mathematical model. NN based inverse model is used as a feed-forward controller to compensate for the hysteresis. In addition, a feedback controller is used to control the engine speed with zero steady-state error.
4.2. Neural Networks Based Inverse Model Control. Inversing the input and output direction and modeling the effect of input on output are the so-called inverse model. The hysteresis is a nonlinear phenomenon. The output of the system relies not only on the current input but also on the past input of the system. According to this characteristic, the inputs of the model should include the current set position, the past set position, and the last state of the actuator. Thus, a 3-input, 1-output, 3-layer BP NN inverse model for position and duty cycle is developed to compensate for the impact of hysteresis. The input neurons are, respectively, the current set position, the last set position, and the last duty cycle. The output is the current duty cycle. The active functions are TRANSIG and PURLIN. The structure of the NN inverse model is shown in Figure 13. The NN is offline trained, based on the experiment data of the hysteresis character. The NN performance is presented in Figure 14, with a learning rate of 0.0013 and a momentum factor of 0.11 [10, 18]. In order to prevent overfitting, the data is divided into three parts for training, validating, and testing. Results of Figure 14 show that the regression coefficient of the testing process is nearly 0.95, and all data regression coefficient is nearly 0.98, which means that the NN based model is feasible in learning the hysteresis relationship between current and PEA position. The overall performance confirms that NN based current position model is capable of compensating for the hysteresis loop as well as improving the PEA position tracing performance.

Speed variation tendency depends on the fuel injection quantity which is determined by the actuator position. The calculation result of the speed loop controller is the expectation of the rack position. Double PID controller, combined with feed-forward control strategy for engine speed regulation, is designed as shown in Figure 15. The speed loop outputs a set position to the NN feed-forward module. The NN is responsible for transmitting a target position to a target current, then the current loop exports a PWM duty cycle [19]. The initial weight coefficient of the NN inverse model is obtained from offline training. The NN online learning is not necessary because the actuator hysteresis is static rather than time varying. The NN offline training is a proved technique which is unnecessary to be discussed in detail in this paper.

4.3. Simulink Based Control Strategy Model. A diesel engine governor control strategy model is developed. A real-time control is then achieved by compiling and downloading the model into the RCP system. The control strategy model includes hardware I/O and control algorithm module. According to the functional requirements of the diesel engine governor, the hardware I/O should include a frequency measurement, three AD channels for converting acquisition to rack position, actuator position and target speed, a bit input channel for stop switch, and a PWM output for actuator driving. The control strategy model is responsible for regulating the PWM duty cycle according to the inputs. The control strategy model mainly includes operating mode judgement, speed closed-loop calculation, NN feed-forward calculation, and current closed-loop calculation. The actuator is driven by RapidPro hardware of dSPACE.

5. Bench Experiments and Results

In order to validate the control performance of the inverse model hysteresis compensator, diesel engine bench experiments are carried out. The experiments contain CCL position tracking experiment and diesel governor performance experiment. The position tracking results present nearly no delay response in the case of reversing operation as depicted in Figure 16. This proves that the designed control algorithm is capable of compensating for the actuator hysteresis.

Inverse model integrated with PID is capable of optimizing the position tracking accuracy of hysteresis system. However, whether the hysteresis should be responsible for the ISF or not needs further investigation. The main purpose of the bench experiments is to validate the performance of the proposed NN hysteresis compensator and confirm the relationship between ISF and hysteresis. According to the requirements of power plant, ISF is the major concerned performance index. Meanwhile, the proper instantaneous speed change rate of the original control algorithm is preserved.

5.1. Start and Idle Stability Experiments. Figures 17 and 18 are respectively the speed and rack position curve for start process and idle speed stead condition. The engine is successfully and stably started within 1.5s, and the ISF is 2.21%. Compared with the results of SCDCL without hysteresis.
compensation in Figure 19, the SF is 1.4% at 1050r/min [1]. The ISF is far better than that of the original strategy without compensation. The reason why the original strategy is validated under 1050r/min condition instead of 700r/min condition is that the original strategy cannot achieve stable operation at the idle speed 700r/min. Figure 20 shows the stability performance under rated speed condition where the SF rate is 0.2%.

5.2. Load Sudden Change Experiments. Instantaneous speed change rate is an essential performance index of diesel engine generator. And the alternating current frequency is directly related with its main shaft angular speed. When engine operates at 1500r/min, the generator has two pairs of pole and the alternating current frequency is 50 Hz. So the frequency of alternating current can be taken as a performance index of the governor. Figures 21 and 22 respectively show the speed
and generator frequency fluctuation. It can be seen that the minimum transient frequency is 47.76Hz, the instantaneous speed change rate is 4.8% and its recovery time is 1.8s when full loaded suddenly. In addition, the maximum transient frequency is 52.3Hz, the instantaneous speed change is 4.6% and its recovery time is 1.7s when full unloaded suddenly.

6. Conclusions

In this paper, a feed-forward control strategy based on NN to compensate for the PWM duty cycle and the hysteresis of a 20 mm long stroke proportional electromagnet is proposed. The hysteresis characteristics of electromagnet are analyzed by means of experiments. Combining hysteresis figure and control force fluctuation, the hysteresis loop and the limited cycle behaviors are described. Hysteresis is supposed to be responsible for the ISF of SCDCL. A 3-inputs and 1-output NN inverse model is designed to linearize and compensate for the hysteresis. An inverse model feed-forward calculation and standard speed-current closed-loop control are developed in RCP. Experiment results indicate that the hysteresis significantly deteriorates the position tracking accuracy of the system, leading to a large ISF. With the proposed NN feed-forward compensator, the position tracking response time is greatly shortened, the ISF decreases to 2.21%, and
the instantaneous speed change rate decreases to 4.8% at the same time. The inverse model control is capable of weakening the influence of hysteresis and inheriting the transient performance of traditional dual-closed-loop controller. This makes it possible to develop redundant electromagnet driving control strategy.

**Abbreviations**

CCL: Current closed-loop control  
H: Magnetic field strength  
ISF: Idle speed fluctuation  
M: Magnetization  
NN: Neural network

**Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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