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The Research on the Motion State Monitoring of Electromagnetic Valve Train of Engine Based on Internet of Things

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ABSTRACT Aiming at real-time monitoring of valve motion online in a new engine valve train that replaces the traditional cam with a self-developed new electromagnetic linear actuator, this paper presents a system scheme for motion monitoring of the electromagnetic linear actuators based on the Internet of Things and support vector machine (SVM) algorithm, which can effectively monitor the running state of the electromagnetic linear actuator and the valve. The system uses the lower computer to collect the current of electromagnetic linear actuator, and real-time transmits the data to the upper computer in the monitoring center. The upper computer firstly extracts the eigenvector of the motion state of the actuator by wavelet packet decomposition method, and then uses the artificial bee colony algorithm (ABC) to optimize the model kernel function parameters and penalty factor C of support vector machine, and establishes ABC-SVM electromagnetic linear actuator's motion state model and training. In this paper, the method is compared with the direct-collected wire-controlled detection method. The results show that the system can accurately and quickly monitor and analyze the electromagnetic linear actuator and engine valve operating state, so it is feasible.

INDEX TERMS Electromagnetic linear actuator, valve train, Internet of Things, artificial bee colony algorithm, online monitoring and analysis.

I. INTRODUCTION

The Internet of Things (IOT) is the Internet of connecting things. It is a network that realizes real-time information sharing based on radio frequency identification, wireless communication and Internet technology. [1], [2] Iot is characterized by comprehensive perception, reliable transmission, intelligent control and data fusion [3], [4].

Electromagnetic linear actuator is also known as "linear motor". Unlike the traditional rotary motor, it can directly converts electrical energy into mechanical energy of linear motion, without any intermediate conversion device. Besides, the electromagnetic linear actuator has advantages of simple structure, fast response, high precision motion performance. At home and abroad, new high-performance electromagnetic linear actuators are still under development. [5]–[7] This research group conducted an in-depth study on the self-developed electromagnetic linear actuator, mainly optimized and improved the implementation of its own structure, control and algorithm, and successfully applied it to the engine valve mechanism to replace the traditional CAM device for experimental research [8], [9].

The traditional engine valve train uses a cam device, which belongs to mechanical type and has better durability, but it cannot arbitrarily change the lift with the change of engine's operating conditions. The new electromagnetic linear actuator replaces the traditional cam valve mechanism, so that the valve can flexibly adjust valve timing, valve lift and valve opening duration according to the operating conditions of the engine, thereby improving the engine performance. [10], [11] At present, the improvement of engine valve mechanism in foreign countries is progressing rapidly, which is mainly exhibited in the optimization and improvement of its structure and control. In terms of the improvement of the valve mechanism's own structure, American Ford company, British Lotus company, Mercorelli, P., and some scholars had developed the valve mechanism based on electro-hydraulic drive; [12] Michigan State University had developed the valve

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mechanism based on electric drive; German FEV company and French Valeo company had developed the valve mechanism based on electromagnetic drive. [13], [14] In terms of control and algorithm improvement and trajectory optimization, Mercorelli, P., and some scholars at home and abroad had proposed many optimization and improvement measures [15].

In order to realize the full flexibility of the valve, the most important key was the control of the electromagnetic linear actuator. Therefore, the motion state monitoring of the electromagnetic linear actuator can ensure the normal operation of the engine. However, due to the complex working environment of the engine, problems such as wear, loss and even failure often occurred in long time use, which made it difficult to ensure the accuracy of valve lift. Therefore, it is necessary for us to monitor the motion state of the electromagnetic linear actuator. Once problems were found, we could warn and deal with it in time to avoid serious consequences. At present, the collection of electromagnetic linear actuator's operating data and the monitoring of status are still transmitted directly to the upper computer through the direct connection method, and there is no networking function.

With the increasing maturity of sensors and Internet technologies, the development of intelligent monitoring systems based on the Internet of Things thinking in the field of vehicle engine testing has become an important trend in the future. At present, many scholars have been researching the monitoring system based on the Internet of things, and its main research directions were ecological environment monitoring, industrial equipment operation status monitoring, fault diagnosis and early warning, health care and so on. Its purpose was to reduce production costs, improve efficiency and productivity, and achieve intelligence. For example: smart cities [16], smart agriculture [17], smart environment monitoring [18], smart industrial control [21], safety and emergency response [22], home automation [19], electronic health [20] and so on. The research on the motion state monitoring based on the Internet of things mainly focuses on intelligent vehicle assisted with driving in order to achieve vehicle positioning, tracking, control and management. Researches on the monitoring of motor equipment are few. For example, Şen M *et al.* [21] used wireless network technology to monitor the industrial motors, it established the hidden Markov model to classify motor faults, and compared the current and voltage parameters of the stator with those of normal operation to predict faults. The research results showed that the motor running state can be reflected by monitoring the motor parameters. Shyamala *et al.* [22] used the Internet of things technology to judge the state of the motor through the key operating parameters of the motor, such as when exceeding the expected parameter limit, the system sounded a warning timely and shut down. The results verified the availability of this method. Ganga *et al.* [23] put forward a monitoring model for the running state of DC motor based on the Internet of things. The vibration signal of the motor was collected, transmitted wirelessly and statistically analyzed.

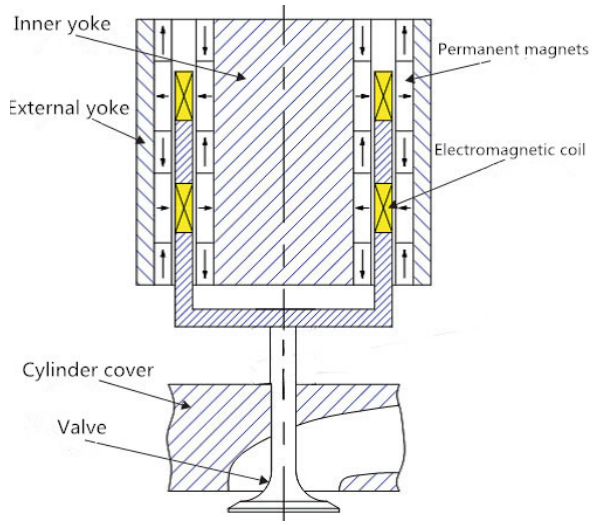


FIGURE 1. Self-developed electromagnetic valve train of engine.

The results show that this method was consistent with the wire-controlled method, and the results verify the reliability of motor running state monitoring based on the Internet of things. The research objects of the above references were all rotary motors, and there was no research literature on electromagnetic linear actuators yet. Therefore, the research on the motion state monitoring system of electromagnetic linear actuator in our paper had certain innovation. The system can realize long-distance transmission and storage of experimental test data, which is beneficial to reduce cumbersome lines as well as assemble and analyze for researchers. It lays a foundation for later testing, and has practical value.

The main points of this paper include the following:

(1) It introduces the composition of the overall structure of the system and separately designs the hardware and software of the system.

(2) It proposes a support vector machine analysis method using artificial bee worm algorithm, and establishes a system model for monitoring the motion state of electromagnetic linear actuator.

(3) It conducts system test experiments and compares it with the directly collected wire-controlled test method.

II. DESIGN OF THE OVERALL SCHEME OF THE SYSTEM

A. PRINCIPLE OF ELECTROMAGNETIC VALVE ACTUATOR

The engine electromagnetic drive valve train designed in this paper adopts the self-developed dynamic coil type electromagnetic linear actuator, as shown in Figure 1. Since the energizing coil is subject to the axial electromagnetic force in the air gap magnetic field, the specific motion law of the valve can be realized by controlling the magnitude and direction of the driving current [8], [9].

Electromagnetic drive valve mechanism is a complex system of mechanical, circuit and magnetic circuit coupling each other, so the subsystem of mechanical, circuit and magnetic circuit is established in the modeling, and the coupling

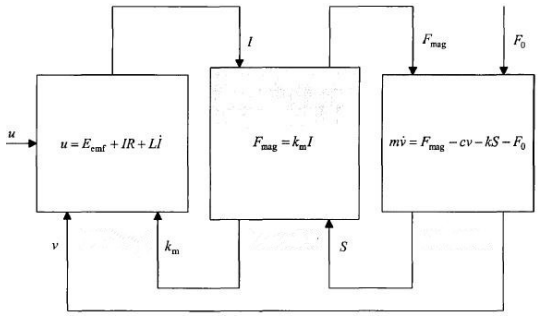


FIGURE 2. Subsystem coupling in the valve mechanism.

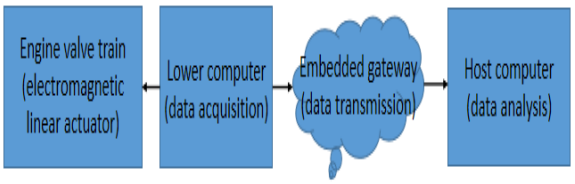


FIGURE 3. Overall structure of the System.

relationship between subsystems is fully considered. As shown in Figure 2.

The differential equations of the electromagnetic linear actuator can be described as follows:

$$\left\{\begin{array}{l} \dot{I} = -\dfrac{R}{L}I - \dfrac{k_m}{L}v + \dfrac{u}{L} \\ \dot{v} = \dfrac{k_m}{m}I - \dfrac{c}{m}v - \dfrac{F_0}{m} \\ \dot{S} = v \end{array}\right\} \tag{1}$$

where u is the power supply voltage, I is the current through the coil, R, L represent the resistance and inductance of the respectively, m is the moving mass, S denotes the mover position, v is the velocity of the mover, k_m is the force sensitivity of actuator, which denotes the ratio of the electromagnetic force to the input current, F_0 is the load force on the gas valve.

Based on the above analysis, the movement of the electromagnetic linear actuator can be monitored and analyzed by collecting the current of the electromagnetic linear actuator in real time and analyzing the current signal.

B. OVERALL STRUCTURE AND FUNCTION OF THE SYSTEM

The overall structure of the online real-time monitoring and analysis system of the engine valve train based on the Internet of Things is shown in Figure 3, which is mainly composed of the following three parts:

a. Lower computer: The collected electromagnetic linear actuator current data is sent to the embedded gateway through the ZigBee network, thereby realizing online real-time monitoring of engine valve operating conditions.

b. Embedded gateway: It is responsible for uploading the current value transmitted by the lower computer to the upper computer of the monitoring center in real time through the GPRS network.

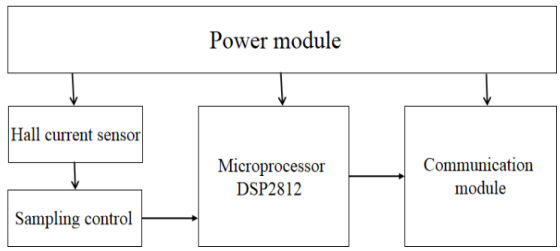


FIGURE 4. Hardware design for the lower computer.

TABLE 1. Parameters of Hall current sensor TBC200LTHA.

Symbol	Quantity	Parameters
V	dc power	±15V
T_r	turn ratio	1 : 2000
I_i	rated input current	200A
I_o	rated output current	100mA
R_S	sampling resistor	30 Ω

c. Host computer: The function is to realize the real-time data monitoring, modeling and analysis of electromagnetic linear actuators.

III. HARDWARE DESIGN OF THE SYSTEM

The system hardware design includes hardware development design of the lower computer and embedded gateway.

A. HARDWARE DESIGN FOR THE LOWER COMPUTER

The lower computer consists of three parts: data acquisition unit, data processing unit and wireless communication unit, including power module, sensor and synchronous sampling circuit, ZigBee network communication module, microprocessor DSP2812 module, etc. The hardware structure of the lower computer is shown in Figure 4.

B. CIRCUIT DESIGN FOR THE SENSOR

The magnetic balance Hall current sensor TBC200LTHA is used in this system. Parameters are shown in Table 1. The Hall current sensor has the advantages of fast response speed, high measurement accuracy, good dynamic performance, and electrical isolation. In order to improve the load capacity of the circuit and filter out high frequency interference, a voltage follower and a second order low pass filter circuit are added at the output of the Hall current sensor. The circuit is shown in Figure 5.

C. DESIGN OF ZIGBEE COMMUNICATION MODULE

The ZigBee communication module of this system uses CC2420 chip of Chipcon As. Characterized by low system

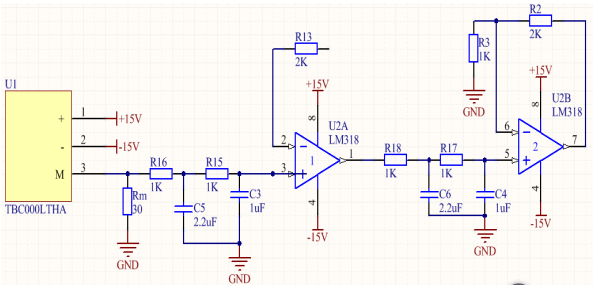


FIGURE 5. Circuit diagram of hall current sensor.

cost, ultra-low current consumption, high receiving sensitivity, high transmission rate, it requires few peripheral components. Furthermore, it can be directly connected to the pins of the microprocessor to realize wireless transmission/reception of data.

D. SELECTION OF MICROPROCESSOR

The microprocessor is the core to realize data acquisition, communication, monitoring and analysis of electromagnetic linear actuators. This system uses 32-bit high-performance, low-power microprocessor DSP2812 of TI Co. dedicated for the motor control.

The embedded gateway is responsible for receiving the current data sent by the lower computer through the ZigBee protocol, and uploading it to the upper computer of the monitoring center through the GPRS network and the TCP/IP protocol after processing. The hardware of the embedded gateway mainly includes the microprocessor module S3C2440, the radio frequency module CC2420, the communication module Q2406A.

IV. DESIGN OF SYSTEM SOFTWARE

The system software design includes the development and design of the lower computer software, embedded gateway and upper computer software.

A. SOFTWARE DESIGN FOR LOWER COMPUTER

The core of the lower computer consists of the DSP2812 module and the CC2420 module. The software programming adopts the combination of CCS and ZStack protocol stack. The software system adopts modular design, and it mainly consists of system main program, initialization subroutine, sensing detection subroutine, and ZigBee communication subroutine. The main program of the system realizes the functions of collecting and transmitting the current data of the electromagnetic linear actuator by calling each subroutine.

B. SOFTWARE DESIGN OF EMBEDDED GATEWAY

The core of the embedded gateway is based on the S3C2440 microprocessor. The underlying driver is written in C language, and the human-computer interaction uses the Linux embedded real-time operating system. The software consists of main program, initialization subroutine, data processing subroutine, Zigbee communication subroutine, GPRS communication subroutine and other modules. It mainly completes the construction and configuration of the wireless sensor network, being responsible for data transmission between the lower computer and the remote monitoring center host computer.

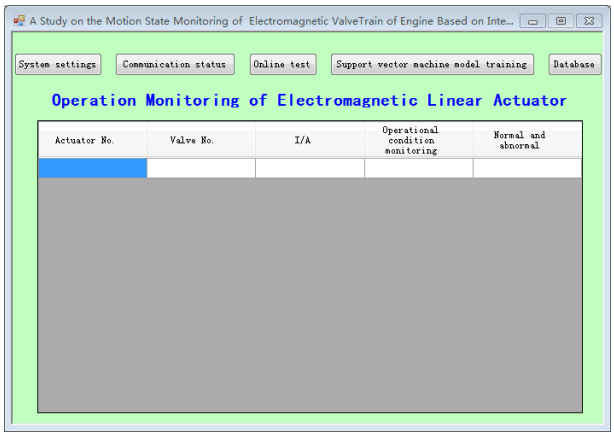


FIGURE 6. Software design for upper computer.

C. SOFTWARE DESIGN FOR UPPER COMPUTER

The upper computer software is jointly developed by C# and Matlab. The main function is to carry out online real-time monitoring, analysis and data storage of the operating state of the electromagnetic linear actuator. The software interface includes the number of each electromagnetic linear actuator, the valve position of the corresponding valve train, the running status monitoring, the support vector machine model training, the SQL data storage and the query. If an abnormality occurs in the electromagnetic linear actuator beyond the operating range, the faulty actuator is immediately displayed and an early warning signal is issued, as shown in Figure 6.

V. OPERATION STATE MONITORING MODEL OF ELECTROMAGNETIC LINEAR ACTUATOR BASED ON SUPPORT VECTOR MACHINE

Electromagnetic actuator execution state model based on support vector machine is the core of motion state monitoring. [24], [25] In view of the advantages of wavelet transform in dynamic signal analysis and the superiority of support vector machine classification in small sample cases, [26] the current signal is analyzed by wavelet packet analysis in this paper, so as to extract the feature vector of the running state of the electromagnetic linear actuator, and then the motion state model of the electromagnetic linear actuator is established by support vector machine, as shown in Figure 7.

A. ESTABLISHMENT OF MOTION SATE MODEL OF ELECTROMAGNETIC LINEAR ACTUATOR BY SVM

Step 1: Giving the training set:

$$T = \{(x_1, y_1), (x_2, y_2), \ldots (x_l, y_l)\} \in (R^n \times Y)^l \quad (2)$$

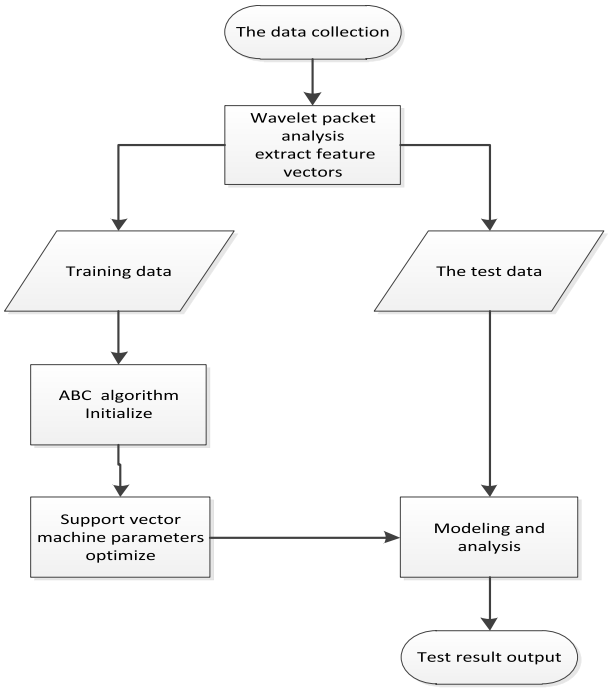


FIGURE 7. Flow chart of modeling.

In the formula, R^n is the n dimensional European space; $x_i \in R^n$ is the input vector; $y_i \in Y = \{-1, +1\}$ is the output, and $i = 1, 2, \cdots, l$.

Step 2: Finding a real value function $g(x)$ in space based on the above conditions, so that the decision function $f(x) = \text{sgn}(g(x))$ can be used to derive the output y of any input x.

Step 3: Introducing the transform $x = \Phi(x)$ from space R^n to Hilbert space H, and the training set T becomes

$$T_\Phi = \{(x_i, y_i)\} \in (H \times Y)^l \tag{3}$$

In the formula, $x_i = \Phi(x_i) \in H$.

Step 4: Finding the linear division hyperplane of this space $(w \cdot x) + b = 0$, so as to derive the partition hyperplane R^n and decision function on the original space $(w \cdot \Phi(x)) + b = 0$:

$$f(x) = \text{sgn}((w \cdot x) + b) = \text{sgn}((w \cdot \Phi(x)) + b) \tag{4}$$

In the formula, w is the weight vector, and b is the threshold value.

Step 5: Solving optimization problem

$$\begin{aligned} &\min_{w,b,\xi} \frac{\|w\|^2}{2} + C\sum_{i=1}^{l} \xi_i \\ &s.t.\ y_i((w \cdot \Phi(x_i) + b) \geq 1 - \xi_i, \quad \xi_i \geq 0 \end{aligned} \tag{5}$$

In the formula, ξ_i is the relaxation variable; C is the punishment parameter and C > 0.

Lagrangian function construction is introduced and convex quadratic programming problems are solved as below:

$$\min_{w} \frac{1}{2}\sum_{i=1}^{l}\sum_{j=1}^{l} y_i y_j (\Phi(x_i) \cdot \Phi(y_j))\alpha_i\alpha_j - \sum_{j=1}^{l} \alpha_j$$

$$s.t.\ \sum_{i=1}^{l} y_i\alpha_i = 0, 0 \leq \alpha_i \leq C \tag{6}$$

In the formula, α is the Lagrange multiplier.

It can be concluded:

$$\left\{ \begin{array}{l} \alpha^* = (\alpha_1^*, \alpha_2^*, \cdots, \alpha_l^*)^T \\ w^* = \sum_{i=1}^{l} \alpha_i^* y_i \Phi(x_i) \end{array} \right\} \tag{7}$$

The component α_j^* of α^* is selected in the open region (0,C), and b^* can be calculated as below:

$$b^* = y_j - \sum_{i=1}^{l} y_i\alpha_i^*(\Phi(x_i) \cdot \Phi(y_j)) \tag{8}$$

Step 6: Constructing the division hyperplane $(w^* \cdot x) + b^* = 0$ and solving the decision function.

$$f(x) = \text{sgn}(\sum_{i=1}^{l} y_i\alpha_i^*(\Phi(x_i) \cdot \Phi(y_j)) + b^*) \tag{9}$$

In the formula, $\Phi(x_i) \cdot \Phi(y_j)$ is called the inner product.

According to the Hilbert-Schmidt rule, as long as choosing the appropriate kernel function $K(x, x')$ in the optimal classification plane, a nonlinear classification can be transform into linear. Therefore, the decision function is

$$f(x) = \text{sgn}(\sum_{i=1}^{l} y_i\alpha_i^* K(x_i \cdot x) + b*) \tag{10}$$

B. OPTIMIZATION OF SVM PARAMETER BASED ON ARTIFICIAL BEE COLONY ALGORITHM

In the process of classification using support vector machine, it is found that its parameters such as penalty factor C, kernel function parameters and kernel function type have a crucial influence on the final result of classification.

In comparison with Genetic Algorithm and Particle Swarm Optimization, Artificial Bee Colony Algorithm (ABC) [27], [28] has good universality and expansibility. It can effectively prevent the algorithm from falling into the local optimal solution, improve global and local search ability. Therefore, this paper uses Artificial Bee Colony Algorithm to optimize the parameter selection of support vector machine [29], [30].

1) SELECTION OF SUPPORT VECTOR MACHINE PARAMETERS

a: SELECTION OF KERNEL FUNCTION TYPE

The most commonly used kernel functions in support vector machines fall into three categories: Polynomial kernel Function, Gaussian Radial Basis Function Sigmoid kernel Function. Among the three kernel functions, the Gaussian radial basis kernel function $K(x, x_i) = \exp\left[-\sigma\,|x - x_i|^2\right]$ has a wide range of application, which is suitable for high-dimensional and low-dimensional small samples, and has a wide convergence domain etc.. It is an ideal classification basis function. In the Gaussian radial basis kernel

function, the selection of parameters σ will affect the optimal classification effect, and only by selecting appropriate kernel parameters can the established classification model have good generalization ability and classification accuracy. Therefore, it is necessary to select kernel parameters.

b: PENALTY FACTOR C

The constant C represents the penalty intensity when the sample is misclassified, the function of which is to reduce the error rate of samples and the complexity of the balancing algorithm in order to improve the performance of SVM. In the Formula (5), when the penalty parameter $C \to \infty$ is used, it means that no sample is misclassified, thus improving the classification accuracy of samples. However, the fitting degree of training samples is too high, the complexity of the algorithm is greatly increased, the training time is long, and the generalization ability of machine learning is reduced. Conversely, when $C \to \infty$, there is no penalty for the sample representing right and wrong scores, the corresponding empirical risk is greater. Although the complexity of the algorithm is reduced, the classification accuracy of training samples cannot be guaranteed. According to the above analysis, Therefore, it is necessary to select the penalty parameter C.

2) OPTIMIZATION OF KERNEL FUNCTION PARAMETERS σ AND PENALTY FACTOR C

In this paper, the most important kernel function parameters σ and penalty factor C of the support vector machine are optimized by the artificial bee colony algorithm.

Step 1: Initializing the parameters of the bee colony algorithm, constructing the d-dimensional vector of honeybee source individuals $(d_1, d_2, \cdots, d_n, C, \sigma)$, setting the maximum number of iterations N, number of honeybee sources S_N, restricted condition of the Scouter, and generating the initial solution set $x_i (i = 1, 2, \cdots, S_N)$;

Step 2: Calculating the fitness value f_i of each honey source individual according to the fitness function;

Step 3: Judging whether the termination condition (the maximum number of iterations) is reached, and it will end if it is met; otherwise, go to Step 4);

Step 4: Generating a new solution v_{ij} (the location of the new honey source) in the leading bee stage according to the honey source updating Formula (11), evaluate the new solution and make greedy selection;

$$v_{ij} = x_{ij} + r_{ij}(x_{ij} - x_{kj}) \tag{11}$$

where, $k \in \{1, 2, \cdots, n\}, j \in \{1, 2, \cdots, D\}$, n is the number of solutions, D is the number of optimization parameters, and $k \neq i$, r_{ij} is a random number of [-1,1].

Step 5: Leading the bees to complete the search, leading the bees to save the solution information and fitness value and following the bees to share;

Step 6: Calculating the probability value p_i of each solution in the stage of Follower according to the honey source probability Formula (12); selecting the honey source

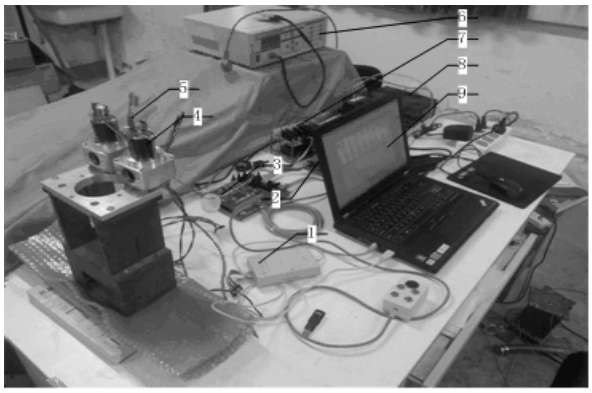


FIGURE 8. Experiment system bench. 1. Embedded gateway; 2. Current sensor; 3. DSP controller; 4. Electromagnetic linear actuator; 5. Displacement sensor; 6. Resistance tester; 7. Power driver; 8. Power; 9. PC.

that is the solution, searching around it, and getting the new solution v_{ij} according to the honey source update formula (11); calculating the fitness value, and making greedy selection;

$$p_i = \frac{f_i}{\sum_{i=1}^{S_N} f_i} \tag{12}$$

where S_N represents the number of honey sources, and f_i means the fitness value of each honey source.

Step 7: If a solution remains the same after comparison with limit times, abandon the solution and the corresponding lead bee of the solution will become a scout bee.

Step8: If there are discarded honey sources in Step 7) in the detection bee stage, a new solution as a honey source will be randomly searched in the feasible solution space according to Formula (13) to replace the old solution.

$$x_{ij} = x_{\min,j} + rand(0, 1)(x_{\max,j} - x_{\min,j}) \tag{13}$$

where, $i \in \{1, 2, \cdots, n\}, j \in \{1, 2, \cdots, D\}$, n is the number of solutions and D is the number of optimization parameters.

Step 9: Determining whether the maximum number of iterations has been reached; if not, return to Step 4) to continue execution; otherwise, it will be the global optimal solution and output the optimal parameters of SVM.

Setting the following initial parameters for the artificial colony algorithm: the initial colony size: 100; maximum number of iterations: 200; parameter conditions of the termination algorithm: 1e-20; number of optimized parameters: 2; condition control times of giving up honey source: 50; lower bound of optimization parameters: 1e-2; upper bound of optimization parameter: 1e3; the search scope of C, σ is [0.1, 100] and [0.01, 1000] respectively.

Final optimization results are: $C = 0.085, \sigma = 9.318$

VI. ANALYSIS OF EXPERIMENT RESULT

In order to verify the actual effect of the monitoring system designed in this paper, a system experimental bench was built, as shown in Figure 8.

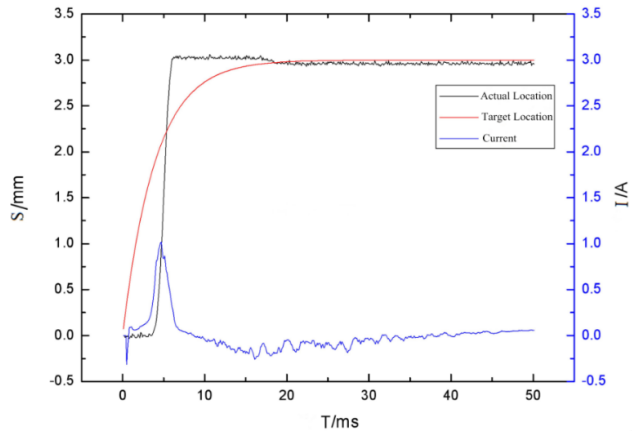


FIGURE 9. Response and current when the valve lift is 3mm.

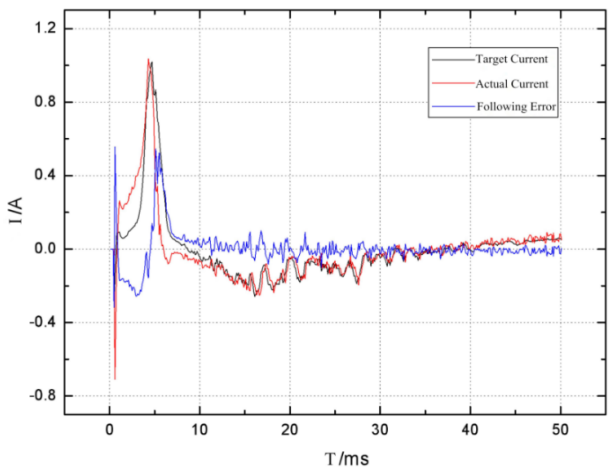
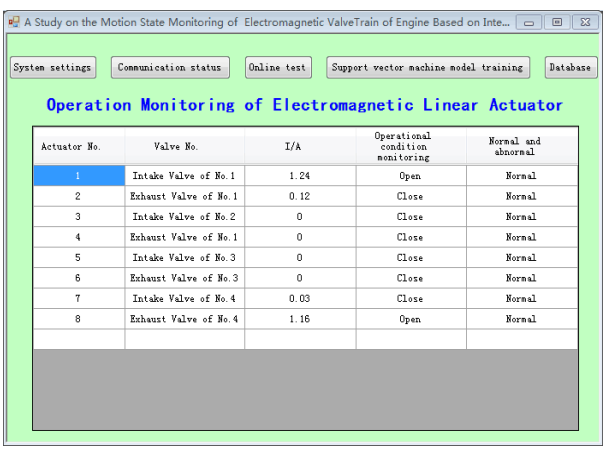


FIGURE 10. Wire-controlled wireless monitoringcurrent and deviation when valve lift is 3mm.



Actuator No.	Valve No.	I/A	Operational condition monitoring	Normal and abnormal
1	Intake Valve of No.1	1.24	Open	Normal
2	Exhaust Valve of No.1	0.12	Close	Normal
3	Intake Valve of No.2	0	Close	Normal
4	Exhaust Valve of No.1	0	Close	Normal
5	Intake Valve of No.3	0	Close	Normal
6	Exhaust Valve of No.3	0	Close	Normal
7	Intake Valve of No.4	0.03	Close	Normal
8	Exhaust Valve of No.4	1.16	Open	Normal

FIGURE 11. Electromagnetic linear actuator and valve operating condition monitoring results.

A. COMPARISON OF EXPERIMENT RESULTS

When the intake valve opening target lift is 3mm, the wireless monitoring and line control detection of the system scheme will be compared. The experimental system is shown in the figure. The response and current test structure of the electromagnetic linear actuator during motion is shown in Figure 9.

The actual current detected by the line control is compared with the actual current of the wireless monitoring as the target current. The result is shown in Figure 10. The experiment results show that that the wirelessly monitored sensor monitoring current and the current collected by the wire-controlled detection are in good agreement, and the deviation is close to zero. It can be proved that it is feasible to use wireless sensing monitoring method instead of wire-controlled detection.

B. MONITORING DISPLAY OF THE OPERATION STATUS

The on-line monitoring result of the operating state of the electromagnetic linear actuator realized by the upper computer software is shown in Figure 11. The monitoring results show that in a certain cycle, the current value of no.1 electromagnetic linear actuator is 1.24A and that of no. 4 electromagnetic linear actuator is 1.16A. The valve opening stroke is 3mm and no fault occurs.

VII. CONCLUSION

This paper puts forward an online real-time monitoring and analysis system for the motion state of the electromagnetic engine Valve train based on the Internet of Things. The performance of the system is verified by contrast experiment. The results show that the system can monitor the current value of the electromagnetic linear actuator in real time, accurately determine the motion state of the engine valve, and provide strong support for the later realization of the engine valve flexibility adjustment, which has the advantages of wireless, network, system, and intelligence.

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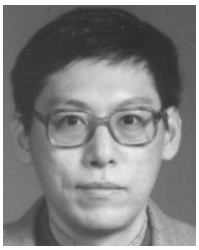

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