Improved Study on Position Measurement System for Linear Motor Applied in Electromagnetic Launch System

Wanzhi Rui, Mingjin Xu, Penghui Guo, and Jin Xu

***Abstract*—The linear motor applied in electromagnetic emission system uses a closed loop position control strategy, which needs a set of position measurement system with high reliability, high resolution and integration to achieve real-time acquisition and analysis of position signals. The existing position controller is based on the simple logic chip design without memory function, and does not have the storage analysis and preprocessing function to position signals. Therefore, the system has insufficient scalability, low integration and reliability. Aiming at the improvement of the existing position measurement system, an intelligent position measurement system integrating the functions of position signals acquisition, processing and uploading, data storage and analysis is proposed in this paper, and its working principle and system composition are discussed in detail. The position, speed and acceleration obtained on the electromagnetic emission platform are in good agreement with the expected value of the system. As results, the feasibility and accuracy of the improved integrated intelligent position measurement system are verified, and the control performance of the system is also satisfied well, which can be good guidance and reference for subsequent engineering practice.**

***Index Terms*—Electromagnetic emission, linear motor, position measurement system, position controller.**

I. Introduction

ELECTROMAGNETIC mission system is a new type of propulsion device that uses the electromagnetic force produced by a linear motor to speed up the load to a given speed (hundreds of km/h) in a limited stroke and a short time (a few seconds), and in accordance with a predetermined trajectory curve. It is an energy conversion device that transforms electromagnetic energy into instantaneous kinetic energy of the emission load [1]-[3]. In the electromagnetic emission process, the linear motor drives the load to the given position and speed to complete the emission task. Therefore, the emission process has high requirements for the position, speed and acceleration of the linear motor, which not only needs the precise position in the steady state, but also needs to ensure the motor accelerates smoothly with small fluctuations in the dynamic process [4]-[6]. In addition, the magnetic chain orientation technology is used in the linear motor control system, in which the orientation angle is provided by the motor position. The motor position error will result in the inaccurate orientation of the magnetic chain and cause the fluctuation of the electromagnetic force, so the motor position is critical to the control of linear motor. The electromagnetic emission system can be regarded as a servo system with closed loop feedback, in which a high reliability, high resolution and integrated position measurement system is needed to achieve the real-time acquisition and analysis of position signal [7].

II. Design And Problem Analysis Of The Position Measurement System

Considering the special requirements of the structure, electric and application environment for the linear motor applied in electromagnetic emission system, the existing position sensors, such as laser interferometer [8], optical grating sensor [9] and magnetic grid sensor [10], cannot be directly applied to the electromagnetic emission system because of such factors as anti-vibration, anti-interference, environmental adaptability and installation accuracy. However, the eddy current sensor has the advantages of small volume, high sensitivity, wide response frequency, high reliability and strong anti-interference ability. It can be used in non-contact measurement occasions, and is suitable for special applications of electromagnetic emission [11]. Since a position measurement system for electromagnetic emission based on the eddy current sensor and the orthogonal coding principle has been designed and achieved good experimental results in References [12],[13], its principle and system composition of the eddy current sensor are briefly introduced below.

A. *Principle of Position Sensor*

The eddy current sensor is used in the position measurement system for electromagnetic emission. Its basic principle is to transform the distance change between the measured conductor and the sensor detection coil to the change of the Q value, the equivalent impedance and the equivalent inductance of the detection coil by the eddy current effect. Then the corresponding measurement circuit is used to extract these

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parameters changes, and transform them into voltage signals as the output. In the position sensor, the differential voltage circuit composed of the detection coil and its auxiliary coil, and the frequency selection amplifying circuit constitute a self-excited oscillation circuit with a positive feedback loop. When the sensor does not induct the metal, the oscillation circuit is in the critical equilibrium state of stopping vibration by reasonable parameter setting. When the metal is near, the weak parameter change of the detection coil will break the balance. Under the effect of the noise signal as the vibration source and the amplification of the positive feedback loop, the oscillator quickly rises and the sensor outputs the switch signal. Therefore, due to the application of the differential circuit and the positive feedback loop in the differential voltage variable eddy current proximity switch, the sensitivity of the equivalent inductance change of the detection coil is greatly improved, and the sensor detection performance is also improved.

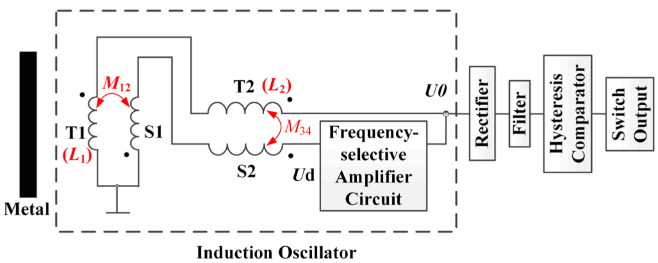

Fig. 1. Principle of the position sensor.

The principle of the position sensor is shown in Fig. 1. The sensor has 4 coils, which are defined as transmitting coil (T1), receiving coil (S1), transmitting compensation coil (T2) and receiving compensation coil (S2), respectively. T1 and S1, T2 and S2 constitute two sets of mutual inductance coils respectively. T1 and S1 are used to induce the eddy current effect of the metal to be measured. T2 and S2 are arranged vertically with T1 and S1, and are not affected by the eddy current field of the metal to be tested. The 4 coils constitute a differential transformer. When the alternating excitation source U_o is applied in the series connection circuit of T1 and T2, T1 and T2 excite the induction voltage in S1 and S2, respectively. Then S1 and S2 are connected to the output differential voltage U_d through the reverse sequence.

$$U_d = j\omega MI\ . \tag{1}$$

Where I is the equivalent current of the eddy current ring, M is the mutual inductance between S1 and the eddy current ring, ω is the angular frequency of the excitation voltage. After pass through the frequency-selective amplifier circuit, U_d outputs U_o as the excitation source of T1 and T2, so the 4 coils and the frequency-selective amplifier circuit together form a self-excited oscillator with positive feedback loop. When there is no external metal interference, the output differential voltage U_d of S1 and S2 can be approximated to zero by setting the coil parameters and the coils position. At this time the loop is in the state of equilibrium and the oscillator does not oscillate. When the metal is near, the equivalent impedance of T1, S1 changes, the equilibrium state is broken and the output differential voltage U_d is no longer zero, then the oscillator starts to vibrate and the vibration condition is as follows [9],

$$k_1^2 > \frac{(L_1+L_2)+A(M_{12}-M_{34})}{L_1+AM_{12}}\ . \tag{2}$$

Where k_1 is the coupling coefficient between T1 and the measured conductor; $L1$ and $L2$ are inductors of T1 and T2, respectively; M_{12} is the mutual inductance of T1 and S1, M_{34} is the mutual inductance of T2 and S2; A is the magnification of the amplifying circuit. Equation (2) is also the switch condition of the sensor. The output oscillating signal is converted to switch signal as the final output of the sensor after rectification, filtering and hysteresis comparison. Since the generation of differential voltage and the mathematical model of induction oscillator has been analyzed in detail in References [12], [13], it won't be discussed in this article.

B. *Composition of The Position Measurement System*

The existing position measurement system for the linear motor is used to detect the motor position accurately in real-time, and then perceives its changes of speed and acceleration, which is mainly composed of the position encoder unit, position sensor array, position controller and position collector. Its structure schematic is shown in Fig. 2. The optical signal generated by the mutual coupling of the position sensor array and the encoder unit outputs four orthogonal position pulse signals through the position controller. When the position pulse signals are transmitted to the position collector to be decode, the absolute position information is obtained and then transferred to the motor controller to get the actual relative position. The position information is used as the outer loop input of the core control algorithm for the motor controller. The realization of the two groups of orthogonal position signals in four roads is the key of the position measurement system. Therefore, the working characteristics of position sensors should be studied in detail, and then the reasonable design is made according to its array parameters and structure parameters.

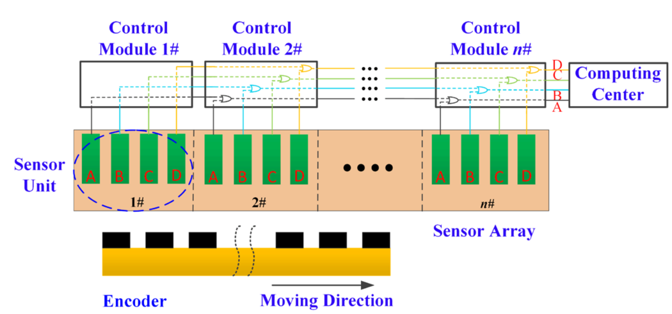

Fig. 2. Structure schematic of the existing position measurement system.

The position sensor unit is evenly arranged on the side of the motor in the position measurement system. Each sensor unit is composed of four position sensors, which are defined as sensor A, B, C, and D. The encoder is mounted on the mover of the linear motor, consisting of a long non-metal matrix and a coded tooth uniformly distributed on the base. When the actuator moves, the coded tooth will periodically enter and leave the detection range of the position sensor, so that the sensor can output continuous square wave sequence [13]. Through the rational design of the structural parameters of the coded teeth and the array parameters of the position sensor, the phase difference of the square wave signals output by the four sensors are 45 degrees respectively, and the two groups of orthogonal signals of A/C and B/D paths are formed.

C. Problem Analysis

In the field of electromagnetic emission with large load, the motion stroke is more than 100 meters long, the linear motor is divided into subsection power supply, and the system consists of tens of position controllers, with nearly 100 cables and plugs. As results, the system has low degree of integration and reliability, while the cost of equipment manufacture and maintenance is high. Besides, the system position controller is based on the simple logic chip design without memory function. On the one hand, the storage management and analysis of the position data in the emission process are all completed by artificial acquisition, there is the risk of leakage and error recovery, and the difficulty of obtaining the original location signals are increased; on the other hand, the preprocessing of position signals is powerless (filtering, shaping, etc.), which leads to the lack of scalability of the system. Considering the safety requirements, it is urgent to optimize the design of the existing position controller, which mainly increases the network communication interface, realizes the automatic acquisition and uploading of the position signals, and automatically completes the recovery, storage, analysis and health evaluation of the position signals by the centralized control console.

III. Overview Of The Improved Controller

A. Improved Design

The main function of the position controller is to convert the received optical signals to the photoelectric conversion, and then send them into the signal processing module. The output signals are transferred to the host computer and computing center after the electro-optic conversion. The principle structure and function of the position controller is shown in Fig. 3.

According to the above problems and deficiencies, the following improvements are made to the existing position controller. In fact, the system chart and principle of the new proposed system and the existing one are the same. The main difference between the two systems lies in the structure improvement and function expansion of the position controller.

(1) The position controller performs the acquisition of position signals independently and automatically, then uploads position signals to the host computer and computing center. The latter completes the reception, recovery, storage, analysis and health evaluation of position signals.

(2) The two PCB boards of the position controller are independent of each other, which process the position signals of A/C paths and B/D paths respectively. This design can ensure that a position feedback signal with half precision (about 8mm) can be realized in the case of one circuit board failure, and the redundancy of position signals also can be improved.

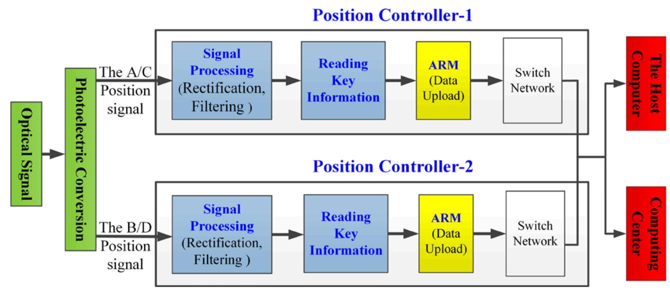

Fig. 3. Structure and function schematic of the improved position controller.

B. Position Signal Processing Module

Structure schematic of the improved integrated position measurement system is shown in Fig. 4. Compared with the existing system, the most significant improvement lies in the function expansion of the centralized position controller, which is responsible for the operation, processing, sampling and uploading of position signals. FPGA chip is used in the processing and sampling module, which can not only perform intelligent preprocessing and logic operation on the original position signals, but also sample the position signals with high frequency, and this greatly improves the expansibility of the position measurement system. The network upload module adopts ARM chip, which is responsible for packing and sealing the position signals after FPGA processing, and then automatically transmitting the data to the host computer. The host computer is responsible for automatic storage and extraction analysis of position signals.

The signal processing module is based on the architecture of FPGA+ARM, receiving electrical signals from the photoelectric conversion board, sending it into the FPGA chip, and output the waveform signals after the logic operation. The key information of the waveform signal (edge relative time) is read in FPGA, and then the data is exchanged with ARM through parallel interface. After receiving effective data, the ARM module encodes the format of the Ethernet data frame and uploads the data through the Ethernet interface, in which the Ethernet can interact through the grid port or the optical network port (controlled by the dialing switch).

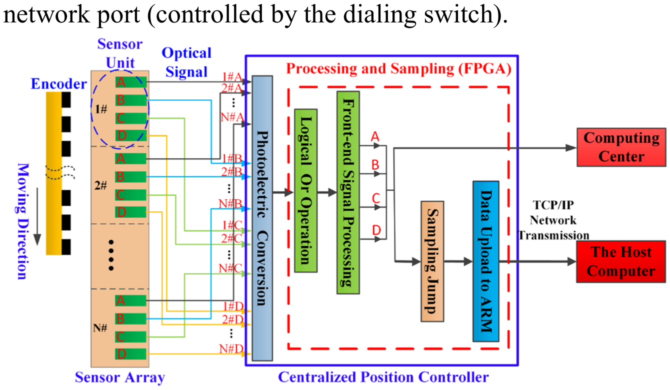

Fig. 4. Structure schematic of the integrated position measurement system.

The position controller based on this architecture conveniently realizes the arithmetic synthesis of the original segmented position signals. At the same time, the automatic acquisition and storage of location signals and the establishment of historical database are also realized. The host computer can analyze the characteristics of location data and realize fault diagnosis and health management of position measurement system.

IV. Experiment

The integrated intelligent position measurement system based on the improved design is tested on the electromagnetic emission platform with 10m-stroke and 100ms-acceleration time, as shown in Fig. 5. There are 7 position collectors evenly distributed on the 10m-stroke and all position signals obtained from position collectors are managed by one position controller.

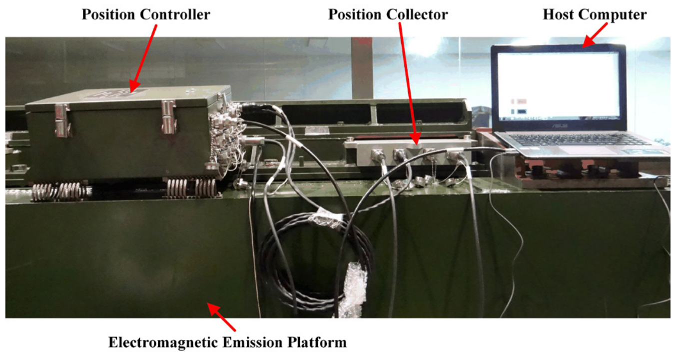

Fig. 5. The experimental platform of electromagnetic emission system.

Fig. 6 is a position curve of linear motor obtained from the electromagnetic emission experiments at working condition. From 0.1s to 0.3s to arrive at a predetermined position, the moving stroke is about 4.7m, and the position curve detected by the position sensor is highly consistent with the given position curve, and the average maximum position deviation is 38mm during 0.2s-0.26s period. Compared with this motion stroke, the position deviation is less than 3%, which indicates the acquisition of position information with high precision under high speed condition.

Through the differential and filtering processing of the position curve shown in Fig. 6, the speed and acceleration curves in the electromagnetic emission process are obtained, as shown in Fig. 7 and Fig. 8 respectively. During the whole electromagnetic emission process, the rotor is continuously accelerating and its speed increases rapidly. The speed obtained from data analysis is in good agreement with the expected speed. The average maximum speed deviation during 0.28s-0.3s period is only 0.8m/s, so the speed error is less than 2% at this time. Since the electromagnetic emission is an instantaneous acceleration process in a short-range, the acceleration requirement for the electromagnetic emission equipment is very high, and usually the instantaneous maximum acceleration can be as high as 37G. During this process, due to the adverse effects of control algorithm and side effect of the linear motor, the acceleration is fluctuated in some extent, as shown in Fig. 8, the average maximum acceleration fluctuation is 2G. Compared with the expected acceleration at that time, the acceleration error is less than 9%. By analyzing the position data obtained from experiments, the actual position, speed and acceleration are in good agreement with the expected value. Based on these analysis, the feasibility and accuracy of the improved integrated intelligent position measurement system are verified, and the control performance of the system is also satisfied well.

The overall performance indexes with a position resolution less than 10mm, a speed accuracy less than 1m/s and a peak-to-average force ratio less than 1.1 are satisfied. Its contribution lies in the improvement of system complexity and function expansion for the existing position measurement system. Compared with the original system, the number of connecting cables is reduced by 50% and the cost of equipment is reduced by about 60%.

However, the improvement effect of its control performance needs further experiments if the proposed improved position measurement system is applied to the electromagnetic emission platform with 100m stroke and seconds acceleration time, which is described in References [12], [13].

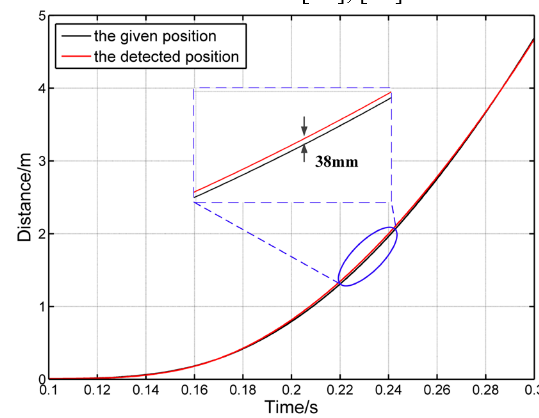

Fig. 6. The position curve of the linear motor.

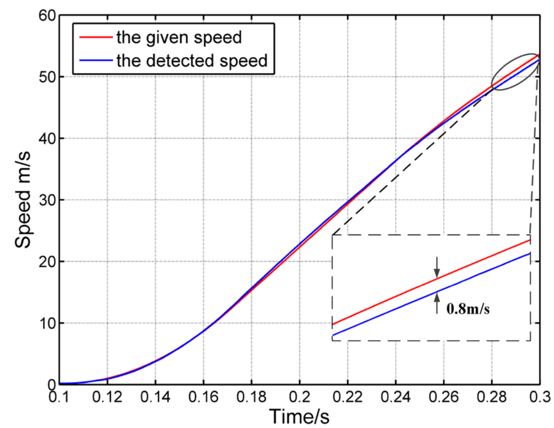

Fig. 7. The speed curve of the linear motor.

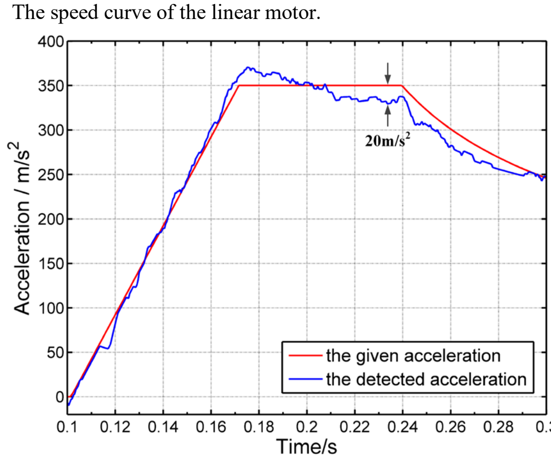

Fig. 8. The acceleration curve of the linear motor.

V. Conclusion

Aiming at the actual requirements of the electromagnetic emission system in special application environment, an improved method of the integrated intelligent position measurement, including position signal acquisition, processing and uploading, data storage and analysis is proposed in this paper, its working principle and system composition are discussed in detail. The tests have been carried out on the electromagnetic emission platform. The errors of position and speed of the linear motor is less than 3% compared with the expected value, and the acceleration fluctuation is within 10%. As results, the feasibility and accuracy of the improved integrated intelligent position measurement system are verified, and the control performance is satisfied well.

Compared with the position measurement system mentioned in References [12], [13], the integration, automation, applicability and expansibility of the current system has been greatly improved, which has good guiding significance and reference value for engineering practice. Based on the above research results, a set of experimental platform for automatic acquisition, intelligent processing and rapid transmission of linear motor position measurement is designed and implemented, which has laid the foundation for further research on the predictive control, fault-tolerant control and position-less control based on the position signal shaping technology.

References

[1] Fair H D. "Guest editorial the past, present, and future of electromagnetic launch technology and the IEEE international EML symposia," *IEEE Trans. Plas. Sci.*, vol. 41, no. 5, 1112-1116, 2013.

[2] Bushway R. R. "Electromagnetic aircraft launch system development considerations," *IEEE Trans. Magnet.*, vol. 37, no. 1, 52-54, 2001.

[3] Ma Weiming, LU Junyong. "Electromagnetic launch technology," *J. Nation. Uni. Defen. Tech.*, vol. 38, no. 6, 1-5, 2016.

[4] Visioli A. "A new design for a PID plus feed forward controller," *Elsev. J. Pro. Cont.*, vol. 14, 457-463, 2004.

[5] Cominos P and Munro N. "PID controllers: recent tuning methods and design to specification," *IEEE Proc. Cont. Theor. Appl.*, vol. 149, no. 1, 46-53, 2002.

[6] Ang K.H, Chong G, Li Y. "PID control system analysis, design, and technology," *IEEE Trans. Cont. Sys. Tech.*, vol. 3, no. 4, 559-576, 2005.

[7] Zhang Xiaoxu, HE Na, WANG Qingyu, et al. "Position sensing system for linear motor based on quadrature encoding principle," *J. Nav. Univ. Eng*, vol. 26, no. 1, 34-37, 2014.

[8] Yu Haili. "Research on large stroke nan-positioning technology and application based on dual-frequency laser interferometer," Beijing: *Chin Acad. Sci.*, 2011 (in Chinese).

[9] Zhong Wenbin. "Research on FPGA-based phase grating interference sensor signal processing system," Wuhan: *Huazhong Univ. Sci. Tech.*, 2014 (in Chinese).

[10] Hu Peng. "Design and research of absolute output magnetic grid sensor," Wuhan: *Wuhan Univ. Tech.*, 2013 (in Chinese).

[11] Wang Qingyu, Ma Weiming, He Na. "Sensitivity analysis of eddy-current sensor applied in grating-type displacement measurement system," *Proc. IEEE Conf. Indus. Elect. Appl.*, Auckland, New Zealand, 2015.

[12] HE Na, Wang Qingyu, Rui Wanzhi. "Position measurement system for linear induction motor applied in electromagnetic emission system," *Elect. Mach. Cont.*, vol. 19, no. 11, 10-16, 2015.

[13] Wang Qingyu, He Na, Rui Wanzhi. "Study on Key Technology of Position Measurement System for Linear Induction Motor Applied in Electromagnetic Emission System," *Chin. Soc. for Elec. Eng.*, vol. 36, no. 5, 1413-1420, 2016.

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