The Optimization Design and Motion Characteristic Experiment of PMLSM Based on GA and TwinCAT

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Abstract **— By analyzing the specific location of a new permanent magnet synchronous linear motor (PMSLM) for the project needs of the national high tech research and development program, the subject establishes the motor mathematical model with the equivalent circuit method. In order to reduce the thrust ripple and increase the power density of PMSLM, the parameters of the motor can be optimized to get the best through the genetic algorithm. By comparing the push force experiment based on LabVIEW with the finite element simulation analysis (FEA) and the motion control experiments based on TwinCAT NC have verified the robustness, validity and reliability of the optimization design of PMSLM. At the same time, the motor has some advantages of less thrust fluctuation, good economy, small size, etc., and accords with the actual needs of the project.**

Keywords - PMSLM; Genetic algorithms; Multi-objective optimization; FEA; TwinCAT

I. INTRODUCTION

Compared with traditional rotary motor, linear motor is a kind of electrical energy directly into linear motion mechanical energy, and does not need the transmission device switching mechanism. It has advantages of simple structure, no wear, low noise, smooth motion, high speed and high precision. It is widely used in industrial automation, transportation, transportation, construction and civil [1, 2]. The permanent magnet linear synchronous motor (PMSLM) fit for the requirements of the project, because of it has the characteristics of high speed, high thrust, low loss, small electrical time constant and fast speed [3,4,5].

At present, thrust fluctuation is the cause of vibration and noise generated by the motor, especially at low speed, it will worsen its servo operating characteristic [6]. Now, the research on how to reduce the thrust fluctuation is mainly studied in two aspects, that is, the structure design of the motor and the control method based on the motor. In the aspect of motor design, many experts believe that the magnetic resistance (force) leads to the thrust ripple, and can also be considered the end force and slot force [7, 8, 9, 10]. References [11, 12] provide the method of Energy Finite Element to analyze the end tooth width and height on the fluctuation of power. But it doesn't get force wave and relations between the sizes of the specific parameters of end tooth. Through the analysis of the orientation force, references [13, 14, 15] puts forward the method to add compensation block. It can neutralize and compensation is good for location force, but the existence of compensation block size and the installation cannot determine the problem in practice. In the other aspect of the control method, in [16], the proportional, integral and derivative (PID) position/ force control with a lead compensator is presented. The approach is applied in a PMLSM drive system with force disturbance compensation. In [17], in order to further suppress the force disturbances of permanent magnetic linear motors a feed forward neural network using the BP algorithm is proposed to approximate and compensate the force ripple.

For the short primary and long subprime of PMSLM, the magnetic resistance fluctuation is the main reason to force the thrust and the law. In addition, thrust characteristic inductance of the motor also has a great influence. In this paper, Model analysis is given for 3 poles 4 slots PMSLM unit motor. A specific position analysis and genetic algorithm optimization (GA) are adapted according to the motor force minimum ripple and permanent magnet force density. The application based on finite element simulation of LabVIEW motor thrust test and parameter values were compared with the one based on TwinCAT NC system motion control experiments to verify the PMLSM robustness, effectiveness and reliability of design optimization.

II. MODELING AND ANALYSIS BASED ON THE SPECIFIC

The new type of PMSLM chooses moving-magnet structure, and eliminating the influence of drag chain is to decrease the volume of the motor. To provide ease of analysis,3 poles 4 slots unit mo- tor is chosen as the analysis object, which selects the special way of concentrated winding, the fractional slot winding, the end opening slot and gapless magnetic steel. Considering the magnetic resistance effect caused by the air gap, permanent magnet, teeth, yoke and slot leakage, ignore the rotor core reluctance, hysteresis and eddy current,

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magnetic flux leakage of the permanent magnet and the influence of temperature on magnetic material. The structure model of the PMSLM is shown in figure 1.

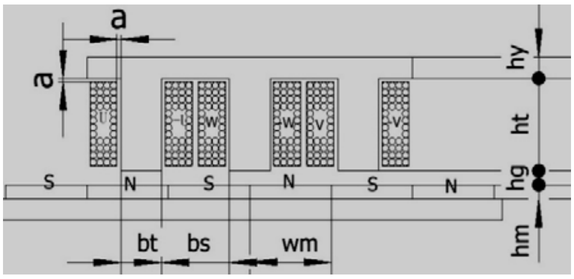

Fig.1 PMLSM Structural Model

This paper takes an electromagnetic analysis based on specific point of transient position. According to figure 1 and figure 2, it can be equivalent to the current of U, V direction based on the method of equivalent circuit. It is referred to long magnetic circuit with the permanent magnet equivalent circuit, as shown in figure 3.The composition equivalent circuit with the permanent magnet and current of W direction is referred to short magnet circuit, as shown in figure 4.

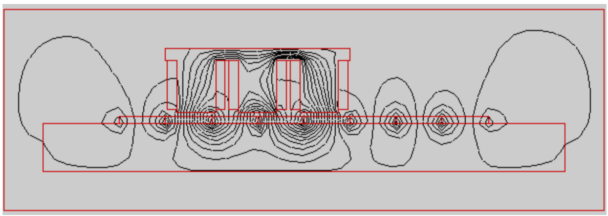

Fig. 2 Distribution of Magnetic Field Lines

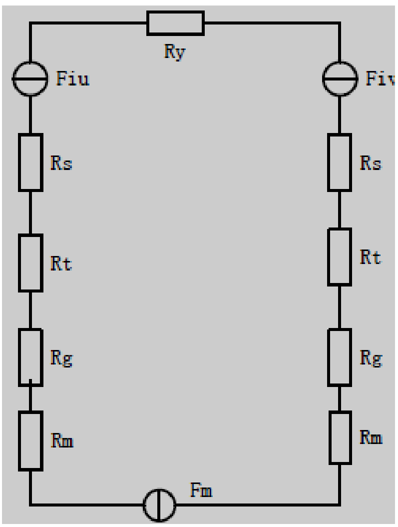

Fig.3 Long Magnetic Equivalent Circuit

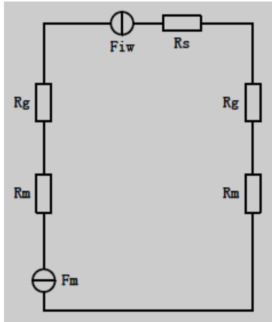

Fig. 4 Short Magnetic Equivalent Circuit

F_{iu} , F_{iv} and F_{iw} are current excitation to produce the equivalent MMFs in Figure 3 and Figure 4. F_m is the permanent magnet to excite equivalent magneto- motive force. R_s , R_t , R_g , R_m , and R_y are slot leakage resistance, tooth magnetic resistance, air gap resistance, permanent magnet and yoke magnetic resistance.

Where: N is the coil winding, I represents the power flow, θ_0 denotes the electrical degree of sinusoidal current, The coil of the electric excitation magnetomotive force deferred to F_i is found as follows:

$$F_i = 2NI\sin\theta_O \tag{1}$$

Where: H_C is the coercive force of permanent magnet, h_m is the magnetization direction of thickness, Permanent magnet equivalent magneto- motive force referred to F_m is found as follows:

$$F_m = H_C h_m \tag{2}$$

Where: R_S is the motor slot leakage, R_g represents air gap, R_m denotes the permanent magnet magnetic resistance, and are calculated as follows [18, 19]:

$$R_S = \frac{2b_t}{\mu_0 h_y l_s} \tag{3}$$

$$R_g = \frac{K_C h_g}{\mu_0 l_s (b_t + b_s)} \tag{4}$$

$$R_m = \frac{h_m}{\mu_r \mu_0 l_s b_t} \tag{5}$$

Where: K_C is the Carter factor, μ_0 represents the magnetic permeability of air, μ_r denotes the magnetic permeability of the permanent magnet, b_t , b_s , l_s , h_m and h_g were tooth width, transverse length, core of lateral length, the thickness of permanent magnet, the air gap size.

Tooth magnetic resistance and yoke iron core is the size of the magnetic resistance and current and permanent magnet flux density. The air gap flux density is produce magnetic coil winding dense and permanent magnet flux density of the stack. Produced by the winding flux density B_{ag} and permanent magnet flux density for B_{mg} as follows:

$$B_{ag} = \frac{2\mu_0 NI \sin\theta_0}{h_g + h_t} \tag{6}$$

$$B_{mg} = \frac{\mu_0 H_C h_m}{h_g + h_m} \int_{\frac{\left(\frac{b_t}{2}+b_s-w_m\right)}{w_m}}^{\frac{\left(\frac{\partial b_t}{2}+b_s-w_m\right)\frac{\pi}{2}}{w_m}} \sin x dx \tag{7}$$

Where: w_m shows the axial length of permanent magnet, h_t indicates the length of the tooth. Tooth of flux density for:

$$B_t = \frac{b_t + b_s}{b_t}\left(B_{mg} + B_{ag}\right) \tag{8}$$

Tooth and yoke magnetic resistance are:

$$R_t = \frac{2h_t H}{3b_t l_s} \tag{9}$$

$$R_y = \frac{(2b_t + 2b_s)H}{h_y l_s} \tag{10}$$

Where: h_y for yoke height. H is selected core material BH curve fit from.

In the position as shown in figure 1, making the three coil windings go through the three-phase current respectively. Each phase has difference of 120 degrees. Then the superposition magnetic flux produced by the electrical stimulation and permanent magnet stimulation is:

$$\phi_{iuv} = \frac{F_m + F_{iu} + F_{iv}}{2R_m + 2R_g + 2R_t + 2R_s + R_y} \tag{11}$$

$$\phi_{iw} = \frac{F_m + F_{iw}}{2R_m + 2R_g + R_s} \tag{12}$$

The winding of electric load referred to A is found as follows:

$$A = \frac{3NI}{2w_m} \tag{13}$$

Motor thrust referred F_1 is:

$$F_1 = \phi_{iuv1} A_{iuv} + \phi_{iw} A_{iw} \tag{14}$$

The above test is the analysis of specific location of the specific motor model based on figure 1. There will also be a similar analysis for motor thrust in other limited special position. The more calculation points are selected, the more accurate the calculation is.

III. OPTIMAL DESIGN OF MOTOR GENETIC ARITHMETIC

Genetic algorithm is a kind of random optimization method based on natural selection principle and natural genetic mechanism, which simulates the evolutionary mechanism of life in nature and then realizes the optimization of specific indicators in the artificial system. The main difference between the genetic algorithm and the traditional optimization algorithm is that genetic algorithm searches the result starting from the set of problem solution, instead of starting with a single solution. This algorithm with wide coverage is conducive to global optimization [20]. In this paper, genetic algorithm was chosen as the optimization method of motor design, specifies the optimal objective function and the specific constraints based on the motor design index, and obtains the optimization results that make thrust fluctuation of the motor smaller and permanent magnetic energy density per unit larger based on genetic algorithm.

A. *The Choice of Optimized Variables*

In the selection of variables, the choice of the variable is determined by different optimization objectives and the specific design requirements [21]. The important parameters of the PMLSM are the size of motor iron core, coil and magnetic steel, also the size of gap between the core and the magnetic steel. There are seven variables are selected as the optimization variable, the air gap, slot width, tooth width, the thickness of the permanent magnet, the height of the iron core tooth, the longitudinal width, the insulating gap between iron core and coil. The optimization variable X can be expressed as:

$$X = \left[h_g, b_s, b_t, h_m, h_t, l_s, \partial\right] \tag{15}$$

B. *constraint condition*

In the optimization design process of the motor, the premise is modeling an accurate mathematical model. By the analysis of the model, a mathematical model has been established for each constraint. Including the force model of motor and electric load model related to dissipate heat. According to the restriction of the system manufacturing size and structure technology, the basic scope of each variable as follows:

$$\left[0.8,5,5,2,10,20,0.5\right] \le X \le \left[2,12,12,5,15,30,1.5\right] \tag{16}$$

Other constraints is found as follows:

$$4w_m = 3b_t + 3b_s,\ 10 \le w_m \le 20,\ 10 \le F \le 20,\ I \le 3,$$
$$50 \le A \le 100,\ 0.65B_r \le B_{mg} \le 0.85B_r,\ B_t \le 2.2 \tag{17}$$

The flat type of synchronous linear motor has a good heat dissipation, A is between 50~100(A/mm); in the practical application of motor, because the motor in the demagnetization curve inflection point is effected by a certain margin, performance, economic and other factors. The working point of the permanent magnet is not designed for maximum magnetic point, but often in (0.65~0.85) Br. The saturation of the magnetic material A3 is 2.2T, so the constraint makes the core is not saturated.

C. Object Function

In the optimization design of the permanent magnet synchronous linear motor, the optimization target is the performance and economy of the motor. The other target is making the thrust fluctuation between the fixed position small, and the force density big. To obtain the optimum solution, there are two specific points and two maximum thrust difference points as the optimization equation. The expression of the objective function is:

$$\min f(x) = f(h_g, b_s, b_t, h_m, h_t, l_s, \partial)$$

$$= \min_{1\le i\le j\le k} \frac{\partial w_m h_m l_s}{F_i + F_j} \sqrt{\left(\frac{F_i - F_j}{F_i + F_j}\right)^2} \quad (18)$$

Simultaneous equations (15), (16), (17) and (18), they can get the optimization mathematical model of the permanent magnet synchronous linear motor.

IV. ANALYSIS OF RESULT

Based on the selection of genetic algorithm and mathematical modeling of the PMSLM, the programming uses MATLAB to optimization design of the PMSLM. The results comparison of the original motor scheme and the optimization one is as table I.

TABLE I. COMPARING THE OPTIMIZE DESIGN PARAMETERS TO THE ORIGINAL MOTOR

Design parameter	Original motor(mm)	Optimization of the motor (mm)
the thickness of the air gap	1	1
transverse length	8	10
tooth width	8	6
the thickness of permanent magnet	2	2
Tooth height	15	15
Longitudinal width	27	27
Thick of Insulation Between Conductor	1	1

Based on table I, the simulation results are obtained by using the finite element analysis software ANSYS. Conducting electromagnetic coupling analysis through the original motor parameters and the optimization ones, the thrust in the different positions of the motor can be got. The simulation result is shown in figure 3.

TABLE II. THE COMPARISON BETWEEN THE ORIGINAL VALUE AND THE OPTIMIZE VALUE OF THE MOTOR

Design parameter	Original motor values	optimize the motor values	Percent Change
Maximum thrust(N)	11.73	15.83	34.94%
Minimum thrust(N)	9.5	14.42	50.76%
Average thrust(N)	10.52	15.35	44.96%
Constant force fluctuations	9.9%	4.6%	
Force density of permanent magnetic (N/m^3)	1.2x10$^{[illegible]}$	1.7x10$^{[illegible]}$	41.66%
Force density of armature winding (N/m^3)	8.1x10$^{[illegible]}$	7.85x10$^{[illegible]}$	-3.21%

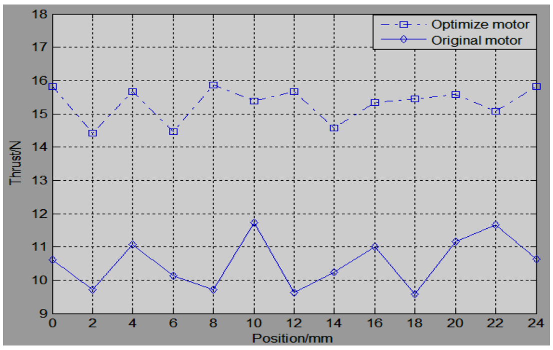

Fig. 5 Finite Element Analysis For Optimizing Motor And The Motor Thrust Waveform

For a better comparison of the motor before and after optimization, and making the permanent- magnet as an invariant when selecting the calculating parameter, the optimized motor maximum thrust is increased by 39.94% than before, minimum thrust increase 50.76%, the average thrust increase 44.96%, the maximum thrust fluctuation is reduced from 2.23N to 1.41N, the thrust fluctuation constant decreased from 9.9% to 4.6%, the thrust performance is improved significantly. The permanent magnet force density increased by 41.66%, coil power density reduced 3.21% relatively. The optimized motor is far better than before optimization one, considering the cost of design.

V. VERIFICATION EXPERIMENT

A. Motor Thrust Test Experiment

The thrust test platform of the PMSLM is built to test the motor thrust of each position in the moving process, and then the simulation results are compared with the ANSYS. To control the motor by Elmo driver, obtain the motor force of each position by force sensor, acquire the

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voltage signal by NI collection card, also with the force testing program of LabVIEW software. To acquire the motor motion period push and pull force by building a force measuring platform of software and hardware. As shown in figures 6 and 7.

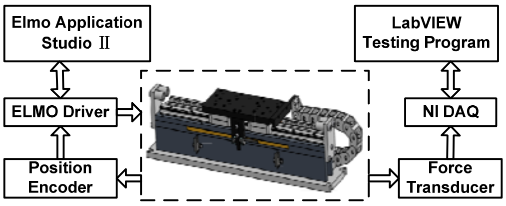

Fig. 6 The Principle Diagram of The Motor Load Platform

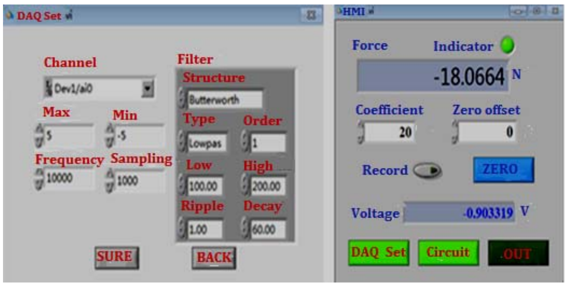

Fig. 7 NI Acquisition Card And LabVIEW Force Interface

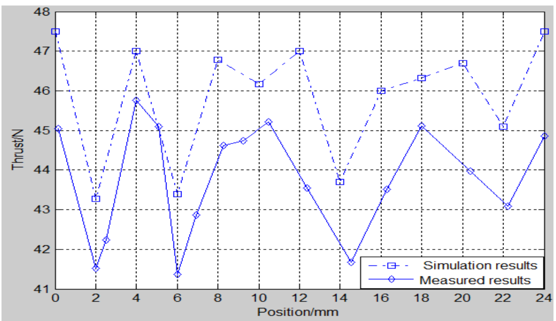

Fig. 8 Motor Thrust Fluctuation Compared With Finite Element Simulations And Experiments

Analysis form the figure 8, the measured thrust waveform of motor is similar with the simulation one by ANSYS. The measured thrust value is smaller than the simulation one. This is because the ANSYS simulation ignores some external factors, as well as the motion resistance of the prototype, and the test value is not accurate. The maximum measured thrust of motor fluctuation constant is 5.0%, basically the same as the simulation of ANSYS 4.6%. To sum up, the ANSYS simulation and experimental prototype is basically the same, the prototype meet the design requirements basically.

B. Control Experiment of The Motion

In order to test the motion characteristics of the motor, the motion control platform is built by PC, controller, ELMO driver, position encoder and DC power supply. The controller uses CX series BECKHOFF platform which is embedded in TwinCAT NC software to realize real-time two-way communication between PC and ELMO driver by EtherCAT. ELMO driver controls the linear motion of the prototype, and feedbacks the real-time position and velocity by the position encoder. After the completion of the platform, the application environment of TwinCAT System Control scans ELMO driver, and sets the motion parameters, and debugs the motion track of the prototype [22].The physical diagram of the motion control platform of the prototype is shown in Figure 9. After the debugging success of the motor, the motor selects the repeated movement patterns, and starts the TwinCAT Scope View monitoring environment by setting unified AMS NET ID. The Scope View monitors the characteristic curve real-timely during normal operation of the prototype, including the actual position, velocity, acceleration and position follow error, etc. The real-time operating characteristic curve of the prototype is shown in figure 10.

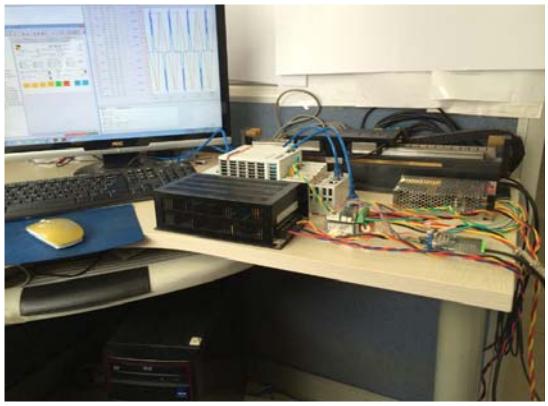

Fig. 9 The Physical Diagram of The Motion Control Platform

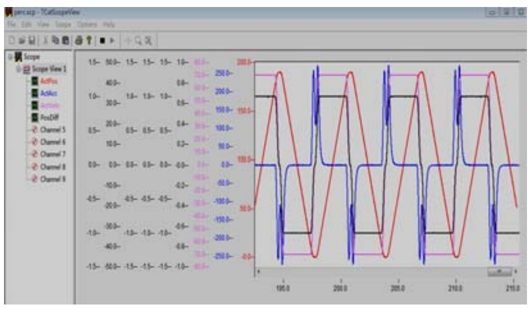

Fig. 10 Real-time Running Characteristic Cure of the Prototype

In Figure 10, the Scope View displays the position curve, the velocity curve, the acceleration curve and the following error curve in real time. By analyzing the movement characteristic and watching the movement process of the prototype, it can be started and stopped

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smoothly, and has not obvious vibration and noise during the movement. The characteristic curve is changed which occurs in the reversing point repeatedly of the prototype and has not obvious mix and latency, and can verify the robustness, validity and reliability of the motor optimization design to satisfy the movement performance of actual requirements of the new PMSLM.

VI. CONCLUSION

According to the characteristics of the moving platform, the permanent magnet synchronous motor is chosen as the linear driving source. According to the structure of the PMSLM, the mathematical model is established and the motor thrust model is deduced by selecting a specific position. Through the genetic algorithm, the thrust fluctuation and permanent magnetic energy density were selected as the optimization goal, and though the multi- objective optimization by linear and nonlinear constraints, the optimal design parameters of motor were obtained. By comparing with the motor thrust test based on LabVIEW software and the finite element simulation value of the optimized parameters, the result shows that the actual thrust of the motor is the same as that of the ANSYS finite element simulation. The motor ANSYS simulation is effective and the thrust fluctuation of the motor is improved obviously, and the robustness, effectiveness and reliability of the PMLSM optimization design are verified by the experiments based on the TwinCAT NC software. The design of the new PMSLM conforms to the actual demand of the subject because of the thrust fluctuation is small, good economy and small volume, and also provides a method of PMSLM optimization design.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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