Modelling and analysis on the mechanism of electromagnetic driven weft insertion

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Abstract. In view of the difficulty in improving the weaving efficiency of the projectile weaving machine based on the traditional technology principle, this research presents the electromagnetic-drive gripper weft insertion mechanism, change the existing mechanical pick principle of weft insertion, its goal is to achieve "zero transmission" friction-free high-speed weft insertion, omit complex mechanical transmission mechanism in picking shaft, and breakthrough the bottleneck of the weft insertion rate, wide fabric problem in principle. Based on the theoretical study of electromagnetic projection and electromagnetic levitation, the structural model and motion model of electromagnetic pick and electromagnetic weft are established by comparing the electromagnetic and permanent magnetic model schemes. In order to meet the requirement of electromagnetic levitation, the linear hall sensor is selected and its driving circuit is designed to obtain the real-time height value of the chip shuttle. Through the analysis of the coil response, the advantages and disadvantages of DC-DC regulation and PWM wave regulation are compared, and the high response hardware circuit of DC-DC regulation is designed. MATLAB simulation ensures the feasibility of PID regulation. The feasibility of the scheme was verified by Maxwell electromagnetic picking simulation and electromagnetic filling insertion simulation. The first phase of picking experiment and static filling insertion experiment were carried out. In order to ensure the stability, the double-row soft iron chip shuttle was used, and good experimental results were obtained, which proved the feasibility of electromagnetic suspension weft insertion scheme.

1. Introduction

The gripper loom is a kind of textile machinery used in the production of high-quality fabrics, it can be used in various yarn weaving, jacquard and industrial wide fabrics [1]. The shuttles are projected by store mechanical energy and torsion shaft to meet the weaving requirements of the shuttles. Due to the limitation of mechanism principle, there exits high impact force, noise, high friction energy consumption, the speed and shuttle efficiency of the machine is low. According to literature [2], the maximum mechanical efficiency is 18.3%. In order to further improve the efficiency of the shuttle loom, it is necessary to optimize its mechanism and improve its material properties.

Due to the low efficiency of the traditional mechanism, electromagnetic projection technology has made great progress in theory and engineering [3]. At the same time, in order to reduce the matter of high friction, vibration and material loss in the process of weft insertion of traditional gripper loom, the new idea of electromagnetic levitation was combined. In this paper, an electromagnetic driving insertion model combined with electromagnetic projection and electromagnetic levitation is presented. The
magnetic coil is used to project the shuttle, and the levitation process is realized by the magnetic levitation array system. This method is a new method to replace torsion shaft and guide in weft insertion process.

2. The principle of electromagnetic driven weft insertion

In the control system of the electromagnetic driver, the shuttle is driven by the speed-response coil and the suspension coil is directly driven, in which the speed-response coil is controlled by the speed-response controller and the suspension coil is controlled by the electromagnetic suspension controller.

The following figure shows the three different states of the shuttle.

2.1. The principle and structure of electromagnetic projecting

The basic principle of electromagnetic projection is that the electromagnetic force drives an electrically charged conductor or a ferromagnetic object in a magnetic field. The electromagnetic projection mechanism is mainly composed of coil and shuttle, and the shuttle body is composed of the shed skeleton and embedded soft iron. Electromagnetic emission model is composed of power supply, switch, coil and shuttle. When the projectile is in front of the coil, the electromagnetic force attracts the projectile to move toward the center of the coil and accelerates the projectile motion. The force slows the coil as it passes through the center of the coil. The continuous acceleration of the coil can be guaranteed by controlling the on-off sequence of the coil [4].

The mechanism uses the electromagnetic force of the coil to accelerate the shuttle. After the shuttle moves to the other side of the coil, the electromagnetic force slow it down reversely. After the bobbin is loaded onto the yarn, the electromagnetic force will re-accelerate the shuttle and repeat the filling process, so that the shuttle does not need to be reversed itself.

The formula derivation is shown in figure 1 as follows:

![Coil magnetic field anatomy](image)

Figure 1. Coil magnetic field anatomy.

According to electromagnetism theory [5], the magnetic flux density $B$ of the axial component generated in the coil is:

$$B = \frac{nl\mu_0}{2}(\cos\beta_1 - \cos\beta_2)$$  \hspace{1cm} (1)

In the equation: $n$ represents the number of turns per unit length; $N$ represents the total turns of the coil; $L$ represents the length of the coil; $I$ represents the coil current; $\mu_0$ represents the permeability of air; $\beta_1$ and the $\beta_2$ represent the angles between the position of the coil on the inner axis and the two ends of the coil.

The magnetic flux $\Phi$ on every turn of the coil in equation (1) is as follows [6]:

$$\Phi = BS = \frac{\pi R^2 nl\mu_0}{2}(\cos\beta_1 - \cos\beta_2)$$  \hspace{1cm} (2)

The magnetomotive force generated by the energizing coil is:

$$F_m = N_i = \Phi R_m F_m = N_i = \Phi R_m$$  \hspace{1cm} (3)
In this equation: \( R_m \) is magnetoresistance, \( R_m = l_m/(\mu A) \); \( \mu \) is the magnetic permeability of the shuttle material; \( l_m \) is the length of magnetic circuit of the shuttle; \( A \) is the cross-sectional area of the magnetic circuit. For the coil, the magnetic flux \( \Phi \) is constant, \( \Phi \) and Ni show linear relationship, the magnetic energy stored in the coil \( W_m \) as follows:

\[
W_m = \int_0^\Phi N_i d\Phi = \frac{1}{2} \Phi^2 R_m
\] (4)

Equation (4) shows that magnetic energy \( W_m \) stored in magnetic field is a function of flux \( \Phi \) and reluctance \( R_m \). \( W_m = f(\Phi, R_m) \). Based on the principle of virtual work, the force exerted on the bobbin in the coil can be derived, that is, the differential of the x direction of the moving axis in equation (5) can be obtained to get the thrust generated by the drive coil on the bobbin [7]:

\[
F_p = \frac{dW_m}{dx} = \frac{d}{dx} \left( \frac{1}{2} \Phi^2 R_m \right) = \frac{1}{2} N I \frac{d\Phi}{dx}
\] (5)

In equation (5), \( d\Phi/dx \) express the change rate of magnetic flux with displacement.

2.2. The principle of electromagnetic levitation
Since the speed of the shuttle is with high speed, it is necessary to design a new reed sitting to reduce the friction between the shuttle and the sitting. The suspension controller is a magnetic levitation device composed of closed-loop electromagnetic structure. When the shuttles are projected onto an electromagnet array system, the suspended shuttles can overcome gravity with the force of the magnetic field and remain suspended in the centre of the reed sitting.

Due to the influence of gravity, the flying shuttle will do parabolic movement, the width of the new shuttle weft is 8 meters. Without the sitting, the vertical difference in altitude during the projectile flight is about 20 mm at the speed of 30 m/s. Due to the difference in height, the new loom will carry out double weft insertion, which indicates that it needs an effective guide. The basic structure of electromagnetic levitation is shown in figure 2.

![Figure 2. Soft iron stress diagram of the shuttle.](image)

Among the picture, soft iron and iron core are ferric materials to improve magnetic permeability of magnetic circuit; The suspension height between the gripper and the coil is \( Z \); Coil current size is \( I \), coil turns number is \( N/2 \) turns per side, coil inner wall area is \( S \), field strength generated by coil is \( B \), magnetic conductivity is \( \mu \).

From the above formula:

\[
\Phi = \frac{F_m}{R_m} = \frac{NI}{2Z\frac{\mu_0 S}{\mu_{Fe} S} + l_{Fe}}
\] (6)

From Maxwell’s suction formula:

\[
F_d = \frac{B^2 S}{2\mu_0}
\] (7)
Formula:

\[ F_d = \frac{S}{2\mu_0} \times \left( \frac{NI}{\mu_0} + \frac{l_{Fe}}{\mu_{Fe}} \right)^2 \]  

(8)

In equation (13), \( F_d \) is the magnitude of the total suction; \( S \) is the effective area of magnetic circuit of magnetic pole; while, \( \mu_0 \) is magnetic conductivity in vacuum; \( N \) is coil turns; \( I \) is coil current; \( Z \) is air gap height; and \( l_{Fe} \) is the equivalent total length of coil core and soft iron in gripper.

2.3. Dynamic analysis

When the soft iron takes the gripper along flying in the suspension electromagnet array, the dynamic stress analysis is shown in figure 3 as follows:

In figure 4, when the gripper is flying from left to the right, the two red mark points on the gripper are the coil-end detecting point and the coil-start detecting point respectively. Suppose the number of driving sources to work simultaneously is \( n \), then

\[ t = 2 \times X + (n + 1) \times L + n \times D \]  

(9)

In figure 5, Let the distance between the left node in the left-most excitation source and the left marking point is \( K \), and the balance equation is:

\[ 2 \times (F1 + F2 + \cdots + Fn) = mg \]  

(10)
\[
\left(\frac{t}{2} - X - K\right) \times F_1 + \left(\frac{t}{2} - X - K - L\right) \times F_1 + \cdots + \left(\frac{t}{2} - X - K - (n - 1)D - (n - 1)L\right) \times F_n \\
+ \left(\frac{t}{2} - X - K - (n - 1)D - nL\right) \times F_n = 0
\] (11)

Due to too many parameters, we cannot be solved it by MATLAB according to equations (9), (10), (11), and we can’t get the relationship of them.

Solution: Set \( n \) (numbers of drivers working at the same time) as known quantity and consider them one by one. We need consider \( n = 2, 3, 4 \).

Reason: limited constraint conditions (there are only four equations: force balance, moment balance, initial condition, termination condition).

It can be seen from figure 6 that the required suspension force is continuous when \( n = 2 \) and \( n = 4 \), which is convenient to achieve.

We can't solve this problem because we have finite constraints when \( n > 5 \).

After analyses of the above three cases, the feasible models are \( n = 2 \) and \( n = 4 \). Considering that increasing the levitation force of the excitation source requires increasing the current, coil heating is more serious. In this sense, the solution is better when \( n = 4 \).

3. Electromagnetic simulation

Before the experiment, we need to use software simulation to predict the feasibility of the experiment. Meanwhile, in the simulation process, the best parameters can be simulated to facilitate the experimental debugging. As shown in figure 6, The experimental model consists of coil array and soft iron. and the coil is accelerated continuously by controlling the on-off of the coil sequence.

Figure 7 shows the time-speed relationship simulation diagram.

Through simulation analysis, the shuttle speed can be up to 6.5 m/s in 0.01 s.

After the projecting is completed, shuttle enters the process of levitation and insertion. At this point, the shuttle should be suspended and flying forward, and a controllable jitter can occur. The control of jitter needs to be adjusted through feedback. In the simulation process, the noise force should be as low as possible, the more stable the suspension force, the better.
Figure 8 shows the dynamic suspension model and simulation diagram.

![Figure 8](image1)

**Figure 8.** Dynamic suspension model and simulation diagram.

Figure 9. The force diagram of suspension direction and motion direction in software simulation.

As can be seen from the figure 9, the speed of the projectile changes from 1 m/s to 0.99995 m/s, which is in a continuous downward trend. It can be seen that the generation of minimal vortexes has a minimal impact on the speed of the projectile. When the gripper flies in dozens of arrays of levitating coil elements, the speed reduction is still very small. According to the simulation results, the weft insertion scheme is feasible in mechanical mechanism layout and suspension principle, and can be adjusted according to the actual application environment. Meanwhile, the feedback control of the levitation force of the coil can be used for stable and reliable adjustment of a good hardware platform.

4. Simulation of static suspension control system

As shown in figure 10, the excitation source is the excited coil, the control object is the suspended object (soft iron), and the hall sensor is located at the bottom.

![Figure 10](image2)

**Figure 10.** Suspension structure diagram.

Set the lower end of the coil as zero, the initial distance as 50 mm, and the target suspension height as 40 mm (10 mm higher than the initial point).

\[
F = K_1 \times \frac{I}{X^3} - mg
\]  

\[
\alpha = \frac{F}{m}
\]  

\[
v_x = \int \alpha_x \, dt
\]  

\[
x = \int v_x \, dt
\]

In the above formula, \(F\) is the total force exerted on the suspension, \(I\) is the exciting current, and \(X\) is the distance. \(K_1\) is the parameter that determines the relation between suspension force and \(I\) and \(x\), and...
Mg is gravity. The driving equation of \( I \) be:

\[
I = -K2 \times (X - Xt) - K3 \times v_x - K4 \times a_x \tag{16}
\]

Let the initial conditions be \( x0=50 \) mm, \( M=0.0125 \), and omit the \( K1 \) parameter (\( K2, K3 \) and \( K4 \) are also parameters). The expected convergence is \( x0=40 \) mm. MATLAB ode45 function to solve.

In figure 11, \( K2, K3 \) and \( K4 \) are respectively the parameters of displacement (\( X \)), velocity (\( Vx \)) and acceleration (\( a_x \)). Because you can't get the instantaneous \( Vx \) and \( a_x \) directly. It can only be inferred from position \( X \) and time. Firstly, the relationship between the magnetic field intensity and the height of the projectile is measured experimentally.

5. Experiment and result analysis

After the software simulation proves that the scheme is feasible, we start the experiment of electromagnetic projection and magnetic levitation. In the process of projection, velocity sensor is used to detect the velocity of the shuttle in real time, and dry battery and large capacitance are used as generating device of the magnetic field in figure 12. Experiments were carried out for different initial positions and different voltages. It can be seen that the experimental results are similar to the simulation results.

In the suspension stage, the real-time magnetic field is monitored through Hall sensor under the shuttle and the coil current is adjusted according to the control requirements. In order to improve response speed, the high speed operational amplifier module is used. Single chip microcomputer is used for voltage regulation responding to a four-way hall sensor, the experimental process is shown in figure 13.
14.

**Figure 13.** Speed comparison diagram with same voltage and Speed comparison diagram with same voltage position.

**Figure 14.** Static suspension experiment diagram.

With the parameters above, as we can see in figure 15, the response time reached 0.1 s, the experimental results show that the shuttle is vibrating up and down (in contact with the sensor and coil).

As we can see in figure 16, by changing the driving mode and subdivision degree, shuttle jitter is reduced by 10 times, which basically meets the experimental requirements. In order to further ensure the stability of the experiment, the high-subdivision, low-deviation DC-DC Analogy adjust circuit needs to be studied. The sensor with high performance and low power consumption is selected at the same time.

**Figure 15.** PWM driver response diagram.

**Figure 16.** DC driver response diagram.

6. **Conclusion**

This paper introduces a new electromagnetic-driven dual-directional weft insertion loom, electromagnetic transmitting mechanism and magnetic levitation system, after analyzes their working principle, makes a detailed comparison with the original gripper loom. The analysis results show that
the structure of the new type of loom simplifies the structure of the loom, it can significantly improve
the rate of weft insertion, and reduces the impact and vibration during the process of weft insertion with
high speed. We use the built-in A/D module of stm32F4 to collect the magnetic field data of hall sensor
HW101, and use the high-speed D/A module TLV5618 as the control unit of the coil output voltage.
With a quick response and feedback, levitation becomes possible. this paper provides a basis for further
research.

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References
[1] Chen M 1981 Torsion bar weft insertion mechanism Journal of East China Institute of Textile
Technology 4 48-55
[2] Xu H Y 2003 Technical progress of projectile loom Beijing Textile Journal 4 43-6
[3] Duan J R 2013 Analysis of weft yarn velocity on the projectile weaving machine Journal of Xi’
an Polytechnic University 6 711-8
[4] Zhang H, Kou B Q, Jin Y X et al 2016 A cylindrical magnetic levitation gravity compensator
with Halbach secondary structure Transactions of Chinese Electrotechnical Society 6 30-7
[5] Liu Z W, Chen X M, Dong J et al 2015 The optimization of multistage electromagnetic launching
system of mini-SHB Journal of Experimental Mechanics 1 9-16
[6] Yan J C Electromagnetism (Hefei: Press of University of Science and Technology of China, 1997)
[7] Wang J, Wu H et al 2016 Performance analysis and optimization of high speed switch valve based
on PWM control mode Journal of Hefei University of Technology (Natural Science)(JHUT) 9
32-5