IOP Conf. Series: Materials Science and Engineering **372** (2018) 012036 doi:10.1088/1757-899X/372/1/012036

Study on magnetic force of electromagnetic levitation circular knitting machine

X G Wu[1,2], C Zhang[1], X S Xu[1], J G Zhang[1], N Yan[1] and G Z Zhang[1]

[1]School of mechanical engineering and automation, Wuhan Textile University, Wuhan, Hubei 430073, China

E-mail: 2006wist@163.com

Abstract. The structure of the driving coil and the electromagnetic force of the test prototype of electromagnetic-levitation (EL) circular knitting machine are studied. In this paper, the driving coil's structure and working principle of the EL circular knitting machine are firstly introduced, then the mathematical modelling analysis of the driving electromagnetic force is carried out, and through the *Ansoft Maxwell* finite element simulation software the coil's magnetic induction intensity and the needle's electromagnetic force is simulated, finally an experimental platform is built to measure the coil's magnetic induction intensity and the needle's electromagnetic force. The results show that the theoretical analysis, the simulation analysis and the results of the test are very close, which proves the correctness of the proposed model.

1. Introduction

With the successful application of EL technology in train, more and more areas are exploring how to introduce the high-tech, maglev knitting technology is one of them [1], the so-called maglev knitting technology using electromagnetic force to drive the needle up and down movement to replace the traditional mechanical connecting rod drive. The driving mechanism of the EL circular knitting machine adopts hybrid drive (EPMH) mode of electromagnetic and permanent-magnet (PM), the electromagnetic field excited by the driving coil, PM and needles are fixedly connected together. In the working process, the control card gives the driving coil electricity in a certain phase sequence, thus the drive coil produces a certain sequence of magnetic field, so the PM and the needle can do regular movement to knit in the magnetic field. By using the electromagnetic drive technology, the EL circular knitting machine can eliminate the middle part of the complex mechanical transmission and realize zero transmission of the needle selecting process compared with the traditional circular knitting machine's drive mechanism of the mechanical triangle cam (A triangular shaped cam that drives the needle motion in a certain phase sequence), the direct drive mode will not produce rigid impact and shortcomings the friction and wear, energy loss and noise, which greatly improves the knitting efficiency of circular machine.

2. Knitting part and working principle

As shown in figure 1, the knitting part of the EL circular knitting machine includes needle, drive coil, sinker, cam, gear, a base and a support member, which are arranged on the corresponding position of the base. In the process of work, the coils drive the needle up and down when the coils are energized, at the same time, the gear drives cam rotation, the rotation of the cam push sinker to do reciprocating

IOP Conf. Series: Materials Science and Engineering **372** (2018) 012036 doi:10.1088/1757-899X/372/1/012036

motion of front and back (the sinker is installed in the groove of the fixed disc and forms a cam with the cam, so when the cam rotates, the sinker is driven to reciprocate) , the combination of the two movements completes the knitting process.

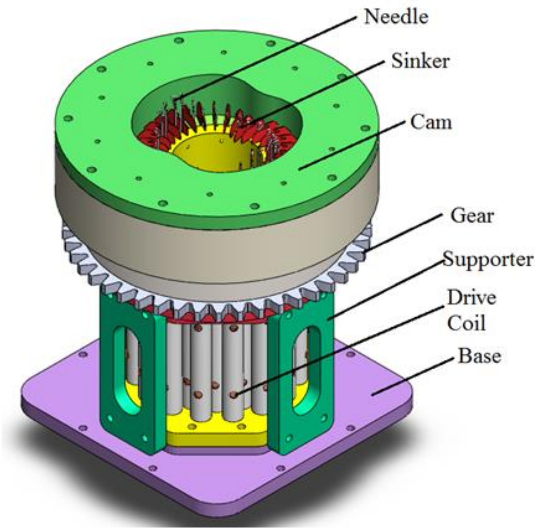

Figure 1. Knitting part of Magnetic levitation knitting circular

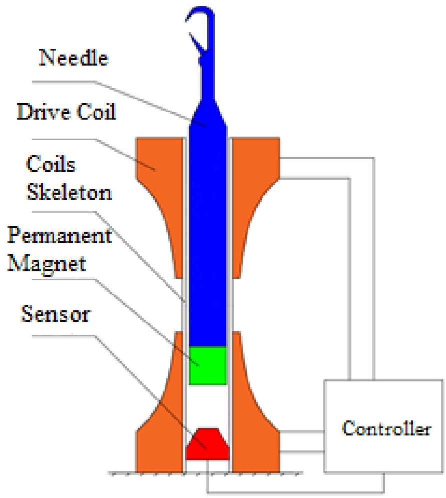

Figure 2. Working principle of Magnetic levitation knitting

Magnetic drive knitting device core component comprises drive coil, PM, coil frame, needle, sensor and controller, the principle of its specific structure is shown in figure 2. From figure 2 we know that as long as the fixed drive electromagnetic coil is electrified, a certain direction of magnetic field will be produced in the vertical direction of the centre, the magnetic field will produce an interaction with the PM magnetic field, thus PM and the needle will be driven up and down. This is an open loop system, which can’t control the time and size of the electricity, so adding a sensor and controller to form a closed loop system, the displacement sensor to detect changes in needle, needle position feedback to the controller, the controller will change the size and direction of the coil current, the size and direction of the coil current will directly reflect the change of the magnetic force and the direction of the magnetic force, the change of the magnetic force of the PM will change the direction of up and down movement of the needle and speed, therefore, precise weaving action will be completed through. the needle reciprocating motion.

3. Theoretical model of electromagnetic force

3.1. PM magnetic field

As shown in figure 2, the force of the conducting wire is equal to the one of the PM in the opposite direction when the PM moves during the knitting process in EPMH mode (Newton’s 3rd law) and the force will be equal to the force of the PM in the opposite direction, therefore, in the process of calculating the magnetic force, the force of the conducting wire in the magnetic field can be obtained by the theory of ampere force, so that the form and size of the force during the movement of the PM can be obtained. According to the *Ampere* molecular circulation hypothesis: the smallest unit that makes up a magnet is a ring current, and if these molecules are oriented in a circular arrangement, they will show N and S poles macroscopically [2].

Expanding a single energized ring into space can create a PM field mathematical model. Let a cylindrical PM radius a, high h, magnet bottom surface centre of the circle as the origin of coordinates, the bottom surface of the *xoy* plane, z-axis positive direction for the magnetization, the establishment of geometric model shown in figure 3.

If the magnet material and magnetization direction unchanged, and saturation magnetization, the magnetization density Js can be regarded as a constant. Calculate the magnetic field strength of any point $P(r\,cos(\theta), r\,sin(\theta), z - z_0)$ in the space, where r and θ are the polar coordinates of the point Q of P on the xoy plane. Select the arbitrary thickness of the PM dz_0 thin layer circulation, the *z-axis* axial height of z_0. While a and α are the polar coordinates of the current element ***dl*** in the plane of dz_0, and $\boldsymbol{R}$ is the radius vector of the current element ***dl*** to the point P.

According to the superposition characteristics of the magnetic field, the total magnetic field strength at any point P in the space of the PM can be given by the following equation (1).

$$\boldsymbol{B} = \int_0^h d\boldsymbol{B} = \frac{\mu_0 J_s a}{4\pi}\int_0^h \oint \frac{dl \times \boldsymbol{R}}{R^3} = \frac{\mu_0 J_s a}{4\pi}\int_0^h \int_0^{2\pi} \frac{\begin{vmatrix} i & j & k \\ -\mathrm{asin}(\alpha) & \mathrm{acos}(\alpha) & 0 \\ rcos(\theta) - \mathrm{acos}(\alpha) & rsin(\theta) - \mathrm{asin}(\alpha) & z - z_0 \end{vmatrix}}{R^3} ddz_0 \quad (1)$$

$R = AP - a = (rcos(\theta) - acos(\alpha), rsin(\theta) - asin(\alpha), z - z_0)$ in the equation (1), μ_0, the vacuum permeability.

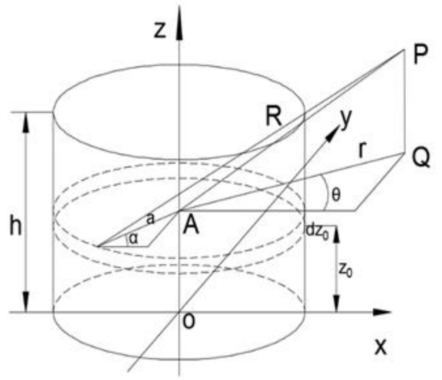

Figure 3. Magnetic field model of cylindrical PM

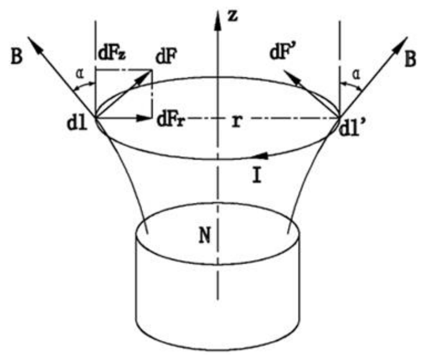

Figure 4. Force model of single electric coil

3.2. Electromagnetic force model

A single coil energized wire in the magnetic field force model as shown in figure 4 above. From the *Ampere* formula, the electric current ***Idl*** receives the electromagnetic force is the following equation (2).

$$d\boldsymbol{F} = Id\boldsymbol{l} \times \boldsymbol{B} \quad (2)$$

Assuming the current direction of the coil is as shown in the figure, the direction of any point in the coil can be judged by the left-hand rule. The decomposition force F is along the z-axis direction F_z and along the coil radial direction F_r, As the strength of the magnetic field at the concentric ring is equal in magnitude and different in direction, so the F_z is equal in size and direction, the F_r points the same point to the centre of the circle and its size is equal. Further analysis shows that F_z is provided by B_x and B_y, and F_r is provided by B_z. Axial force only needs to be known during needle movement. therefore, it is only necessary to study the effect of B_x and B_y on the conducting wire.

The electromagnetic force of the single coil current element obtained by substituting the equation (1) into the equation (2), which is represented by the following equation (3).

$$d\boldsymbol{F} = \frac{\mu_0 J_s a}{4\pi} Id\boldsymbol{l} \int_0^h \int_0^{2\pi} \frac{\begin{vmatrix} i & j & k \\ -\mathrm{asin}(\alpha) & \mathrm{acos}(\alpha) & 0 \\ rcos(\theta)-\mathrm{acos}(\alpha) & rsin(\theta)-\mathrm{asin}(\alpha) & z-z_0 \end{vmatrix}}{R^3} d\alpha dz_0 \quad (3)$$

$dl = (-rsin(\theta), rcos(\theta), 0)d\theta$ in the equation (3), substitute it into equation (3) and integrate $d\theta$ to obtain the electromagnetic force on the whole single coil, which is represented by the following equation (4).

$$\boldsymbol{F} = \frac{\mu_0 J_s a I}{4\pi} \int_0^{2\pi} \int_0^h \int_0^{2\pi} \frac{D}{R^3} d\alpha dz_0 d\theta \quad (4)$$

Which D is as follows equation (5).

$$D = \begin{vmatrix} i & j & k \\ -rsin(\theta) & rcos(\theta) & 0 \\ \mathrm{acos}(\alpha)(z-z_0) & \mathrm{asin}(\alpha)(z-z_0) & a^2 - ar(\sin(\theta)\sin(\alpha) + \cos(\theta)\cos(\alpha)) \end{vmatrix} \quad (5)$$

As mentioned earlier, there is only need to calculate the axial force for the PM, so the z axial force F_{sz} is shown in the following equation (6).

$$F_{sz} = -\frac{\mu_0 J_s a I}{4\pi} \int_0^{2\pi} \int_0^h \int_0^{2\pi} \frac{ar(\cos(\theta)\cos(\alpha) + \sin(\theta)\sin(\alpha))}{R^3} d\alpha dz_0 d\theta \quad (6)$$

This is a single-coil force model in the magnetic field, for any multi-turn coil, the force can be calculated by the force can be superimposed features. Assume that the inner diameter of the coil is r, the outer diameter is $f(z)$ and $f(z)$ is the function of the outer diameter with respect to the z axis, the coordinates of the coil in the axial direction are z_1 and z_2. Also consider the existence of gaps between the coils, the axial density ρ_z and radial density ρ_r is Introduced. In turn, the axial force and the radial force of the single coil are integrated. Finally, the total force of the coil in the z axis of any shape can be expressed as the following equation (7).

$$F_z = \rho_z \rho_r \int_r^{f(z)} \int_{z_1}^{z_2} F_{sz}\, dzdr \quad (7)$$

If any certain force F_z is given, the shape of the corresponding coil can be calculated.

4. Simulation and measurement of magnetic field and electromagnetic force

4.1. Simulation of magnetic field and electromagnetic force

According to the previous experimental study [3], knitting, the needle can smoothly hook yarn to provide conditions for the electromagnetic force is about 85mN in the process of weaving needle, the presupposition condition into equation (7) obtained a curved coil as shown in figure 5. In order to increase the needle stroke, the coil bipolar symmetrical layout, the opposite direction, through 12 V DC. Through the *Ansoft Maxwell* magnetic field finite element simulation software, the magnetic induction intensity simulation cloud chart under the actual working condition is shown in figure 6.

At the same time, the electromagnetic force of the PM and the needle during the movement is simulated, the simulation model is shown in figure 7, where *Region* is the boundary solution area and *Band* is the movement area. The electromagnetic force simulation curve of the PM during the movement is as shown in figure 8.

4.2. Measurement of magnetic field and electromagnetic force

Under the same power-on condition, the magnetic field induction strength of the drive coil and the magnetic force of the needle in the working stroke were measured with a Gauss meter and a dynamometer, respectively. The measurement interval is 1 mm, and the magnetic field strength curve and the magnetic force curve in the working stroke are shown in figures 9 and 10 respectively.

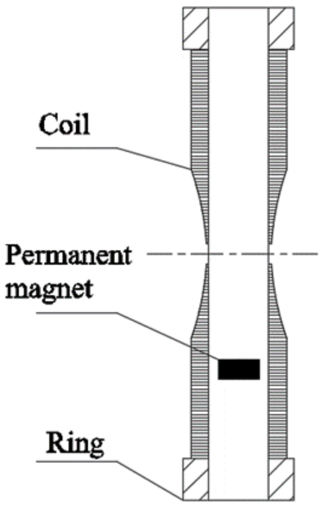

Figure 5. Coil structure model

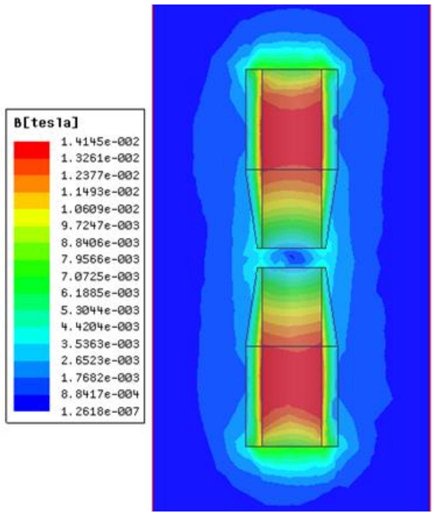

Figure 6. Simulation of magnetic field strength of coil

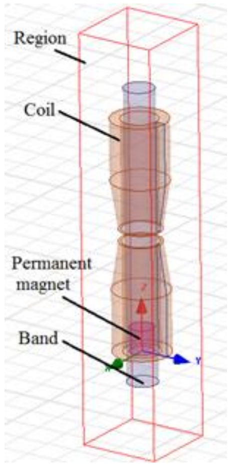

Figure 7. Magnetic force simulation model

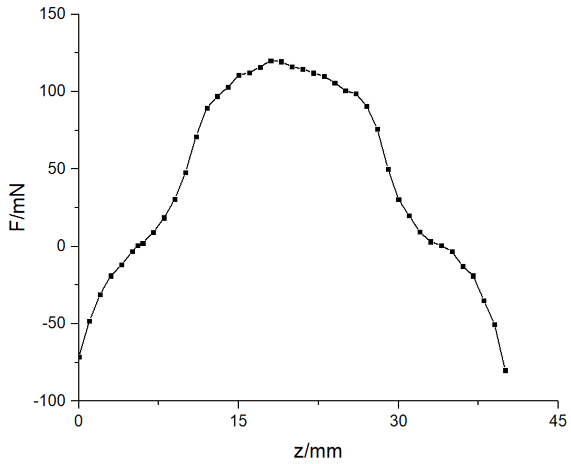

Figure 8. Simulation magnetic force diagram

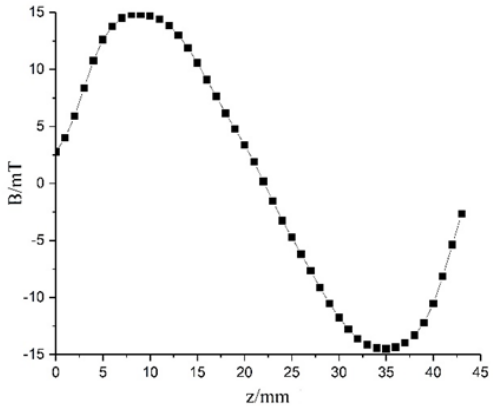

Figure 9. Magnetic induction intensity of measurement

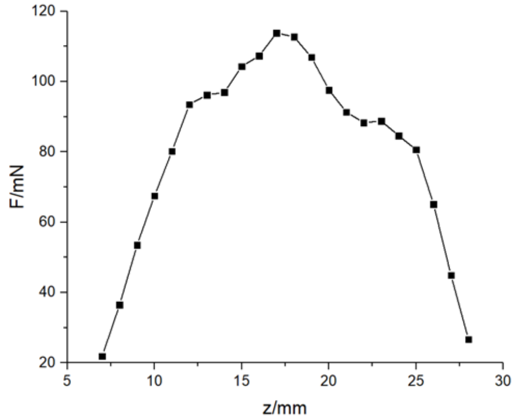

Figure 10. Magnetic force of measurement

Comparing figures 9 and 6, the simulation results of the magnetic induction intensity of the bipolar symmetric driving coil are in good agreement with the measured results, the magnetic fields of the two coils arranged symmetrically in the up and down direction are opposite and mainly concentrate in the middle of the coil with an average of 14 mT. Comparing figure 10 with figure 8, we can see that the electromagnetic force simulation result and the measurement result are similar, and the electromagnetic force is stable within the working stroke (position from 10 mm to 25 mm), about 95 mN, which meets the driving requirement.

5. Summary

This paper introduces a direct-drive circular knitting machine based on electromagnetic drive. Based on the basic law of electromagnetic field, a theoretical model of electromagnetic force is established and a kind of curved coil is determined. *Ansoft Maxwell* software was used to simulate the magnetic field and magnetic force of the established coil, the magnetic field and magnetic force were also measured. The results show that the simulation results of the magnetic field and magnetic force of the coil are in good agreement with the measured results, which can meet the demand of stable and accurate drive motion for knitting.

Acknowledgments

This research is a Textile Industry Federation guidance project and was financially supported by the National Science Foundation of China (51175384) and the Key Laboratory of Digital Textile Equipment Foundation of Hubei Province (DTL2017003 and DTL2017002).

References

[1] Wan D Y, Wu X G and Zhang C 2017 Study on needle electromagnetic force and coil profile optimization of magnetic suspension drive *J. Knitting industry* **8** 9-12
[2] Zhao K H and Chen X M 2003 *Electromagnetics* (Beijing: Higher Education Press) pp 85-137
[3] Wu X G, Zhang C and Yuan B 2017 Research on magnetic force coupling and magnetic force coupling of magnetic suspension driven needles *J. Knitting industry* **1** 13-7