Electromagnetic and FEM analysis of a novel electric driving knitting needle of moving coil stack PMLM schema

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Abstract. A novel electric driving knitting needle of moving coil PMLM schema is put forward in this paper. Magnet elements are arranged in a matrix form and 3-phase coil windings are epoxy packaged as the knitting needles that reciprocating along the air gaps inside the magnet matrix. Both the static magnetic flux density in air gaps and the unbalanced magnetic force on each magnet element are put forward in analytical formula. 2D and 3D FEM analysis have been carried out both in static magnetic field analysis and transient electromagnetic field analysis. It’s verified that both the structure rigidity and the motion performance are safe, and the performance of approximately 7 N peak hauling force and 20 mm movement at 20 Hz are able to be fulfilled. Future research will be reported and focused on the prototyping and the driving circuit & control strategy.

1. Introduction
Knitting is the process that bending threads into loops and connecting the loops to form a fabric. Needle action is repeatedly driven by a cam box as it moves along certain trajectory at two or three needle stationary positions where it actively holds a stitch, and a new loop is pulled through the existing loop. Such mechanism has been working as the heart of any knitting machine for several centuries. However, as the versatile requirements arise nowadays, it is expected that pictures could be weaved into fabrics, and random size and random colours could be used. Knitting needle selector had been invented to fulfill this objective, see figure 1, however, the knitting needles are still driven by traditional cam mechanism with extra electromagnetic or piezoelectric accessories. As a result, the complexity of needle selection and motion control is quite challenging, moreover, both the needle and the cam box lifetime are limited and should be evaluated in only few months [1]. This paper puts forward a novel electric driving knitting needle schema instead of the cam driving mechanism [2]. Each needle is going to be designed as an ultra-thin linear motor by less than 1 or 2 mm in thickness, and the knitting action is expected to be approximately 20Hz by about 20mm reciprocating motion with about 10 N peak force output so that thread or yarn could be hauled out from feeder.

However, such specifications are extremely strict in linear motor design and the most difficult problems mainly concern about two issues: (1) the structure stability due to the ultra-thin thickness, (2) the motion performance that decides the knitting efficiency. Schemas such as LSRM (Linear switched reluctance motor) [3][4], piezoelectric ultrasonic linear motor [5], thick film magnet small motors [6], horizontal vibrating linear motor (HVLM) [7]etc. may be able to satisfy the thickness constrain, but none of them is able to output big force and maintain a stacked motor array structure at the same time according to knitting machine requirements.
2. Electric Knitting Needle Design by Ultra-thin Thickness Linear Motor Schema

2.1. Knitting needle design constrains analysis

For any reciprocating movement, there exists the kinematic constrain that limits the reciprocating movement frequency:

\[ f = \frac{\pi}{2} \cdot \sqrt{\frac{A}{A_{\text{max}}}} \cdot \sqrt{\frac{\pi^2}{8}} \cdot \frac{A}{A_{\text{max}}} \]

where \( f \) represents reciprocating frequency, \( A \) is the movement range, \( A_{\text{max}} \) is the full stroke of the needle, and \( f_{\text{max}} \) is the maximum frequency allowed. Because the knitting machine productivity mainly depends on needle motion frequency \( f \) (about 20Hz) and motion amplitude \( A \) (about ±10 mm), any linear motor that drives knitting needle should be able to accelerate at minimum peak value 158 m/s^2.

The thickness of knitting needles usually ranges from E12–E32, which means 12 or 32 needles per inch or about 2 mm to 0.7 mm thick per needle. Moreover, each needle should be able to move independently so that the property of every thread looping could be respectively specified.

With respect to basic electromagnetic laws, the performance of linear motor mainly relies on the magnetic field. The stronger the magnetic field, the greater the thrust force and the better the motion performance. It’s obvious that PMLM (permanent magnet linear motor) is the first choice for such kind of application, at the meantime, the structure rigidity and applicability should be carefully verified at the very beginning.

Topologically, two PMLM schemas should be considered regarding above constrains, which are the moving coil slider PMLM and the moving magnet slider PMLM. Since the penetration of strong magnetic field is too much powerful, only the moving coil slider PMLM is applicable in electronic driving knitting needle design so that adjacent knitting slider would not be affected and each needle movement could be controlled independently.

2.2. Static magnetic field distribution of studied PMLM stack model

The stack PMLM model of moving coil with 2D permanent magnet matrix is employed, as shown in figure 2.
Static magnetic field distribution could be illustrated by Poisson equation \[^{[8]}\]:

\[
\frac{\partial^2 A_M}{\partial x^2} + \frac{\partial^2 A_M}{\partial y^2} = -\mu_0 \frac{\partial M(x, y)}{\partial x}, \quad m\delta \leq y < m\delta + h_m
\]

\[
\frac{\partial^2 A_M}{\partial x^2} + \frac{\partial^2 A_M}{\partial y^2} = 0, \quad m\delta + h_m \leq y < (m+1)\delta
\]

The magnetic field in the air area is \[^{[8]}\]

\[
B_A\bigg|_{s=\tau} = \sum_{k=1}^{K} \left[ \sum_{j=1}^{n} \sinh \left\{ m_k \left[ y - (n+j)\delta + \frac{\delta - 3h_m}{2} \right] \right\} \right]
+ \sum_{j=n+1}^{n} \sinh \left\{ m_k \left[ y - (n+j)\delta + \frac{\delta + h_m}{2} \right] \right\} + \sum_{j=1}^{n} \sinh \left\{ m_k \left[ y - (n-j)\delta - \frac{\delta + h_m}{2} \right] \right\}
+ \sinh \left\{ m_k \left[ y + \frac{\delta - h_m}{2} \right] \right\} \cdot \cos \left( m_k x \right)
\]

\[
B_A\bigg|_{s=\tau} = \sum_{k=1}^{K} \left[ \sum_{j=1}^{n} \cosh \left\{ m_k \left[ y - (n+j)\delta + \frac{\delta - 3h_m}{2} \right] \right\} \right]
+ \sum_{j=n+1}^{n} \cosh \left\{ m_k \left[ y - (n+j)\delta + \frac{\delta + h_m}{2} \right] \right\} + \sum_{j=1}^{n} \cosh \left\{ m_k \left[ y - (n-j)\delta - \frac{\delta + h_m}{2} \right] \right\}
+ \cosh \left\{ m_k \left[ y + \frac{\delta - h_m}{2} \right] \right\} \cdot \sin \left( m_k x \right)
\]

, where \( m_k = \frac{k\pi}{\tau}, M_{nk} = \frac{4M_0}{\pi} \sin \left( \frac{k\pi}{2} \right) \sin \left( \frac{m_k \tau \delta}{2} \right) \), and \( K = \frac{\mu_0 M_{nk} \sin \left( m_k \frac{h_m}{\delta} \right)}{\sin \left( m_k \left( n\delta + h_m \right) \right)} \).

### 2.3. Structure rigidity of magnet matrix

Magnets inside the stack model are subjected to unbalanced attracting forces on both sides because the magnetic field is not uniform distributed according to formula (2). According to Maxwell force on the interface between air and magnet \( F = \frac{1}{2} \frac{B^2}{\mu_0} S \) (\( S \) is the area of surface), the magnetic pressure applied on every magnet along the \( m \)-th column is:

\[
f_m = \frac{F_m}{dS} = \frac{1}{2\mu_0} \left[ (B_A|_{y=m-(m-1)\delta})^2 - (B_A|_{y=m-(m-1)\delta+h_m})^2 \right]
\]

The magnetic pressure distribution is symmetric to the central plane of magnet matrix, and the more the magnet offsets from the matrix symmetric plane, the greater the magnetic pressure would be. There’s no deflection in the central magnets in symmetric plane. A test prototype matrix has been made in the past, as shown in figure 3. Unfortunately, because the magnet length is chosen to be too large, deflection is obvious along the columns adjacent to the yokes and it’s difficult to arrange thousands of sliders in a standard knitting needle style. It means that the magnet matrix geometry optimization and another prototype should be made to satisfy desired performance.
Figure 3 Magnet deflection in outer column by magnet L=90 mm,  $h_m=1$ mm,  $m_\tau=10$ mm

Besides, extreme thin thickness (usually no more than 1 mm) further weakens the rigidity of each magnet element because overall thickness of every knitting needle is restricted as small as lower than 2 mm. Unexpected vibration is sure to happen on magnets when sliders move back and forth in high frequency. The unbalance force should be depressed as much as possible and the magnet rigidity should be ensured.

Each magnet is fixed at both end, see figure 3, as a result the largest deflection locates in the middle of magnet length as $f_m L^4 \over Eh_m 32$, where $f_m$ is the unbalanced magnetic pressure on its surface.

The largest deflections always happen along the outer columns in magnet matrix.

It’s obvious that the little the L, the better the rigidity. On the contrary, the little the L, the less the Lorenze force output could be obtained. To achieve a reasonable knitting force, appropriate PMLM topological parameter should be considered including magnet geometry, coil number and geometry, winding phase and control, etc.

2.4. Stack PMLM model

There’s an implied constrain in PMLM model that the slider should be able to pause or retract to the opposite direction at any desired position by reasonable precision of about 1 mm without any extra movement sensors, such as optical linear encoder, etc., because each slider is supposed to be controlled independently and ordinary encoder usually has a huge encoder reader even for only one slider. Since the number of needle is in thousands, and the cost of linear encoder would be unacceptable, the only possible PMLM model is to employ the hall-switch brushless controlled sliding coil winding schema, which agrees with conventional brushless DC motor (BLDC). The position test resolution is about one sixth of the magnet pitch in such configuration. By double the number of hall sensors, position resolution could be doubled too. In this way, the novel electric driving knitting needle model has been prototype modelled by 12 rows and 13 columns of magnet matrix with 12 sliders, wherein each magnet is $h_m=1$ mm,  $m_\tau=10$ mm,  $L=25$ mm; $\delta$ is 2.2 mm, and  $\tau$ is 12 mm.

The geometry of sliding coil stack PMLM model is illustrated in figure 4. Theoretic position resolution is supposed to be 1 mm by properly arranged six hall sensors. PMLM motion control would be in an open loop and hall sensors work as three-phase winding switchers as well as position marks.

Figure 4 Stack PMLM model

Six coils and six hall sensors are packaged by epoxy resin into a moving slider beneath 1 mm in thickness. Hall sensors are in SOT23 package and grinded to 0.9~1 mm thick. Each coil is wounded to 450 turns by 0.1 mm electromagnetic wire. Six coils compose a three phase winding set by 120 mm along motion direction that exactly match 10 pitches of magnet period in length. Overall mass of each slider is no more than 13 gram.
Two magnet matrix holders maintain the geometric topology of the magnet matrix. Guiding rails are slotted between adjacent two columns of magnets, and carefully designed slider shoulders slide inside the rails to maintain exact linear reciprocating motion.

Ferro yoke is made of 20# steel. Together with two matrix holders in both flanks, two yokes make up a closed loop magnetic circuit of the magnet matrix as well as a mechanical rigid framework.

3. FEM analysis and verification

The objective of FEM analysis is to verify the applicability of studied stack PMLM schema with the help of electromagnetic FEM software ‘Maxwell 2016’, both in structure rigidity and in electromagnetic driving & motion performance. Magnet material is N35H whose Br is about 1.2 T. Peak driving current is specified to 250mA due to the 0.1 mm diameter wire limitation. Each PMLM slider is driven by three phase rectangular wave according to conventional BLDC control mode.

3.1. Static magnetic field analysis

2D static magnetic field FEM has been carried out for the purpose of an ideal rectangular magnetic field distribution which is supposed to be strong enough and takes a rectangular wave shape. It’s necessary that every slider inside the magnet matrix works in the same magnetic field so that every slider demonstrates the same performance. What’s more, the magnitude of magnetic field should be as large as possible in order to reduce the current and the harmful thermal effect. They are the fundamental criteria for future electric knitting machine implementation because there’re thousands of needles stacked in a compact volume in knitting machines. Otherwise, every electric needle has to have an independent controller, and it’s impossible to implement such a great number of different configured PMLM controllers in only one machine.

![Figure 5](image)

Figure 5 Magnetic distributions by 2D static FEM and Maximum unbalanced force by 3D static FEM

In figure 5, every flux streamline is parallel to each other when horizontally passes through the magnet elements. From the viewpoint of conventional PMLM schema, twelve columns of air gap penetrate the six runway shape closed-loop magnetic fields, and all the straight segments of the flux lines display the same green colour and represent a uniform or equivalent magnetic flux density.

![Figure 6](image)

Figure 6 Magnetic wave shapes along motion direction and horizontal cross-section direction

Figure 6 displays the magnetic flux density in both directions. It’s obvious that a double sided rectangular magnetic wave has been achieved along motion direction, which agrees with conventional PMLM air gap magnetic field distribution very well. The magnitude of the magnetic flux density is about 0.53 T. The magnet flux density takes a valley shape along the magnet thickness direction and the minimum is right in the middle, although the difference between maximum and minimum is less than 2%. Such a small difference makes no difference in driving force, but it would apply a deflection
force on magnet according to formula (3). For better precision, 3D static magnetic field analysis has been carried out for further verification, shown in figure 5. The same configuration has been adopted in 3D analysis as that used in 2D analysis, and the greatest force appears along the outer most columns of magnets, which is about 0.34 N for studied magnetic elements. This force is small enough to be neglected and would not affect the matrix structure rigidity. The stacked magnet matrix would be strong enough to sustain such a small unbalance forces.

3.2. Transient magnetic field analysis
3D transient magnetic field analysis has been carried out for the purpose of driving force verification. By shrinking the mesh grid from the maximum of 10 mm to the minimum of 1 mm, FEM result would converge and the driving force of slider with respect to its movement position is shown in figure 7.

BLDC rectangular driving current wave has been employed and the peak current is 250mA. Only 3D transient FEM is considered because the 2D transient analysis assumes the geometry to be unique in depth in Maxwell2016 software. But in the studied schema, the geometry of each coil is a pad or round shape, and the end effect should not be neglected.

The hauling force is approximate 7 N in average and it varies little in 3D FEM transient analysis. The variation mainly originates from concentrated winding and magnet field end effects. What’s more, because the slider mass is no more than 13 gram, the maximum acceleration would be 538m/s², which would achieve about 35 Hz reciprocating movement. Considering better magnet material and greater driving current could be used in future prototype research, it’s applicable to adopt such a PMLM stack model in novel electric driving knitting needle design.

![Figure 7 Hauling force by 3D transient magnetic field FEM analysis](image)

4. Conclusion
The novel stack PMLM model is applicable to output about 7 N hauling forces and its magnet matrix is rigid enough in structure. Expected 20 Hz and 20 mm reciprocating movement could be achieved by studied moving coil stack PMLM schema. Future work would be reported concerning the prototype and control circuit development in the near future.

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