Research on the Thrust Characteristics and Temperature Rise of Slot-less Tubular Linear Motor for Active Vehicle Suspension

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Abstract
This paper presents a Slot-less Tubular Permanent Magnet Linear Motor (ST-PMLM), which does not have the cogging structure in the stator. Meanwhile, its lateral stator core doesn’t split, so the motor only has longitudinal edge effect. Since the ST-PMLM is supposed to be used as the active damper for vehicle suspension system, this paper focus on two aspects: increasing the output thrust and restraining the thrust fluctuation of the motor. Firstly, the equivalent magnetic circuit model of the ST-PMLM is established. The influences of structural parameters, including the thickness of the magnetic pole, the length of the air gap, the thickness of primary iron core and the thickness of primary winding, on the air gap flux density and the output thrust are analyzed. Then, the distribution of the magnetic field at the end of the primary iron core is observed. Length compensation in the end of primary iron core is adopted in order to reduce the thrust fluctuation. Finally, the prototype of ST-PMLM is developed and the experiment test bench is built. Based on the no-load test of the prototype, the effectiveness of the primary core length compensation in suppressing end effects and inhibiting fluctuations are verified.

Keywords: Tubular linear motor, Slot-less structure, Thrust characteristics, Detent force optimization, Active vehicle suspension apparatus.

1. Introduction
Translational motion is the most basic form of movement. The majority of the translational movement in life is transformed from the rotational movement through the transmission mechanism, just like cars achieve moving from the wheels rotating on road. Compared with traditional rotary-to-linear electrical actuators, linear electrical machines have no mechanical gears and transmission systems. Hence, they possess higher dynamic performance, high precision and improved reliability.

There are various linear motor topology[1]. Tubular linear permanent magnet synchronous motors (TL-PMSM) are particularly attractive since they have higher thrust density, higher efficiency, and no end windings. Moreover, compared with planner linear motors, the iron-core of TL-PMSM is continuous along the circumferential direction, hence, there is only axial end effect in TL-PMSM and zero net attractive force between the stator and the mover[2]. Accordingly, the tubular linear motor can be applied in many fields, such as medical device [3], power generation (wave energy conversion [4,5], stirling generator [6], vibration energy harvester [7]), electro-hydraulic actuator [8], active shock absorber [9], electromagnetic launcher [10] and so on. How to improve the thrust characteristics of TL-PMSM has always been a hot issue, including how to increase the thrust density and reduce the thrust fluctuations.

Normally, a combination of a mechanical spring and a hydraulic damper is used as the vehicle suspension system. According to the literature, the adjustment of conventional damper in their force reaction to a movement is limited, which affects the traveling comfort. A linear motor would be a more suitable active component, since the thrust can be easily controlled and it allows fast dynamic force changes without additional gears. How to improve the thrust characteristics of TL-PMSM has always been an important issue, including how to increase the thrust density and reduce the thrust fluctuation. Many new topology have been proposed, including the transverse flux linear motor, switching flux linear motor, etc. The TL-PMSMs with these topologies could be seen as the evolution of a rotating electric machine with the similar principle. Therefore, these motors have a higher thrust
density in theory, while the structures are also more complex. On the other way, it is shown that the thrust density can be improved by optimizing the shape of the magnetic poles, by adopting Halbach array, U-shape PM array, V-shape PM array, T-shape PM array, etc. Another problem with TL-PMSM is that it is difficult to use a silicon steel sheet to laminate a perfect cogging structure of the primary core. In some researches, an approximate cylindrical structure or a solid iron is adopted, bringing more cogging force or more core loss.

This paper presents the analysis and design of an improved slot-less tubular linear permanent magnet synchronous motors (STL-PMSM) in which the primary core only consists of silicon steel yoke and copper windings. Accordingly, the cogging effect on the thrust ripple of the motor is negligible due to the absence of teeth and slots. Therefore, the end effects become the most important factors on the thrust fluctuation. Firstly, this article investigates the influence of structural parameters on thrust characteristics of STL-PMSM, in order to obtain a higher output thrust. Then, the detent force of STL-PMSM is reduced by optimizing the structure of the primary core, which improved the thrust characteristic. Finally, a prototype of short primary long secondary STL-PMSM has been manufactured and the test bench has been set. Experiment results illustrate the validity of the simulation and optimized design method.

This paper is organized as follows. In Section 2, the structure of the TL-PMSM and the equivalent magnetic circuit model of ST-PMLM are demonstrated. In Section 3, based on the finite element simulation, the influence of structural parameters on thrust characteristics of ST-PMLM is discussed. In Section 4, the prototype is manufactured and the test bench is illustrated. The proposed optimization method to improve the performance of ST-PMLM is validated by experimental results. Conclusions are then drawn in the final section.

### 2. Structure and model of ST-PMLM

The typical topology of ST-PMLM consists of two parts, the stator (the primary part) and the mover (the secondary part), as shown in figure 1. The stator is composed of annular windings, yoke and two bearings disposed at both ends. And the mover consists of permanent magnets with opposite polarity, iron cores placed between PMs and a shaft in the center of the mover.

The equivalent magnetic circuit model of the ST-PMLM is shown in figure 2. As there is no teeth in the primary iron core with the ST-PMLM, the windings are also part of the air gap. The main dimensions of the proposed ST-PMLM are shown in table 1.

### 3. Influence of structural parameters on thrust characteristics of ST-PMLM

The electromagnetic thrust of linear motor is directly related to magnetic load and electric load. Therefore, in order to improve the thrust, the electromagnetic load distribution of the motor need to be analyzed in detail.

#### 3.1 Influence of the thickness of permanent magnet on ST-PMLM

As can be seen from figure 3, the air gap flux density and thrust increase with the increasing of the PM ring thickness. When hm increases to a certain value, the increasing of the magnetic flux density is not obvious. This means that the thrust of ST-PMLM

**Table 1. Main dimensions of ST-PMLM**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of air gap</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Iron core length of the primary</td>
<td>306.2 mm</td>
</tr>
<tr>
<td>Internal diameter of the primary</td>
<td>45.8 mm</td>
</tr>
<tr>
<td>The outer diameter of the primary</td>
<td>75.2 mm</td>
</tr>
<tr>
<td>Thickness of the primary iron core</td>
<td>5 mm</td>
</tr>
<tr>
<td>Width and thickness of single coil</td>
<td>7×9.2 mm</td>
</tr>
<tr>
<td>Axial length of secondary iron core</td>
<td>2 mm</td>
</tr>
<tr>
<td>The outer diameter of the secondary</td>
<td>44 mm</td>
</tr>
<tr>
<td>Size of the permanent magnet</td>
<td>12×13.2 mm</td>
</tr>
<tr>
<td>The pole pitch</td>
<td>21.12 mm</td>
</tr>
</tbody>
</table>
could be improved by increasing the thickness of magnets, but when the PM thickness increases to a certain extent, the effect is not obvious, also increasing the cost as the price of PM is very expensive.

3.2 Influence of the air gap length on ST-PMLM

The length of air gap (δ) is directly related to the intensity of air gap magnetic field. It is an important factor that determines the magnetic load of linear motor and then influences the thrust of linear motor, especially for the permanent magnet linear motors with slot-less structure. The simulation results of the magnetic field and thrust of the ST-PMLMs with different air gap length are shown in figure 4. With the increase of air gap length, the amplitude of air gap flux density decreases. When the air gap length increases to a certain value, the air gap flux density decreases rapidly. The variation of thrust is similar to that of air gap flux density.

3.3 Influence of the thickness of windings on ST-PMLM

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As a result of adopting the slotless structure, the effective air gap of the ST-PMLM is the sum of the winding thickness (hw) and the air gap (δ). Meanwhile, winding is also the source of copper loss and temperature rise. Therefore, the size of the winding will affect the thrust and efficiency of the motor. The simulation results of the thrust and the copper loss of the ST-PMLMs with different winding thickness are shown in figure 5. With the increasing of winding thickness, the output thrust increases first and then decreases. This is because, along with the winding thickness increases, the diameter of copper wire and the number of conductors per slot increase. This is beneficial to improve the thrust of the motor and reduce the copper loss at the same time. But for the slotless PMLM, the winding is also a part of the equivalent air gap, which makes the equivalent air gap of the motor increase with the increasing of the winding thickness. When the winding thickness is too large, it will depress the thrust of the motor to improve. However, the copper loss will decrease as the winding thickness increases. Therefore, there is an optimal design for the winding thickness.

3.4 Optimization of the thrust fluctuation and detent force with ends compensation

A Theory section should extend, not repeat, the background to the article already dealt with in the Introduction and lay the foundation for further work. In contrast, a Calculation section represents a practical development from a theoretical basis.
The structure of ST-PMLM with end compensation is shown in figure 6.

Fig. 6. ST-PMLM with end compensation structure

Take the 2 poles 6 slots ST-PMLM as an example, shown in table 1. The pole pitch is 21.12mm and the length of primary part is 52.8mm, therefore, when the length of end compensation is 4.32mm, the thrust fluctuation could be minimum. Simulation results of thrust with a small current are shown in figure 7. With the increase of the compensation length at the end of the primary yoke, the average thrust of the ST-PMLM varies little, but the thrust fluctuation decreases first and then increases. And, when the length of compensation is 4.32mm, the thrust ripple of the motor is very small, which agrees well with the theoretical analysis.

Fig. 7. Influence of end compensation length on average thrust and thrust fluctuation

4. Experiments and Discuss

A prototype of ST-PMLM is built and a test bench is set, as shown in figure 8. The parameters of the prototype are shown in table 1. The length compensation on the ends of the primary yoke is 4mm. The experimental results of the static thrust of the motor are shown in figure 9. The experiment results are slightly higher than the simulations. The detent force of the ST-PMLM is shown in figure 10. The results show that the end compensation structure can effectively reduce the fluctuation of the detent force, and the results of theoretical analysis and simulation are verified well.

Fig. 8. Prototype and test bench of the ST-PMLM

Fig. 9. The static thrust curves of the ST-PMLM

Fig. 10. The detent force curves of the ST-PMLM
5. Conclusions

In this paper, a prototype of ST-PMLM for active vibration damping system of automobile is studied. ST-PMLM has high overload capacity and small thrust fluctuation, which can improve the controllability of active vibration damping system and improve travelling comfort. The primary winding thickness has a great influence on the thrust characteristics of the ST-PMLM. The end compensation of primary yoke can effectively improve the thrust ripple characteristics of the motor. The experimental results verify the validity of theoretical analysis and simulation results. The results show that the ST-PMLM can be used as the actuator of the active vibration.

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Reference
