Comparative Analysis of Halbach and Conventional Linear Motors for Precision Positioning and High Speed Control

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I. Introduction
The control of linear motion over short and long strokes is increasingly required in many applications, such as the semiconductor industry, precision manufacturing, and etc. Brushless permanent magnet (PM) linear motors could offer significant advantages over conventional actuation devices, such as motor driven fans, linkages and pneumatic rams - in terms of efficiency, operating bandwidth, speed and thrust control, stroke and positional accuracy. The motors consist of the rotor with the permanent magnets and the stator with stator windings. Magnetic flux is guided by permeable material, which is used in the stator and backing iron of the rotor.

Conventionally, salient-poles are used to maximize magnetic flux density in air gap where stator coil is wounded. Brushless PM linear motors with salient-poles, however, have the force ripple originated from the reluctance between stator and rotor. The ripple is referred to cogging force. The force ripple is detrimental to precision positioning of the motor for its non-linearity. Non-salient stator can be adopted to remove the force ripple, however, traction force of the motor is not sufficient for it has lower magnetic flux density than salient motor.

The alternative to remove the ripple and to improve the traction force of linear motor is introducing Halbach magnet array (HMA). Using the magnet array, the magnetic flux density can be so highly confined to stator winging that traction force of the motor can be high. There is no salient-pole that there is no magnetic reluctance variation with respect to rotor motion. The reluctance variation is cause of the cogging force.

In this paper, we modeled conventional surface-mounted PM linear motor and HMA linear motor, and analyze the performance of the motors via finite element method (FEM). The conventional motors consist of the rotor with standard permanent magnet array and the stator with salient-poles. The HMA motor has HMA in rotor and non-salient permeable magnetic flux guide. And then we compare performances of the two motors under constraints of same exciting current, same coil windings, and small cogging force. The performances are actuating force production capability and ripple force suppressibility.

II. Conventional brushless PM linear motor with salient poles

Conventional BLPMLM with salient poles is constructed as Fig. 1. If the rotor moves there is force ripple, namely cogging force, without energizing current in coil. Rotor pulls stator so strongly that guide mechanism must support this attraction. If air bearing is used as guide mechanism load capacity of the bearing is about a few tens of kgf.

In order to suppress cogging force under 5% of maximum traction force and reduce the attractive force under 10 kgf, the specification of BLPMLM has selected ad table 1. In the motor the air gap is nearly same as magnet length. Cogging force and attraction becomes larger as the gap is smaller.
Fig. 1 2-dimensional model of BLPMLM: 2 phase/2 pole (Only one phase coil is presented)

<table>
<thead>
<tr>
<th>parameters</th>
<th>nomenclature</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pole pitch</td>
<td>( t_p )</td>
<td>5.08 cm x 0.5</td>
</tr>
<tr>
<td>magnet width</td>
<td>( t_m )</td>
<td>5.08 cm x 0.9</td>
</tr>
<tr>
<td>slot pitch</td>
<td>( t_s )</td>
<td>( t_p \times 0.5 )</td>
</tr>
<tr>
<td>slot width</td>
<td>( w_s )</td>
<td>( t_s \times 0.5 )</td>
</tr>
<tr>
<td>magnet length</td>
<td>( l_m )</td>
<td>( t_p \times 0.5 )</td>
</tr>
<tr>
<td>current of coil</td>
<td>( i )</td>
<td>2 A</td>
</tr>
<tr>
<td>winding number of coil</td>
<td>( n )</td>
<td>300 turns</td>
</tr>
<tr>
<td>motor depth</td>
<td>( L )</td>
<td>10 cm</td>
</tr>
</tbody>
</table>

III. Halbach Magnet array linear motor without salient poles

Trumper has proposed HMA in Fig. 2.[2] The motor has no cogging force and attractive force between rotor and stator is very smaller than conventional BLPMLM for there is no high permeable material in rotor components. Therefore the air gap can be selected much smaller than BLPMLM. In the HMA linear motor air gap is selected as a quarter of magnet length.

Fig. 2 2-dimensional model of HMA motor: 2 phase/2 pole (Only one phase coil is presented)
IV. Comparative analysis: BLPMLM vs. HMA linear motor

We analyze the motor's performance using finite element method. The following Fig. 3 and 4 are magnetic flux line of each model.

Fig. 3 Finite analysis result of BLPMLM:
magnetic flux line

Fig. 4 Finite analysis result of HMA linear motor:
magnetic flux line

In the analysis, traction force or actuating force of linear motor is calculated when only one phase coil is energized. Then the force with respect to rotor position is as Fig. 5. From the figure, the actuating force production capability is comparable under condition of small cogging force and attraction force. In BLPMLM, maximum cogging force is 4.9 % of maximum actuating force and maximum attraction force is about 6 kgf.

Generally, actuating force of coreless motor is smaller than that of cored motor. If we must consider cogging force and attraction force, however, HMA linear motor can be strongly recommended even if the force is also important. So, HMA linear motor can be widely used in area precision positioning and high speed actuator needed.
Fig. 5 Actuating force with respect to rotor position for each motor

Reference
