Evaluation of Various Permanent Magnet Arrangements on Linear Actuator

F. Azhar*1, M. Norhisam*2, H. Wakiwaka*1, K. Tashiro*1, M. Nirei*3

Linear actuators are used to provide linear motion in the absence of a motion translator. By using the linear actuator, the linear motion can be produced with high degree of efficiency. Linear actuators can be designed with and without slots; moreover, there are various types of magnetization arrangements that can be applied to the mover. In this paper, ten different magnetization arrangements were used to evaluate slot and slot-less linear actuators. Nine different performance characteristics were used to find the best structure of linear actuator. Results show that, the slot-less types of linear actuators generally have a better dynamic performance, while the slot types of linear actuators have a better static performance. Four different structures with different magnetization arrangements were selected as the best models of linear actuators.

Keywords: Linear actuator, magnetization arrangement, permanent magnet.

1. Introduction

Conventionally, linear motion is achieved by conversion of rotational motion via a motion translator such as a crank shaft, gear, ball screw, belt or motor coupling system [1-4]. However, the conventional linear motion system often functions with low efficiency due to mechanical friction and wear [1,2]. Moreover, the system operates with low acceleration and low impact power, in addition to an increase in the mechanical complexity [5].

Currently, most linear motion systems employ linear actuators, in a system called direct linear motion. The direct linear motion produces a linear motion without the need of a motion translator [4,6]. This system offers high efficiency and flexibility of operation, eliminates the requirement of lubrication and reduces the total number of components used in the system [1,4,6,7]. However, by applying this system, the overall cost will increase as the length of displacement is increased.

Due to numerous advantages offered by direct linear motion systems, this system has been applied to various applications. Beginning with its use in transportation systems, linear actuators are currently being implemented in various applications such as automated manufacturing [8], embedded power generation [9,10], healthcare [11,12] and household appliances [5,13].

Several researchers have been put significant effort in the development of different types of linear actuators with several types of shapes, structural arrangements, and most of the time, permanent magnet types of linear actuators are considered [1-7,10-13]. Furthermore, due to advantages such as high power density, strength of field, low weight, and high efficiency, the moving magnet structure of the linear actuator is chosen for study. The moving magnet linear actuator is mostly designed in a tubular shape. In order to strengthen the mover, the ring shape of the permanent magnet attached to the shaft is used. The coil is wound at the stator side of the linear actuator and a gap between the stator and the mover allows the mover freely oscillate along the axial air gap [14].

Apart from being designed as tubular shape with a moving magnet structure, the linear actuator can be classified as either a slot type or a slot-less type. The classification depends on the type of stator used. Even though the slot type of linear actuator has shown its advantage in static performance such as static thrust [15], the slot-less type has better dynamic performance such as with inductance and when under time constants. Therefore, a proper comparison between these structures is essential in order to decide which type of structure will be used, depending on the appropriate design target.

On the mover side, the arrangement of the permanent magnet magnetization arrangement is a significant factor in determining the performance of the linear actuator. Presently, various permanent magnet magnetization arrangements have been invented in order to improve the linear actuator performance by directing the magnetic flux to flow in a certain path.

A revolution of permanent magnet magnetization direction has occurred since its first implementation in a linear actuator. Several researchers have tried different magnetization directions, from simple N-S arrangement either in the axial [16-18] or radial [19-21] direction, to the halbach array [21-23] in order to evaluate linear actuator performance.

In this study several permanent magnet magnetization arrangements of tubular shape linear actuators were evaluated. Even though no specific design target has been set up, the evaluation was performed in order to observe the effect of permanent magnet mag-
2. Structure of the permanent magnet linear actuator

In this study, two types of stator were simulated: a slot type and a slot-less type. In order to make a valid comparison between these types of linear actuators, several parameters of the stator part need to be fixed, specifically the coil pitch \( \tau_c \), input power \( P_{in} \), and number of coil turns \( N \). Therefore, the size of both stators type was slightly different in order to fix the parameters. Six coils and three phase power supply with 50W input power, \( P_{in} \) and 70 Hz frequency were set. Fig. 1 shows the structure of the slot and slot-less types of linear actuators.

Ten magnetization arrangements of permanent magnets were used in this study. The magnetization arrangements were taken from several sources of reference of previous studies. To make a valid comparison between these models, magnetic pole pitch, \( \tau_{PM} \) and radius of permanent magnet, \( r_{PM} \) were fixed. The stroke direction of the mover in the Y axis is shown in Fig. 1. Each model of linear actuator is set so that it makes a 3-slot 4-pole structure. Fig.2 shows the magnetization arrangement of the permanent magnet that was used. Table 1 shows the structural parameters of the both slot and slot-less types of linear actuators.

<table>
<thead>
<tr>
<th>Part</th>
<th>Parameter</th>
<th>Unit</th>
<th>Slot-less</th>
<th>Slot type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator</td>
<td>Coil pitch, ( \tau_c )</td>
<td>mm</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Turns</td>
<td></td>
<td>704</td>
<td>704</td>
</tr>
<tr>
<td></td>
<td>Coil resistance, ( R )</td>
<td>( \Omega )</td>
<td>14.89</td>
<td>18.26</td>
</tr>
<tr>
<td></td>
<td>Height of coil, ( h_c )</td>
<td>mm</td>
<td>5.5</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>Yoke thickness, ( t_y )</td>
<td>mm</td>
<td>2.5</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>Length of stator, ( l_y )</td>
<td>mm</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Mover</td>
<td>Magnetic pole pitch, ( \tau_{PM} )</td>
<td>mm</td>
<td>11.25</td>
<td>11.25</td>
</tr>
<tr>
<td></td>
<td>PM radius, ( r_{PM} )</td>
<td>mm</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Gap</td>
<td>Gap length, ( \delta )</td>
<td>mm</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>
3. Performance characteristics of the linear actuator

The performance of a linear actuator is evaluated using several criteria. Most researchers use thrust, $F$ as the main factor to design a high performance linear actuator [1,2,15,21]. At the same time, characteristics such as the thrust constant $k_t$, the motor constant $k_m$, the total displacement $x$, the volume $v$, the electrical time constant $\tau_e$, and the mechanical time constant $\tau_m$ also need to be considered in order to design the linear actuator [3,4,16,29,30].

In order to evaluate the performance of linear actuators with different permanent magnet magnetization arrangements, nine criteria were used:

i. Average thrust, $F_{ave}$.
ii. Ripple thrust, $AF$.
iii. Thrust constant, $k_t$.
iv. Motor constant, $k_m$.
v. Motor constant square density, $G$.
vii. Tangential thrust, $\sigma$.
viii. Total weight, $W$.
ix. Electrical time constant, $\tau_e$.

Fig. 3 shows an example of the thrust characteristics of slot and slotless linear actuators at full displacement. The first six criteria (i - vi) will use some of the information as shown in the thrust characteristics of linear actuator. The criteria of linear actuators are indicated in (1) - (6).

The total weight of the linear actuator $W$ was calculated based on the structure size. The volume of each element of the linear actuator was calculated and multiplied with its corresponding material density. The total weight of the linear actuator is indicated in (7).

$$F_{ave} = \frac{1}{x_f} \left( \int_{-x}^{+x} F(x)dx + \int_{-x}^{-x} F(x)dx \right)$$

$$= \frac{1}{45} \left( \int_{-22.5}^{+22.5} F(x)dx + \int_{0}^{0} F(x)dx \right)$$

(1)

$$\Delta F = \frac{F_{max} - F_{min}}{F_{ave}} \times 100\%$$

(2)

$$k_f = \frac{F_{ave}}{I_{rms}}$$

(3)

$$k_m = \frac{F_{ave}}{\sqrt{P_{in}}}$$

(4)

$$G = \frac{F_{ave}^2}{P_{in}} \times V$$

(5)

$$\sigma = \frac{F_{ave}}{S}$$

(6)

$$W = \rho_{iron} V_{yoke} + \rho_{copper} V_{copper} + \rho_{magnet} V_{magnet}$$

(7)

$F_{ave}$ is the average thrust in N, $x_f$ is the total displacement of the linear actuator in millimeters, $\pm x$ is the most positive displacement of the linear actuator in mm, $AF$ is the ripple thrust in $\%$, $F_{max}$ is the maximum thrust in N, $F_{ave}$ is the average thrust in N, $k_f$ is the thrust constant in N/A, $I_{rms}$ is the root mean square of input current in A, $k_m$ is the motor constant in N/√W, $P_{in}$ is the input power in W, $G$ is the motor constant square density in N²/Wm³, $V$ is the linear actuator volume in m³, $\sigma$ is the tangential thrust in N/m², $S$ is the area of permanent magnet surface corresponding to the area of thrust developed in m², $W$ is the total weight in kg, $\rho_{iron}$, $\rho_{copper}$, $\rho_{magnet}$ is the particular material density in kg/m³ and $V_{iron, copper, magnet}$ volume of each element linear actuator structure in m³.

The electrical time constant $\tau_e$ is used to measure the current response of the linear actuator. The mechanical time constant $\tau_m$ is used to measure the response of the linear actuator's mover. Lower time constants correlate to a good response for the linear actuator's current and mover. These characteristics are calculated in steps (8) and (9).

$$\tau_e = \frac{L}{R}$$

(8)

$$\tau_m = \frac{mR^2}{k_f}$$

(9)
where \( \tau_e \) is the electrical time constant in ms, \( L \) is the linear actuator inductance in mH, \( R \) is the linear actuator resistance in \( \Omega \), \( \tau_m \) is the mechanical time constant in ms, and \( m \) is the mass of linear actuator's mover in kg.

4. Comparison of linear actuator performance characteristics.

Fig. 4 shows the comparison of characteristics between the slot and slot-less linear actuators at different permanent magnet magnetization arrangements. Based on the comparison, it is shown that the slot type of linear actuator has better static performance characteristics such as average thrust \( F_{ave} \), thrust constant \( k_t \), motor constant \( k_m \), motor constant square density \( G \) and tangential thrust \( \sigma \). Conversely, the slot-less linear actuator has slower current and mover response.

The comparison of the slot-less linear actuator performance characteristics is shown in fig. 4 (a). Based on the plot, all models of the slot-less type of linear actuators have a similar value of all performance characteristics except for the electrical time constant \( \tau_e \) and mechanical time constant \( \tau_m \). However, the slot-less linear actuator with permanent magnet magnetization arrangement 6 and 7 have the lowest performance in almost all characteristics except for the electrical time constant \( \tau_e \) compared to other models of slot-less linear actuators. Due to elimination of the slot-less linear actuator models with permanent magnet magnetization arrangement 6 and 7, the model with permanent magnet magnetization arrangement 5 and 9 was observed with the lowest thrust ripple \( \Delta F \) and electrical time constant \( \tau_e \). However, it gave a low performance on other characteristics, especially average thrust \( F_{ave} \) and the mechanical time constant \( \tau_m \). On the other hand, the slot-less linear actuators with permanent magnet magnetization in arrangement 8 and 10 are seen as the best two models for the slot-less linear actuator since they have the best performance in all performance characteristics except for the ripple thrust \( \Delta F \) for both models and electrical time constant \( \tau_e \) for the slot-less linear actuator with permanent magnet magnetization arrangement 8.

The comparison of the slot type linear actuator performance characteristics is shown in fig. 4 (b). Based on the plot, the slot type of linear actuator has a similar value of total weight \( W_{total} \) and mechanical time constant \( \tau_m \). Nevertheless, the slot type linear actuator with the permanent magnet magnetization arrangement 5, 6 and 7 have the lowest performance in almost all performance characteristics except for electrical time constant \( \tau_e \), where the model with permanent magnet magnetization arrangement 5 has the best performance compared to other models. Even though the model with permanent magnet magnetization arrangement 9 gives the lowest value of thrust ripple \( \Delta F \), it gives the lowest value in other performance characteristics, especially on average thrust \( F_{ave} \), motor constants \( k_m \) and motor constants square density \( G \), with the exception of models with the permanent magnet magnetization arrangement 5, 6 and 7. Apart from other models which were observed with similar performance characteristics, the slot type linear actuator with permanent magnet magnetization arrangement 4 and 10 have the best performance in all characteristics except the thrust ripple \( \Delta F \) and the electrical time constant, \( \tau_e \). Table 2 shows the summary of comparison between the best two models of slot type and slot-less type of linear actuators.

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**Fig. 4** : Performance comparison of linear actuator models
Table 2: Comparison of best two model of slot-less and slot type linear actuator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Slot less linear actuator model array 8</th>
<th>Slot less linear actuator model array 10</th>
<th>Slot type linear actuator model array 4</th>
<th>Slot type linear actuator model array 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average thrust, $F_{ave}$</td>
<td>N</td>
<td>48.70</td>
<td>47.77</td>
<td>153.03</td>
<td>147.06</td>
</tr>
<tr>
<td>Ripple thrust, $\Delta F$</td>
<td>%</td>
<td>23.79</td>
<td>25.76</td>
<td>75.96</td>
<td>86.04</td>
</tr>
<tr>
<td>Thrust constant, $k_t$</td>
<td>N/A</td>
<td>37.63</td>
<td>36.91</td>
<td>130.74</td>
<td>125.65</td>
</tr>
<tr>
<td>Motor constant, $k_m$</td>
<td>N/W</td>
<td>6.89</td>
<td>6.76</td>
<td>21.64</td>
<td>20.80</td>
</tr>
<tr>
<td>Motor constant square density, $G$</td>
<td>$\times 10^6$ N/m$^2$</td>
<td>0.44</td>
<td>0.42</td>
<td>4.34</td>
<td>4.00</td>
</tr>
<tr>
<td>Tangential thrust, $\sigma$</td>
<td>kN/m$^2$</td>
<td>8.61</td>
<td>8.45</td>
<td>27.06</td>
<td>26.00</td>
</tr>
<tr>
<td>Total weight, $W$</td>
<td>kg</td>
<td>0.87</td>
<td>0.87</td>
<td>0.96</td>
<td>0.95</td>
</tr>
<tr>
<td>Electrical time constant, $\tau_e$</td>
<td>ms</td>
<td>0.15</td>
<td>0.37</td>
<td>0.11</td>
<td>0.18</td>
</tr>
<tr>
<td>Mechanical time constant, $\tau_m$</td>
<td>ms</td>
<td>3.62</td>
<td>4.34</td>
<td>0.48</td>
<td>0.48</td>
</tr>
</tbody>
</table>

As shown in table 2, the linear actuator models with permanent magnet magnetization arrangement 10 and 8 are listed as the best two models for the slot-less type of linear actuator. The best models for the slot type of linear actuator were observed to be arrangement 10 and 4. Arrangement 10 uses a halbach magnetization arrangement of permanent magnet. The model with permanent magnet magnetization arrangement 8 uses the axial magnetization direction and each permanent magnet faces the same pole of each other. Meanwhile, the model with permanent magnet magnetization arrangement 4 uses a similar halbach arrangement but has a magnetic spacer on the outer side and inner side of the permanent magnet.

4. Conclusion

Previously, linear motion is produced by converting the rotational motion to linear motion by using a motion translator. However, this linear motion system comes with an operational limitation. In order to eliminate this drawback, a direct linear motion system that consists of a linear actuator can be used. The structure of the linear actuator can be designed with either a slot or slot-less type of stator structure. On the mover side, various permanent magnet magnetization arrangements can be implemented in order to obtain high performance of the linear actuator. In this study, 10 different magnetization arrangements were used to evaluate the performance of a linear actuator. The performances of the linear actuators were measured using several criteria, and nine characteristics were used to obtain the best model, specifically force, size and response related characteristics. The force related characteristics used were average thrust $F_{ave}$, ripple thrust $\Delta F$, thrust constant $k_t$, motor constant $k_m$, motor constant square density $G$ and tangential thrust $\sigma$. The size related characteristics used were total weight $W$, and the response related characteristics were the electrical time constant $\tau_e$ and the mechanical time constant $\tau_m$. Based on the results, the slot type of linear actuator has higher force related characteristics compared to the slot-less type of linear actuator. On the other hand, the slot-less type of linear actuator has smaller size and faster response related characteristics compared to the slot type of linear actuator. Furthermore, for the slot-less type of linear actuator, the permanent magnet with magnetization arrangement 8 and 10 are the best two models, while for the slot type of linear actuator, the permanent magnet with magnetization arrangement 4 and 10 are the best two models.

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References


