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EFFECT OF DUAL PERMANENT MAGNETS ON LOW-SPEED MOVER HAVING DIFFERENT PITCH: LINEAR OSCILLATORY ACTUATOR INTEGRATED WITH MAGNETIC GEAR

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Abstract

This paper investigates the effect of dual Permanent Magnets (PMs) of low-speed mover having a different pitch on a linear oscillatory actuator performance. Basically, the machine is proposed to be applied for harvesting work of oil palm Fresh Fruit Bunch (FFB). The design includes two main sections, which included a slot-less linear permanent magnet motor and a linear magnetic gear. The magnetic gear is purposely integrated to the linear permanent magnet motor in order to achieve a longer displacement and higher thrust for the cutting operation. Throughout this paper, the design is focusing on the further study of the low-speed mover part by implementing a dual PMs pole-pairs having a different pitch. The main purpose of this study is to increase the thrust force while possibly having a minimum size for the whole structure. Effect of the dual PMs pole-pairs to the machine's performance is analysed by the Finite Element Method (FEM). The simulation results verify the machine validity by comparing to a reference design.

Keywords: Dual permanent magnets pole-pairs, Finite element method (FEM) pole pitch, Linear magnetic gear, Linear motor, Low-speed mover.

1. Introduction

Exposure of agriculture technology in Malaysia has a large gap that can be improved by researchers due to the majority of farmworkers are preferred to use conventional tools instead of machinery. In fact, the demand for palm oil for manufacturing has been increasing in recent years. Today, Malaysia has become one of the main suppliers of palm oil in the world. Therefore, mechanised agriculture is recommended to be expanded more. Based on studies by Shukor [1], Azhar et al. [2] and Norhisam et al. [3], an electrical machine for harvesting oil palm fruits, which is named as E-cutter has been developed. The E-cutter is electrically operated by a generator. It supplies current to a linear actuator that shifts a sickle knife linearly to cut the oil palm Fresh Fruit Bunches (FFBs).

Linear actuator technology is widely used in industries and machine tools. One of them is electromechanical linear actuators. Basically, the mechanism operates by converting the rotational motion of a motor to linear motion. However, motors that operate linearly are already available in the market for quite a long time. Therefore, the linear motor can be used for linear actuator applications instead of rotational motors. One of the advantages is that it is more efficient as linear motion can be directly produced from the motor without conversion.

According to Shukor [1], Azhar et al. [2] and Norhisam et al. [3], the linear actuator developed uses a linear motor. However, it has drawbacks, which need to be improved. The cutting time is not comparable to the machine available in the market due to a lower displacement. One modification that can be made to the machine is by introducing a gearing system to the linear motor [4]. The technology of gearing has advanced in recent years where magnetic gears have been introduced to replace mechanical gears [5]. It has contactless transmission and oil maintenance is not required. In addition, it is highly efficient with low acoustic noise. The gear ratio of a magnetic gear is based on the number of permanent magnets (PM) pole-pairs. A gearing mechanism is capable of adjusting speed, force, and displacement based on the gear ratio. The movement of a higher number of PM pole-pairs shifts the lower number pole-pairs to a longer displacement. Hence, a linear magnetic gear is possibly reliable to be integrated with the linear actuator.

Misron et al. [4] explained that the motor thrust and transmission thrust could be optimized by increasing the size of the linear oscillatory actuator. As reported by Norhisam et al. [6], the thrust constant is proportional to the size of the linear oscillatory actuator. However, in order to make it practical for use in the fields, the size of the linear actuator design should be concerned. In this paper, dual permanent magnets on the lower-speed mover having different pitch are introduced. The linear motor and linear magnetic gear parts are magnetically separated by iron to increase the thrust force without increasing the total length [7, 8]. The idea is proposed due to the limitation on the total length.

2. Basic Structure and Operational Principle

Figure 1 illustrates the linear oscillatory actuator structure in 2-dimension. It consists of a linear permanent magnet motor section and a linear magnetic gear section. The linear motor moves within one coil pitch for half cycle of AC and the rest is another one coil pitch in reverse direction. It comprises a slot-less, air-cored, single-phase windings, which are attached to back iron. The moving part of the

linear motor is dual permanent magnets, low-speed mover. It includes two movers, which has a different pitch while an iron holder is used to divide the upper and lower part of the low-speed mover. The pole pitches of the lower and upper part are independent of each other. The longer pitch and lower number of PMs form the upper part while the shorter pitch and greater number of PMs are designed for the lower part of the low-speed mover.

Apart from the low-speed mover, the linear magnetic gear section also made up of a high-speed mover having a lower number of PM pole pairs. The PMs are arranged in a radial configuration. The magnetic flux that flows from the PMs is modulated by ferromagnetic pole-pieces located between the low-speed and high-speed movers. The ferromagnetic help to transfer magnetic flux between the movers as it activates with the existence of magnetic flux. The transmission of flux from the low-speed mover causes the high-speed mover to move linearly in a different direction. A shaft is attached to the high-speed mover, which is mutually moving to move an output load. The material for the shaft is iron and it also could provide a suitable path for a better flux flow. The lower number of PMs on the high-speed mover produced a higher speed and longer displacement to the output just like the conventional gearing system.

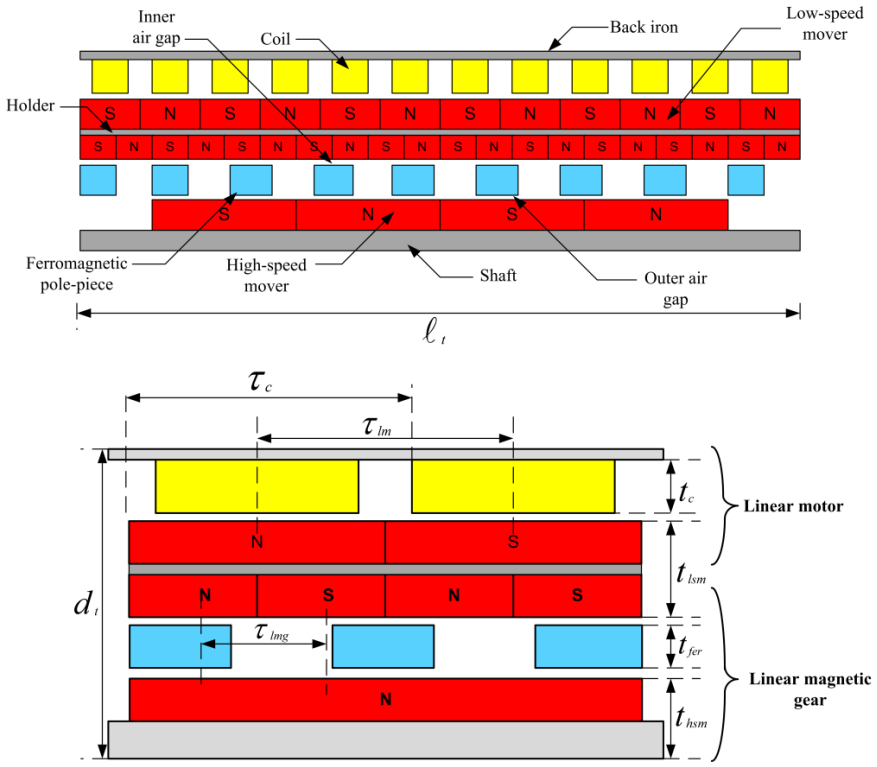


Fig. 1. Two-dimensions structure of linear oscillatory actuator having dual permanent magnets on low-speed mover.

Figure 2 shows the 3-dimensions structure of the linear oscillatory actuator. According to Misron et al. [4], basically, the whole structure is based on the

proposed design that will be used as the reference in this study. The difference of the design compared to reference is on the PM pole-pairs configuration of a low-speed mover, which is dual. Table 1 summarises the parameter design for the structure. The thickness of the PM pole-pairs is 5 mm, which is similar to the reference. The number of pole-pairs, as well as ferromagnetic pole-pieces, are increased, but with a similar gear ratio. The total diameter is slightly increased due to the dual PMs pole-pairs that form the dual low-speed mover structure. However, the most important is the total length is fixed.

Table 1. Parameters of proposed design.

Parameter	Value
Total length, ℓ_t	178 mm
Total diameter, d_t	64 mm
Thickness of low-speed mover, t_{ls}	10 mm
Thickness of high-speed mover, t_{hs}	16 mm
Thickness of ferromagnetic pole-pieces, t_{fer}	4 mm
Thickness of coil, t_c	5 mm
Coil pitch, τ_c	14 mm
Pole pitch of upper part low-speed mover, τ_{lm}	14 mm
Pole pitch of lower part low-speed mover, τ_{lmg}	8.4 mm
No. of active low-speed pole-pairs, P_{ls}	8
No. of active high-speed pole-pairs, P_{hs}	2
No. of active ferromagnetic pole-pieces, N_{fer}	10
Gear ratio, G_r	4

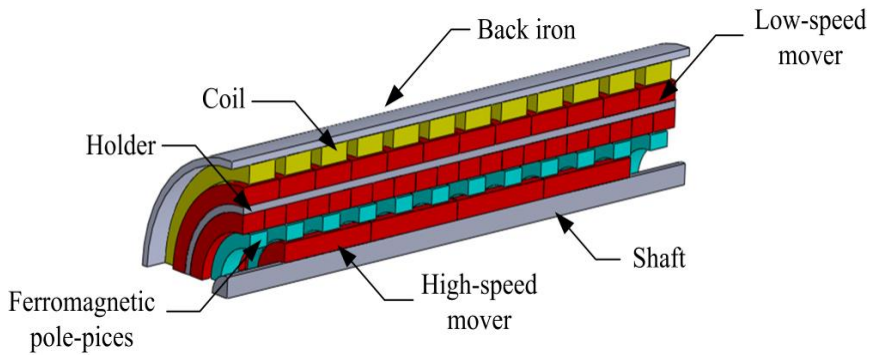


Fig. 2. Three-dimensions structure of the linear oscillatory actuator having dual permanent magnets on the low-speed mover.

2.1. Operational principle of linear motor

The speed of the linear permanent magnet motor is proportional to frequency. The low-speed mover shifts linearly only within one coil pitch, τ_c for each direction. Assuming all magnetic energy is stored in air-gap and no losses and considering current, I across a coil with a number of turns, N, which given the energy stored in the magnetic field, W in Eq. (1) [9].

$$W = \frac{1}{2}NLI^2 \tag{1}$$

$$\Phi = \vec{\beta} \times \vec{A} \tag{2}$$

Magnetic flux, Φ can be derived as in Eq. (2) and $L = \frac{d\Phi}{dI}$ is substituted in Eq. (1). $\vec{A} = \ell\vec{z}$ is the area of a conductor, and L is the self-inductance.

Then, the magnitude of linear motor thrust force, F_m corresponding to W in the direction movement of z is determined by:

$$F_m = \frac{W}{z} = \frac{1}{2}\frac{NLI^2}{z} = N\beta I\ell \tag{3}$$

Hence, the thrust force can be increased if the magnetic flux density, β is increased.

2.2. Operational principle of the linear magnetic gear

The magnetic gear ratio, G_r is formed between the PM pole-pairs on the low-speed mover, P_{ls} and high-speed mover, P_{hs}., N_{fer} is the total number of ferromagnetic pole-pieces, which is based on the total of PMs pole-pairs on the movers.

$$G_r = \frac{P_{ls}}{P_{hs}} \tag{4}$$

$$N_{fer} = P_{ls} + P_{hs} \tag{5}$$

The movement by the higher number of PM pole-pairs on the low-speed mover triggers a repulsive force to the lower number of PM pole-pairs on the high-speed mover to shift in the opposite direction. The ferromagnetic pole-pieces between the two movers are used to modulate the flux flow in order to ensure either the attraction force from like poles is lower or higher than the repulsion force from, unlike poles. Hence, the direction of motion is constant without changing.

The speed and displacement correspond to the gearing mechanism as the lower ratio number of PM would inherit the higher speed and longer displacement. The speed of the high-speed mover, v_{hs} can be determined by the gear ratio to the speed of the low-speed mover, v_{ls}. It can be expressed as in Eq. (6).

$$v_{hs} = -\frac{P_{ls}}{P_{hs}} \times v_{ls} \tag{6}$$

Similarly, the displacement of the high-speed mover, z_{hs} can be expressed from the gear ratio of the mover where the displacement of the low-speed mover, z_{ls} would be lower.

$$z_{hs} = -\frac{P_{ls}}{P_{hs}} \times z_{ls} \tag{7}$$

3. Configuration of the Low-Speed Mover

Several models, which have a different structure of low-speed mover were simulated in order to finalise the best design. Each model has a different configuration of permanent magnet pole-pairs. Misron et al. [4] proposed that the linear oscillatory actuator that was introduced is set as a reference design to analyse and compare the performance of each model. Basically, there are two types of configuration, which would be discussed namely as single and dual permanent magnets. Based on Eq. (2), the magnetic field density, β is proportional to magnetic flux, Φ covering an area of 1 m^2, placed with its plane perpendicular to the magnetic field. Hence, from Eq. (3), if a greater number of permanent magnet pole-pairs are placed on a given area, it may increase the magnetic field density as well as the thrust force. Each model has a different thrust force, and the performance differences are analysed and compared.

3.1. Single permanent magnet configuration

Misron et al. [4] commented that the integrating linear magnetic gear with a linear permanent magnet motor to form a linear actuator has been discussed, in which, is represented in Model 1 as a reference. Figure 3 shows Models 1 and 2 that used a single permanent magnet configuration for the low-speed mover structure. It is called a single configuration since the low-speed mover is shared by the linear motor and linear magnetic gear. Further studies were conducted by placing more number of PM pole-pairs as it was expected to increase thrust force.

Model 2 was designed with more number of PM pole-pairs with the ratio set to 2:8 on high-speed and low-speed mover respectively. As a result, the total length is longer since the number of pole-pairs is increased. The dependence of the pole pitch to coil pitch causes the total length has to be increased in order to get a higher thrust force. Therefore, by decreasing the pole pitch for maintaining the total length would reduce the coil pitch as well. Consequently, the electromagnetic energy source acting on the force of the movers would be lower. In order to achieve good operation in Model 2, the similar pole pitch in Model 1 is installed and this would certainly increase the total length.

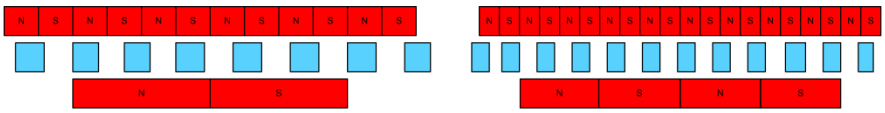


Fig. 3. Single permanent magnet configuration.

3.2. Dual permanent magnets configuration

Figure 4 shows two designs of dual PMs configuration for the low-speed mover. There are two sets of PM pole-pairs that are isolated by an iron. The idea is proposed in order to keep the total length fixed as in Model 1. The total length is decreased compared to Model 2, but the total diameter is slightly increased. More importantly, it is advantageous for the thrust force as the magnetic flux density would be greater. As discussed by Azhar et al. [2], the thickness of PM pole-pairs could increase the thrust force. It means that the dual configuration would duplicate the thickness of PM pole-pairs. As a result, the thrust force would be higher than Model 1 with the same total length.

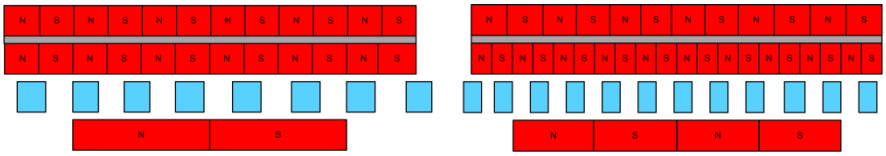
However, Model 3 may not be as high as Model 2 due to its number of pole-pairs is more for the same ratio. Therefore, in order to optimise the thrust force more, a similar gear ratio of Model 2 is used for Model 4. The advantage of the dual configuration is the holder has decoupled the dependence of the pole pitch to the coil pitch. The pole pitch can be reduced without decreasing the coil pitch, so more pole-pairs can be placed in Model 4 without increasing the total length. Eventually, the thrust force would be increased.

Table 2 shows the differences between each model for the low-speed mover structure. The single configuration shares the same pole-pairs while the dual configuration has two sets of pole-pairs on the low-speed mover. However, it can be observed that the diameter of the dual configuration is greater than the single configuration. Though, Model 2 has the longest total length. The ratio between the

low-speed mover and high-speed mover of Model 4 and 2 is greater due to the greater number of pole-pairs. However, the total length of Model 4 is constant. The pole pitch is shortened therefore enabling the total length to be fixed.

Table 2. Structural differences between models.

Model	1	2	3	4
Low-speed mover configuration	Single	Single	Dual	Dual
Ratio (hs:ls)	1:4	2:8	1:4	2:8
Pole pitch of upper part low-speed mover, τ_{lm} (mm)	-	-	14	14
Pole pitch of lower part low -speed mover, τ_{lmg} (mm)	14	14	14	8.4
Total diameter, d_t (mm)	56	56	64	64
Total length, ℓ_t (mm)	178	346	178	178



(c) Model 3 (d) Model 4

Fig. 4. Dual permanent magnets configuration.

4. Results and Performance Analysis

All models of the linear oscillatory actuator design were analysed by Finite Element Method (FEM). This method is commonly used to verify the performance of machine design. The best performance is determined by comparing the results of motor thrust force and transmission thrust force using Model 1 as the reference. Motor thrust is the force acted by electromagnetic energy produced from coil windings to shift the low-speed mover in the linear motor section. Transmission thrust is the force generated in the linear magnetic gear section from the low-speed mover to the high-speed mover. The best model is aimed to have higher thrust force and shorter total length.

4.1. Effect of dual permanent magnet on motor thrust

Figure 5 shows the results of motor thrust for each model. The proposed model, which is Model 4 produced the highest thrust followed by Model 3, Model 1 and Model 2. By adding more number of permanent magnets for the same ratio, there is a significant increase in thrust force from the linear motor section in Model 4. Model 2 also has a similar number of pole-pairs with Model 4, but the results show it produced the lowest motor thrust. It happened due to the lower pole pitch therefore, lower magnetic flux is produced to trigger the low-speed mover. It also affects the motor thrust to be saturated. The electromagnetic energy produced from the copper coil to move the low-speed mover is not adequate. In order to increase the motor thrust for Model 2, the coil pitch has to be increased.

Models 3 and 4 proved that dual PMs configuration could increase the motor thrust. The lower pole pitch on the lower part of the low-speed mover in Model 4 showed that with the same total length, the motor thrust can be improved. The thrust force increased due to more number of pole-pairs were placed within the same area. Thus, the greater magnetic flux density is produced in the area.

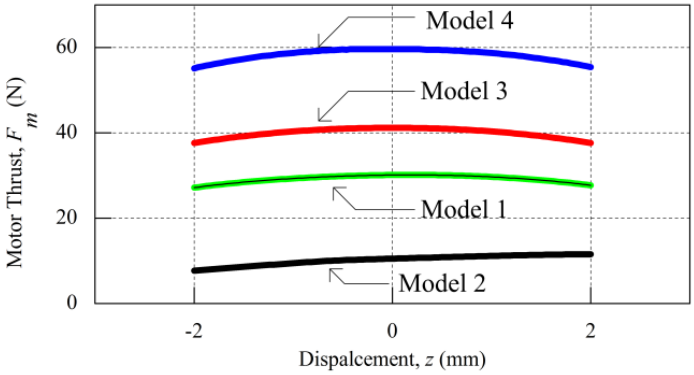


Fig. 5. Motor thrusts of all models.

4.2. Effect of dual permanent magnets on transmission thrust

Transmission thrust of all models between the low-speed and high-speed mover is shown in Fig 6. It can be observed that Model 4 has the highest value of transmission thrust followed by Models 2, 3 and 1 accordingly. For Model 2, the transmission thrust is comparable to Model 4 due to a similar number of pole-pairs on the low-speed mover. However, its motor thrust is the lowest and total length is the longest. Thus, Model 2 is not suitable to be applied for a prototype. The transmission thrust of Model 4 is higher than Model 3 due to more number of pole-pairs within the same area. The transmission thrust is increased even though the pole pitch of the lower part in Model 4 is decreased. It shows that the effect of dual PMs on the low-speed mover having different pitch increases the transmission thrust significantly.

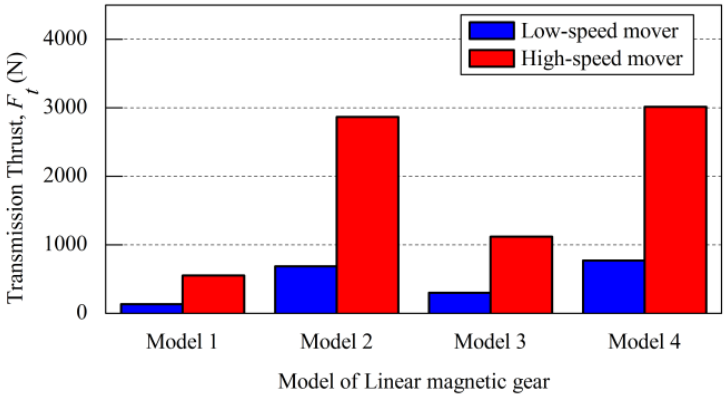


Fig. 6. Transmission thrusts of all models.

4.3. Dual permanent magnets of low-speed mover

After analysing the performance of each model, the best design would be selected among the models based on the motor and transmission thrust with corresponding minimum size. The size is important to be considered in order for it to be reliable for use.

Table 3 summarises the performance analysis of each model. The motor and transmission thrust of Model 4 is the highest among the other models. Besides, the total length is among the lowest, which is similar to Model 1. Despite the total diameter is greater than Model 1, the difference in thrust forces are significant. Hence, Model 4 is selected to be the most promising design and the size is practical to be used on the field.

Figure 7 shows the result of motor thrust for Model 4 when excitation current to the coil was increased from 1A to 5A. The result shows motor thrust is proportional to the increase in current. The thrust force produced is greater than model 1 when supplying the same value of current. It strengthens the reasons that the performance of Model 4 is the most preferred design.

Table. 3 Comparison of performance between all models.

Model	1	2	3	4
Total length (mm)	178	346	178	178
Total diameter (mm)	56	56	64	64
Average Motor Thrust (N)	29	10	40	58
Average Transmission Thrust of low-speed mover (N)	553	2868	1117	3013
Average Transmission Thrust of high-speed mover (N)	131	687	300	770

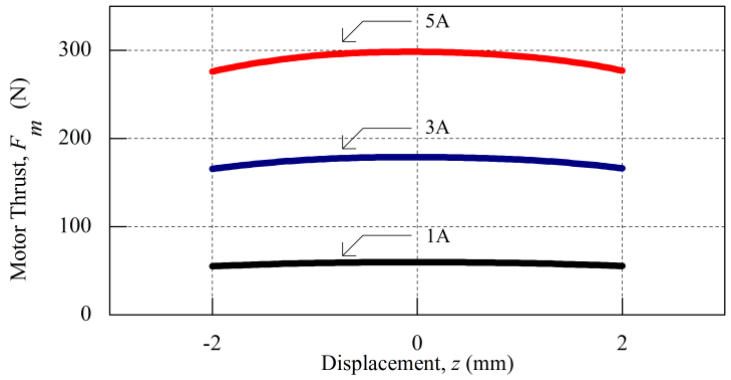
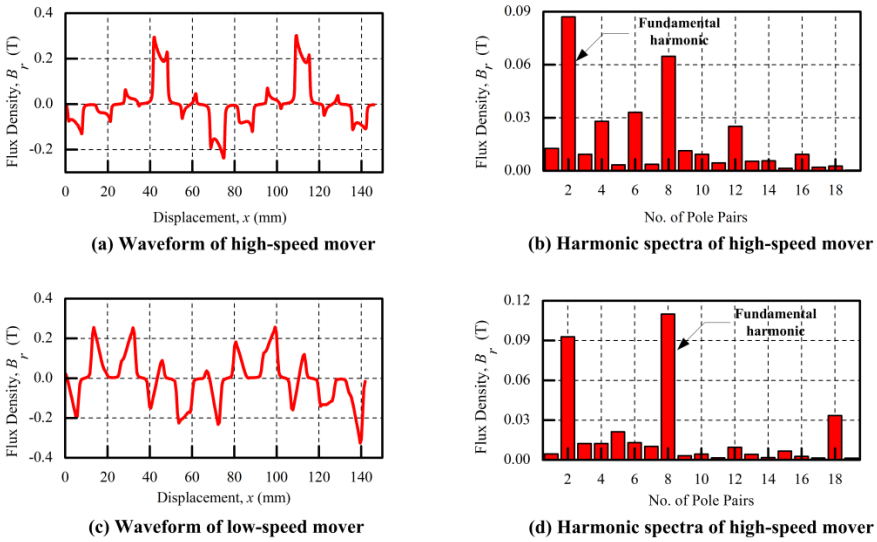


Fig. 7. Motor thrust of Model 4 when increasing supplied current.

Figure 8 explains the corresponding waveforms and harmonic spectra of Model 4. The fundamental harmonic indicates the number of active PM pole-pairs on both the low-speed and high-speed movers, which represent the gear ratio. Figures 8(a) and (b) show the flux density calculated at the outer air gap, which is located between the low-speed mover and ferromagnetic pole-pieces. The low-speed mover is set as field excitation and the high-speed mover is set as airspace. The fundamental harmonic in the harmonic spectra is recorded as two, which corresponds to the number of pole-pairs on the high-speed mover. Figures 8(c) and (d) show the flux density characteristics in the inner air gap, the air gap is between the high-speed mover and pole-pieces. In order to calculate the flux density, the low-speed mover is set as air-space while the high-speed mover operates as the field excitation. The highest order of eight in the harmonic spectra corresponds to the number of PM pole-pairs on the low-speed mover, which gives the gear ratio

of Model 4 as 2:8. The spectra verify the results show a similar gear ratio is used, which is aligned with the setting.



(a) Waveform of high-speed mover **(b) Harmonic spectra of high-speed mover**

(c) Waveform of low-speed mover **(d) Harmonic spectra of high-speed mover**

Fig. 8. Waveforms and harmonic spectra of Model 4.

5. Conclusion

Four different models of low-speed mover structure for linear oscillatory actuator were designed. The effect of dual permanent magnets on the performance of the linear oscillatory actuator was analysed using Finite Element Method (FEM). The performance of each model was compared to reference based on the motor thrust and transmission thrust. Model 4, which consist of a dual permanent magnet configuration having different pole pitch showed the best performance among the other models. The structure has a number of PM pole-pairs on the lower part of the low-speed mover with a reduced pole pitch. The results verified that the dual permanent magnet configuration produces a significant increase in thrust forces without increasing the total length of the machine.

Nomenclatures

A	Area of conductor
d_t	Total diameter
F_m	Motor thrust
F_t	Transmission thrust
G_r	Gear ratio
I	Current
L	Self-inductance
ℓ_t	Total length
N	Number of ferromagnetic pole pieces
N_{fer}	Thickness of ferromagnetic pole-pieces
P_{hs}	Number of PM pole-pairs on high-speed mover
P_{ls}	Number of PM pole-pairs on low-speed mover

t_c	Thickness of coil
t_{fer}	Thickness of ferromagnetic pole-pieces
t_{hs}	Thickness of high-speed mover
t_{ls}	Thickness of low-speed mover
W	Magnetic energy
v_{hs}	Speed of low-speed mover
v_{ls}	Speed of high-speed mover
z_{hs}	Displacement of high-speed mover
z_{ls}	Displacement of low-speed mover

Greek Symbols

β	Magnetic flux density
τ_c	Coil pitch
τ_{lm}	Pole pitch of upper part low-speed mover
τ_{lmg}	Pole pitch of lower part low-speed move
Φ	Magnetic flux

Abbreviations

FEM	Finite Element Method
FFB	Fresh Fruit Bunch
PM	Permanent Magnet
S	South
N	North

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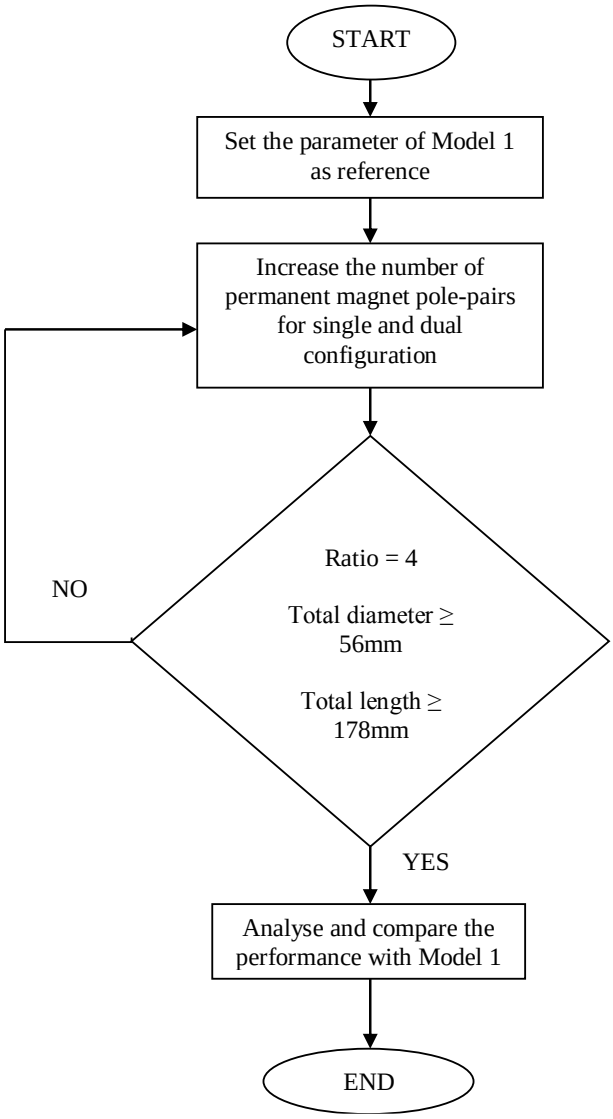
Appendix A

Figures of Design Chart