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DESIGN OF A LINEAR DC MOTOR FOR HIGH THRUST CONSTANTS CHARACTERISTICS

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ABSTRACT

Traditionally a linear motion system consists of a rotational motor and motion translation component. However, the traditional systems inherit several drawbacks that contribute into operational limitation. Currently, use of a linear motor is seen as an alternative to produce direct linear motion without use any motion translation. Linear DC Motor (LDM) is one type of linear motor. Previously, a LDM has been developed to be use in a linear displacement system. Based on experimental result, it could achieve a desired displacement with fast settling time and low overshoot. However, in order to improve the system performance especially in term of time response, a new LDM need to be designed. In this paper, a LDM for similar application was designed. The shape of the LDM has been change from a rectangular to quarter circle due to changes in shape of permanent magnet. Furthermore, material of the permanent magnet also has been changed from ferrite to NdFeB to increase the magnetic flux density in air gap. Based on the designed, the LDM has produce about 3.1 N/A and 35.12 ms in term of thrust constant, k_f and mechanical time constant, T_m respectively. In comparison with previous LDM, it only produced about 1.6 N/A and 111.72 ms in term of thrust constant, k_f and mechanical time constant, T_m respectively.

Keywords: linear DC motor thrust constant, mechanical time constant.

INTRODUCTION

A linear motion can be produced by using a rotational motor coupled with motion translation part such as gears, ball screw, belts and etc. Despite of vast application, this system inherits several drawbacks such as speed and stroke limitation, backlash and need for complicated alignment and lubrication system. In order to eliminate these drawbacks, a linear motor was introduced. The linear motor produces direct linear motion without any motion translation. Besides eliminates drawbacks of conventional linear motion system, the linear motor also offers simple construction and increase system reliability due to lower number of component used (Lee *et al.*, 2000).

Linear DC Motor (LDM) is one type of linear motor. It can produce a linear motion in one axis only by a step voltage. Depending on the polarity of the step voltage, mover of the LDM will move either in forward or reverse direction. This style of operation made the LDM is suitable to be used in a linear displacement system (Shen *et al.*, 2011, Liyi *et al.*, 2010). Similar LDM for a linear displacement system has been developed in (Norhisam *et al.*, 2006) and (Norhisam *et al.*, 2011). In these papers, a LDM with having thrust constant, k_f of 1.6 N/A has been designed. With excitation current, I of 0.5 A, the LDM could achieve displacement, x of 10 mm with about 38 ms of settling time.

As discussed in Norhisam *et al.*, 2011, a quadruple force stage able to improve response of the LDM's mover. Instead of make the LDM mover response faster, it also improve other transient response parameters such as overshoot and settling time. On the other hand, response of the LDM is also depends on it's thrust, F. The higher thrust, F develop, the faster response obtain. Yet, by improving thrust constant, k_f, higher thrust, F will be obtained at similar excitation current, I (Mizuno *et al.*, 2005, F. Azhar *et al.*, 2015, Tavana *et. al.*, 2013).

Therefore, in this paper, design of a new LDM was discussed. It is to increase the thrust constant of the LDM, hence improve the speed response of the linear displacement system. In preference to a rectangular shape, a quarter circle shape of permanent magnet has been used to the LDM structure. On top of that, a NdFeB permanent magnet has been used at the stator in order to increase magnetic flux density in the air gap, hence increase the thrust constant, k_f. The LDM has been designed and manufactured. The thrust characteristic of it has been measured. As a result, a LDM with 3.1 N/A of thrust constant, k_f has been obtained.

BASIC PRINCIPLE OF LINEAR DC MOTOR

Figure-1 shows comparison between the LDM structure as in Norhisam *et al.*, 2006, 2011 and the structure that has been used in this paper. In the new structure of the LDM, shape of permanent magnet has been changed from rectangular to quarter circle shape of permanent magnet. Furthermore, type of permanent magnet's material also has been changed from ferrite to neodymium iron boron (NdFeB). This change was made to increase magnetic flux density, B in the air gap to increase thrust constant, k_f. Figure-2 shows comparison of BH curve between ferrite and neodymium iron boron (NdFeB) of permanent magnet.
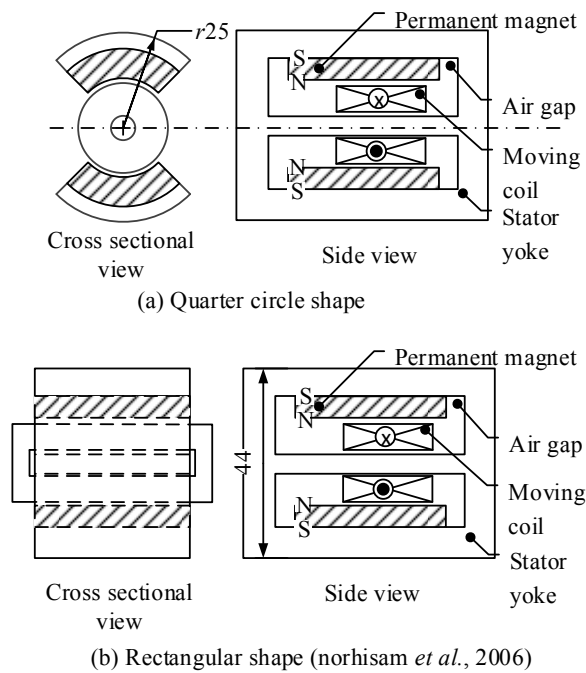
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(a) Quarter circle shape

(b) Rectangular shape (norhisam *et al.*, 2006)

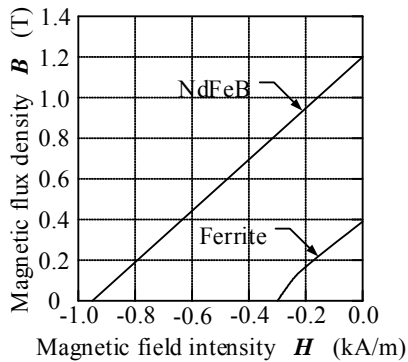**Figure-1**. Comparison of the LDM structure (unit : mm).

Figure-2. Demagnetization curves of permanent magnet materials.

The LDM operates in one axis. The permanent magnets are placed in facing same pole so that the flux density in air gap will be double up. There are two source of magnetic flux which is permanent magnet and excited coil. When the coil was excited, a magnetic flux will induce. Interaction between magnetic flux produced by the permanent magnet and induced by the coil will produced thrust and made the moving coil move back and forward in linear direction thus thrust is produce. Generally, the thrust produce depends on the magnetic flux density in air gap. To have higher thrust density, the air gap between the permanent magnet and the coil has to be kept as minimum as possible (Norhisam *et al.*, 2006) and (Norhisam *et al.*, 2011).

The thrust of the LDM is derived from basic *iBl* laws. Thrust in the moving coil can be expressed as,

$$F_m = N_c I B_g l_c \tag{1}$$

where F_m is the thrust in (N), N_c is the coil turns, I is the current in (A), B_g is the magnetic density in the gap in (T) and l_c is the length of the coil in (m).

The thrust constant of the MCLDM depends on the value of N_c, B_g and l_c. These parameters are fixed when the motor has been designed. Therefore, the force produced by the motor can be controlled by controlling the amount of current supplied to the coil. Assuming motor thrust constant k_f as,

$$k_f = N_c B_g l_c \tag{2}$$

By substituting Equation. (2) into Equation. (1) final expression of thrust can be representing by,

$$F_m = k_f I \tag{3}$$

Thus, it implies that the thrust constant, k_f produced by the motor is proportional to the magnetic flux density in air gap, B_g. The higher magnetic flux density in air gap, B_g of the LDM, the higher thrust constant, k_f produced by the motor. For example, the LDM as designed and developed in (Norhisam *et al.*, 2006) and (Norhisam *et al.*, 2011) has a thrust constant, k_f of 1.6 N/A.

Response of the LDM's mover is evaluate using mechanical time constant, T_m. The lower of mechanical time constant, T_m represent the faster mover response (Mizuno *et al.*, 2000). The mechanical time constant, T_m is calculate using below,

$$T_m = \frac{mR}{k_f^2} \tag{4}$$

where T_m is the mechanical time constant in (s), m is the mover mass in (kg), R is the coil resistance in (Ω) and k_f is the thrust constant in (N/A).

Based on Equation (4), instead of the mover mass, m and coil resistance, R, the mechanical time constant, T_m can be reduce by increasing the thrust constant, k_f. Therefore, improving the thrust constant, k_f through designing process, it also can improve the response of the mover.

DESIGN OF LINEAR DC MOTOR

The LDM was designed using finite element method (FEM). Several models of the LDM has been created with difference structural parameters and best model has been selected. In order to validate simulation result, the best model of the LDM has been manufactured and it static thrust characteristics has been measured. The measured static thrust characteristics was then compared with simulation output and it agreement has been observed.

Basic model and structure parameter of the LDM is as shown in Figure-3. Several structure parameters of the LDM was fixed as listed in Table-1. During designing the LDM, height of the permanent magnet, h_{pm}, height of the coil, h_c and gap between yoke and permanent magnet, l_1 have been varied within fixed structure parameters as listed in Table-1.

The design processes consist of two stages. The first stage, the gap between yoke and permanent magnet, l_1 was set to 0 mm while the height of the permanent magnet, h_{pm} was varied from 1 mm to highest possible of value by considering the other structure parameters. Due to fixed of total radius, r_{total}, increment of the height of the permanent magnet, h_{pm} will reduce the height of the coil, h_c accordingly. Each model of the LDM was simulated and static thrust characteristics at full range of the mover displacement, x has been observed and the model of the LDM produce highest thrust has been identified.
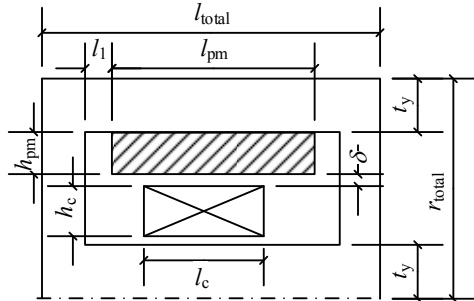

Figure-3. Structure parameters of the LDM.

Table-1. Fixed structure parameters of the LDM.

Structure parameter		Value
Coil length, l_c	(mm)	20
Air gap, δ	(mm)	1
Yoke thickness, t_y	(mm)	5
Total radius, r_{total}	(mm)	25
Total length, l_{total}	(mm)	74

Based on the best model from first stage of design, the gap between yoke and permanent magnet, l_1 was varied within fixed of total length, l_{total} during the second stage of design. While the the gap between yoke and permanent magnet, l_1 was increased, the length of the permanent magnet, l_{pm} was decreased accordingly. Each models of the LDM have been simulated and model that produced lowest thrust difference, ΔF was identified. The design flow of the LDM design is as shown in Figure-4.
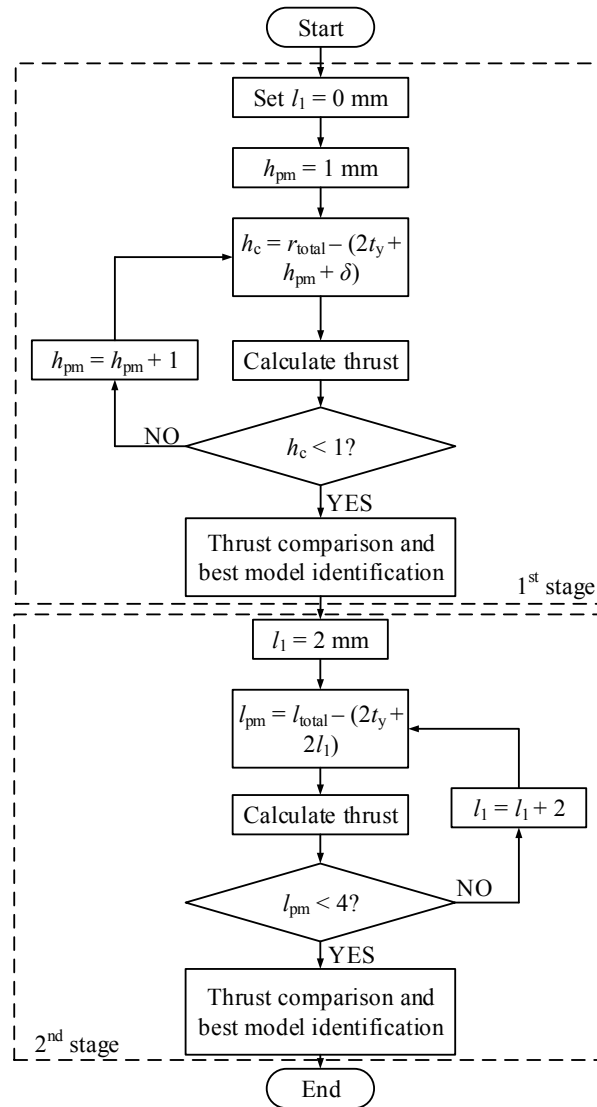

Figure-4. Design flow.

RESULT

Thrust comparison of the LDM models

During first stage of design, a combination of height of the permanent magnet, h_{pm} and height of the coil, h_c that produce highest thrust was examined. For each models of the LDM with different structure parameters have been simulated and its thrust have been compared. Figure 5 shows comparison of thrust of the LDM models. It is shown that, higher the height of the permanent magnet, h_{pm} made thrust is increasing. However, the thrust, F is decreasing once it reach a maximum point even though the height of the permanent magnet, h_{pm} is increased.

Total magnetic energy supplied to the LDM were from the permanent magnet source and the excited coil. The increment of the thrust, F before it reached maximum point is due to higher magnetic energy supplied to the

LDM as the size of the permanent magnet was increased. At the same time, even though the size of coil was reduced, the decrement of the energy supplied by the excited coil was not influence the thrust production. However, after reach it maximum point, the thrust; F is reducing even though the height of the permanent magnet, h_{pm} was increased. Despite of increment of magnetic energy supplied by the permanent magnet, the reduction of magnetic energy supplied by the coil due to smaller of coil size was significantly affect the thrust, F production. Therefore, the thrust, F is decreasing even though the size of the permanent magnet was increased. As a result from the first stage of design, the highest thrust obtains at combination of height of permanent magnet, h_{pm} and height of the coil, h_c of 5 mm and 14 mm respectively.
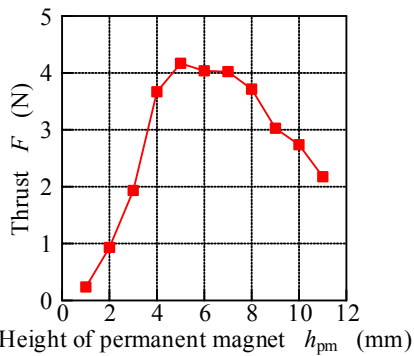

Figure-5. Comparison of thrust on first stage of design.

During the second stage of the design, gap between permanent magnet and side yoke was designed. The aim of the design is to minimize difference between maximum and minimum thrust of the LDM. Figure-6 shows comparison of thrust characteristics of the LDM with difference gap between yoke and permanent magnet, l_1. Thrust characteristics of the LDM has a almost constant value if the coil area at various displacement is covered by the permanent magnet. However, if the gap between yoke and permanent magnet, l_1 is set to 0 mm, magnetic flux produced by the permanent magnet will only flowing near to the side yoke area made the effective area of thrust production is reduced, hence produced lower thrust. It is shown in Figure-6 where if the gap between yoke and permanent magnet, l_1 set to 0 mm, the thrust produced especially at displacement, x between -20 mm and -16 mm is lower compared to if the gap between yoke and permanent magnet, l_1 set to 4 mm. However, if the gap between yoke and permanent magnet, l_1 set more than 4 mm, on certain displacement, x, the coil area is not fully cover by the permanent magnet. Therefore, the thrust produced at left and right end of the LDM is lower compared to at the center, hence produced higher thrust difference, ΔF. The thrust difference was calculated using,

$$\Delta F = \frac{|F_{max} - F_{min}|}{F_{max}}\% \qquad (5)$$

where ΔF is the thrust difference in (%), F_{max} and F_{min} are the maximum and minimum thrust respectively in (N).
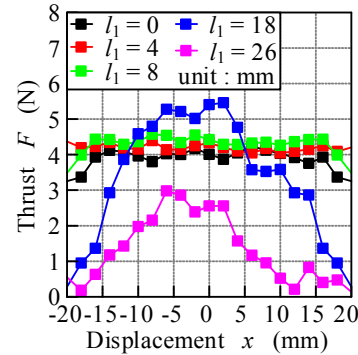

Figure-6. Thrust characteristics of the LDM with difference l_1.

Figure-7 shows maximum and minimum thrust, F_{max} and F_{min} and thrust difference, ΔF of the LDM with difference gap between yoke and permanent magnet, l_1. It is shown that, even though at gap between yoke and permanent magnet, l_1 of 4 mm not producing the highest maximum thrust, F_{max}, however, it has lowest thrust difference, ΔF compared to other models. Based on the result, Figure-8 shows the final structure parameters of the LDM.
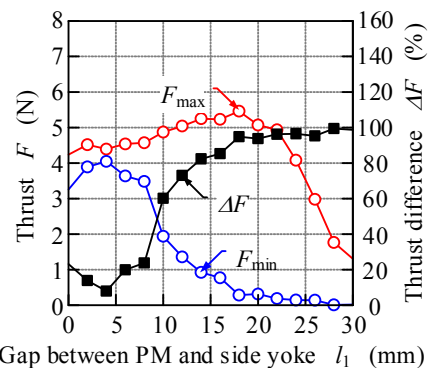

Figure-7. Comparison of thrust (F_{max}, F_{min}) and thrust difference ΔF.
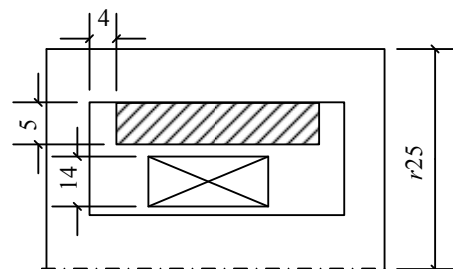

Figure-8. Final structure parameters of the LDM (unit in mm).

Experimental verification of thrust constant and mechanical time constant of the LDM

In order to validate design output, the LDM has been manufactured based on its final structure parameters. The manufactured LDM is as shown in Figure-9. For the coil parameters, it has 550 turns of coil turns with 4.5 Ω of DC resistance and 0.075 kg of it weight.

The thrust characteristics of the LDM was measured with the same conditions as it simulation. The experiment setup of the thrust characteristics measurement is as shown in Figure-10. The thrust characteristics was measured using load cell (UMM-10 kgf). The load cell (UMM-10 kgf) was connected to a digital indicator (DN-10W). The digital indicator (DN-10W) will give an equivalent thrust in voltage, (mV) and the analog output of the digital indicator (DN-10W) also was connected to 4 ch digital oscilloscope. The 4 channel DC power supply was used to varied the voltage in range of 1 V - 10 V. The laser displacement sensor (Keyence LB-70) was used to measure the moving coil displacement. The thrust characteristics for the LDM then was captured and analysed.
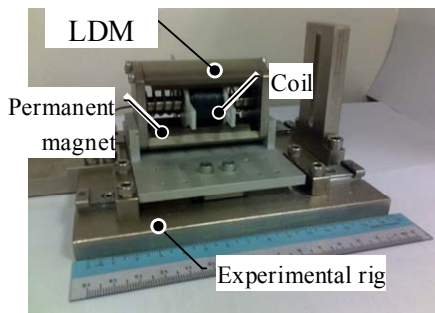

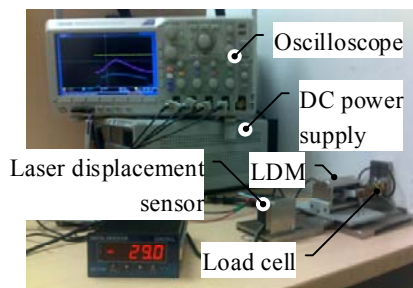**Figure-9**. Manufactured LDM rest on an experimental rig.

Figure-10. Experiment setup for thrust characteristics measurement.

The thrust characteristics at several voltage of the LDM is as shown in Figure-11. It is shown that, higher voltage gives higher thrust, F. The comparison of the thrust characteristics of the LDM between simulation and measurement is as shown in Figure-12. The comparison was done at similar voltage which is 4 V. It is shown that, the measurement result is agreed to the simulation result.

The thrust at $x = 0$ mm, $F_{x=0}$ at several voltage was identified. The voltage then converted to equivalent current, I. The effect of current, I to the thrust at $x = 0$ mm, $F_{x=0}$ is as shown in Figure-12. Linear fit analysis was done to the measured thrust in order to estimate the thrust constant, k_f. The thrust constant, k_f was calculated using,

$$k_f = \frac{F_{x=0}}{I} \tag{6}$$

where k_f is the thrust constant in (N/A), $F_{x=0}$ is the thrust in (N) and I is the current in (A).
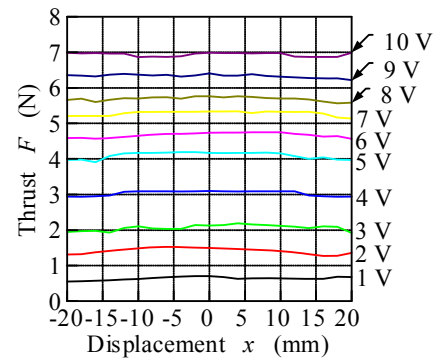

Figure-11. Thrust characteristics of the LDM with difference voltage.
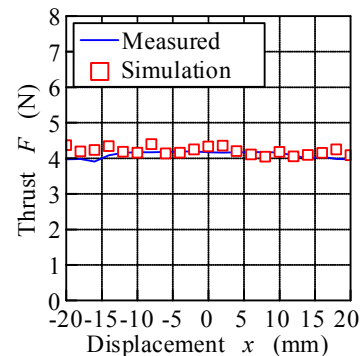

Figure-12. Comparison between simulated and measured LDM's thrust.

Despite of measured thrust, the Figure 13 also shows the simulation output. Based on the Figure-13, it is shows that, the effect of current, I to thrust, F is agreed between two difference techniques. It is also found that, the LDM was produced thrust constant, k_f of 3.1 N/A. Based on the (Norhisam *et al*., 2006) and (Norhisam *et al*., 2011); the rectangular shape of the LDM was given thrust constant, k_f of 1.6 N/A. Even though in this research, the LDM is having almost similar outer dimension compared to the LDM in (Norhisam *et al*., 2006) and (Norhisam *et al*., 2011), the thrust constant, k_f has been increase about twice. It is shows that, the LDM designed in this research is seen to have a better performance if it is applied in similar application as the MCLDM in (Norhisam *et al*., 2006) and (Norhisam *et al*., 2011).

The mechanical time constant, T_m of the LDM was calculated using Equation (4). It depends on the mover parameters such as mover weight, m, coil DC resistance, R and thrust constant, k_f. Table-2 shows comparison between these parameters and mechanical time constant, T_m between LDMs. Based on Table-2, the LDM that has been designed not only improve the thrust constant, k_f, it is also has been improved the mechanical time constant, T_m. It is estimated that, the designed LDM will having faster mover reponse compared to its counterpart.
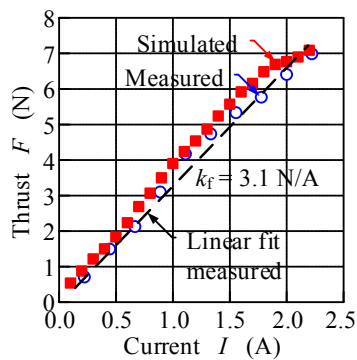

Figure-13. Effect of current to the LDM's thrust.

Table-2. Comparison of the LDM and the LDM as in (Norhisam *et al.*, 2006) parameters and performance.

Parameters	The LDM	LDM in the (Norhisam *et al.*, 2006)
Mover weight, m (kg)	0.075	0.055
DC resistance, R (Ω)	4.5	5.2
Thrust constant, k_f. (N/A)	3.1	1.6
Mechanical time constant, T_m (ms)	35.12	111.72

CONCLUSIONS

In this paper, design of a LDM has been discussed. The LDM was intended to be implementing in linear displacement system. Previously, the LDM for similar application has been design in rectangular shape. However, in this paper, the LDM has been designed by using quarter circle shape of permanent magnet. On top of that, the material of the permanent magnet also has been change to NdFeB. The LDM has been underwent two stage of designs. The aim to make sure the LDM having highest as possible thrust thus having higher thrust constant, k_f and lower mechanical time constant, T_m. Based on design result, the LDM has been manufactured. The thrust characteristics of the LDM has been measured and compared with the simulation output. Based on the comparison, the simulation output and measurement result has a good agreement. As a result, the designed LDM produced higher thrust constant, k_f, and lower mechanical time constant, T_m.

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