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Design Analysis of Taper Width Variations in Magnetless Linear Machine for Traction Applications

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Abstract. Linear motors are being used in a different application with a huge popularity in the use of transport industry. With the invention of maglev trains and other high-speed trains, linear motors are being used for the translation and braking applications for these systems. However, a huge drawback of the linear motor design is the cogging force, low thrust values, and voltage ripples. This paper aims to study the force analysis with change in taper/teeth width of the motor stator and mover to understand the best teeth ratio to obtain a high flux density and a high thrust. The analysis is conducted through JMAG software and it is found that the optimum teeth ratio for both the stator and mover gives an increase of 94.4% increases compared to the 0.5mm stator and mover width.

1 Introduction

Electric motors are devices that convert the electrical energy to magnetic energy and ultimately into mechanical energy. Electromagnetism is the basis of motor operation in order to produce the magnetic forces required for the production of rotational or linear motion[1]. As one of the fastest growing industries, electrical motor manufacturing represents a major industry worldwide, where electric motor driven systems account for approximately 45% of total global electricity consumption and are expected to rise to 13,360 terawatt hour (TWh) by 2030[2]. Recent developments in the industry have brought forth linear machines that provide mechanical translation without intermediate gears, screws or crankshafts. In a linear motor, either the moving or stationary member must extend over the entire range of motion of the moving member[3]. The motion occurs because of the electromagnetic force developed in the actuator. All types of motor configurations and topologies can be produced in the linear fashion, i.e. dc, induction, synchronous and reluctance[4]. Linear electric machines are associated with long linear progressive motion, such as transportation and other similar applications. The most prominent application of linear motors is the utilization of these motors in transport systems, specifically railway system in the use of train thrust and in braking [5]. Linear reluctance motors are popularly used in electrodynamic braking of high-speed trains. These brakes

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operate on the principle of converting the traction motors of the train to a generator that convert the kinetic energy of the train into electrical power [6]. To overcome the problem of adhesion between the wheel tread and the rail, the braking force in electromagnetic brakes are achieved through strong magnetic forces that are induced with large electromagnets attached to the vehicle over the top of the rails [7]. In Electromagnetic rail brakes, the frictional forces are produced between the electromagnets and the rail [8]. If the electromagnetic fields generate eddy currents in the rails, creating forces acting in the opposite direction of the movement of the train, it is a linear eddy current brake system. However, these brake systems are still susceptible to the cogging effects of the permanent magnets due to the magnetic retention, which greatly reduces the efficiency of the motor [9]. A linear reluctance motor that does not utilize permanent magnets have been introduced, thus minimizing the cogging force and decreasing the weight of the linear motor. The objective of this paper is to study the different teeth ratios of the linear reluctance motor and to propose a ratio for the best thrust/force characteristic.

2 Literature Review

Linear Electric Machines are in general three-phase machines fed through power electronic controllers and taking advantage of regenerative electric braking for fast, robust, and precise thrust, speed, or position control. The topology of a linear switched reluctance motor is similar to that of a stepping motor with variable reluctance platen. In addition, it is equipped with position sensors [10]. The turn-on and turn-off instant of the input current is synchronized with the position of the moving part. The thrust is very sensitive to the turn-on and turn-off instant. In these type of motors, the rotor tends to move to a position where the inductance of the excited winding is maximized or the reluctance is minimized.

In the case of a linear stepping or linear switched reluctance motor, the speed υ of the moving part is as in Equation (1).

$$v = v_s = f_{sw}\tau \tag{1}$$

Where f_{sw} is the fundamental switching frequency in one armature phase winding and τ is the pole pitch of the reaction rail. For a rotary stepping or switched reluctance motor $f_{sw} = 2p_r n$ where $2p_r$ is the number of rotor poles and n is rotational speed in rev/s. The fundamental energy conversion equation for linear electric machines is as in Equation (2).

$$F\dot{x} = vi \tag{2}$$

Where F is mechanical force (N), $\dot{x}$ is mechanical velocity (m/s), v is the Voltage (V), and i is current (A). It is assumed that F and $\dot{x}$ are in the same direction. Numerous studies have been conducted into increasing the thrust of these linear motors such as, [11] where slots are used to decrease harmonic components of the thrust force. These slots can be in the form of skewed or fractional slot [12]. This allows the analysis of rated performance calculation and effects such as cogging torque, ripple torque, back-emf form prediction. Analysis which combines the orthogonal optimization algorithm for tooth shifting and pole shifting of a double-sided slotted permanent magnet synchronous linear motor are carried out in [13]. This study achieves a model with a suppressed thrust ripple which in turn increased the efficiency. A 9-pole 10-slot structure of a short primary permanent magnet

LSM is proposed in N. Bataar et.al. which is focused on reducing the cogging force through detent force minimization by optimizing the length of armature core and shape of the exterior teeth simultaneously by using (1+lambda) evolution strategy coupled with response surface method using multi-quadric radial basis function [14]. Other studies are focused on establishing a platform for the analysis and test of characteristics such as thrust ripples and detent force of the permanent magnet linear motor [15]. It is predicted that thrust ripples are generated by the distortion of the stator flux linkage distribution, reluctance force due to the relative position between the mover and stator, Y. Zhu et.al. aims to rectify this through the utilization of predictive control algorithm [16], which result in the minimization of the voltage ripple by high precision control. The same result is obtained through moving node techniques in research conducted by Ki-Chae et.al [17]. Linear Motor Systems which has electromechanical multi-parameter and strong coupling is difficult to control. W. Ai et.al proposes an analysis of relative weights of various factors for thrust fluctuations in permanent magnet LM [18], using the fuzzy analytic hierarchy process to reduce these fluctuations in the thrust. It can be seen through these research that the cogging force deteriorates the performance and even excite the mechanical resonance thus decreasing the efficiency and also the lifespan of the motor [19]. This paper look into the teeth size variation for obtaining the highest force in the mover and the stator of the linear motor [20]. The paper outline the method of analysis and then propose the results of the study, finally discussing the results and propose a ratio for the best stator and mover teeth gap for a linear reluctance motor based on the results of the study.

3 Methodology

Three basic structures; the stator, which is the stationary nonmoving part, the mover, which consists the coil and is the linear translation component are studied. Figure 1 shows the arrangement of the structure. The parameter that is to be studied is the teeth gap of both the stator and mover to show which is the best ratio of teeth width gap for obtaining the highest thrust from the linear motor. Figure 2 below shows the parameter to be studied while figure 3 gives an in-depth analysis for obtaining the ratio.

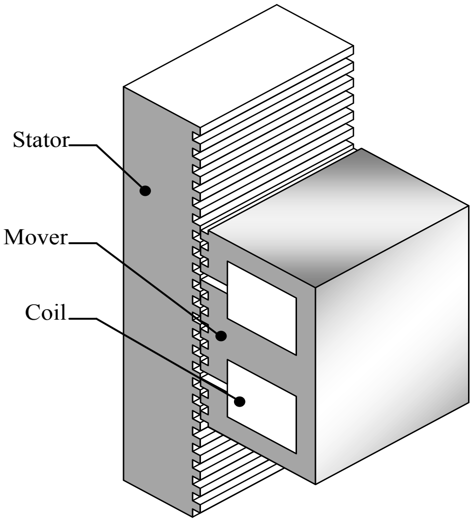


Fig. 1. The Linear Reluctance Motor.

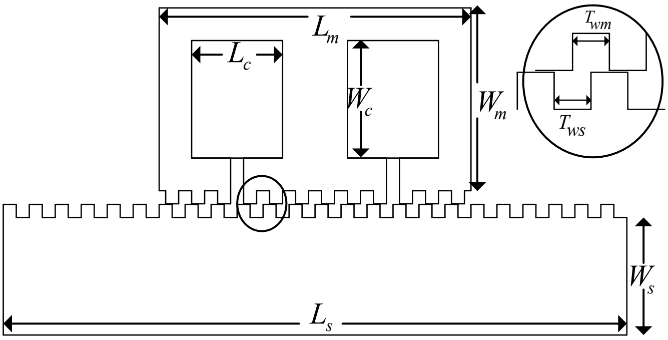


Fig. 2. Parameter to be studied

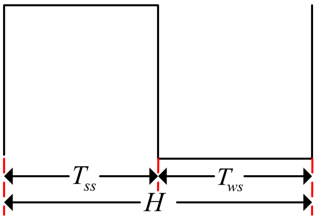


Fig. 3. Teeth ratio

As seen from figure 3, the total pole width of the motor is to be kept constant at 4mm therefore, the teeth gap for the stator is denoted in equation 3.

$$H_s = T_{ss} + T_{ws} \tag{3}$$

where, H_s is the total width of the pole and T_{ss} is the gap where the tooth protrudes and T_{ws} is the dip in the teeth. The parameter T_{ws} is then changed while keeping H_s constant. The same parameter for the mover's teeth are also varied to obtain the best ratio for the teeth and the combination of the ratio of the teeth in both stator and mover to obtain the highest thrust. The dimensions of the stator and mover are summarized in Table 1. The simulations are run on FEM software JMAG. The parameters used for the coil is 330 turns with a total resistance of 4.6Ω. The material and circuit parameters are kept constant for the whole analysis. A total of 49 simulations are carried out with different combinations of T_{ws} and T_{wm}

Table 1. Parameter List

Parameter	Sign	units	Value
Length of stator	$\boldsymbol{L_s}$	(mm)	96
Width of stator	$\boldsymbol{W_s}$	(mm)	18
Teeth height of stator		(mm)	2
Length of mover	$\boldsymbol{L_m}$	(mm)	48
Width of mover	$\boldsymbol{W_m}$	(mm)	28
Teeth height of mover		(mm)	2

Length of coil	$\boldsymbol{L_c}$	(mm)	14
Width of coil	$\boldsymbol{W_c}$	(mm)	18
Number of turns in coil			330
Resistance of coil		Ω	4.6

4 Results and Discussion

The analysis is run using JMAG software, in order to obtain the flux lines, magnetic flux density, an absolute force of translations and other parameters. For this study, the force in the Y direction of the motor is considered, since the increase in the force shows the decrease in cogging force which shows an increase in the efficiency of the motor. As seen in figure 4, an increase in the teeth width of both the stator and the mover, increases the absolute force to a certain point, however, further increase shows a decrease in the force that is generated. This can be seen in all of the stator teeth width measurements from $0.5T_{ws}$ to $3.5T_{ws}$. The force in Y direction of $0.5T_{ws}$ increases from 24N to 63N at $2.5T_{ws}$ and then decreases to 52N at $3.5T_{ws}$. This effect is better illustrated in Figure 5. As seen the force increases with an increase in the teeth gap showing that the magnetic flux density increases. This is because as the teeth gap T_{ws} increases the, extruded part of the teeth which is the T_{ss} decreases, since total teeth width H_s is kept constant. This decrease in T_{ss} decreases the surface area of extrusion, thus forcing the magnetic flux to be concentrated, increasing the density and hence increasing the force. However, a further increase of the gap from $3.0T_{ws}$ decreases the force since the extruded part of the teeth T_{ss}, is too small and the magnetic flux leaks from the teeth gap as shown in figure 6. This leakage decreases the density of the magnetic flux thus decreasing the force of the motor. The same effect can be seen for the mover teeth width T_{wm}, for which the force increases from 47N at 3.5 T_{wm} to 52N at 3.0 T_{wm} and then decreases to 19N at $0.5T_{wm}$ at a constant stator teeth width of 3.5 T_{ws}. Based on these results it is best to identify which ratio of teeth width for both the stator and the mover provides the highest force, thus increasing the efficiency of the motor. The highest force obtained for each stator width is illustrated in figure 7. As shown by the curve in figure 7, the highest absolute force for the motor design is at 463N which is achieved at $2.5T_{ws}$. The graph also shows that the best teeth width for the mover is at 3.0 T_{wm}, since all of the maximum force for the stator is achieved at this teeth width. However, motor the design should also take into consideration the manufacturing process and the materials required. The 2.5mm teeth width is better since this decrease the material costs for the motor production.

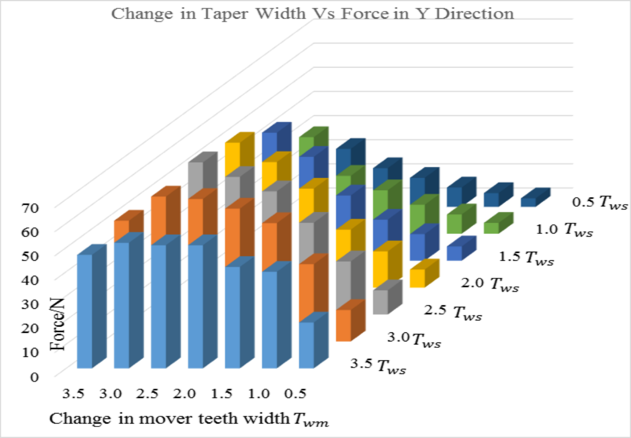


Fig. 4. Analysis of the taper width of stator and mover based on absolute force

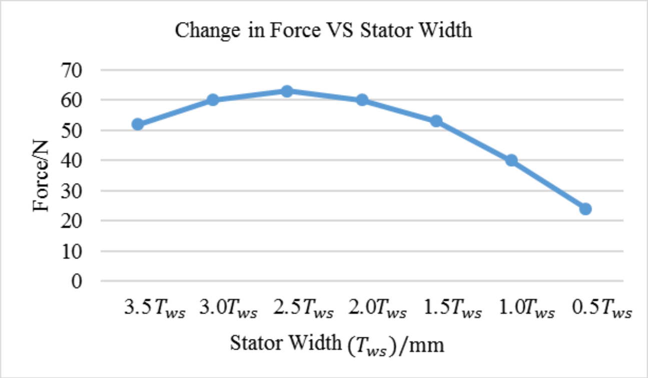


Fig. 5. Change in Force with Change in Teeth Width

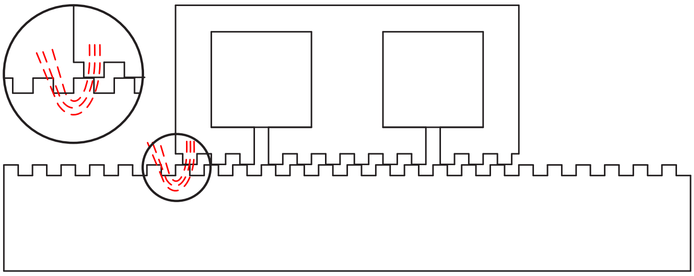


Fig. 6. Leakage of magnetic flux

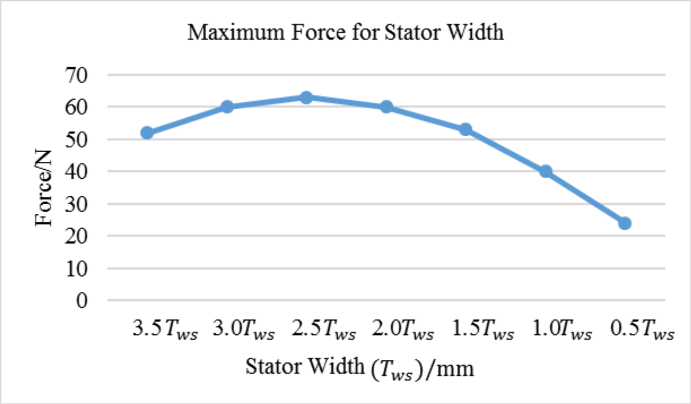
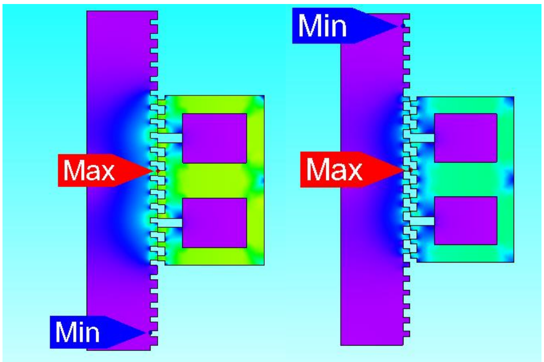


Fig. 7. Maximum force for each stator width.



(a) Flux density at 1.5T_{ws} at 3.0T_{wm}

(b) Flux density at 2.5T_{ws} at 3.0T_{wm}

Fig. 8. Flux Distribution for 1.5 T_{ws} and 2.5 T_{ws}

The flux density for this size is also the best since there the distribution is more uniform and the motor shows areas of lower flux concentration which shows that continuous operation of the motor is stalled due to excessive heat buildup in the body which result in a lower life span for the motor. The comparison of the flux density for the motor is shown in figure 8. Based on these results it can be seen that the best stator tooth width is 2.5mm for T_{ws} and the mover teeth width is 3.0mm for T_{wm}. Both of these ratios provide an increase in 94.4% force compared to 0.5mm for both the stator and mover, and a 25.4% increase compared to 3.5 mm teeth width for both the stator and mover.

5 Conclusion

Linear motors are used for different applications and are gaining popularity in the transport industry mainly in railway systems. The main disadvantage of the current motor types is the cogging force by the use of permanent magnets, and voltage ripple which decreases the thrust force of the linear motor. This study aims to analyze the effects of the linear reluctance motor's taper width of both the stator and mover to identify the best ratio of teeth gap to obtain the highest force values. The analysis is done through the software JMAG, by changing the parameters of the teeth gap while keeping the other parameters such as motor dimensions, materials, circuit, coil resistance and a number of turns constant. The teeth gap of stator T_{ws} and mover T_{wm} is changed to obtain the results. As seen from the analysis the best results for the teeth gap can be found at $2.5T_{ws}$ and $3.0\,T_{wm}$ which gives an increase of in 94.4% force compared to 0.5mm for both which is the lowest teeth width that both the stator and mover can achieve. Further analysis and studies can be conducted by changing the teeth shape and obtaining the optimum teeth shape for increased thrust, a decrease in cogging force, and higher efficiency.

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