Inductance variations on performance of linear reluctance accelerators and appropriate selecting of projectile to increase launcher performance

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ABSTRACT

Linear reluctance motors have many applications due to their simple structure.A set of them are linear reluctance accelerators .These motors have simple structure and yet are difficult to design. One of the important parameters in such motors is inductance and its variotions during displacement of the rotor. This paper has examined inductance calculation methods and the way of changing inductance regarding to rotor dimension and has compared the results by femm software. Also it has been shown that calculation relation between force and inductance variotions can be generalized regardless of the length of the coil and the rotor. By increasing the length of the rotor , maximum inductance will increase and rotor output speed will decrease.It is shown that , a slight increase in the length of the rotor will improve performance.

Keywords: Inductance variotions, rotor,femm software,coil

1. INTRODUCTION

Various applications of linear motors have long been the main cause of paying attention to such motors [1],[4]. Linear motors have different types that can be cited to reluctane type. These motors with their simple structures have allocated extensive uses to themselves. A type of linear reluctance motors, are reluctance accelerators [4],[6]. These accelerators that work based on the path reluctance changing and because of its simple structure has been the subject of attention. Reluctance accelerators are formed of both the stationary (stator) and a movable part(rotor). Motor stator is formed of a magnetic coil on a non-magnetic cylindrical tube. Motor rotor or the same projectile that make the linear displacement within the stator is made of a steel material with magnetic properties. The rotor of these motors is lack of any kind of windings and therefore can be used in different environments with high reliability possess. On the other hand, existence of backward and forward forces together causes the engine design difficult and requires a careful design in this regard. In these engines generating force acting on the projectile is very important. This force is directly related to the amount of the inductance variotions according to relation (1) [2].At [6] inductance variotions and maximum force is studied in case of the rotor's and stator's dimensions are equal. Obtaining the inductance variotions is of necessary points at these motors. For this purpose, at the paper , variation of inductance and obtaining maximum inductance based on the dimensions of the rotor for accessing maximum efficiency will be examined

$$f = 0.5\ i2\ dL\ dx \qquad (1)$$

1.1 Calculation of inductance and its variation

Clearly, when the rotor is compeletly out of the stator, inductance of the system has its minimum value and by positioning the rotor within the stator completely,the inductance reaches to its maximum value. In the first case means there is no rotor,system is a coil or an inductor with air core which has N turns winding. So it is neccessory obtain the inductance of an air core inductor. For this a variety of equations is available of that, equations of refrences [5]-[7] can be mentioned. To get the inductance of an air core inductor as shown in Figure 1, equations (2), (5) or (6) can be used.

$$L = \varphi d N^2 (\mu H) \qquad (٢)$$

Where N is the number of windings, d is the average diameter, φ is equal to:

$$\varphi = \frac{0.1\,\pi^2}{0.45+\alpha+\rho+(2/3)\alpha\rho[(\alpha+1)/(\alpha+2)]} \qquad (٣)$$

That:

$$\alpha = \frac{l}{d} \text{ and } \rho = \frac{c}{d}$$

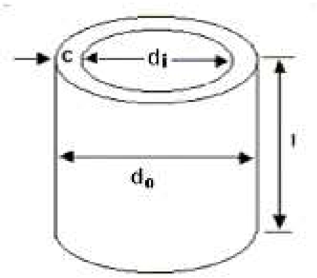

Figure 1. A view of an air core coil

$$L = \frac{\mu_0 \times N^2 \times r^2 \times \pi}{l} \times \frac{1}{1+0.9r/l+0.32c/r+0.84c/l} \qquad (٤)$$

In (4), c is coil thickness, l is the length of the coil and r is the coil average radius.

$$L = \frac{0.0315\,N_m{}^2 r^2}{6r+9l_m+10c} \qquad (٥)$$

Wheren L_m is the length of magnetic path , N_m is:

$$N_m = N_1 \cdot N_2 - \frac{1}{2}N_2$$

Calculated inductance by each of these equations is the same minimum inductance. By calculating the minimum, with coming the rotor into the stator,the inductance starts to rise that its variotions can be considered according to reference [3] the same as Equation 6.

$$L = L_m\left(1+\cos\left(\frac{\pi}{l}x\right)\right) + L_{min} \qquad (٦)$$

That:

$$L_m = \frac{L_{max} - L_{min}}{2}$$

x indicates the position of the rotor within the stator (Fig. 2). If the rotor is perfectly placed within the stator, the value of x will be considered null and l is the length of the rotor, which is equal to the length of the stator. Reference [8] is considered equation (7) as a way of changing the reluctance motor inductance.

$$L = L_{min}\left(\frac{k}{l^2}(l-|x|)^2 + 1\right) \qquad (٧)$$

That:

$$k = \frac{L_{max}}{L_{min}}$$

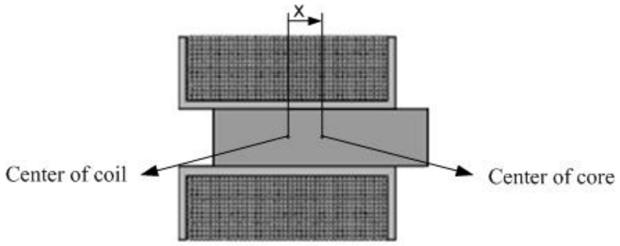

Figure 2. The position of the rotor within the stator

Observed that in both equations (6) and (7) the minimum and maximum inductance value must be entered.The method of calculating the minimum inductance regarding to represented equations has been specified and just maximum inductance in where the rotor is completely placed within the stator must be obtained.For the coil of figure 3 with a magnetic core reference [9] is provided equation (8) to obtain the inductance.

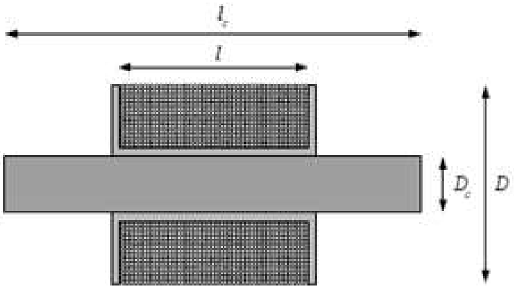

Figure 3. A view of a coil with magnetic core

$$L = N^2 \cdot \frac{\mu_0 \cdot \mu_c \cdot A}{l_c} \cdot \left(\frac{l}{l_c}\right)^{-3/5} \qquad (٨)$$

In this equation , μ_c obtains according to equation (9).

$$\mu_c = \frac{\mu_r}{1+n(\mu_r - 1)} \qquad (9)$$

In the recent equation μ_r is relative permeability coefficient and n is the core anti-magnetic coefficient that is related to the length (l_c) and the diameter (D_c) of core (rotor) and according to (10) is obtained.

$$n = \frac{{D_c}^2}{{l_c}^2}\left(ln\frac{2l_c}{D_c} - 1\right) \qquad (١٠)$$

Also (11) can be used.

$$L = \frac{N^2 \mu_c A}{l} \qquad (١١)$$

where μ_c called the effective permeability and can be achieved from(12) [11].

$$\mu_c = \frac{\mu_0 \mu_r}{1+\frac{\mu_r l_g}{l_c}} \qquad (١٢)$$

Where l_g is the length of the air gap and l_c is the length of magnetic path.For the sample coils of table 1 results of inductance calculation is shown in table 2 and are compared using femm software.

Table 1. characteristics of the studied coils

Number of turns per layer NL	Number of layers NL	Coil length mm	Outer radius mm	Inner radius mm	Copper wire radius mm	Coil No.
٤٩	٧	٥٢	١٥	١٠	٠.٥	١
٣٠	٧	٣٠	٢٣.٥	١٥	٠.٥	٢

Table 2. inductance of coils with iron rotor(core)

Femm	Equation 11	Equation ٨	Coil No.
٥.٦	٢٨.٦	١٧٧	١
٤.٤٧	٦٥.٣	٤٧٠	٢

Regarding to obtained results of table 2 it is shown that the obtained results of equation 8,11 have high errors and these equations can not be used for calculating inductance of iron core coils. In [4] it is shown that the way of inductance variotions by changing the position of the iron core (rotor) is the same as Equation 6. Practical results and femm analysis for calculating the inductance of the coil number one is given in Table 3.

1.2 Effect of core (rotor) length on inductance

Table 3. Results of the calculation of inductance coil No. 1 with 52 mm iron core at various locations of core placement

practical	femm	The position of the rotor inside the coil x
١.٠٤	١.١٨	-٥٢
١.٣٨	١.٧٠	-39
٢.٤٨	٢.٩٦	-26
٣.٨٣	٤.٦٣	-13
٥.٣٥	٥.٦٠	٠

From the results in Table 3 it is observed that the maximum inductance happens , when the dimensions of the rotor and the coil is equal , where the rotor is placed entirely inside coil. Simulation results of inductance variotions are given once again in Table 4 assuming one time rotor is two times longer than the coil length and another time is half of it.

Table 4. Results of the calculation of inductance coil No. 1 with 104 mm iron core at various locations of core placement

rotor length 26mm		rotor length 104mm	
femm	The position of the rotor	femm	The position of the rotor
١.١	-52	١.١٨	-78
١.٦	-39	١.٨٠	-65
١.٨	-26	٣.٤	-52
٢.١	-13	٦.١	-39
٢.٣٦	٠	٩.١	-26
		١١.٢	-13
		١١.٨	٠

From the results in Table 4 it is observed that when the rotor length is more or less than coil length,maximum inductance happens when the center of the rotor is placed in the center of the coil.Maximum inductance of coil No. 1 with rotar length equal to coil length is 5.35 milli Henry. By using a rotor larger than the coil length , it is observed at figure 4 that maximum inductance increased from 5.35 to 6.43 milli Henry.

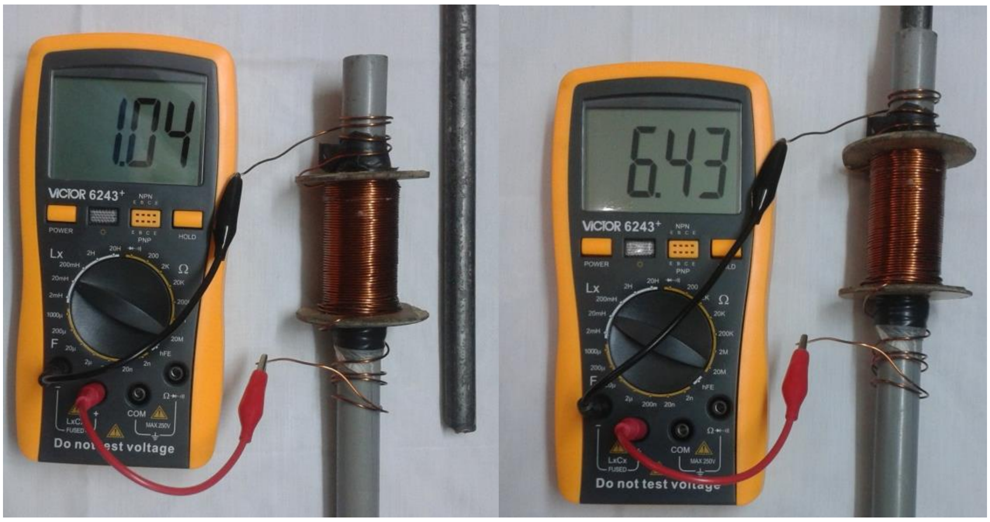

Figure 4. increasing coil inductance using a rotar longer than the coil

How changing the maximum inductance of the coil No.1 by changing the length of the rotor is given in Table 5.It is observed that by increasing the maximum length of the rotor, inductance and its variations also increases.

Table 5. Results of calculation of coil rotor No.1 inductance with different lengths

$\frac{\Delta L}{\Delta x}$ *H/m*	maximum *inductance mH*	Rotor lengthn *mm*
٠	١.١	٠
٠.٠١٢	١.٥	١٣
٠.٠٣٢	٢.٣٦	٢٦
٠.٠٨٢	٥.٣٥	٥٢
٠.١٢	٨.٩	٧.٨
٠.١٣٧	١١.٨	١٠٤
٠.١٥٠	١٦.٧	١٥٦
٠.١٥٤	٢١.١٨	٢٠٨

The inductance variation in different positions of the rotor is according to Equation 6. In this equation l is the coil or rotor length that are equal to each other. In other words, when the rotor and coil lengths are equal to each other this equation can be applied. For this studied sample when the coil length is 1 and is equal to its rotor, inductance variotions' diagram in x by the equation 6 and femm software is plotted below.

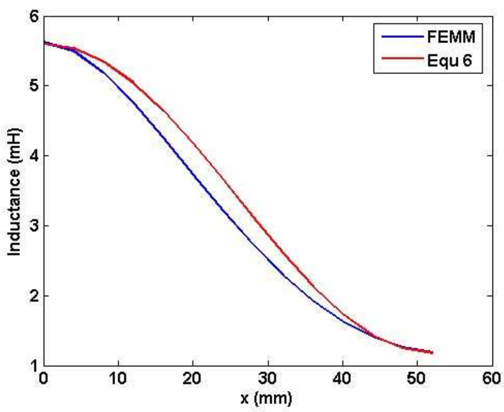

Figure 5. The inductance variotions for position of the rotor(rotor length 52 mm)

Changing the inductance of the coil 1 with rotor length of 104 mm simulated by femm software is in figure 6.

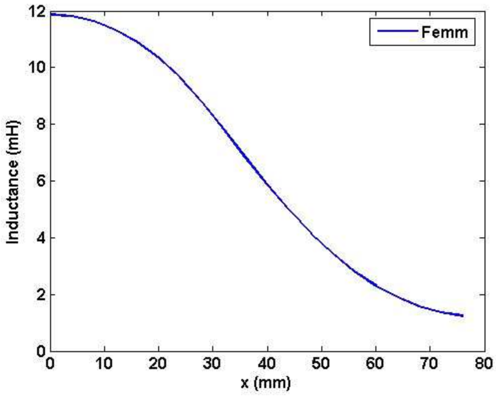

Figure 6. The inductance variotions against position of the rotor(rotor length 52 mm)using FEMM

From Figure 5, it is observed that the inductance variotions for different rotor positions , when it is longer than the the coil , is also similar to a cosine curve. By changing the definition of l in Equation 6 it can be shown that this variotion is as the cosine function but l is the sum of the half length of the rotor and half length of the coil. By the same difination of l, the same equation can be used to show inductance variotions of coil for different rotor positions , when the rotor is smaller than the coil .Figure 7 shows variotions for 104 mm rotor length with femm software and equation 6 ,Figure 8 shows these variotions for the rotor with a length of 20 mm.

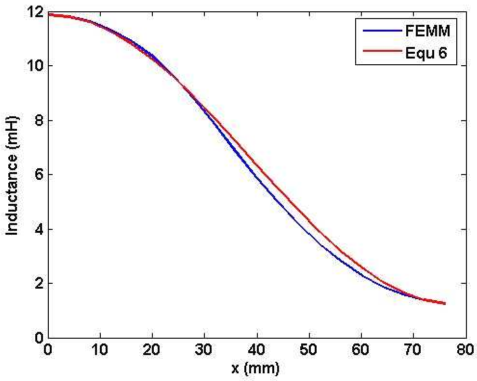

Figure 7. inductance variotions against different rotor positions(rotor length:104 mm)

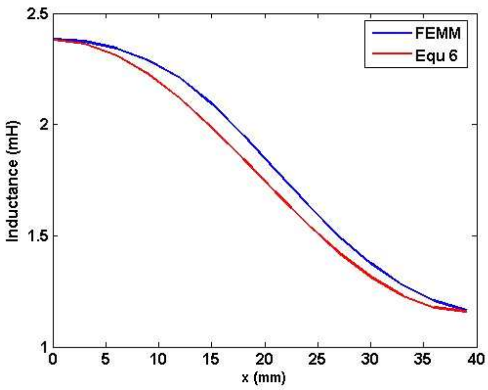

Figure 8. inductance variotions against different rotor positions(rotor length:20 mm)

3.Energy

Equation (1) shows the force exerted on the rotor of a linear reluctance motor. For a constant current to obtain the maximum force it is better that inductance variotions have more intensitivity. It was shown that by increasing the rotor length,the inductance variotions also increase and cause the force on the rotor to be increased. On the other hand, increasing the length of the rotor associated with an increase in mass and according to equation 13 force exerted on the rotor is directly related to its weight and acceleration . By putting equation (1) and (13) equal , and assuming the current is constant , there will be:

$$f = ma \qquad (١٣)$$

$$f = ma = 0.5\, i^2 \frac{dL}{dx} \rightarrow a = 0.5 i^2 \frac{\frac{dL}{dx}}{m} = k \frac{\frac{dL}{dx}}{m} \qquad (١٤)$$

At constant current the inductance variations are not greater than the weight variotions,So it reduces the acceleration and speed of the rotor. Typically,by increasing the rotor length from 52 mm to 104 mm , rotor weight will become twice heavier and the inductance variotions will become 1.67 times more than before . So fraction (dL / dx) / m is equal to 0.83 and acceleration has declined 17% compared to the initial state.Table 6 shows the velocity and acceleration variotions against the length of the rotor.

Table 6. Proportion of acceleration and inductance variations over the length variotions

Proportion of decreasing the acceleration	Proportion of inductance variotions	Proportion of increasing the rotor length (coil length and primary of rotor 52mm)
۰.۵۸	۰.۱۵	٤/١
۰.۷۸	۰.۳۹	٢/١
١	١	١
۰.۹۷	١.٤٦	٢/٣
۰.۸۳	١.٦٧	٢
۰.٦	١.۸۳	٣
۰.٤۷	١.۸۸	٤

From table 5 we can understand that by increasing the length of the rotor, the inductance variotions increase but because of increasing the weight of the projectile, it generally causes reducing output speed of the rotor. So the maximum acceleration happens when the coil and the projectile are equal in length. When the projectile is exiting if the coil current is not zero,backward forces cause the output speed to be reduced.It is clear that getting current to zero in a moment is practically impossible so the backward forces would be created.But if the rotor length considered a little longer than the coil,the speed decrease will not have a significant difference, and more time is in hand to approach the coil current to zero , so the backward forces at the moment of exiting the rotor will vanish and they can not cause the rotor speed to decrease a lot. From the table 5 it is clear that, typically if rotor length considered 1.5 times longer than the coil ,acceleration will only 3 percent decline which have little effect on output speed but grant the required time for approaching the coil current to zerro. With new definition of l in equation 6 and the result of equation 1 the force exerted on the rotor can be obtained from equation 15.

$$f = -0.5 i^2 L_m \frac{\pi}{l} \sin\left(\frac{\pi}{l} x\right) \qquad (15)$$

1.3 Conclusion

Rotor dimensions have changed the way of inductance variations and due to the fringing of the flux , the time to time of the rotor movements affect the inductance variotions, and by increasing the length of the rotor these variotions increase. It is shown that some equations are valid only when the rotor and coil are equal to each other in length. Therefore, by changing the length definition , that equations have been generelized and so these equations can be easily used for showing the way of the inductance variotions and force exerted on the rotor , regardless of dimension variotions of the rotor and coil. Furthermore, it was shown that increasing the length of the rotor reduces the output speed of the rotor and so if the rotor is as long as the coil ,maximum speed will be obtained. Also, if the length of the rotor is considered a little more than the coil length,more time for making coil current zero and elimination of the backward forces without significant changes in speed will be provided.

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