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Research Article

Analysis of the Geometric Parameters for High Thrust Force of the Tubular Linear Voice Coil Motor

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Abstract

Tubular linear voice coil motor has been preferred in linear motion applications in recent years. Because the tubular linear voice coil motor has a high thrust force and a simple driving circuit. The geometric design parameters have different effects to ensure high operating performance, such as high thrust and fast response. In this study, the effects of some selected geometric parameters on the average and instantaneous thrust forces of the motor are investigated. For this purpose, motors designed in different geometric dimensions are compared using the finite element analysis. Thus, a motor geometry with higher thrust force than the first motor geometry has been obtained. In this way, a beneficial approach is presented to the motor model that can provide higher thrust in small volumes.

Keywords: Design, Thrust force, Tubular linear voice coil motor

Borulu Lineer Ses Bobini Motorunun Yüksek İtme Kuvveti için Geometrik Parametrelerin Analizi

Öz

Son yıllarda lineer hareket uygulamalarında borulu lineer ses bobini motoru tercih edilmektedir. Çünkü borulu lineer ses bobini motoru, yüksek bir itme kuvvetine ve basit bir tahrik devresine sahiptir. Geometrik tasarım parametreleri, yüksek itme gücü ve hızlı tepki gibi yüksek çalışma performansı sağlamak için farklı etkilere sahiptir. Bu çalışmada, seçilen bazı geometrik parametrelerin motorun ortalama ve anlık itme kuvvetleri üzerindeki etkileri incelenmiştir. Bu amaçla, farklı geometrik boyutlarda tasarlanan motorlar, sonlu elemanlar analizi kullanılarak karşılaştırılmıştır. Böylece, ilk motor geometrisinden daha yüksek itme kuvvetine sahip bir motor geometrisi elde edilmiştir. Bu sayede, küçük hacimlerde daha yüksek itme kuvveti sağlayabilen motor modeline faydalı bir yaklaşım sunulmuştur.

Anahtar Kelimeler: Tasarım, İtme kuvveti, Borulu lineer ses bobini motoru

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1. Introduction

The tubular linear voice coil motor (TLVCM) is a linear moving electric machine consisting of a cylindrical soft iron, a solenoid coil, and cylindrical permanent magnets (PMs). A simpler winding is used compared to the windings of single-phase or three-phase electrical machines that are widely used in the industry. The windings are wrapped in a cylindrical non-ferromagnetic material. There is no end of winding outside the magnetic field, so copper losses are low. Due to the nature of the linear motion, mechanical losses are also low compared to other electrical machines that rotate. Therefore, it can be said that mechanical loss and copper loss are low [Sun et al, 2018]. On the other hand, the driving circuit is simpler than the driving circuits used in other electrical motors. The average thrust force depends on the air gap magnetic flux [Jiao et al, 2017]. However, it has a considerably greater magnetic resistance than the air gap in the other electrical motors is very large. This is the most important effect on the operation of the TLVCM. Therefore, high current is required for high thrust force and this situation is tried to be tolerated by using high magnetic energy PMs. Looking at the industrial applications of TLVCM, it is seen that it is used in many applications requiring high precision [Hsu and Tzou, 2007; Kim et al, 2004; Wang et al, 2010; Ummaneni et al, 2007; Choo and Park, 2017; Ko et al, 2011].

Electrical machine designs focus on geometric design to provide fast response and high dynamic performance. This is because the most important recommendation in TLVCM designs is to obtain geometry that will provide high average thrust force as well as low thrust ripple. In fact, the most important point in the design is that the air gap magnetic flux is high and uniform [Li et al, 2011; Luo et al, 2020; Luo et al, 2019]. Therefore, the magnetic leakage flux should be reduced [Lemarquand et al, 2010]. In linear operation, as the amount of flux that cuts the winding decreases, the thrust force decreases, which causes an increase in the thrust ripple [Luo et al, 2017].

The TLVCM's geometry is not symmetrical. Therefore, the magnetic equivalent circuit of the motor is also not symmetrical. However, due to the non-linear structure of the motor, the operating performance depending on the load may change. The large air gap opening in the center of purple can cause too much magnetic flux leakage. In this respect, it is difficult to model the magnetic circuit very precisely. Designing the magnetic circuit to include each reluctance of the motor will have a positive effect on the results [Mutluer, 2021]. However, although every reluctance in the magnetic circuit [Luo and Sun, 2019] is important, simplified equivalent circuits are preferred for their ease of calculation [Luo et al, 2019]. The results obtained according to magnetic modeling are compared with finite element analysis (FEA) of the motor. Due to the nonlinear nature of TLVCM, its use as an FEA optimization tool improves results.

In order to obtain high thrust force in TLVCM designs, the study of the motor geometry is of great importance. In this study, the effects of some selected TLVCM parameters (extra yoke, interval of windings/magnets, end-iron and bottom yoke) on average thrust are investigated. The thrust ripple is also studied. For this, the finite element model of the TLVCM is created and other geometric parameters are were accepted as constant.

2. Material and Method

2.1. Structure of the TLVCM

The skeleton of TLVCM is cylindrical. Windings, ferromagnetic cores and PMs are concentric. It is appropriate to choose the windings as pistons in order for the motor to react quickly. 3D view of TLVCM is given in Figure 1. PMs are mounted on the internal yoke. The electromagnetic pole arrangement of the windings is compatible with PMs. In this study, two magnets are used and the direction of magnetic flux is radial. In TLVCM, the two sides of the cylindrical structure are generally not symmetrical, with one side open for motion and the other closed for magnetic flux. The volume of the motor is small, 60mm in length and 44mm in outer diameter as indicated in Table 1.

In order to maintain a consistent output direction of the TLVCM thrust force, linear motion is performed at low pole pitch size [Sun et al, 2018]. In this way, thrust ripple is also reduced. The extra yoke is the core between the bottom yoke and the first permanent magnet. The interval between the windings and the interval between the permanent magnets are the same. The last core part of the piston in the direction of movement is the end iron. Reluctance decreases due to the end-iron and the flux moves towards the end of the motor. The thrust force increases to the point where the winding and PMs meet, then decreases as the amount of winding cut by the air gap magnetic flux decreases.

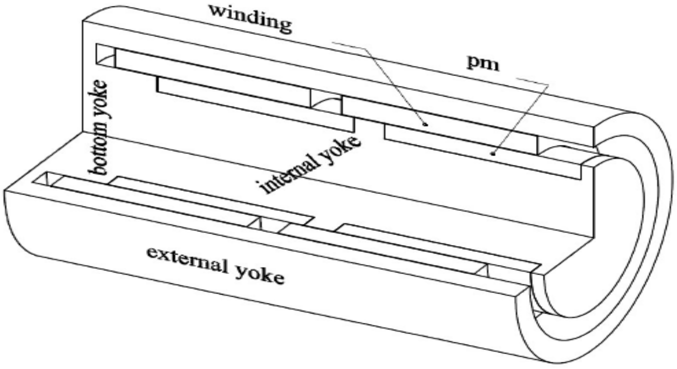


Figure 1. 3D view of the TLVCM

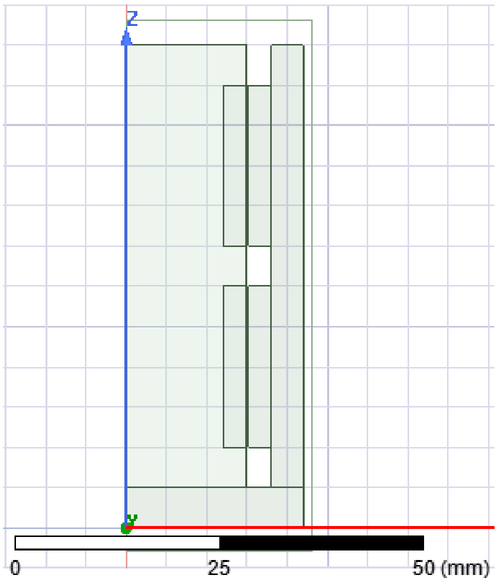


Figure 2. Finite element program image of the TLVCM

2.2. Finite Element Analysis Modelling

Finite element analysis is used in both analysis and design optimization of electrical machines. The most important reason for this is that analytical modeling of electrical machines is difficult due to their non-linear structure. For this reason, finite element analysis has a positive effect on the study results by giving results close to reality. In Figure 2, finite element analysis visual of the starting model of the TLVCM whose design is examined is given.

3. Application of the TLVCM Analysis

3.1. Results

For simplification, some assumptions have been made in advance.

1. The iron material is linear and has a constant material permeability.
2. Magnets and iron material are identical.
3. The drive system is out of evaluation.

Table 1. Geometric parameters and values of the initial TLVCM

Structure Parameter	Value (mm)
Length of TLVCM	60
Radius of TLVCM	22
Radius of winding	16.5
External radius of PMs	15
Width of PMs	3
Length of airgap	3
Length of winding	20
Length of PMs	20
Length of extra yoke	5
Pole pitch	25
Length of bottom yoke	5
Interval of windings	5
Length of end iron	5

The number of windings of the TLVCM is 100, the dc current is 5A and the stroke length is 10 mm. The geometric dimensions of the first designed motor are given in Table 1. Finite element analysis is performed according to the motor values given in Table 1 and the average thrust force of the motor is obtained as 32.7N. Its maximum and minimum thrust forces are 37.1 and 26.5N, respectively. Thrust ripple is 34.2%. The thrust graph is given in Figure 3.

The lower and upper limits and steps of the four geometric variables of the TLVCM are given in Table 2. The most effective output in the operation of the TLVCM is the average thrust force. Therefore, the parameters chosen are the important geometric dimensions that affect the thrust of the motor, according to experience. It should be noted that, air gap size or magnet size are also effective design components. However, in the study, the change in the thrust force depending on the geometry change in the existing air gap and magnet dimensions is investigated. In fact, the situation affecting the thrust force is the change in flux distribution by changing the reluctance of the core. The highest average thrust values obtained for each parameter are given in Table 3.

Table 2. Variables and limits

Structure Parameter	Limits and Steps (mm)
Bottom yoke	1:1:10
End iron	1:1:10
Extra yoke	1:1:10
Internal windings	1:1:10

3.2. Discussion

When the results in Table 3 are evaluated, average, maximum and minimum thrust forces are generally compatible with each other. According to finite element analysis, a motor geometry with average thrust force higher than the starting motor geometry is obtained as 34.76N for 8mm end-iron length. This means that the increased magnetic reluctance at the end of the motor will direct the magnetic flux to the front of the motor, increasing the thrust force. Also, since the stroke length and other parameters of the motor are kept constant, it will be difficult to make a comment depending on the maximum and minimum thrust forces. On the other hand, the fact that the geometry with minimum thrust ripple is parallel to the highest average thrust force geometry increases the importance of end motor reluctance. It is also noteworthy that the best extra yoke length is almost half the stroke length, because in TLVCM designs the stroke length is chosen twice as long as the extra yoke, providing the best thrust ripple [Luo et al, 2017]. The results obtained are better than the initial thrust force, the average thrust force of the motor has improved. Thrust graphs are given in Figure 4 as a result of the TLVCM analysis.

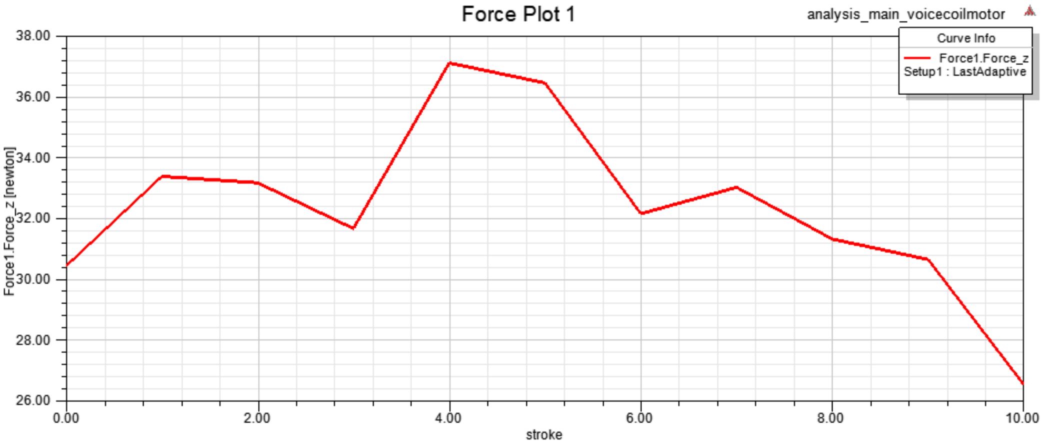
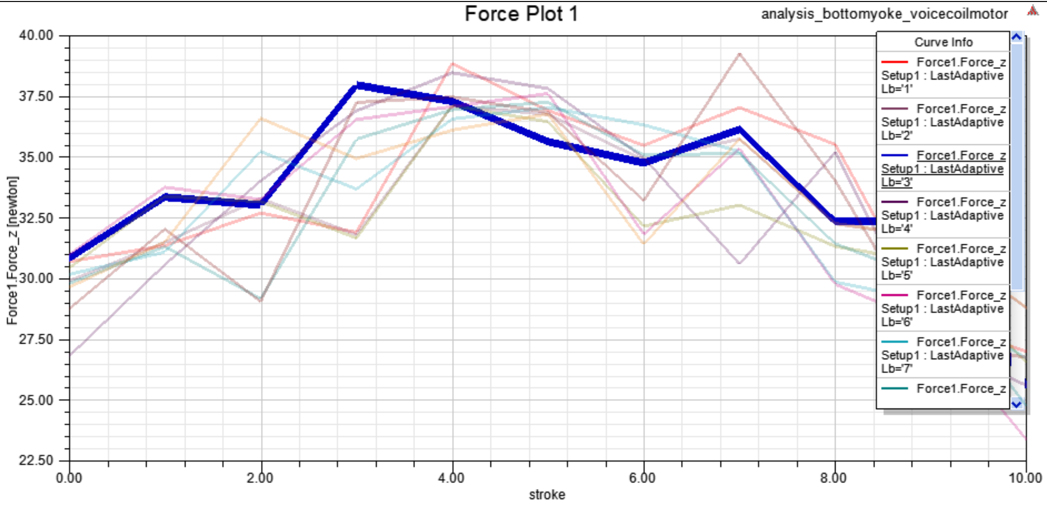


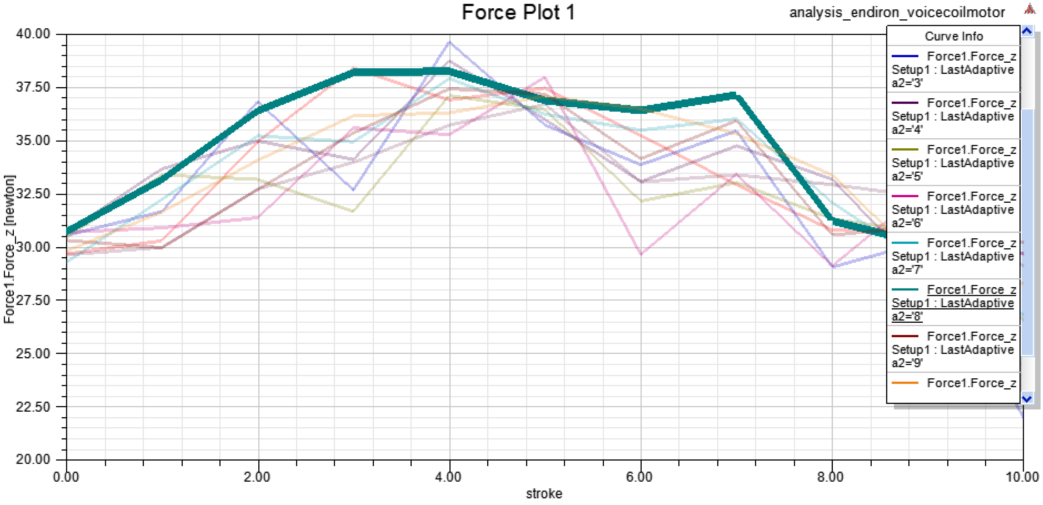
Figure 3. Thrust force graphic of the initial TLVCM

Table 3. Results for Highest Thrust Force

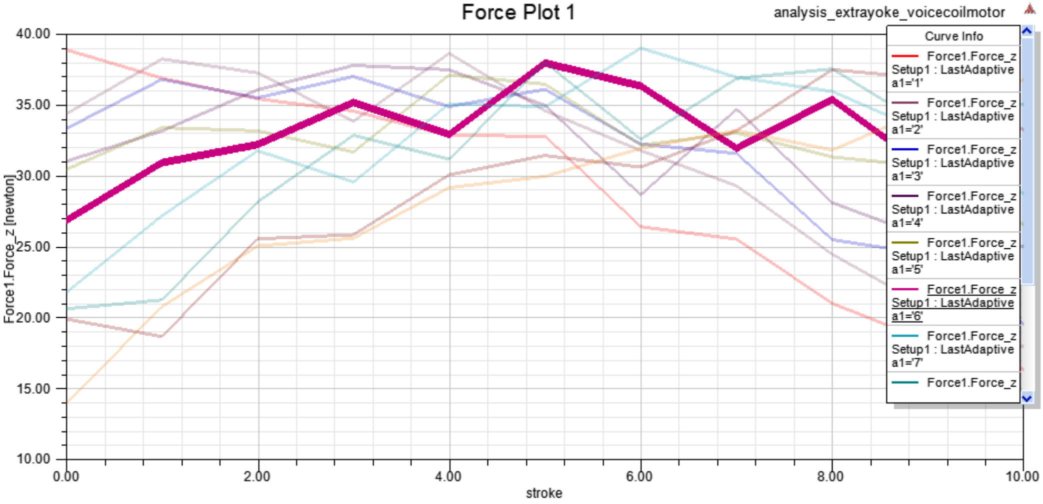
Structure Parameter	$F_{average}$	F_{max}	F_{min}	Thrust Ripple (N)	Thrust Ripple (%)
Initial Values	32.70	37.10	26.50	10.60	32.42
Bottom yoke = 3mm	34.11	37.96	25.51	12.45	36.50
End iron = 8mm	**34.73**	38.24	28.47	**9.77**	28.13
Extra yoke = 6mm	33.08	37.95	26.86	11.09	33.52
Internal windings = 2mm	34.00	39.60	25.67	13.93	40.97



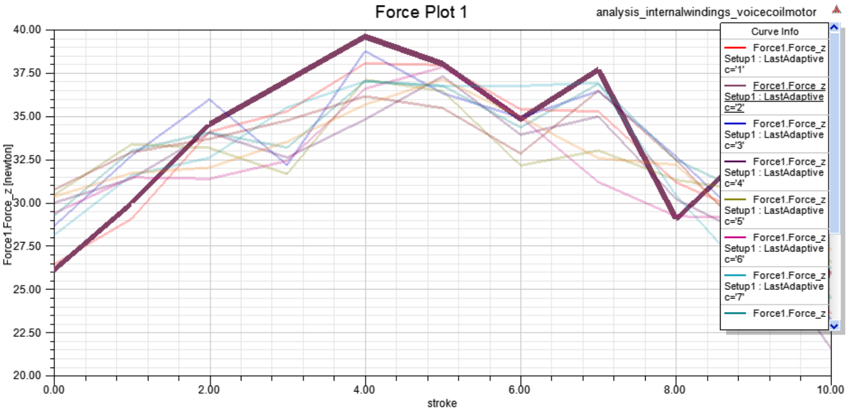
a) bottom yoke



b) end iron



c) extra yoke



d) internal windings

Figure 4. Thrust force graphics of the analyzed TLVCMs

4. Conclusions and Recommendations

The thrust force must be high in TLVCMs, as industrial applications require fast response. In order to achieve this performance in low volumes, geometric design should be done well. In this study, finite element analyzes of the tubular linear voice coil motor are carried out to examine the effect of different geometric parameters on the thrust force. For this purpose, four independent parameters such as extra yoke, interval of windings/magnets, end-iron and bottom yoke are selected as independent variables and other parameters are accepted as constant. As a result of the analyzes, a motor model with an average thrust force of approximately 6.2% higher than the starting motor model is obtained. At the same time, a better thrust ripple is achieved with the motor model obtained.

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