ON THE DESIGN OF OSCILLATING LINEAR SINGLE PHASE PERMANENT MAGNET MOTORS

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ABSTRACT

This paper reports on the design of a linear single phase permanent magnet oscillating motor aimed at application in a domestic refrigerator. An initial prototype has been designed and tested which has allowed the validation of the design techniques used. From this basis the effect of the various design parameters has been investigated. This investigation helps in optimising the cost and efficiency of the design. It is found in this paper that the mover SMC parts can be shaped to reduce their weight. Also the paper shows the influence of the length of the stator teeth on the stroke. Moreover, the simulations show that mover legs can be reduced in length significantly without affecting the force. Furthermore, it is found that changing length between magnets affects the stroke. Also, the paper investigates the effect of changing the length of the stator slot opening on inductance. Finally, the mover thickness effect and the distance between the axis of symmetry and the middle of air gap are investigated in this paper.

Keywords: Linear single phase motors, key dimensions, oscillating motor, linear motor design.

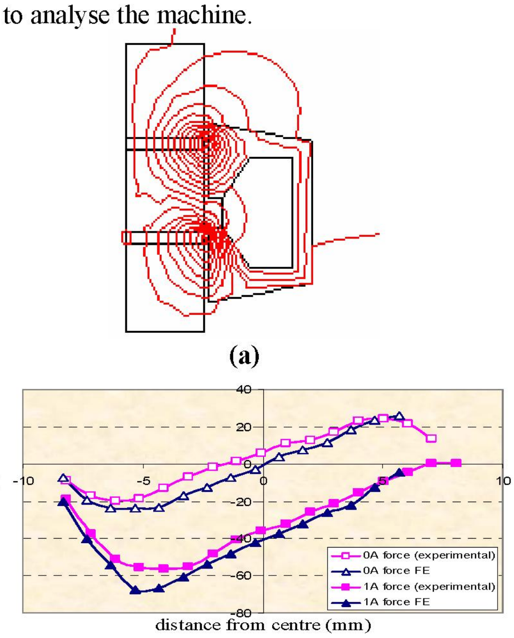
1 INTRODUCTION

Compressors are an integral part of modern life. For instance refrigerators, freezers, air conditioning systems are all based on Carnot cycles comprising compression and expansion. There are various forms of compressor system but probably the most common are based on reciprocating pistons. In the current market place the necessary reciprocating motion is derived from a rotating motor and a crank mechanism. It is clearly attractive to directly drive the piston using an oscillating linear motor since the crank pin and gudgeon pin bearings are removed. There have been moves towards linear motors in the market place using single phase permanent magnet machines [1]. These systems are equipped with spring systems to make them mechanically resonant at the supply frequency. The net result is a system which will self start and can be driven using simple voltage magnitude control techniques. In these machines the stator core carries oscillating fields and hence they need to be subdivided to avoid high eddy current loss. Using laminations to achieve this subdivision requires that the laminations lie in a radial/axial plane which causes difficulties in construction due to the unnatural requirement for a varying lamination thickness which is proportional to radial position in the core. This application provides a good application for Soft Magnetic Composite (SMC) which is formed from compacted insulated iron powder which is ideally suited to three dimensional geometries of this type [2].

This paper reports on the design of a linear single phase permanent magnet oscillating motor aimed at application in a domestic refrigerator. An initial prototype has been designed and tested which has allowed the validation of the design techniques used. From this basis the effect of various design parameters has been investigated.

2 INITIAL PROTOTYPE

The geometry considered here employs a single phase winding in the form of a simple hoop coil. The stator is formed from two hollow rings pressed from SMC. The rotor uses a flux concentrating buried magnet arrangement using two magnets which are simple rings magnetised in the axial direction [3]. The geometry is shown in Fig. 1 (a) which shows a solution from the axi-symmetric finite element model which has been used to analyse the machine.



(a)

(b)

Figure 1: initial prototype; (a) geometry of the initial prototype motor in FE, (b) force against position from experimental and FE analysis.

The static force from this prototype has been tested and is compared with the calculated finite element results. As can be seen from Fig 1 (b) the comparison is good lending confidence to the design methods used.

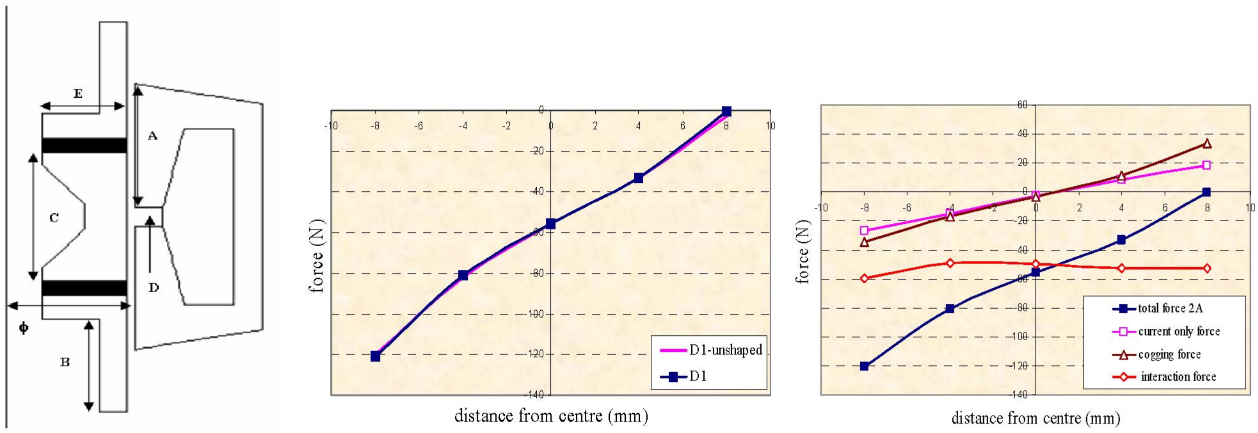
From the force-position graph in Fig. 1(b), it is obvious that this prototype can be efficiently used over a 12 mm stroke as the relation between force and position linear from downward 6mm position to the position of 6mm upward. If the mover goes downward beyond 6mm the, curve goes to zero and the relation is not linear anymore. Consequently, the average force will be reduced. For applications of strokes more than 12 mm, the design should be modified. Theoretically, the length of the stator teeth should equal to double the stroke plus the magnet depth in addition to some margin. Hence, for 16mm stroke, which is commonly used in the compressors of modern domestic refrigerators as in [1], the initial prototype design would need to be modified by increasing the stator length. Also to have a maximum stroke, the two magnets should leave each stator tooth at the same time. Consequently, the distance between the magnets should be equal to the length of one stator tooth plus the length of the slot opening minus the depth of the magnet. Depending on the above theoretical statements, a new model has been developed and simulated in FE.

3 DESIGN STUDY

As may be seen from Fig. 1(b), there is considerable static force acting to centre the mover. This actually is beneficial as it helps reduce the size of the spring necessary. In these machines the key requirements are efficiency and cost. The lighter the mover the lower the size of the spring required and hence the lower the cost hence this is a key design goal, this buried magnet topology has a major advantage over the current market leader [1] in that the magnets are simple rings which are easily magnetised. They do however offer an intrinsically heavier mover. As may be seen from Fig. 2(a), which is a development from the initial prototype, the mover soft magnetic components can be shaped to reduced their weight yet must be simply shaped to keep the SMC pressing costs down. The initial prototype dimensions have been modified to be suitable for 16mm stroke applications and the mover thickness, E in Fig. 2(a), has been reduced by 3.5mm in the new geometry to study the effect of changing the distance between axis of symmetry and the middle of air gap, Φ in Fig. 2(a). Consequently, the average force decreases due to the magnet width reduction. More modification has been done to the mover to reduce its weight by shaping the SMC parts as can be seen from Fig. 2(a). This modification does not have any influence on the force graph as can be seen from Fig. 2(b) as the saturation has been avoided by choosing suitable dimensions.

Different components of force acting on the mover, reluctance or current only force, cogging force, currents-magnets interaction force and total force, along the 16mm stroke have been shown in Fig. 2(c). From the figure, it can be seen that the current-magnets interaction force is almost flat with only a small variation with mover position. It is clear that the reluctance force does not do any work but it enhances the action of the spring.

To examine the effect of the design dimensions, the following key dimensions have been chosen to be investigated in this paper as follows:



(a) (b) (c)

Figure 2: : Modified design; (a) key dimensions in the geometry D1 (b) unshaped and shaped geometry force against position (c) different components of force against position

Table 1: Key dimensions of D1

Section	A	B	C	D	E	Φ
Dimension (mm)	20	14.875	30.75	3	12	17.5

3.1 Length of the stator teeth (A):

In Fig.3, two designs with different stator teeth lengths are shown; the prototype with 14.7mm tooth length and design D1-A with 20mm tooth length. Note that both designs have the same magnet dimensions. The results clearly show that increasing the tooth length increases the effective length of the stroke but the average force falls as the tooth length rises in effect the force x distance relates to the energy storage in the magnets. Clearly, the prototype motor is not suited to 16mm stroke as its force drop away rapidly beyond ± 5mm.

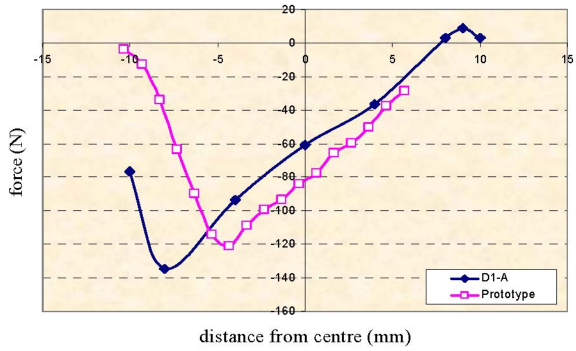
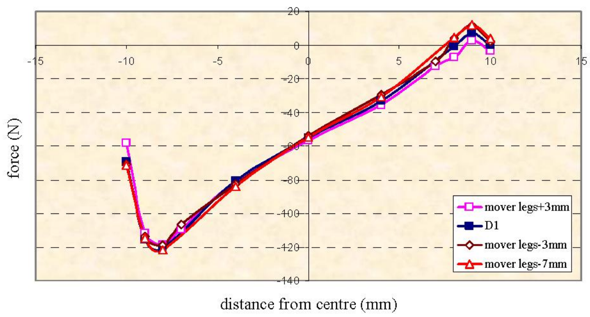


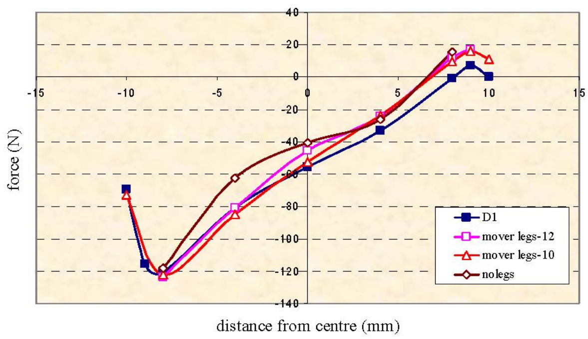
Figure 3: influence of long stator teeth

3.2 Length of mover legs (B):

The length of the mover legs of the original design, which is 14.875mm, can be reduced by 7mm with hardly any reduction in force. However, when it is reduced by 10mm, 12mm or more, the force is marginally affected as can be shown in Fig.4.



(a)



(b)

Figure 4: influence of length of mover legs; (a) 3mm longer and 3 and 7mm shorter (b) 10, 12 mm shorter and without legs

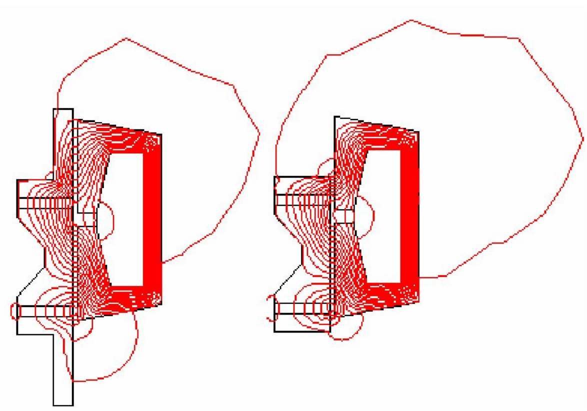


Figure 5: flux in 8mm position for mover with and without legs

Even when the legs are completely removed, the average force is only almost 25% down.

From the flux contours in Fig.5, it is obvious that the flux and hence the force are still high although all of the legs have been removed. This means that the weight of the mover is significantly reduced with only a small force reduction.

3.3 Distance between magnets (C):

By doing many simulations, it can be concluded that the two magnets should leave stator teeth edges at the same time to have maximum average force for a certain stroke. So, at the zero position, each magnet should be exactly at the middle of the stator tooth facing it. Hence increasing or decreasing the distance between the magnets at that position leads to force reduction or shorter stroke as can be seen in Fig.6.

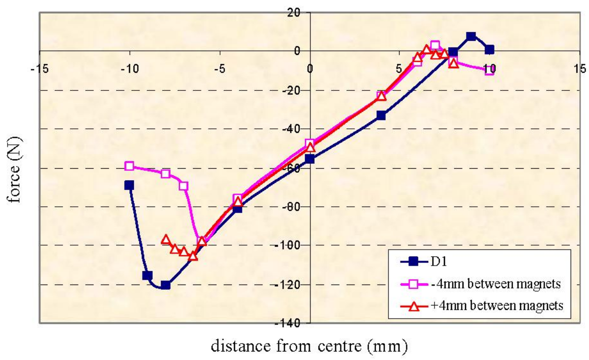


Figure 6: influence of changing the distance between magnets

3.4 Length of stator slot opening (D):

From simulations, it was found that increasing or decreasing slot opening does not affect the maximum average force of a certain stroke keeping the same length of stator teeth. However, increasing the slot opening reduces the inductance as can be shown in Fig.7.

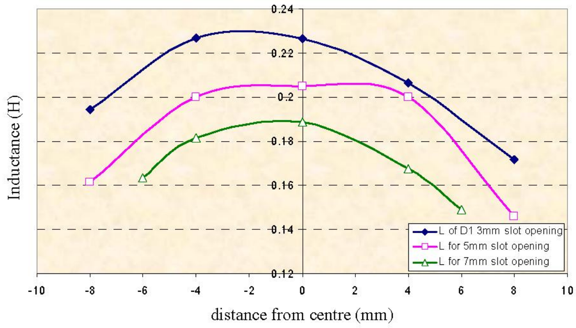


Figure 7: effect of slot opening length on Inductance

3.5 Mover thickness (E):

It is clear from Fig.8 that decreasing the mover thickness by about 22 percent, 3.5mm, causes a reduction in average forces by about 11 percent. This means that the weight of the magnets has been reduced by about 22 percent and the mover weight is accordingly reduced while the force remains high. As the width of the magnet has been reduced, it is expected that the force will be reduced with lower slope which is exactly what happened to D1-C curve in Fig.8.

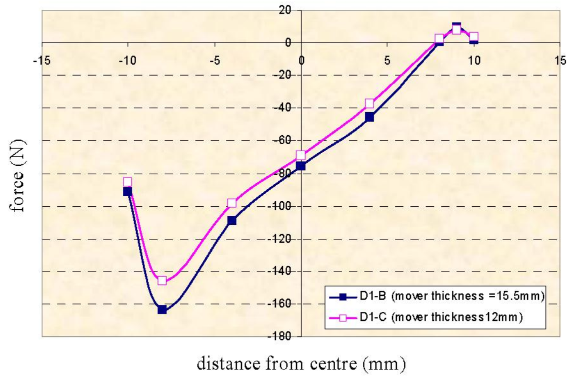


Figure 8: effect of changing mover thickness

3.6 Distance between the axis of symmetry and the middle of air gap (Φ):

The force is proportional to Φ . As a result, the curve of D1-C in Fig.9 is expected to be shifted down, as the interaction force has been increased, and the slope is increased, as the reluctance and cogging forces have been increased. This is what can be seen from the FE results in Fig.9.

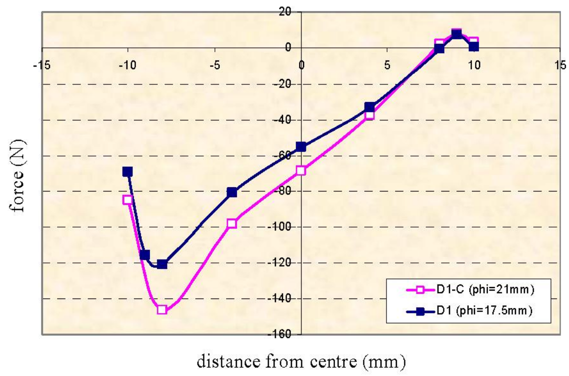


Figure 9: Influence of changing Φ

4 CONCLUSION

The paper has presented the effect of stator teeth length, length of the mover legs, the distance between the magnets, length of slot opening, the mover thickness and the distance between the axis of symmetry and the middle of the air gap as key dimensions of the design.

As those key dimensions of the design have been investigated in this paper, a design with required stroke and force and optimised inductance and weight of magnets and SMC and hence cost can be more easily reached.

5 REFERENCES

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