Comparative Analysis of Linear Motor Geometry for Stirling Cryocoolers

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ABSTRACT

Compared to rotary motor driven Stirling cryocoolers, linear motor coolers are characterized by small volume and long life, making them further suitable for space and military applications. The linear motor Stirling coolers are directly driven by a linear motor and both the components are integrated into a single unit. Therefore, the motor characteristics have direct effect on the operation of the cooler. In this perspective, ample scope exists in understanding the behavioural characteristics of linear motor systems. In the present work, the authors compare and analyze the moving magnet linear motor with and without teeth to finalize the geometry suitable for the Stirling cryocooler. The required axial forces in the linear motors are generated by the current flowing in a magnetic field. The compact size, commercial availability of permanent magnets and low weight requirement of the system are quite a few constraints for the design. The finite element analysis using Maxwell software serves as the basic tool to analyze the magnet movement, flux distribution in the air gap and the saturation levels on the core. A number of material combinations are tried out for core before finalizing the design. The effect of varying the core geometry on the flux produced in the air gap is also analyzed. From the analysis, it is observed that the motor without teeth is advantageous over the motor with teeth in terms of effective utilization of magnetic flux in the air-gap in order to provide the required force.

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INTRODUCTION

Deployment of unique linear drive mechanism in Stirling cryocooler makes them most attractive for space and military applications because of high reliability over extended periods.

Linear motors generate force in the direction of travel of the piston. They are capable of extreme high speeds, quick acceleration and accurate positioning.

Moving coil motors are haunted by its inherent life limiting problems such as rupture of lead wires and out-gassing by the coil lamination.

Compared to moving coil linear motor, moving magnet type offers numerous advantages such as less magnet volume and good thermal dissipation characteristic of the coil windings [1,2].

This paper presents a comparative study of various possible configurations of radially energized moving magnet linear motor based on geometrical and electromagnetic parameters.

Available permanent magnet (PM) materials are studied and the linear motor with and without teeth are analysed in detail.

LINEAR MOTOR

The linear motors work on the Lorentz force principle. According to this principle, if a current-carrying conductor (or coil) is placed in a magnetic field, a force (F) will act on it. The magnitude of this force determines by the magnetic flux density (B) current (i) and orientation of the field and current vector.
The force is generated by the interaction between the magnetic field created by the permanent magnet or dc windings and the current carrying conductor.
Every magnet structure consists of a permanent magnet and a steel return path. The heat transfer from the coil winding to the stator (outer core) is efficient due to the absence of insulating air gap between them, compared to moving coil design.

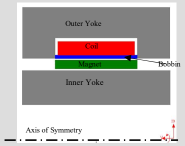

Figure 1. Linear Motor Components

MOTOR GEOMETRY

Figure 2. Motor with flat and extended teeth

Moving magnet linear motor can be categorized into two in terms of stator core geometry: one with flat teeth and another with extended teeth.
The flux density in the air gap, which is produced mainly by the PM influences the back EMF generated by the motion of the magnet. The force generated is directly dependent on the air gap flux density [3,4].
It has been observed from the finite element analysis that the material of the PM and core also influence the force generated.

The figure 3 below shows the different geometrical variations modelled for analysis. All being moving magnet type, have inner and outer yokes, permanent magnet and the coil wound over the magnet and placed in the outer yoke as can be visualized from the half-cross sectional view (symmetric about the axis) shown.

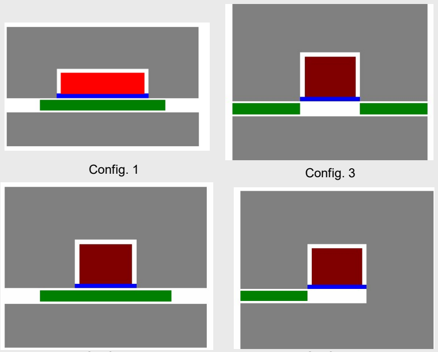

Figure 3. Linear Motor Variations considered for Analysis.

RESULTS

The flux density in the air gap, generated by the combined effects of the PM and current carrying coil, influences the back EMF by the motion of the magnet
In a configuration, where the ratio of gap length to gap width is large, a uniform magnetic field is established across the gap.
The positioning of the magnet in second configuration in figure 3 results in providing a better utilisation of the air gap magnetic flux and thereby leading to a higher electromagnetic thrust force.
The variation in generated force is due to the difference in the superposed field distribution of magnet and the current carrying coil.
The peak value of electromagnetic force is reached, when the magnet just moves from the balanced position. This is in agreement with the parametric study conducted.
When the magnet moves away further from the balanced position, the interaction of the magnetic fields (of coil and magnet) varies and hence the force.
The increased magnet thickness will have a good flux distribution and the superimposed fields will generate a higher force compared with the smaller thickness magnets.

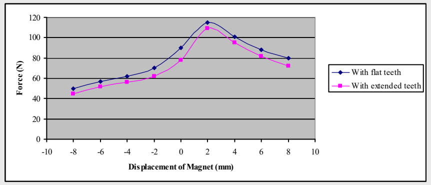

Figure 5. Force generated at different PM positions.

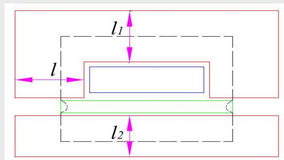

Figure 6. Dimensions of core for the linear motor.

DISCUSSION

Figure 5 shows the variation of force generated at different magnet positions.
The leakage flux is relatively higher in the case of motor with teeth and it will finally end up in a reduction in the effective force production.

The peak value of electromagnetic force is reached, when the magnet is just begins its travel from the balanced position.
It is attributed to the fact that the effective utilization of the flux flowing through the core and that generated in the current carrying coil.
When the magnet moves away from the balanced position, the interaction of the magnetic fields (of coil and magnet) varies and hence the force also reduces.
The dimensions of the inner and outer core of the motor are shown in Figure 6. The saturation thickness of the core *l*, *l1* and *l2* are evaluated theoretically using the electromagnetic equations. The saturation flux density of the core is given by equation (1),

$$B_{sat(core)} = \frac{\phi_{\max}}{\pi\left(d_{0(mag)} + airgap\right)l}$$

where the numerator represents the maximum flux available for use, *d0(mag)*- is the outer diameter of the PM, *airgap* is the radial dimension of the air-gap between the cores and *l* is the saturation thickness [5].

CONCLUSIONS

Out of the various geometries, the one which can keep the permanent magnet under the yoke in the maximum displacement condition comes out to be the better option in terms of electromagnetic thrust force, less leakage flux at the ends and compact geometry.
The outer core ends need to be designed to facilitate enough room for the magnet movement under the operating conditions. This is on the grounds that the magnet will remain within the structure, when displaces to extreme strokes at either ends and will reduce the leakage flux at the ends and core losses as well.
Cold rolled grain oriented silicon steel can be a better option over the other alternatives considered based on the saturation levels in the core and the crucial electromagnetic force.

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