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LINEAR COMPRESSORS: MOTOR CONFIGURATION, MODULATION AND SYSTEMS

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ABSTRACT

Many linear motor configurations are potentially applicable to linear compressors. Problems associated with some of these are discussed. Properties of, and experimental data relating to a particular configuration that has proven itself in many applications are presented. Two methods of linear compressor control that have been successfully applied are described. Refrigeration systems that can use the flow rate modulation capability of a linear compressor advantageously are briefly discussed.

INTRODUCTION

In a free-piston linear compressor the piston is not rigidly attached to a driving mechanism such as a crank. It is rather driven by a linear motor which applies a force directly on the axis of reciprocation. The reciprocating mass may be resonated by force generated by gas and mechanical springs attached to the piston. Both the stroke and mean position of the piston change and are dictated by the mechanical, magnetic and pressure forces acting on it. The piston motion is not pre-defined, making it necessary to have some mechanism to control its position, particularly when fragile parts might collide. This, however, makes the machine more versatile since the piston motion can be adjusted continually to achieve optimum performance. Another advantage of a free piston over a crank compressor is that, because all the driving forces act along the line of motion, side-loads on the piston can be very low, reducing friction losses and associated wear and allowing use of gas bearings for oil-less operation. Linear motors are basically simple devices in which axial forces are generated by currents in a magnetic field, according to the well known equation:

$$force/unit\ volume = current\ density\ X\ magnetic\ field$$

Each term in the equation is a vector and X means cross product. Current density can exist in wires or as a surface density of magnetic current, according to the equation:

$$magnetic\ surface\ current\ density\ (amps/meter) = M\ X\ n$$

where M is intrinsic magnetization in amps./meter and n is a unit normal to the surface.

Analysis of moving magnet linear motors by means of magnetic surface currents is simple, accurate and physically transparent. It also helps in understanding problems that can occur with some configurations.

LINEAR MOTOR TYPES

Moving Coil

A typical application and analysis is given in Ref. 1. In this case, current is alternating and exists in moving wires and the magnetic field with which the current interacts is generated by a permanent magnet. Analysis shows that required magnet volume is many times greater than that needed by a moving magnet configuration of the same power output and efficiency. Since magnets are the most expensive constituent of most linear motors, moving coil motors of this type are only suitable for cost insensitive applications. For a given efficiency, the mass of moving copper wire far exceeds the mass of moving magnet in an equivalent moving magnet motor. This mass must be approximately resonated with springs in order to avoid excessive reactive currents in the motor. Thus a moving coil motor will require much more spring mass than a comparable moving magnet motor. One clear advantage of the moving coil motor is the absence of radial forces, open circuit axial forces and torques on the moving coil. Such forces and torques are present in some other linear motor types and can cause serious practical difficulties.
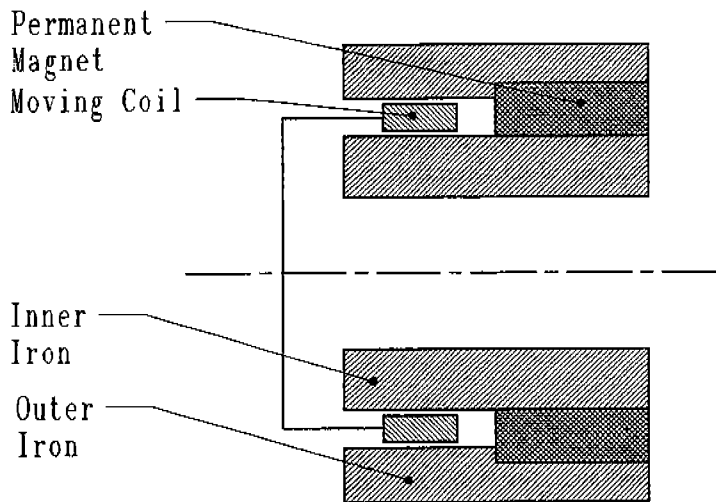
Permanent
Magnet
Moving Coil

Inner
Iron

Outer
Iron

**Fig. 1: An Example of a Moving Coil Motor. Adapted from Ref. 1.**

Moving magnet

These have been made in several configurations, distinguished by presence or absence of moving iron, whether the moving magnets leave the air gap during the reciprocation cycle, and orientation of the lamination plane. Two motors using magnets that partly leave the air gap are illustrated in Figs. 2 and 3. Further information on the first of these can be found in Refs. 2, 3 and 4. All such motors have the potential for serious eddy current loss in their surroundings, because of strong, relatively long range time-varying fringing fields generated by the emerging magnets. A less serious disadvantage is difficulty in accurately predicting power output, which depends partly on interaction of fringing field of the coil currents with magnetization surface currents outside the air gap. Another disadvantage is the existence of axial magnetic forces when the magnets are not centered. These forces are difficult to calculate and can affect machine dynamics.

If a linear motor is axially symmetric, its magnetic fields lie in planes passing through the symmetry axis, which planes must then also be the planes of the laminations comprising the flux path. Ideally, this means tapered laminations. Practically, multiple stacks of nearly radial laminations can keep eddy current loss to levels insignificantly higher than that of tapered laminations. In either case, tapered or multiple stack, construction of the iron flux path is more complex than that of a conventional AC rotary motor, which needs only a single stack of laminations oriented perpendicular to the axis of rotation. Two linear motors that use the same sort of flux path construction as a rotary AC motor are the Corey and Shtrikman types. Further information on these motors can be found in Refs. 5 and 6 respectively. One disadvantage of such construction is inefficient use of copper compared to an axially symmetric configuration. Another is that fringing fields of both coil and magnets enter the laminations perpendicular to their plane and therefore can induce eddy current losses. In the case of the Corey type motor, magnet fields within the iron adjacent to the air gap cross the lamination plane and will induce eddy currents.
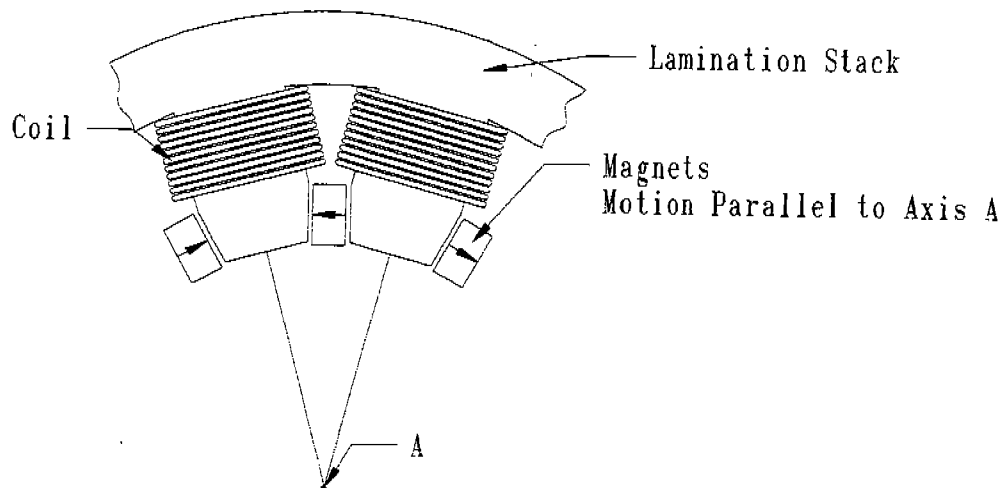
Fig. 2: An Example of a Corey Type Moving Magnet Alternator
with Axially Stacked Laminations. Adapted from Ref. 5
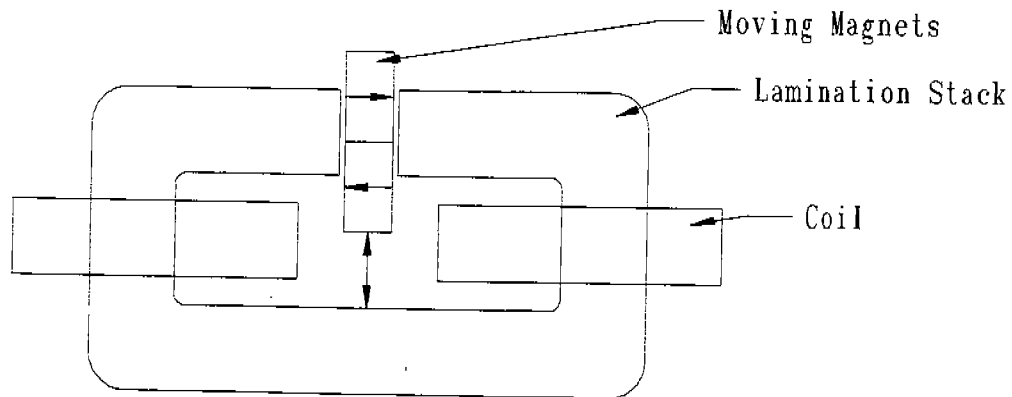
Fig. 3: An Example of a Shtrikman Type Moving Magnet Configuration.
Adapted from Ref. 6.

Some linear motors, e.g. the Bhate type (Ref. 2), use moving iron in the flux path, which can cause serious practical difficulties as a result of rotational instability of the entire moving structure around axes perpendicular to the axis of reciprocation. The structure tends to rotate and close the air gap, and may overpower gas bearings or even oil lubricated bearings.

A configuration that has proved itself in many applications at power levels from 40 W to 15 kW is described in Ref. 7 and illustrated by Fig. 4. It is relatively insensitive to its surroundings because the magnets do not leave the gap and because the magnet fringing fields are not time varying even though the magnets move within the air gap. It uses no moving iron and therefore subjects supporting bearings to very low forces and torques. The design of this machine using magnetization surface currents is simple and has proved to predict performance accurately. Fringing fields are of secondary importance since they only affect the motor inductance. They can be estimated with acceptable accuracy by using simple permeance approximations. An equivalent circuit based on the physics of this motor is shown in Fig. 5. The physical basis for the equivalent circuit can most easily be explained by temporarily considering R1 to be an open circuit. Vapplied is then the sum of the IR drop in the winding and the voltage induced in the winding by time varying flux. The induced voltage is the sum of voltage induced by motion of the magnets (Vgenerated) and the voltage induced by current in the winding (L dI/dt, where L is the winding inductance). A series connection of Vgenerated, L and a resistance R2 follows. Resistor R1 accounts for core losses which, at a particular frequency, are proportional to the square of the resultant core flux, i.e., to

the square of the induced voltage. R1 is therefore connected across the total induced voltage. It is worth noting that there is a loss in R1 even if I=0, provided that the magnets are moving so that Vgenerated is not zero. Under these conditions, loss in R2 is associated with braking by hysteresis and eddy currents in the core and has been referred to as shuttle loss. Typically it is about 2% of the rated power. Resistor R2 is the sum of DC winding resistance and loss resistance associated with losses induced in the motor surroundings (exclusive of core losses) by time varying field generated by winding current. All of the quantities appearing in the equivalent circuit can be determined from static measurements and, once found, they suffice to predict the performance of the motor under any load conditions.
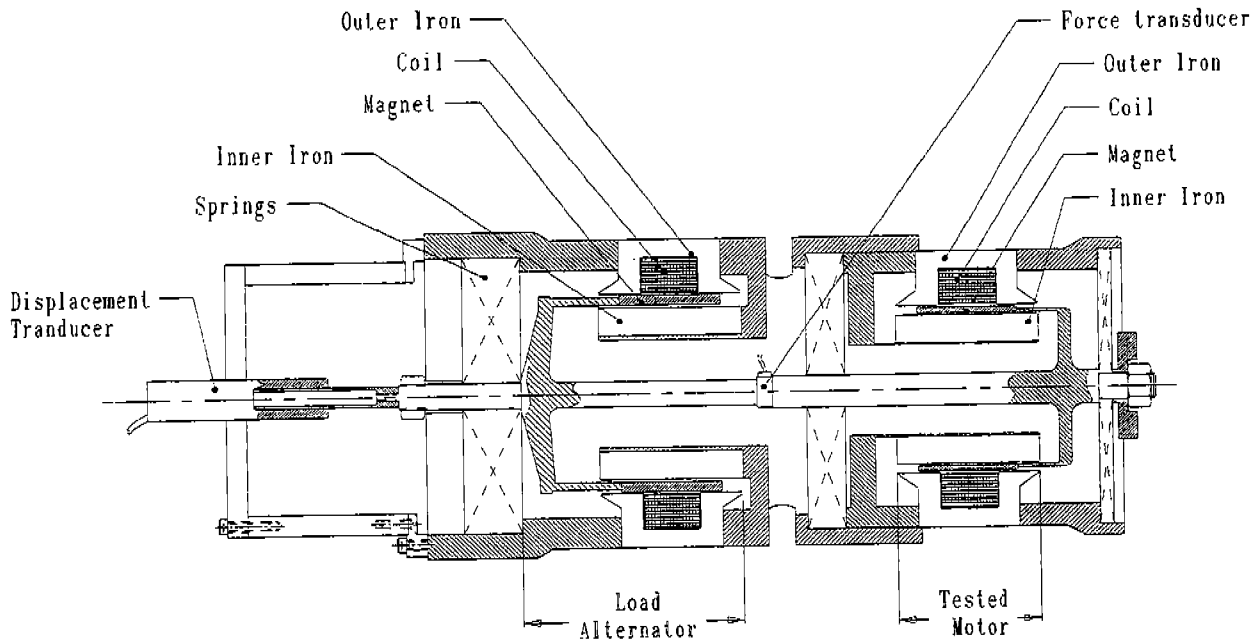
Fig. 4: Linear Motor Dynamometer Coupled to Redlich Type Linear Motor

Force on magnets = alpha x I

Vgenerated = alpha x magnet velocity

Fig. 5: Equivalent Circuit for Redlich Type Linear Motor
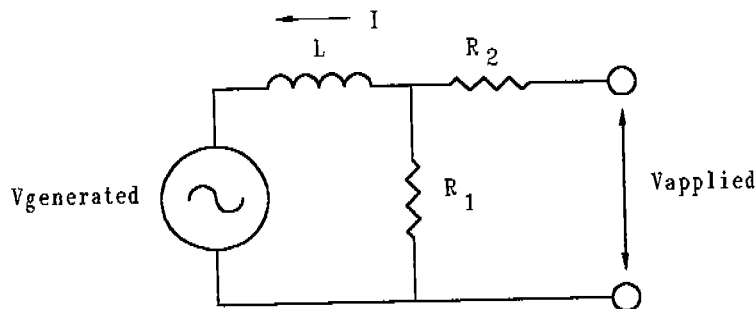
The equivalent circuit as determined by static measurements for a 250 watt motor was verified with dynamometer measurements. One such measurement was direct determination of the machine constant, alpha, in two different ways, the first as the ratio [Vgenerated / (magnet velocity)], the second as the ratio [(force on magnets) / I]. The average of seven measurements of the first type was 89.0 volt seconds/meter. The average of seven measurements of the second type was 89.7 newtons/amp. Agreement was within experimental error and is considered strong confirmation of the basic theory of the motor. Fig. 6 shows the results of another set of measurements in which efficiency and amplitude of magnet motion were measured with the linear dynamometer in Fig. 4 and compared with the same quantities as calculated from the

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equivalent circuit and measured values of Vapplied and I. Agreement is within experimental error and is considered confirmation of the predictive ability of the equivalent circuit. Noteworthy in Fig. 6 is the fact that efficiency is maintained at low power levels. This can be important in refrigeration compressors.
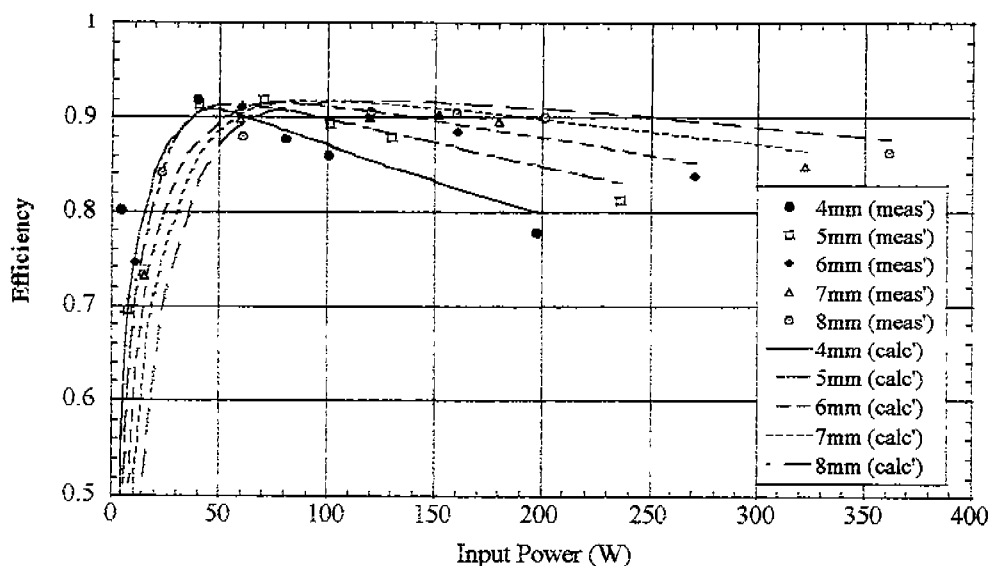

Fig. 6: Efficiency Curves for Linear Motor: Comparison of Test Data to Theory

CONTROL

Since the moving parts of a linear compressor are not constrained by a rigid crank mechanism, closed loop control involving feedback from sensed piston position to voltage applied to the linear motor is necessary. The demands imposed on the control system for a linear compressor in a refrigerator are rigorous. Clearance between piston and valve head at top dead center (TDC) must be kept within a few tenths of a millimeter to keep hysteresis losses down. The entire discharge phase typically takes place in about 1 mm before TDC, hence 0.1 mm change in piston position at TDC has a significant effect on flow rate. Collisions must be avoided, and the control must function over a temperature range of about 60 °C. This feat of control must be reproducible and inexpensive, particularly in the case of domestic refrigeration.

Control using a position sensor

Satisfactory control has been achieved using an inductive position sensor in which the inductor is a small stationary coil wound on a ferrite core. The high frequency inductance of the sensor is reduced by a moving aluminum band that enters the flux path of the inductor at about 4 mm before TDC. Electronics convert minimum inductance to a signal that is compared with a set point signal. The difference between the two signals modulates the firing angle of a triac so that if the piston is closer to the head than it should be according to the set point signal, the triac fires later and the effective applied voltage is reduced, thus reducing stroke and moving the piston away from the head.

Control using the linear motor as a sensor

For a motor of the type described at the end of the preceding section, the parameter alpha is independent of magnet position within less than 0.5% provided the magnets come no closer to the end of the air gap than about 1/2 of the gap dimension, and provided the iron does not saturate. If these conditions are met, Vgenerated, the "back EMF", is an accurate measure of piston velocity. Vgenerated can be recovered by an analog or digital calculation based on the equivalent circuit and measured values for Vapplied and I. Both of the required measurements can be made external to the

compressor. After deriving piston velocity, piston position can be obtained by integration and used for control of a triac. As just described, the steady state piston position recovered by a motor analog will have no average component because of the limitations of practical integrators. Actual piston position, however, does have a very significant average component because the average pressure over a cycle is positive and moves the piston out against the springs used to resonate piston mass. Average position can be recovered by a calculation based on the dynamics of piston motion during suction, when the pressure force on the piston is practically zero so that all the forces on the piston are accessible from the motor analog. Details of this computation can be found in Ref. 8. Sensorless control of this type has been successfully applied to refrigerator compressors. Difficulties encountered with such control have been associated with recovery of average piston position, which requires an analog of piston acceleration and thus a differentiation, which is noise sensitive. Use of a triac exacerbates noise problems because of discontinuities in applied voltage associated with triac control. Careful filtering has been found to be necessary, but the control scheme now appears to be practical, and work is in progress on adapting it to a production setting.

MODULATION

The flow rate of a linear compressor whose TDC position is controlled by a closed loop feedback system is easily changed by changing the reference TDC position with which the measured position is compared, thus changing the spatial extent of the discharge phase. Reference TDC position will be in the form of a control signal that can readily be altered, a simpler process than variability of frequency needed to modulate rotary compressors. A linear compressor powered by a motor of the type shown in Fig. 4 can be modulated to power levels as low as 20% of rated power before significant degradation of motor efficiency occurs (Fig. 6). A linear compressor with controlled TDC position thus has inherent flexibility to continuously respond to changing conditions with changes in flow rate. This property can be used to advantage in many systems, such as air conditioners, in which reduced flow at part load increases efficiency by reducing the temperature drop across each of the heat exchangers (Ref. 9).

CONCLUSIONS

Choosing between different linear motor configurations involves obvious considerations like cost, size and efficiency. Evaluation of less obvious factors is also appropriate, such as: radial and rotational instabilities; sensitivity of losses to materials in the motor surroundings; ease of design and ability of the design procedure to accurately predict performance; springing requirements for the reciprocating mass; existence of significant axial magnetic forces under open circuit conditions and suitability of the motor type for use as a transducer if sensorless control is contemplated. Control of a linear compressor for refrigerators must meet rigorous requirements but has been accomplished with either a position sensor or by using the linear motor as a sensor. Many compressor applications could benefit from the modulation capability of a linear compressor.

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