Electromagnetic launch using novel linear induction machines

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SYNOPSIS

Linear induction machines are in use for leisure ride launching and have been proposed for use in aircraft carrier launchers. A typical launcher topology consists of a double-sided long stator arrangement with a short conductive plate secondary. When using a plate secondary, end effects are present which detract from machine performance. This topology also requires relatively large magnetic gap and high resistance rotors.
This paper concerns the use of wound rotor type linear motors, and their application to launcher systems. Computational results of plate and wound rotor systems are compared and contrasted, as well as results from experimental systems. Computational methods are developed in order to efficiently design wound rotor systems.

INTRODUCTION

The linear induction machine can be made in many different topologies. These include short stator and short rotor geometry in single-sided and double-sided forms. The most usual launcher topology uses a double-side long stator arrangement with a short secondary carried on the moving carriage.
In 1996 a major technical advance was achieved in the leisure industry, with the first successful application of LIMs as a catapult launch system for 2 roller coaster rides in USA. This has since been followed by 13 more launch systems in USA, China and Canada where vehicles weighing up to 7-8 tonnes are accelerated to 70mph in less than 4 seconds.
The above developments have shown that LIMs may be successfully applied to high-speed applications. Over the past eight years fundamental design work has been ongoing into LIMs for high-speed applications such as UAV launchers and ultimately aircraft launchers.
In all of the configurations mentioned above the secondary conductor is normally a simple conducting plate that corresponds to a squirrel cage in a rotary machine. End effects are present which detract from the machine performance. In rotary machines wound rotors are sometimes used, leading to some advantages in starting and speed control by rotor resistance insertion. It has been suggested that wound rotors are also applicable to linear machines (Yamamura[12]) and that the end effect will be reduced in the case of the short-rotor long stator arrangement. This configuration is important since it is proposed for launcher duty. It is the purpose of this paper to investigate these possibilities by modelling and practical comparisons of wound and plate secondary arrangements.

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LINEAR INDUCTION MOTOR TOPOLOGY

A linear induction motor (LIM) is essentially a conventional 3 phase rotary induction motor opened out flat as the single sided LIM arrangement (Fig 1). When connected to a 3-phase AC supply it produces a travelling magnetic field that generates straight-line force in the rotor, rather than torque in the case of a rotating machine.

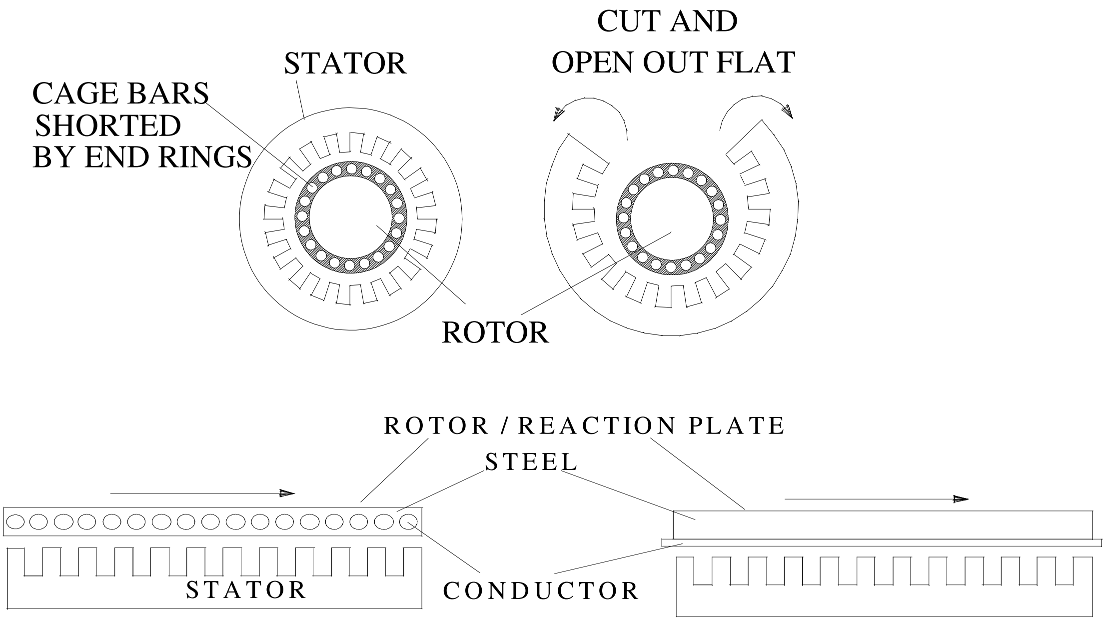

Fig 1 The concept of a linear motor

The 'motor' consists of two parts; the stator, which is very similar to its rotary counterpart, and the rotor, which is changed considerably.

The stator and rotor

The stator is made from slotted laminations. These can be welded or bolted together to form the core, into which pre-wound coils are inserted in a conventional manner (Fig 2).

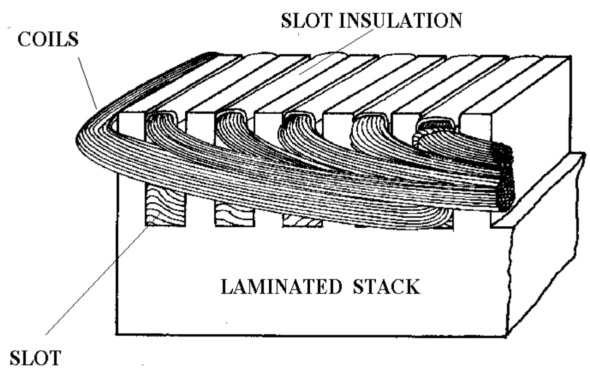

Fig 2 Components of a linear stator

The rotor, now called the reaction plate, has both its iron and conductor bars 'smoothed out' into the form of flat sheets. Thus the conventional 'squirrel cage' is replaced by a flat aluminium sheet backed by a sheet of steel, as shown in Figure 1. It must provide a low reluctance path for the stators magnetic flux and a low resistance path for the induced electric currents. The width of the reaction plate should be chosen to give an acceptable end ring (Fig 3).

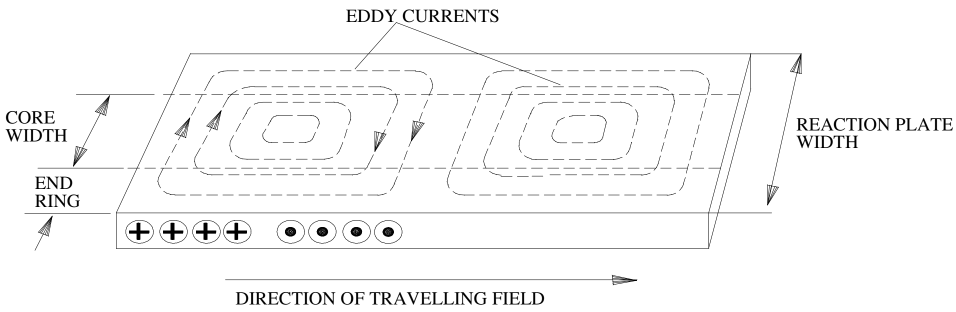

Fig 3 Eddy current patterns induced in a plate rotor

Double sided LIMs

If two LIMs are mounted face to face either side of a sheet conductor (Fig 4), the need for steel in the reaction plate is eliminated. Each stator now completes the other's magnetic circuit. This is often used to reduce the moving mass and also to eliminate any normal (vertical) force on the plate.

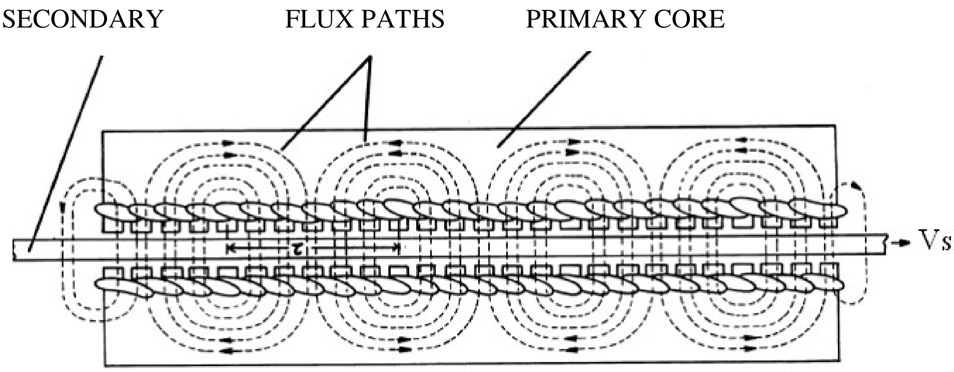

Fig 4 Flux paths in a double sided linear motor

Short stator and short rotor LIMs

For continuous action either the secondary or the primary member of the linear machine has to be shorter than the other member.
The short stator, sometimes called a short primary LIM, is a machine in which the rotor is longer than the stator (Fig 5a). The short rotor, sometimes called a short secondary is a machine in which the rotor is shorter than the stator (Fig 5b). These classes of machine can either be single sided or double sided.

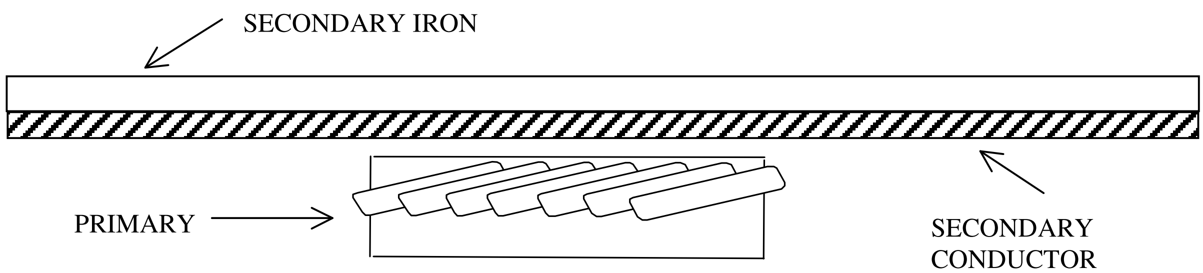

Fig 5a Single sided short stator linear induction motor

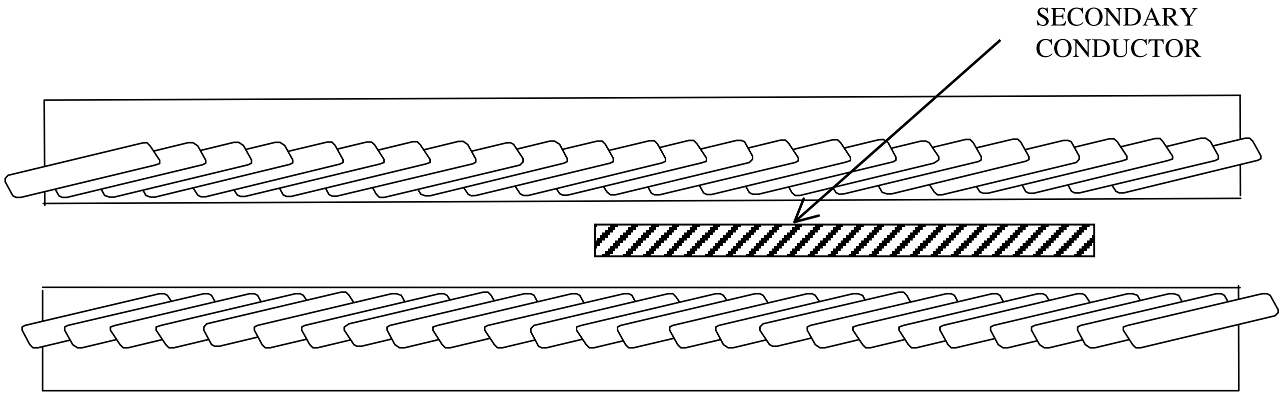

Fig 5b Double sided short rotor linear induction motor

WOUND ROTOR LINEAR MACHINES

Wound secondary linear induction machines are known (Yamamura[12], Onuki[3]) but comparisons with plate rotor machines are sparse and in addition a simple accurate equivalent circuit calculation technique is needed.

Double layer windings

There are many forms of AC machine windings, and the most common for standard induction motors is the double-layer construction (Fig 2). It can be seen that the first or leading side of the coil occupies the top half of a slot whilst the second side is positioned in the bottom of a slot one coil pitch away from the first side. In a four pole linear motor (Fig 6) it can be seen that the winding has to terminate at each end so that either half - filled slots or coil sides over the ends of the machine must be used. In the figure both techniques are illustrated with two half empty slots and two coils outside the ends of the machine

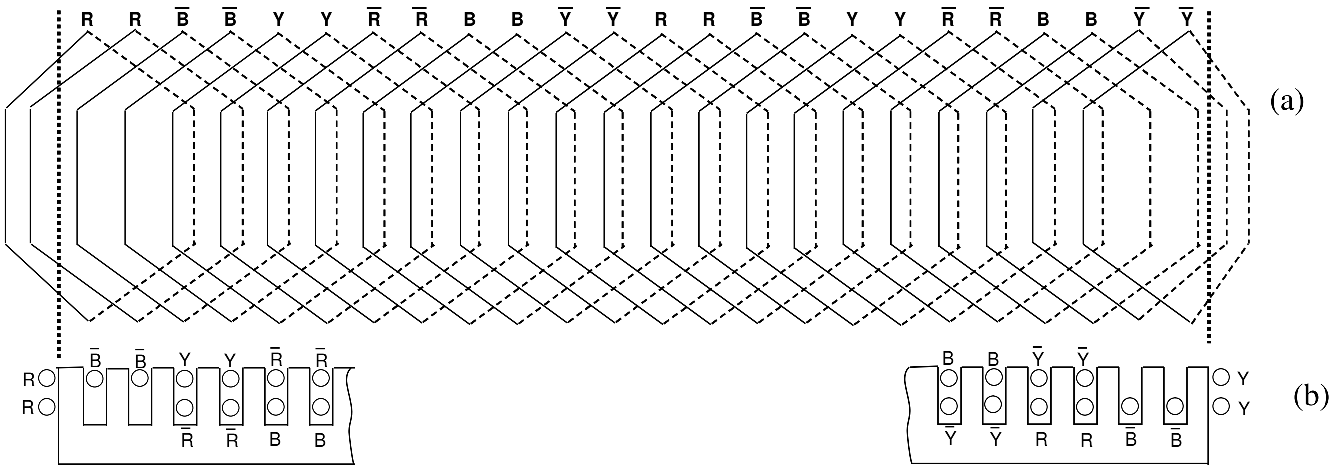

Fig 6 Linear machine with a double layer winding: (a) Plan view, (b) Part longitudinal cross sectional view

Single sided wound rotor system

Figure 7 shows a single sided short-secondary wound rotor linear motor where both the primary and secondary windings are contained in slotted cores. The primary has a long double layer winding provided with excitation currents and the secondary carries a double layer winding which is short-circuited so that currents can be induced in it by the long stator.

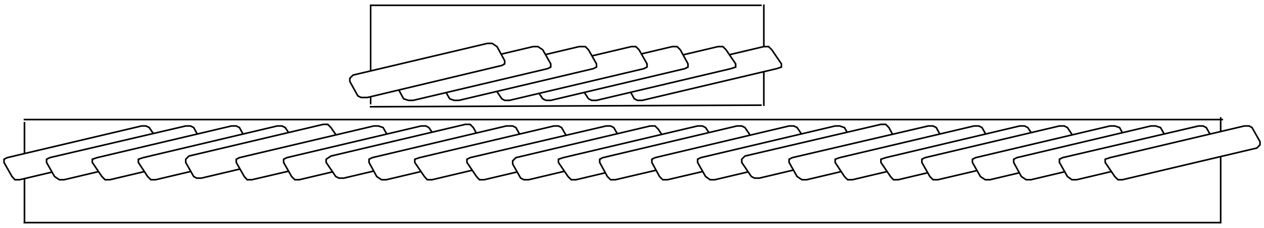

Fig 7 Wound primary with a short wound secondary

A special rotor winding for the single sided system

Magnetic locking can be produced between the primary and secondary of an induction machine particularly if a whole number of slots per pole and phase are used for both of them. The locking can be reduced by a number of techniques for example in rotary machines the slots of one member are often skewed. This could of course be applied to linear machines however it is also possible to devise a special winding that produces the same pole pitch as the conventional winding but uses one slot less over the machine length. Such windings have been designed for this project.

Doubled-sided wound rotor system

Double-sided stators can be used with a doubly slotted secondary as shown in Figure (8). Since the main flux is directed through the secondary the dimension A on the figure is decided by mechanical strength. This system is inherently robust.

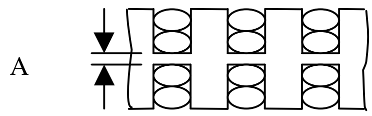

Fig 8a Cross section through a double sided wound rotor

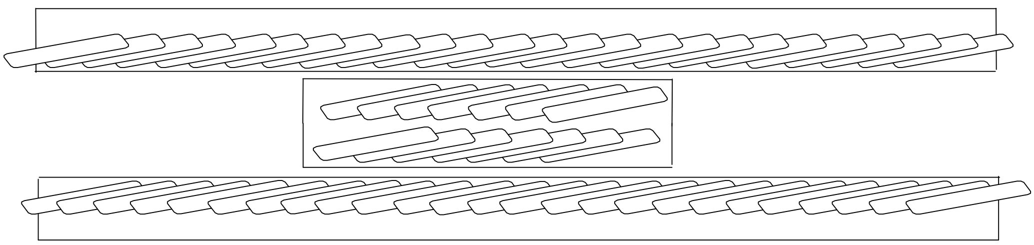

Fig 8b A double sided wound rotor

ELECTROMAGNETIC MODELLING

Finite element modelling

The motor configurations were modeled using 2D Finite elements (FE). In 2D, electromagnetic fields can be modeled using the magnetic vector potential, **A**, the governing equation is:

$$\nabla \times \frac{1}{\mu} \nabla \times \mathbf{A} + \sigma \frac{\partial \mathbf{A}}{\partial t} = \mathbf{J} \qquad (1)$$

where:
μ is the permeability in henries/metre
A is the magnetic vector potential in webers/metre
σ is the conductivity in siemens/metre

This can be transformed into a system of equations by using the finite element method together with the Galerkin weighted residual procedure.

In order that the dynamic behavior of the motors is simulated, a time-stepping scheme, which takes into account the transient nature of the supply to the motor, and the dynamic motion of the rotor was used. The movement of the rotor was handled by a special sliding surface FE scheme. In this scheme, the stator and rotor of the motor are represented by separate FE meshes, which touch each other at a common interface. In our case, this common interface was located at the middle of the air-gap. The stator and rotor mesh are allowed to freely slide relative to each other along the interface and in so doing enables the dynamic motion of the rotor to be handled without the need of any re-meshing. Figure (9) shows a magnified view of the stator and rotor mesh touching each other at the middle of the air gap.

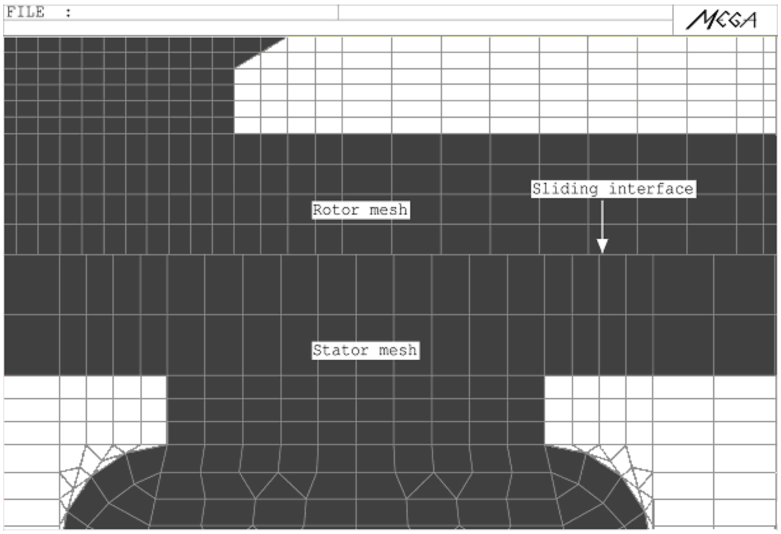

Fig 9 A finite element mesh

To couple the meshes electromagnetically, the LaGrange Multipliers technique was used. The method essentially enforces the following constraint (Equation 2) at the interface of the stator and rotor mesh.

$$A_s - A_r = 0 \qquad (2)$$

where A_s and A_r are the vector potential unknowns at the stator and rotor interface nodes respectively.

The stator windings were modeled as current forced coil regions. Winding resistance and end winding inductance components were incorporated into the simulation as components in an external circuit coupled to the FE model.

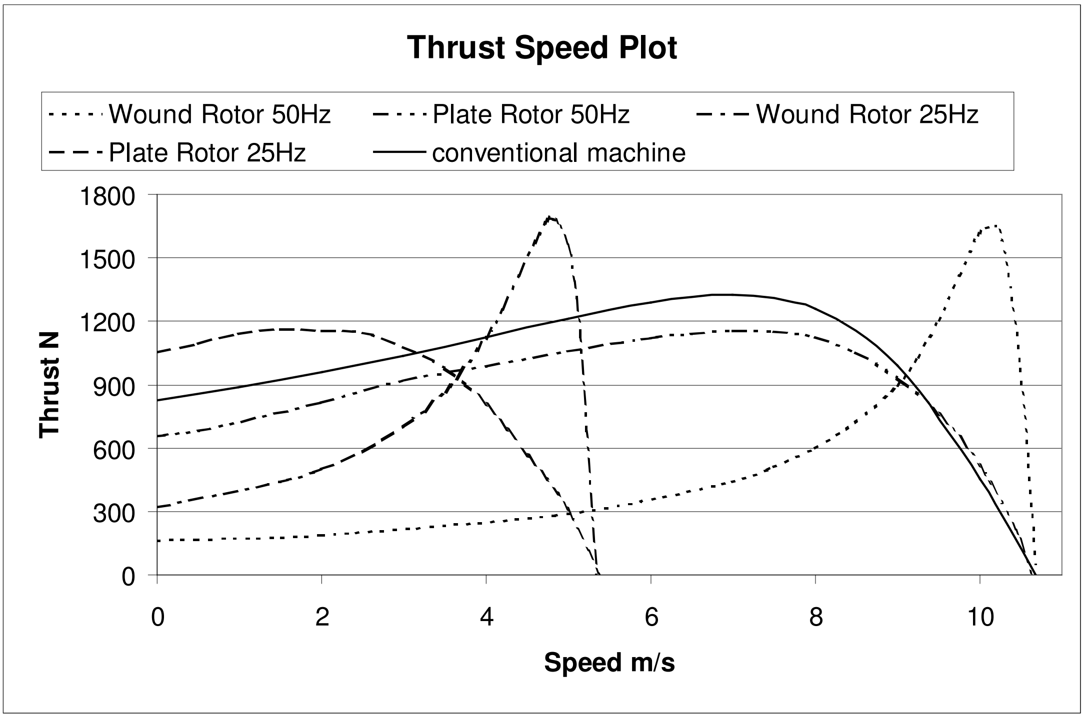

Fig 10 Calculated thrust speed curves for wound and plate rotors at 50 and 25 Hz

Figure 10 shows the results of the analysis of force using a single- sided long stator machine carrying a conventional LIM winding as described in relation to Figure 6 with two different secondary members:

- A plate-conductor rotor 4 pole–pitches in length backed with an iron core. For comparison with this, the results from a "drag cup" style plate rotor in a conventional rotary machine are also shown.
- A slotted secondary carrying a special winding as previously described.

The results are shown for two different frequencies namely 50 Hz and 25 Hz at the same constant stator winding current. The rotor efficiency at peak force in the wound rotor case was 92% whilst the efficiency where substantial force was produced (7 m/s) in the plate rotor case was 62%

Equivalent circuit method

If only the principal harmonic is considered then a cylindrical induction motor can be analysed with the aid of the equivalent circuit shown in Figure (11).

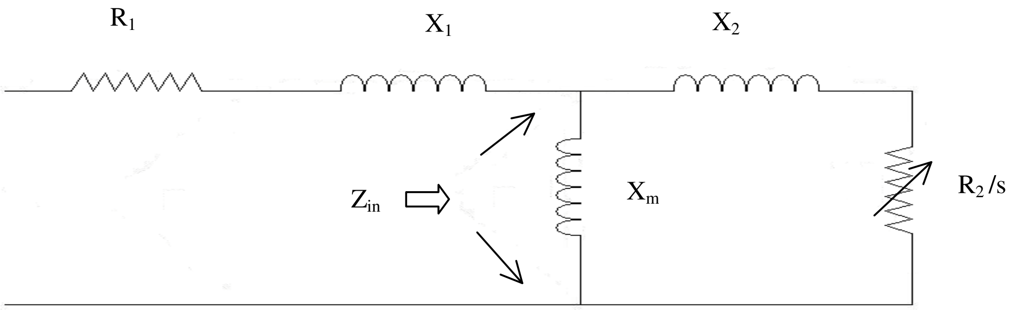

Fig 11a A linear motor equivalent circuit

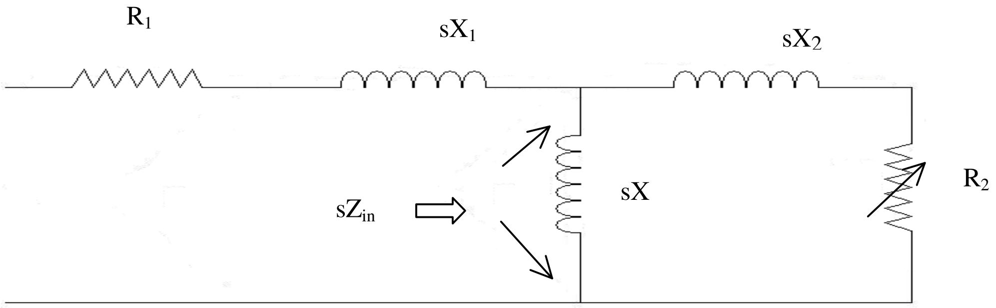

Fig 11b A standstill linear motor equivalent circuit

Here R_1 and X_1 are the stator resistance and leakage reactance, X_m is the magnetising reactance, R_2 and X_2 are the rotor resistance and leakage reactance and s is the slip given by Equation (3):

$$s = (V_s - V_r)/V_s \quad (3)$$

where:
V_s is the field velocity, = $2\ T_p\ f$ in metres/second
T_p is the pole pitch in metres ; f is the frequency in Hz
V_r is the rotor velocity in metres/second
The behaviour of a linear induction machine is different to that of a cylindrical version mainly because the ends of the stator or rotor cause discontinuities. Longitudinal space transients are produced in the air-gap flux patterns by the edges. If the one harmonic approximate equivalent circuit is used in an analysis then this is equivalent to ignoring the longitudinal edge effects.

ANALYTICAL RESULTS

Time stepped finite element analysis takes into account the edge effects from a short rotor machine. The equivalent circuit analysis uses only one harmonic field therefore does not. Since the force results from the finite element work and the equivalent circuit analysis are in close agreement (Fig 12) it can be adduced that the edge effects in a wound rotor linear machine are negligible for the geometry analysed. The time taken to compute the equivalent circuit analysis is only a few seconds whereas the time step solution can take several hours.

Figure 10 shows the forces calculated for a plate rotor first as a short rotor machine curve and secondly as a conventional rotary machine curve. It will be observed that the edge effects present in the short rotor case have reduced the force by about 15%. The results given in reference (Laithwaite[4]) which analysed a thin sheet approximation also show a force reduction.

Further comparisons can be drawn from figure 10 with regard to the performance of wound and plate rotor short rotor machines as indicated by Figure 10. Here it will be seen that the force speed curve for the wound rotor has a high force low slip characteristic indicating that the rotor resistance is low and the magnetising reactance is high. Conversely, the plate rotor shows a drooping characteristic indicating that the rotor resistance is higher and the magnetising reactance is lower. It is not possible to reduce the resistance in the plate rotor case without reducing magnetising reactance because the quantities are linked. For example, increasing the plate thickness to reduce the resistance results in an increased magnetic gap and hence a reduced magnetising reactance. This means that the shape of the force speed curve cannot be significantly altered without a change in plate materials.

However in the wound rotor case the two quantities are independent, the magnetising reactance depends on the clearance only and the resistance is an independent variable depending on factors such as the slot depth.

The force speed curve shape change results in the rotor efficiency being considerably larger in the wound case (92% at peak force) compared with (62% at peak force) in the plate rotor case. The peak force available is also 41% greater in the wound rotor case.

Launcher machines are generally supplied at variable frequency from an inverter. (Fig 10) also shows that the peak force available from the wound rotor remains as high at 50% frequency.

TEST RESULTS FROM AN EXPERIMENTAL RIG

To verify the results of finite element and circuit theory modelling, a practical wound rotor model has been made. A conventionally designed 4-pole stator was constructed to use as the primary together with a wound secondary of identical pole pitch. This used a special winding in order to minimise locking forces. The secondary phases were connected in star at both ends to give the required rotor current paths.

The stator was mounted to a test bed, and the wound rotor was mounted above the stator, on a rig instrumented to record static thrust. The stator was fed through an inverter and the feed was instrumented to display the relevant inputs to the stator.

In order to gain results for various velocity points, variable frequency testing was used (Eastham[5]). This test allows the prediction of dynamic performance from static test conditions.

The process can be explained with the aid of figure 11b. This shows a standstill version of the equivalent circuit of figure 11a which is fed by the same current as that of figure 11a but at a frequency sf rather than f.

The power input to the figure 11a circuit is:

$$\text{Power input} = \mathrm{Re}(Z_{in})I^2 \qquad \text{watts} \qquad (4)$$

and the force produced is then

$$\text{Force} = \text{Power / Field speed} = \mathrm{Re}(Z_{in})I^2 / V_s \qquad \text{newtons} \qquad (5)$$

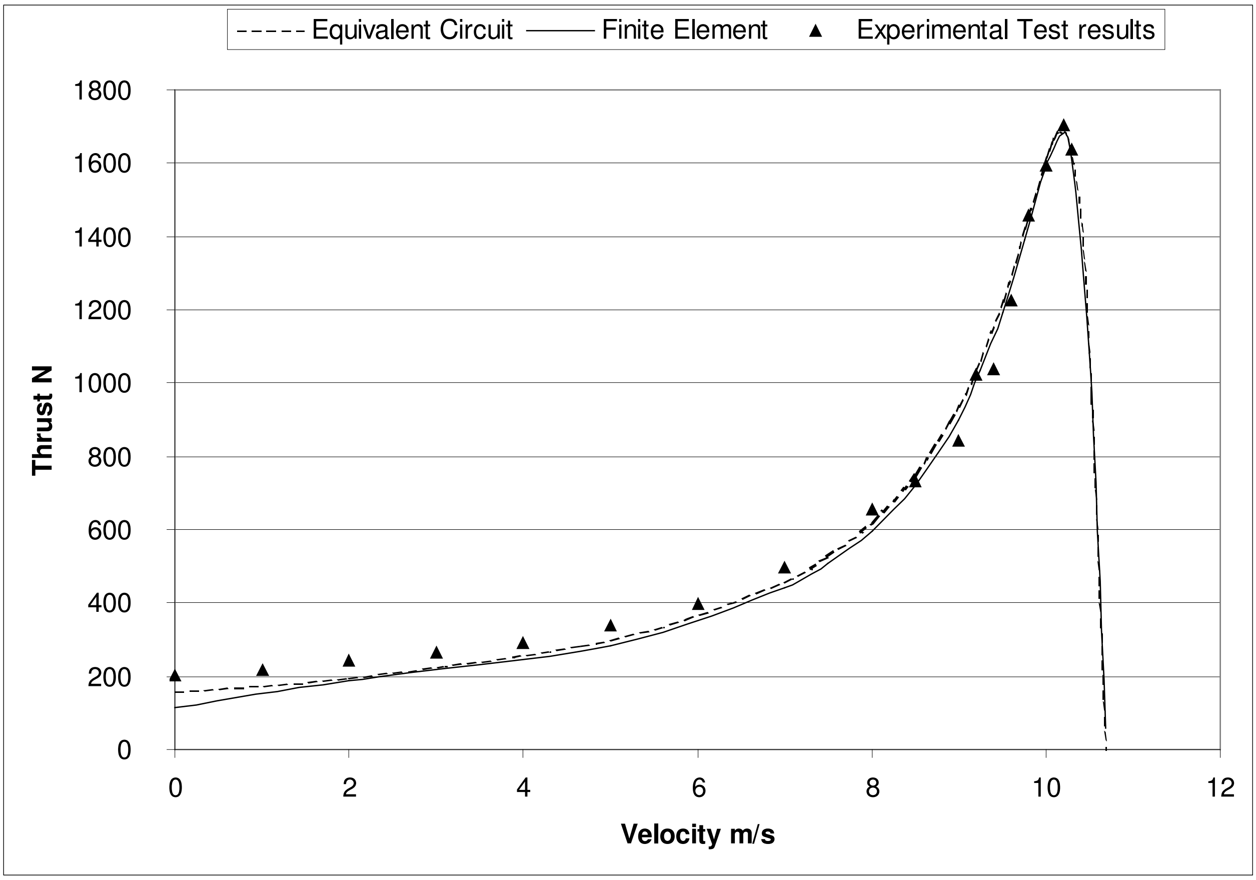

Fig 12 Results for the wound rotor modelled with circuit theory, finite element analysis and experiment

The power input to the standstill variable frequency circuit figure 11b is

$$\text{Power input} = \text{Re}(s\overline{Z}_{in})I^2 \qquad {}^{w}\text{atts} \qquad (6)$$

and the force produced is then

$$\text{Force} = \text{Re}(s\overline{Z}_{in})I^2 \,/\, sV_s \qquad (7)$$

$$= \text{Re}(\overline{Z}_{in})I^2 \,/\, V_s \qquad \text{newtons} \qquad (8)$$

where:
I is the input current to the equivalent circuit in amperes
$\text{Re}(Z_{in})$ is the real part of the impedance measured at the point shown on figure 11a, in ohms
$\text{Re}(sZ_{in})$ is the real part of the impedance measured at the point shown on figure 11b, in ohms

It can be deduced from equations (5) & (8) that taking results from standstill tests at frequency sf gives the same force as those produced by the same machine at a slip s.

The results of the testing are shown in figure 12, along with the results of finite element analysis and simple equivalent circuit modelling. It will be observed that the agreement between the calculated results and the experimental results is excellent.

CONCLUSIONS

The use of wound rotors enables design freedom. This means that higher forces and efficiencies become available, with the ability to generate high thrusts at lower slips and a reduced size and cost of the overall system, including a reduction in the size and cost of power conditioning equipment. In addition, wound rotors do not exhibit edge effects, resulting in enhanced performance.

Single-sided machines of both plate and wound rotor types suffer from normal forces between the primary and the secondary and problems of secondary weight. There is evidence that the normal force in the wound type will be generally larger than in the plate type. Therefore, the single–sided wound machine is more apt for urban transport systems (where a horizontal gap is of advantage) rather than EM catapult launch systems. Double-sided machines are usually favoured for EM launch and double-sided iron-cored arrangements of the type shown in figure 8(b) are possible. These largely deal with the normal force problem but the weight penalty remains. For some applications an air-gap type wound rotor construction could be advantageous. An iron-less wound rotor would have a higher efficiency than a standard plate rotor, therefore reducing the size of the power conditioning equipment and minimising the rotor weight.

A simple equivalent circuit method for calculating the performance of wound rotor linear machines has been validated by comparison between time-stepped finite element solutions and test results.

ACKNOWLEDGEMENTS

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