Investigation of short-rotor linear induction motors using finite element modelling

T Cox**, Prof. J F Eastham*, Dr H C Lai*, J Proverbs**

*Electronic & Electrical Engineering Department, University of Bath, Bath, UK
Tel +44(0)1225 386707 e-mail eesjfe@bath.ac.uk
**Force Engineering Ltd, Old Station Close, Shepshed, UK
Tel: +44(0)1509 506 025 – Fax: +44(0)1509 505 433 e-mail: tom@force.co.uk

Topics: 11, 61, 71

1. Introduction

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. In this configuration rotor end effects are present which detract from machine performance. This topology also requires a relatively large magnetic gap. The configuration has been considered for conveyor application [1]. It is the objective of this paper to use mathematical modelling to compare the performance of short rotor machines having various plate lengths with conventional machines of the same air gap geometry.

2. Double-Sided Geometry

A double-sided short rotor linear induction motor is illustrated in Fig 1. The long stators are shown as continuous blocks but in practice may be constructed of separate sections arranged with a minimum of longitudinal gap between a motor and its neighbour. The analysis in this paper assumes that these gaps are small and that the stators are long so that the input current may be considered to be constant due to dominant impedance of the stators outside the plate region.

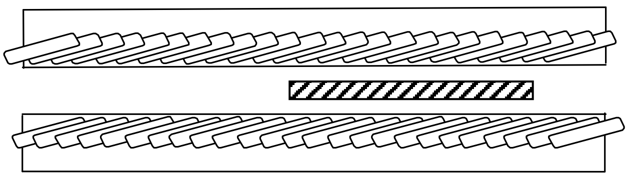


Fig 1 Double-sided short rotor linear induction motor

3. Finite element Modelling

2D finite element analysis (FEA) was used to model the motor configurations. The University of Bath Mega package was employed. 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/meter
A is the magnetic vector potential in webers/metre
σ is the conductivity in siemens/metre

By using the finite element method together with the Galerkin weighted residual procedure this can be transformed into a system of equations.
To simulate the dynamic behavior of the moving plate secondary, a time-stepping scheme was used, this takes into account the transient nature of the supply to the motor, as well as the dynamic motion of the rotor. The movement of the rotor was modeled by a special sliding surface FEA scheme. In this arrangement, the stator and rotor of the motor are represented by separate meshes joined by the interface. Due to symmetry only a half of the machine needs to be modeled i.e. one stator and a half of the plate secondary. The common interface was located at the middle of the clearance gap between the rotor surface and the adjacent stator surface of the half model. A view of the stator and rotor mesh is shown in Fig 2.

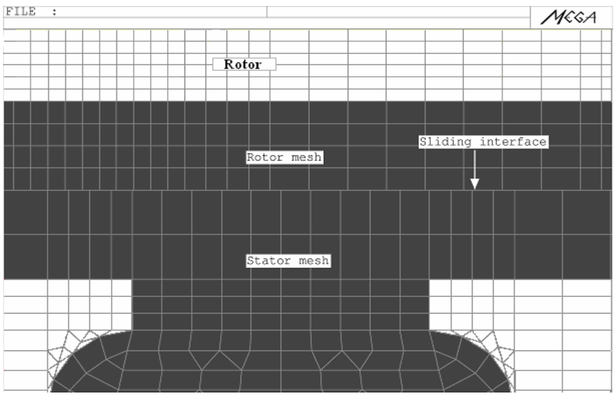


Fig 2 A finite element mesh

The stator and rotor mesh can slide freely relative to each other along the interface and in so doing enable the dynamic motion of the rotor to be handled without the need of any re-meshing.
A further improvement to the 2D finite element modeling comes from the use of the Russell & Norsworthy Factor to modify rotor resistivity in order to simulate the secondary end ring effects present in the practical case [2].

4. Analytical Modelling Method

An analytical method [1] was evaluated. This gives a method of modelling short rotor behaviour without the need for complex and lengthy FE solutions.

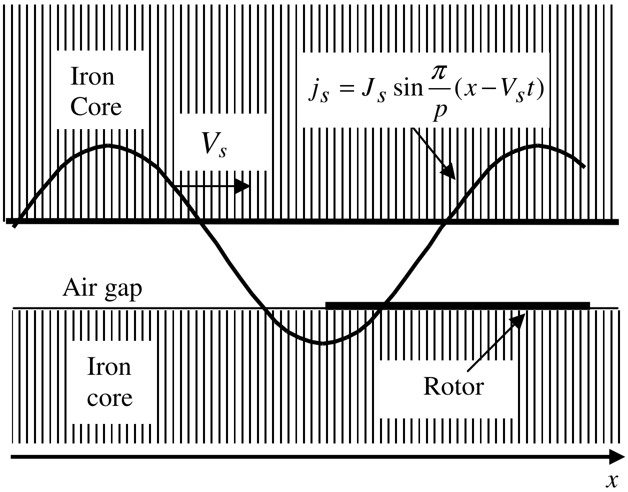


Fig 3. Geometry assumed by [1] to develop the analytical force expression.

This method uses the idealised geometry shown in Fig 3. This as in the FEA case needs to represent only one half of the problem. Here the stator and rotor core iron are both considered to be infinitely long, to have zero conductivity, and to have infinite permeability. The rotor and stator currents are assumed to be concentrated in infinitely thin sheets that lie on the surfaces of the cores, the stator sheet is infinite in length whilst the rotor current is confined to the length of the short rotor. The air-gap flux is assumed to have no component in the direction of motion so that the flux crosses the gap normally. The equation for the force per meter of stack length, F, developed in the reference for these conditions is given below:

$$F = \frac{1}{2} J_s^2 a \frac{\rho_r}{v_s} . \frac{\sigma}{\sigma^2 + 1/G^2}[1 + Y(Z_1 + Z_2)] \tag{2}$$

where

$$Y = \frac{1}{k[\cosh 2mk - \cos 2mk]} \tag{3}$$

and

$$Z_1, Z_2 = \frac{1}{m^2 + (m \pm 1)^2} \left[\begin{array}{l} [(m \pm 1)\sin 2mk - m \sinh 2mk \\ - 2(m \pm 1)\sin mk . \cos k . \cosh mk \\ + 2m \cos mk . \cos k . \sinh mk] \\ + \sigma G [m \sin 2mk + (m \pm 1)\sinh 2mk \\ - 2m \sin mk . \cos k \cosh mk \\ - 2(m \pm 1)\cos mk . \cos k . \sinh mk] \end{array} \right] \tag{4}$$

With Z_1 taking the upper and Z_2 the lower signs and:

$$G = 2p^2 \mu_0 f / \pi \rho_r g \tag{5}$$

$$k = \pi a / p \tag{6}$$

$$m = \sqrt{\sigma G / 2} \tag{7}$$

Where:

σ = slip
a = plate length, m
Js = Current density A / m
$V_s = 2pf$ = field velocity in m/s
f = supply frequency in Hz
p = pole pitch, m
x = Instantaneous position along x axis at which to find point value of current sheet, m
ρ_r = surface resistivity in ohms including factor taken from [2] to allow for the plate side effects
g = magnetic air-gap including Carter's coefficient to allow for the effects of stator slotting, m

5. Flux conditions

There are two distinct air-gap flux regions in a series connected short rotor machine. First the plate region where the rotor currents oppose the stator currents and give a lower flux and secondly the rest of the machine where the stator currents are unopposed and so produce a larger gap flux.
This flux distribution pattern can be seen clearly in Fig 6, which shows finite element modelling of the flux distribution for the 8 pole machine at stall and at peak thrust, 18 m/s.

6. Results

Sample force per meter plate length results were calculated using time stepped FEA with typical dimensions for an electromagnetic launcher machine. Plate rotors of length equal to ½, 1, 2, 4, 6 and 8 stator-winding pole pitches were considered. They were compared with a 'conventional' machine modelled again with FEA as a continuous stator, continuous rotor linear machine of the same length as the plate and which used the same geometry. Fig.7. illustrates these results.
The short rotor results differ from the conventional machine results because of edge effects that occur both at the leading and trailing edges of the plate. One significant difference occurs in stall thrust, with the stall thrust actually higher from the short rotor machines than that of the conventional machines. This finding correlates with [1].
The reason for this is regions of high plate current density found at the ends of the short rotor, which are not present in the continuous rotor of a conventional machine. Rotor current density for continuous and short rotor machines at stall and peak thrust is plotted in Fig 8.
At Stall, the high current regions are caused by the changes in the flux linking the edges of the plate. As the field moves relative to the plate, plate current increases to oppose this change of flux. At peak force, the difference between plate speed and field speed is much smaller, so the change of flux linking the ends of the plate is lessened, as is its effect on plate current.
It is evident from the results that the effects are much reduced for plate lengths equal to or greater than 4 poles as far as the peak torque is concerned. This implies that

if under inverter control the machine is run at constant slip velocity conditions near to the force peak the effect of the short rotor effects is minimal.

Fig 9 details the short rotor Finite Element prediction results compared with short rotor thrust predictions using equation (2). This figure shows that the analytical method can predict short rotor performance to within 18% of peak thrust, for short rotors 4 poles and above, and the method becomes even less accurate for shorter rotors.

For machines of four poles and above, it can be seen from Fig 7 that their performance in terms of force per meter of reaction plate is within 10% of that of a conventional continuous rotor induction machine. This indicates that prediction of short rotor machine performance for a rotor of 4 poles or greater length may be achieved simply by treating the case as a conventional machine.

7. Conclusions

Finite element modelling has shown that the peak force per meter length of plate produced by short rotor induction machines of rotor length greater than 4 stator pole-pitches is closely the same in magnitude and slip as that from a conventional machine of the same air-gap geometry.

Extremely short rotors of 1 pole or less in length have a significantly increased starting torque, which may be of benefit in certain applications. This behaviour is currently only predictable using FEA, as simple modelling methods do not account well for irregular rotor current density.

8. References

1. Laithwaite, E.R., Tipping, D. and Hesmondhalgh, D.E. “The application of Linear Induction Motors to Conveyors” Proc. I.E.E. 107 (A), 290 (1960)

2. Russell, R.L. and Norsworthy, K H. “Eddy Current and Wall Losses in Screened Rotor Induction Motors” Proc. I.E.E. Paper No. 2525 U, Apr 1958 (105 A, 163)

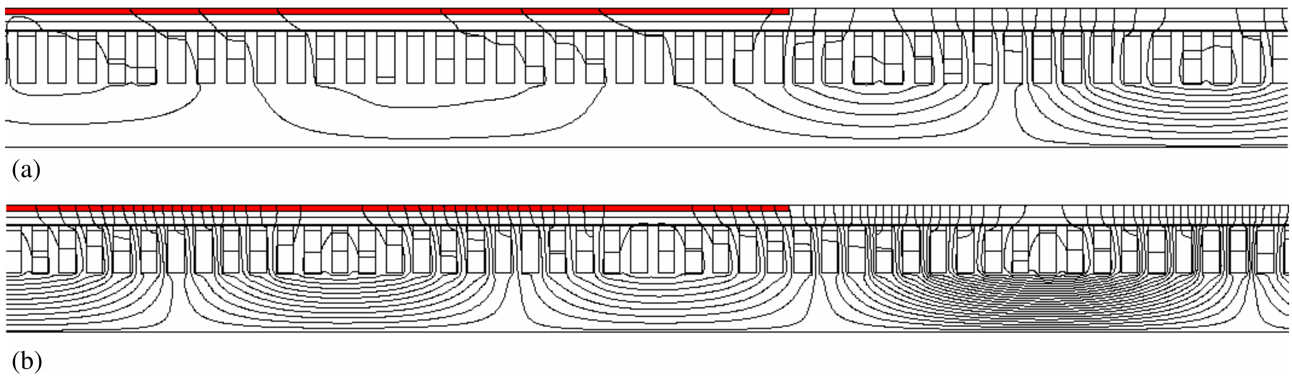


Fig.6. Air gap flux distribution in an 8-pole rotor short rotor machine at stall (a) and at peak thrust, 18 m/s (b)

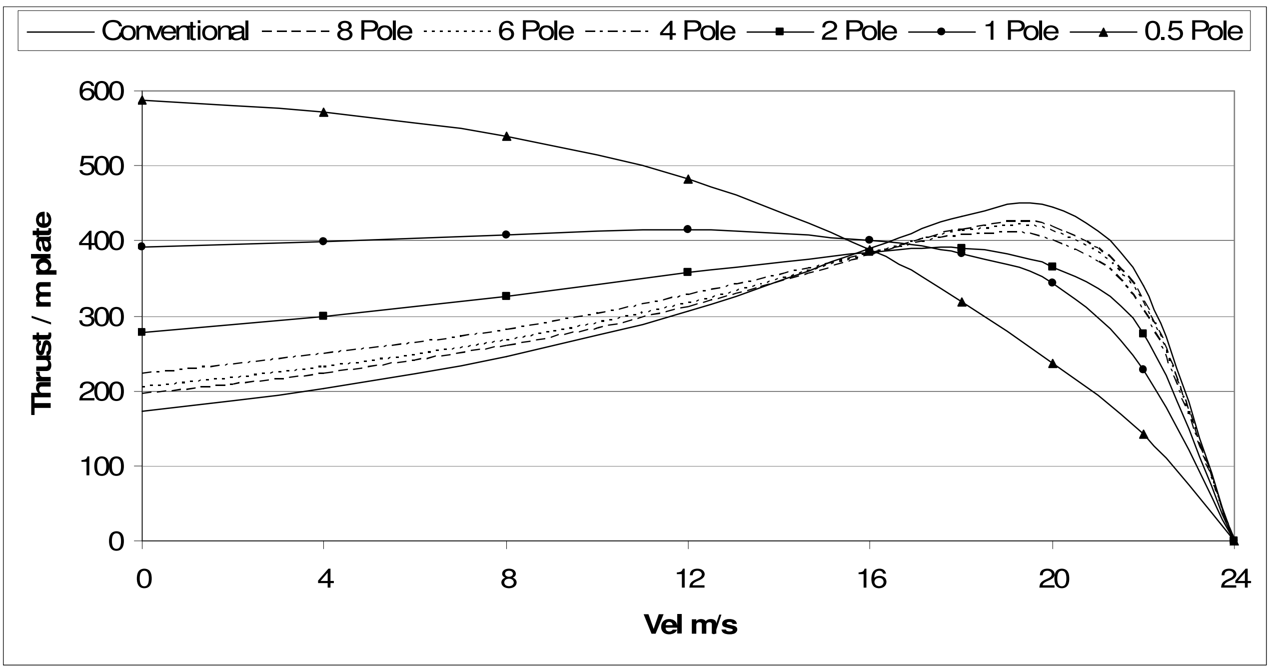
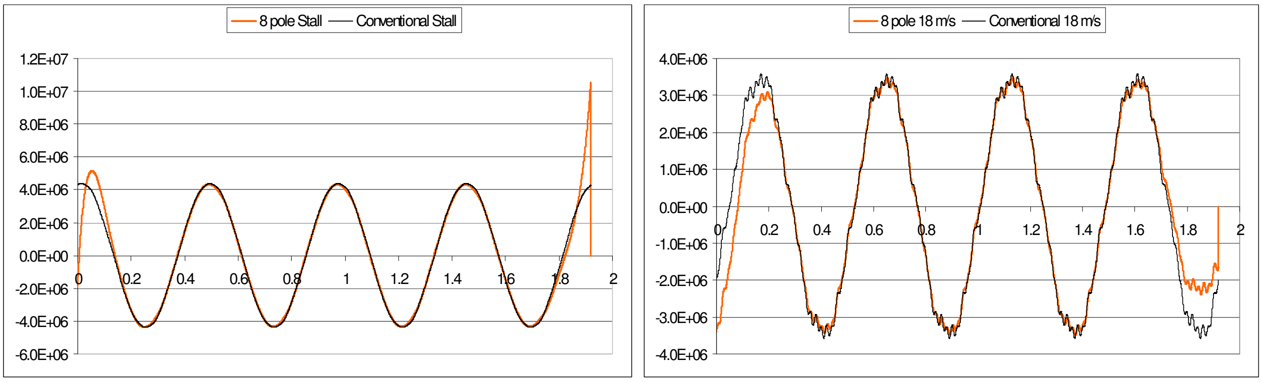
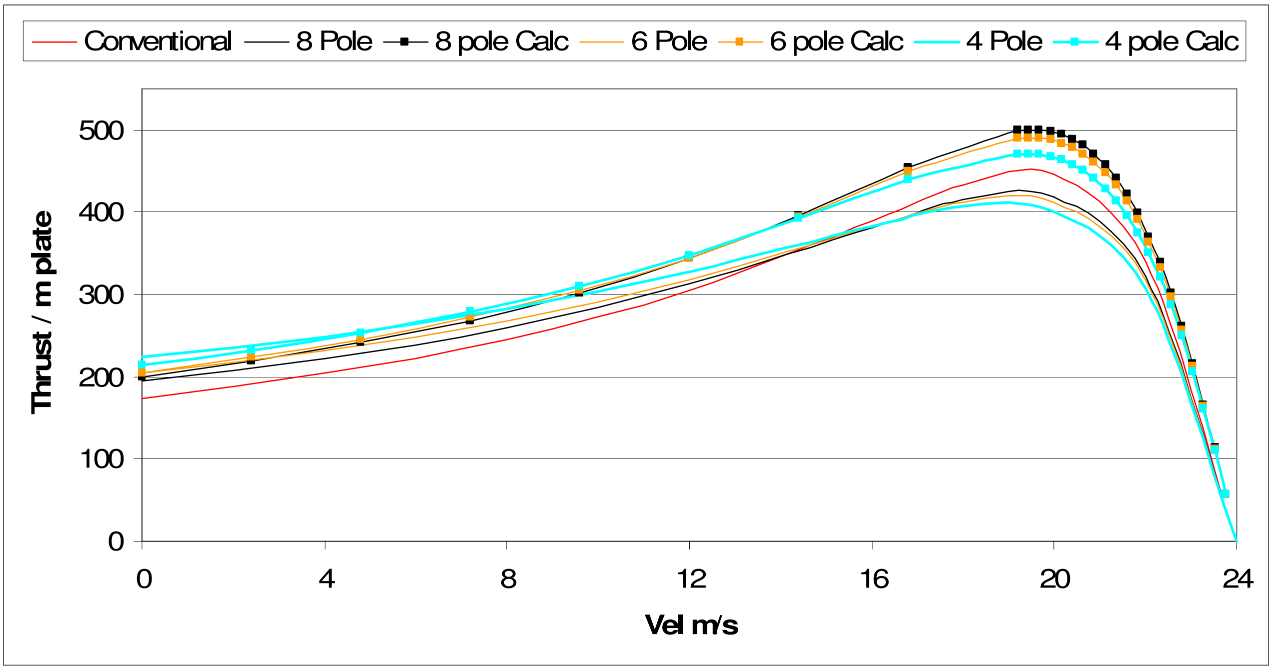


Fig.7. Force per meter length of plate against speed results using finite element time-stepping analysis for different short rotor lengths

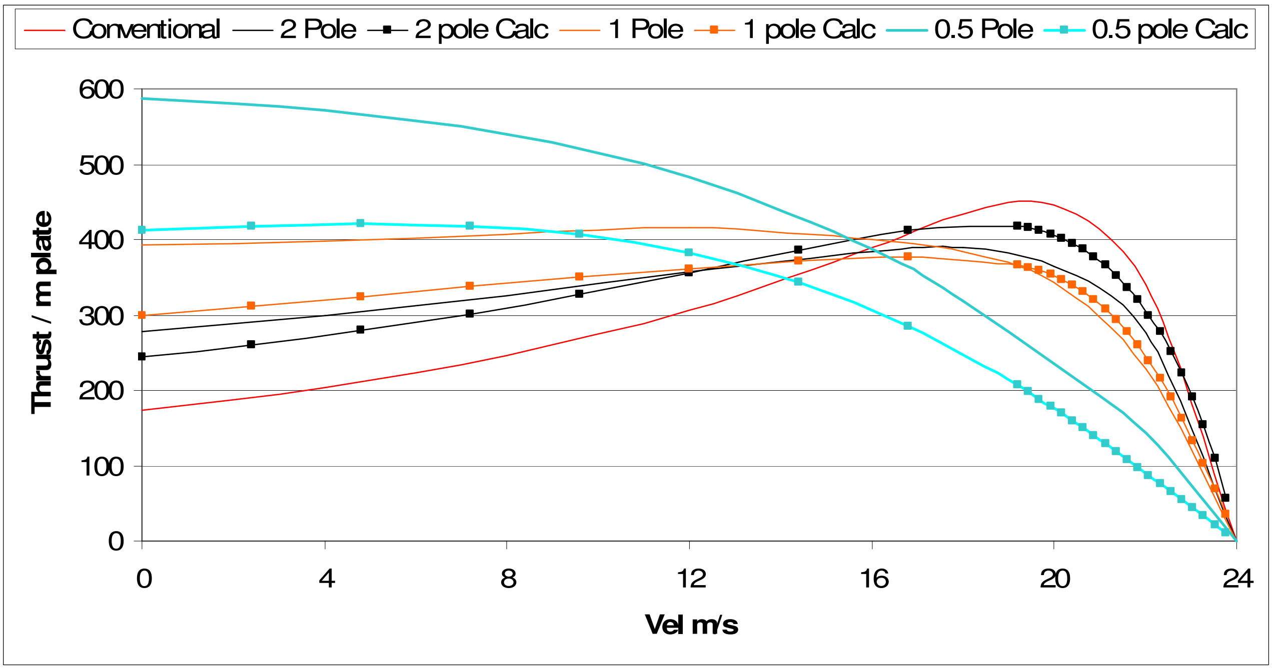


(a) (b)

Fig.8. Current density in the plate for conventional and 8 pole short rotor plates at stall (a) and peak thrust 18 m/s (b)



(a)



(b)

Fig.9. Short rotor FEA results and short rotor equation (2) predictions for 8-4 poles (a) and 2-0.5 poles (b)