Linear Induction Motor Variable Frequency Standstill Tests to Predict Operational Velocity Performance

J. F. Eastham, P.C.Coles
EnigmaTec Ltd
The Close,Claverton
Bath BA2 7BG
Tel/fax + 44 (0)1225 464703
jfeastham@aol.com

M. Benarous
Goodrich Ltd
York Road, Hall Green
Birmingham B28 8LN
Tel + 44 (0)121 6276600
maarmarben@aol.com

J. Proverbs, A Foster
Force Engineering Ltd
4 Old Station Close
Shepshed Leicestershire
Tel + 44 1509 506025
jeff@force.co.uk

***Abstract*— The purpose of this work is to show how variable frequency results from a linear induction motor static test rig can be used to predict the performance of the machine when it is travelling at different velocities.**
***Key words*- Induction, Linear, Machine, Testing**

1. INTRODUCTION

There are two methods of testing large high-speed linear motors dynamically. First, for research and development purposes, the machine can be made in the form of an arc and tested on a rotating rig using either a disc or drum secondary. Secondly use can be made of a test track. For product testing of straight motors the rotating rig method is, of course, not applicable and a high-speed test track is expensive in both installation and running costs. In many cases therefore static measurements must suffice. It is the purpose of this paper to show how the use of static rigs can be extended using variable frequency testing so that predictions of the machine dynamic performance can be obtained.

2.THE PHYSICAL BASIS OF THE METHOD

If only the principal harmonic is considered the relative velocity between the stator field and the rotor governs conditions in the rotor of an induction motor.
The relative velocity at standstill with a stator frequency of sf is the same as that at a slip s with a stator frequency of f and it follows that the rotor frequency and skin depth are also the same. Further the rotor current will be the same at the same air-gap flux. The induced voltage in the stator at the same air-gap flux is sV where V is the voltage at slip s.
These standstill conditions are commonly used for the approximate finite element analysis of induction motors with the advantage that moving rotor solutions are not required. They have been used at Force Engineering for some time for linear induction motor testing with the benefit that a simple standstill test at variable frequency can simulate the conditions at speed.
The standstill conditions are easy to set up in the analytical case since the model can have zero resistance but in the practical test case allowance has to be made for its effect.

3. APPLICATION TO LINEAR MACHINES

The behavior of a linear induction machine is different to that of a cylindrical version mainly because of the ends of the machine cause discontinuities. The effect of these can be thought of in two ways, a first way is to consider the longitudinal space transients produced in the air-gap flux patterns by the edges. Alternatively the effect can be taken into account by using an assembly of the harmonics found from the analysis of a short section of excitation on a circular equivalent model [1]. If only the principal harmonic is used in an analysis then this equivalent to ignoring the longitudinal edge effect. Therefore using the one harmonic approximation as outlined above to find the behavior of a linear machine at speed means that the longitudinal end effects are ignored. It is one aspect of this work to show the effect this has on the accuracy of the simulation when it is applied to a large high-speed machine.

Equivalent circuits

Approximate equivalent circuits can be used to find the applied voltage for the standstill test. If only the fundamental space component is considered then the approximate equivalent circuit for a linear machine is the same as that for a conventional machine. It is shown in Fig.1 for a slip 's' and a supply frequency of 'f'. The equivalent circuit for the same machine at standstill when supplied with a frequency of 'sf' is shown at Fig.2. By comparing the equivalent circuits, with the stator resistance ignored, it will be seen that the input impedance for the standstill circuit of Fig. 2 is 's' times that for the velocity circuit at Fig.1. It follows that if the stator resistance is ignored then applying a voltage of 'sV' at a frequency 'sf' to the circuit of Fig. 2 will drive exactly the same current as applying a voltage of ‘V’ at a frequency ‘f’ to the circuit of Fig. 1. The currents in the corresponding circuit branches will also be the same.

The thrust is given by the power dissipated in the equivalent rotor resistance divided by the field velocity (v). Hence the thrust for the velocity conditions of Fig.1 is $I_2^2 R_2 / s\ v$ where I_2 is the rotor branch current. This is the same as for the standstill conditions of Fig.2. Again since the coil currents are the same in the two circuits it follows that the flux densities will also be the same ignoring stator eddy currents.

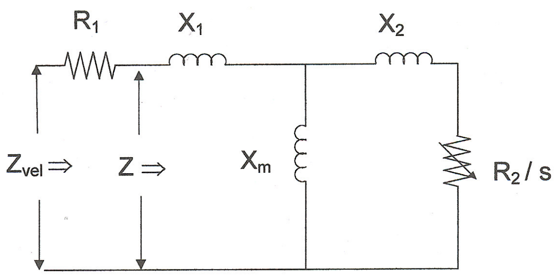

Fig.1 Equivalent circuit, applied voltage V

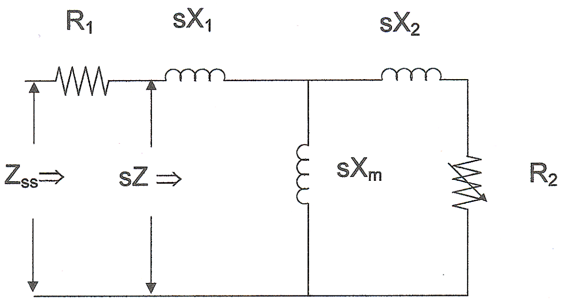

Fig.2 Equivalent Circuit, applied voltage first V and then V_{ss}

Test conditions

It is evident that by neglecting the stator resistance approximate results can be obtained from a test machine at standstill by applying a frequency ‘sf’ at a voltage ‘sV’ to find the performance of the machine at a slip ‘s’ when a voltage ‘V’ at a frequency ‘f’ is applied. However better results can be obtained by using the initial results as obtained above when applying ‘sV’ to find the input impedance and using it to correct the input voltage for the effect of the stator resistance.

Applied voltage calculation for the standstill test

Using the variables defined on Figs. 1 & 2.
The input impedance from the initial standstill test is given by:

$$Z_{SS} = sV / I \qquad (1)$$

where sV is the phase voltage and I is the phase current.

The components of Z_{SS} are:

$$R_{SS} = Z_{SS}\ \varphi \text{ and } X_{ss} = Z_{SS} \text{ sq rt} (1- \varphi^2) \qquad (2)$$

where φ is the power factor.

Hence:

$$\mathscr{Re}(sZ) = R_{SS} - R_1 \qquad \mathscr{Im}(sZ) = X_{ss} \qquad (3)$$

$$\mathscr{Re}(Z) = \mathscr{Re}(sZ) / s \qquad \mathscr{Im}(Z) = \mathscr{Im}(sZ) / s \qquad (4)$$

$$Z_{vel} = \text{sq rt} ((\mathscr{Re}(Z) + R_1)^2 + (\mathscr{Im}(Z))^2) \qquad (5)$$

For the same current in the standstill case as in the velocity case:

$$V / Z_{vel} = V_{ss} / Z_{SS} \qquad (6)$$

and the applied voltage, $V_{ss,}$ in the standstill test must be corrected to: $V_{ss} = V \times Z_{SS} / Z_{vel}$ (7)

to allow for the effect of the stator resistance.

4. MODELLING RESULTS

The accuracy of the method has been assessed by computer modelling using as an example a design for a large linear machine aimed at fairground ride launch applications. This is double sided, 1.4m long and 0.23m wide and has 8 poles.

Modelling methods

Two methods namely 2D Finite Element Analysis (FEA)[2] and 2D Layer Theory[3],[4] have been compared for this work. The 2D FEA uses vector potential and the Minkowski Transform is employed to model the reaction plate velocity. The plate resistivity is modified to allow for the ‘end ring’ effect of the plate sides outside the pole regions by a factor developed from a paper by Russell and Norsworthy.[5] This same factor is used for the Layer Theory method in which the approach is again 2D with the problem space divided into a number of laminar regions parallel to the air-gap, of infinite extent in the plane of lamination, and of arbitrary thickness. These two methods were successfully compared with experimental results from a small linear induction motor in a recent paper[6]. The results for this modelling for one half of the machine are shown in Fig.3 and 4 and it can be seen that the results are in good agreement. Either method therefore could be used for the comparative modelling and the layer theory method was chosen because the computer time involved is very much less.

Comparison between results

The comparative results are shown in Fig. 5 and Fig.6. The applied voltages at the three frequencies considered 30, 60 and 90Hz have been adjusted as is usual to produce similar peak forces. In each case the curve labelled ‘Layer Theory’ was

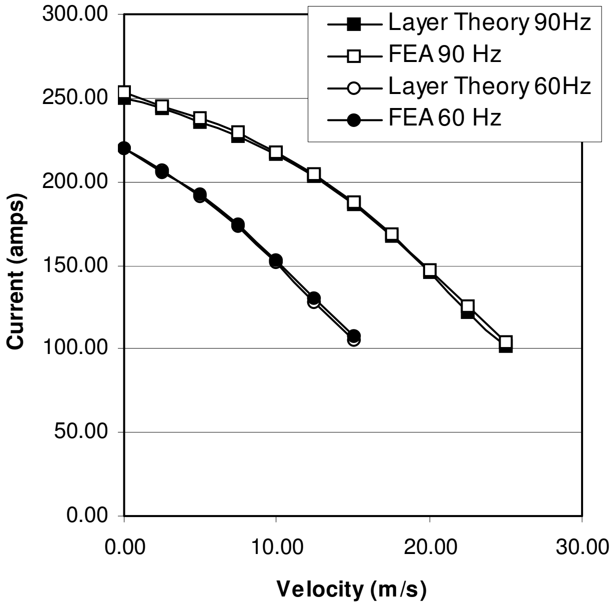

Fig.3 FEA vs Layer Theory: Current Calculation

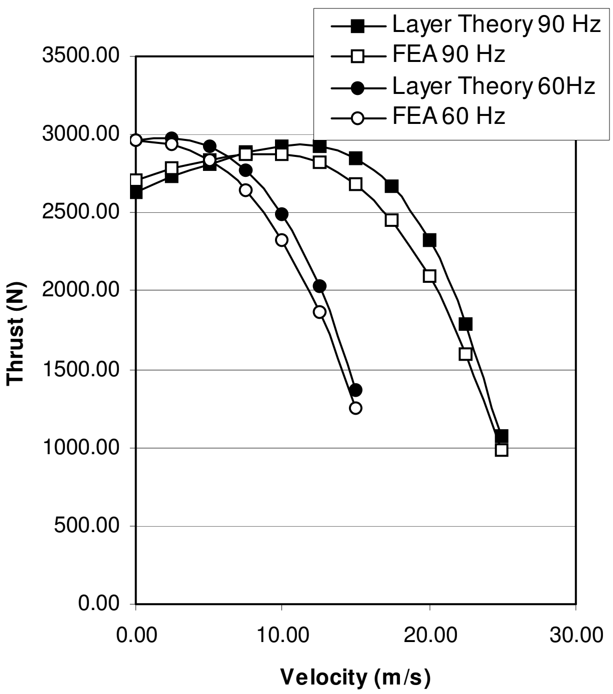

Fig.4 FEA vs Layer Theory: Thrust Calculation

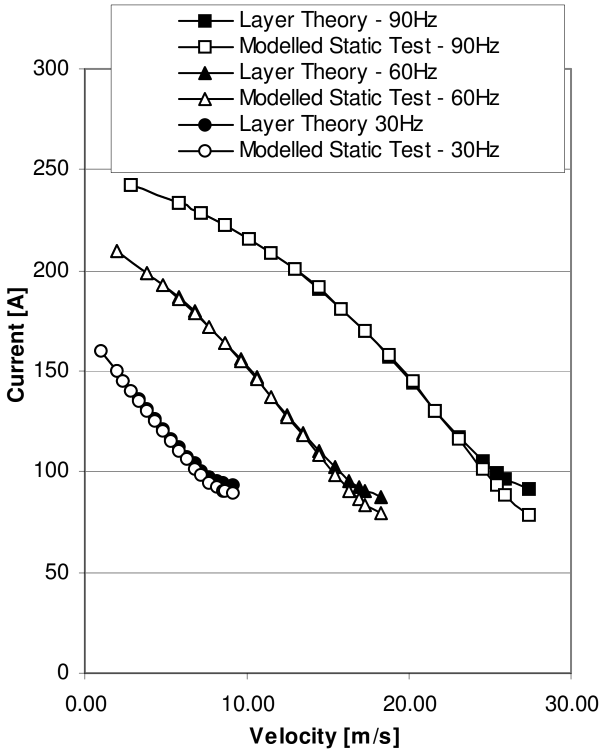

Fig.6 Comparison between Layer Theory and Modelled Static Test: Current Calculation

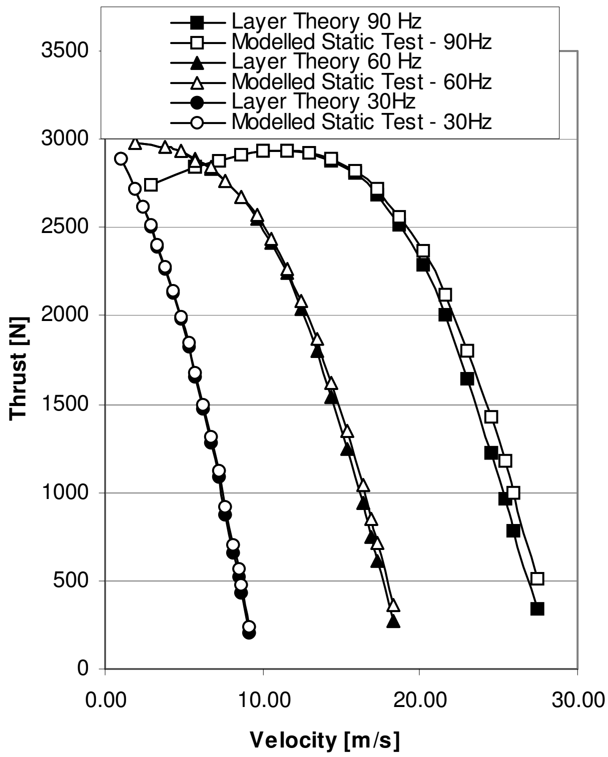

Fig.5 Comparison between Layer Theory and Modelled Static Test: Thrust Calculation

obtained by the conventional use of the method which calculates the performance at a set of speeds whilst the curve labelled 'Modelled Static Test' used standstill results from the same 'Layer Theory' method. These were obtained at slip frequency using the voltage correction method described in the section above so that the process simulates the practical static variable frequency test technique. It will be observed that the agreement is generally very good confirming the value of the technique. As can be expected the results show the largest divergence where the longitudinal edge effects are largest, that is at small slips and high frequencies. Normally the controller for a variable frequency LIM drive system is set for a particular constant slip velocity. It is interesting to observe that if this is taken as 10m/s then the results for current show a negligible error at all frequencies whilst the largest error for the thrust is of the order of 4%.

In addition to the above results the flux densities in the machine predicted by the static test and the results at speed were also compared and the errors were similar to those for thrust.

5. CONCLUSIONS

The computer simulations have shown that static testing of a linear induction machine using a variable frequency supply can predict the dynamic performance accurately. The applied test voltage is calculated using the measured standstill impedance and resistance.

The example chosen is a large machine suitable for a fairground ride application

6. REFERENCES

1. J.H.H.Alwash, and J.F.Eastham "Permeance harmonic analysis of short stator machines" Proc. IEE, Vol 123, No12, December,1975, pp 1382-1389
2. J.F.Eastham, M.J.Balchin and D.Rodger "Measurements and calculation of rotor-core flux densities in axial flux linear induction machines", IEE Proceedings Part B, Volume128, No 65, Nov, 1981
3. J.Geig, and E.M.Freeman "Travelling wave problem in electrical machines" Proc. IEE, Vol.114, No.11, Nov. 1967,pp 1681-1683.
4. M.J. Balchin and J.F.Eastham "Performance of linear induction machines with air-gap windings" Proc IEE, Vol.122, No 12, December 1975, pp1382-1389.
5. R.L.Russell and K.H.Norsworthy "Eddy current and wall losses in screened-rotor induction motors" Proc IEE, 1958, 105A, pp 163-175.
6. M.Benarous, J.F.Eastham, J.Proverbs, A.Foster "Linear machine eddy current braking techniques" LDIA 2001 Nagano, JAPAN pp 90-94