

Aspects of electro-magnetic aircraft launch and linear machine development

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SYNOPSIS

The history of electromagnetic launch using linear motors, which dates back to World War II and the Westinghouse Electropult system is outlined. Modern developments in electromagnetic aircraft launch are described. These modern systems are considerably improved over the earlier form and use double-sided linear induction machines and variable frequency power electronic converters.

Three novel developments in linear induction motor systems are described. Firstly, the use of windings with parallel connected phase groups in high speed launch systems is explored and the benefits of this connection type are outlined. Secondly the benefits of the use of alternate forward and reversed connections for a stator array are explored. Finally, the use of economical planar single layer windings in an offset configuration is discussed, and the significant advantages to this construction method are given.

All of these developments are shown to offer significant benefits compared to modern aircraft launch systems that use more conventional winding systems. Comparisons are made using time stepping finite element analysis and the method is validated by the use of algebraic expressions for a simple case.

INTRODUCTION

Aircraft launch from ships has been employed for over 100 years, and is a key part of the defence capability of many nations. Linear electrical machines have been applied to aircraft launch for many years. The Electropult, an early development, was constructed by Westinghouse in the USA during World War II and successfully launched 4.5 tonne aircraft¹. However, the Electropult design was viewed as too costly and heavy and was overtaken by the British invention of the steam catapult.

The conception of the double-sided linear induction motor and the increasing availability of power electronics in the last few years have led to improved launcher configurations with some significant advantages compared with steam catapults. Currently there are major projects in electromagnetic aircraft launch in both the UK and The USA.

Some of the issues involved in designing the linear machines for electromagnetic launchers are explored, and a simple and robust stator design suitable for use in launching aircraft from the latest generation of carriers is revealed.

Author's Biographies

Jeff Proverbs retired as the Technical Director of Force Engineering Ltd and works as a consultant for the company. He obtained an MPhil degree from Nottingham Trent University, is a chartered engineer and a Fellow of the IET and IMechE. He was actively involved in the development of Linear Motor design software, design of permanent magnet brakes, Linear Motors and control systems for Linear Motor accelerators with experience of control systems, PLC's, relay logic, power electronics and high voltage switch gear.

Steve Colyer is the Technical Director of Force Engineering Ltd. He obtained a bachelor degree in Electrical & Electronic engineering from Bradford University, is a chartered engineer and a member of the IET. He is now responsible for the implementation of standard inverters to achieve custom speed and position control of systems driven by linear induction motors. He is also responsible for the continued development and application of linear motors, application modelling software, and the implementation of the companies QA system.

Dr Tom Cox received his 1st class Masters degree in Electronic & Electrical Engineering from Loughborough University and his PhD, for research into novel linear machines, from the University of Bath. After working for several years on a program which successfully took novel technologies and embedded them into industry, he accepted the role of senior project engineer with Force Engineering, a world leader in linear induction machine development. Since his appointment he has worked on numerous technical development projects for Force Engineering and has authored several papers on the use of improved linear motors in electromagnetic launch systems.

Professor Eastham is a Professor Emeritus at Bath University. During his time at Bath he has held the position of Head of the Electrical Engineering Department, and Pro-Vice Chancellor. He is a Fellow of the Royal Society of Edinburgh, and the Royal Academy of Engineering. His field of engineering interests includes machines, power electronics and electromagnetics. His defence related work has included appointment to the Register of Independent Members of the Defence Scientific Advisory Council (DSAC).

A BRIEF HISTORY OF AIRCRAFT LAUNCH

The first fixed wing aircraft launch from a ship occurred in January 1911, when Eugene Ely successfully landed on, and took off from, a temporary wooden landing strip mounted on the USS Pennsylvania. During the second world war, Westinghouse made the first known electromagnetic aircraft launch system, the 'Electropult' launcher (Fig 1), a description of which appears in the September 1946 copy of the 'Westinghouse Engineer'¹. They were intended to serve as launchers for heavily loaded planes taking off from short runways on Pacific atolls. The machines themselves were short-stator single-sided induction machines in form (Appendix 1 Fig A2) with a powered primary attached to a wheeled trolley linked to the aircraft and fed by brushes running on slip tracks. The stationary track mounted secondary was in the form of linear conductive bars in iron slots. This enabled the secondary resistance to be varied by the use of secondary bars of differing resistance in the manner of a wound rotor induction motor, using high starting and low running rotor resistance. In the larger of the two electropults the track was 1382 feet long and the maximum speed was 225 mph. The secondary bar resistance profile kept the force substantially constant at about 5 tonnes. The trolley was stopped at the end of its run by a combination of dynamic braking and d.c. injection. The current supplied to the trolley was about 7kA during acceleration and 10kA during braking. The power plant used an aircraft type petrol engine driving a d.c. generator. This in turn supplied a d.c. motor coupled to the a.c. generator supplying the linear machine and a flywheel for energy storage. During a launch 95% of the power required was taken from the flywheel. The electropult in the configuration used was never brought into general use as it was viewed as costly and heavy, and was overtaken by the British invention of the steam catapult in its modern form by Commander Colin Mitchell RNVR. Trials on HMS Perseus from 1950 showed its effectiveness, and steam catapults capable of launching the heavier jet fighters were introduced by various Navies.

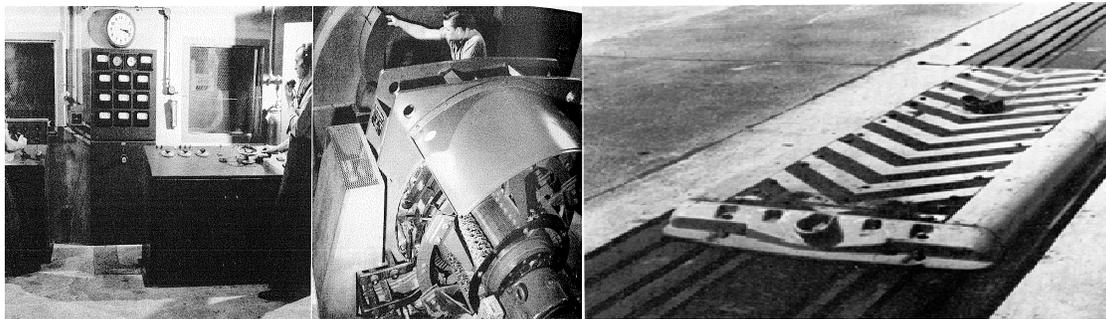


Fig 1 Left to right; Control Room; DC motor driven flywheel; Linear motor primary and secondary track (Westinghouse engineer 1946)

NEW ELECTROMAGNETIC LAUNCHERS

During the past twenty years electromagnetic aircraft launch technology has once again been under development in an effort to replace steam catapults. Some of the motives for replacement are²:

- Steam catapults are heavy and large.
- They operate without feedback control and can impart large transient loads to the airframe.
- Heavier faster aircraft will soon result in a launch energy requirement that cannot easily be met by the steam catapult.
- Steam is not as readily available on the newest generation of largely electric drive ships, particularly those without nuclear reactors.
- Modular stators and power supplies can allow for the failure of a part of an electromagnetic launch system without critically compromising the overall performance of the catapult³.

There are two key technological developments that have contributed to the improvement of electromagnetic launchers in comparison to steam catapults.

Firstly, power electronic inverters that can provide a high level of control over motor acceleration are now available. For synchronous linear machines the inverter provides a variable frequency supply in step with the speed. For linear induction machines the accelerating launcher is again supplied at increasing frequencies to give small slip conditions and high efficiencies.

Variations in linear motor topology⁴ and in particular the use of double-sided machines (Appendix 1 Fig A4-5) have been suggested. In the double sided configuration the unwanted attraction force between the secondary and the track is avoided. This force can be several times the tractive force in the single sided case.

Two major projects to develop a full scale aircraft launch system are currently in progress; EMALS⁵ at General Atomics USA which will be used on the USS Gerald R. Ford (CVN-78) carrier and EMCAT⁶ at Converteam UK which is projected for the Queen Elizabeth class carrier, and has recently been demonstrated on a smaller scale as the EMKIT⁷ UAV launcher.

Both of these projects use a system layout similar to the Electropult, with a primary generator, power storage, power conditioning system and a linear motor. One significant difference is that whereas the Electropult used a moving short primary fed through brushes, the modern systems both use a static double sided primary with a moving short secondary³. This configuration can use either a permanent magnet synchronous machine (LSM) or a plate conductor secondary induction machine (LIM). There have been several studies^{8,9} which compare the attributes of the two approaches and there is little doubt that the LSM is smaller, lighter and requires a somewhat reduced size of power supply. Despite this, both of the current major projects EMCAT and EMALS use LIMs.

The main reasons for the choice of LIMs over LSMs are:

- The optimum pole pitch for the LSM is short, leading to a supply frequency of 300-700Hz. This leads to a switching frequency that borders on the limits of existing technology. In contrast the optimum pole pitch is longer for the LIM leading to frequencies well within the range of existing technologies³.
- The LSM requires a supply which is matched very precisely to the speed and position of the secondary and the complexity and reliability of the control and measuring system is challenging¹⁰.
- Demagnetisation of permanent magnets in LSM systems can occur which will cause a permanent loss of magnetisation and reduced performance.
- The supply of the rare earth permanent magnets used in LSM systems is limited, increasingly costly and is currently dependent on materials from China.

LINEAR INDUCTION MOTOR DEVELOPMENTS

Electromagnetic launch arrangement

The common electromagnetic launch arrangement is shown in (Fig 2). The stators are made in separate blocks to facilitate construction resulting in a discontinuous excitation. The gaps between the stators are generally as small as possible, but some discontinuity must be present. The rotor is of a length that spans a small number of stator blocks and the stators may be switched on and off as the rotor progresses.

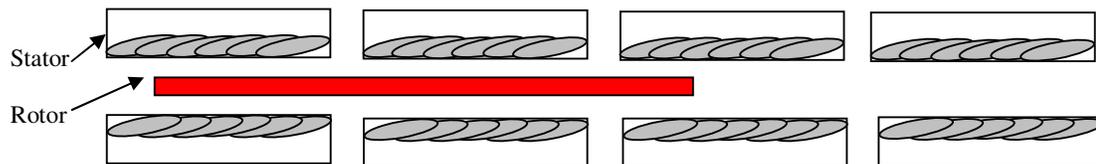


Fig 2 Electromagnetic launch arrangement

Flux conditions in a simple case

The operating conditions for launchers are relatively complex; the rotor is accelerating rapidly and the plate edge eddy currents change as the geometry varies. Arguably the only way to analyse the situation is to use a transient time stepped finite element analysis (FEA). It is however instructive to look at a simple case based on a physical approach¹¹ in order to better understand and validate any results from FEA. The case is illustrated by (Fig 3).

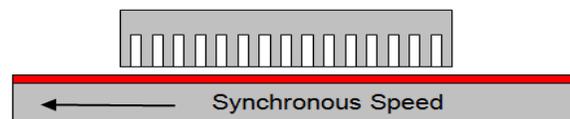


Fig 3 Simple case with rotor moving at synchronous speed

A given conductive loop on the rotor carries no current when it is immediately outside of the stator and has no flux linkage. Since the flux through the loop cannot change instantaneously it follows that the gap flux is zero at the start of the block. This is achieved by the rotor acquiring a current equal and opposite to the instantaneous

stator current at the time of entry. This transient current dies away at a rate governed by the rotor coupled time constant as the rotor progresses, since without relative velocity there is no mechanism to maintain it.

Rotor current loading is

$$j = J e^{-t/\tau} \quad (1)$$

where J is the rotor current at the entry point and

$$\tau = p^2 \mu_o / \pi^2 \rho_r g \quad (2)$$

where τ is the rotor coupled time constant, p is the pole pitch, ρ_r is the surface resistivity and g is the magnetic gap

At a point remote from the entry the rotor current must be zero and the gap flux B_g must be the same as in a conventional machine B so the peak airgap flux is

$$B_g = B \{1 - e^{-t/\tau}\} \quad (3)$$

where

$$B = J_s p \mu_o / \pi g \quad (4)$$

As a loop on the rotor approaches the end of the stator it carries a flux B_e which again cannot change instantaneously so the rotor acquires a current sufficient to maintain this flux.

The current and flux die away at a rate that is defined by the rotor coupled time constant τ_o when the rotor is outside the stator block

$$B_o = B_e e^{-t/\tau_o} \quad (5)$$

A comparison can now be made of the calculated air-gap flux envelope from simple theory and time stepping FEA using a conventional series connected winding (Fig 4).

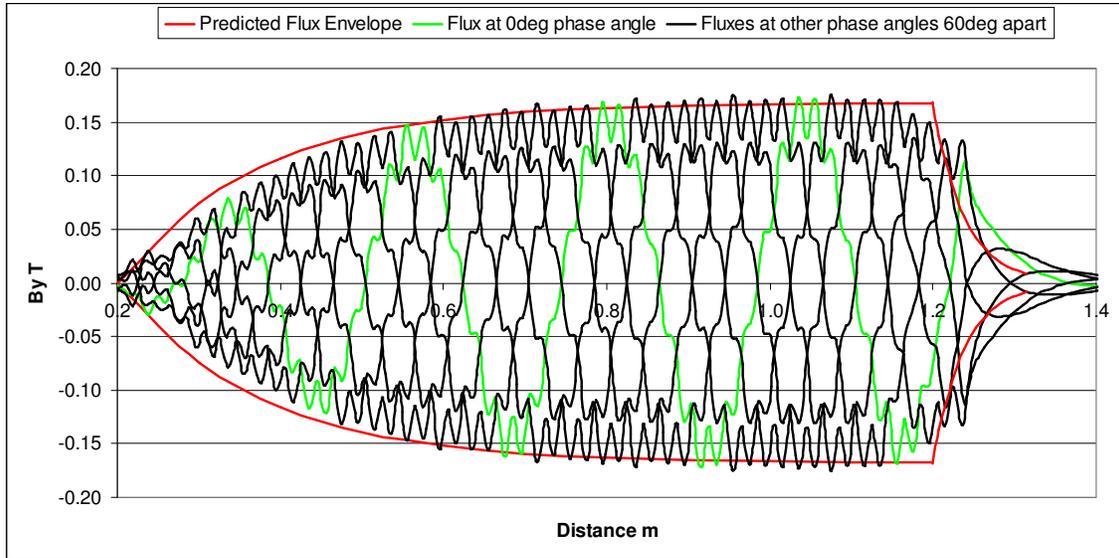


Fig 4 Calculated air gap flux for a series connected machine using simple theory and time stepped FEA at various phase angles

It can be seen from (Fig 4) that the agreement between the two analyses is favourable and it can be argued that the physical basis of the simple theory has merit, giving flux envelope results equivalent to those from FEA, but without time consuming dynamic FEA analysis.

If the secondary is travelling between discontinuous stator blocks then the behaviour is more complex, as some current may remain in the rotor from previous stators. The flux at the entry point of a block may be either aiding or be in opposition to the excitation resulting in either enhanced or reduced force. This condition depends on the rotor speed as the decaying wave from a previous block will change phase as the rotor speed varies.

Series and parallel connections

The behaviour of the machine is clearly affected by the entry and exit conditions and the force is reduced due to the space transient nature of the air gap field. It is possible to use parallel connections to force the flux to be more uniform. In one arrangement each phase group of a winding is connected in parallel^{12,13} as in (Fig 5). This tends to force the flux linking each phase group to be the same and the action will be independent of the rotor current.

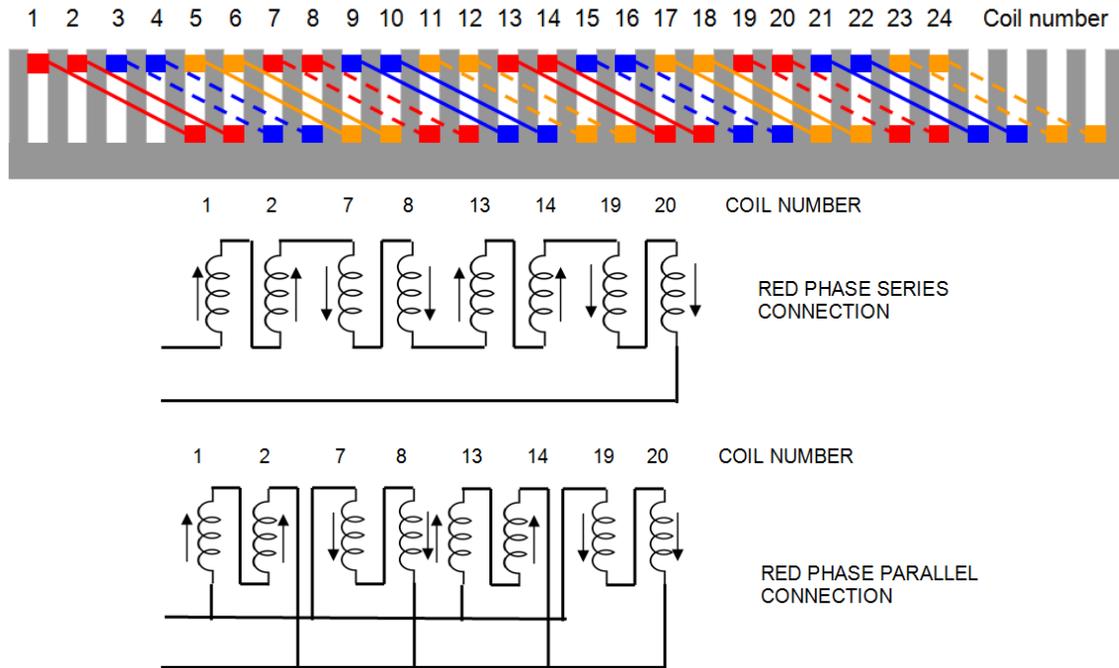


Fig 5 Series and parallel winding connections for double layer 4 pole 2/3 chorded winding

The resulting airgap flux for comparison with (Fig 4) is shown on (Fig 6) and it can be seen that the flux is now uniform.

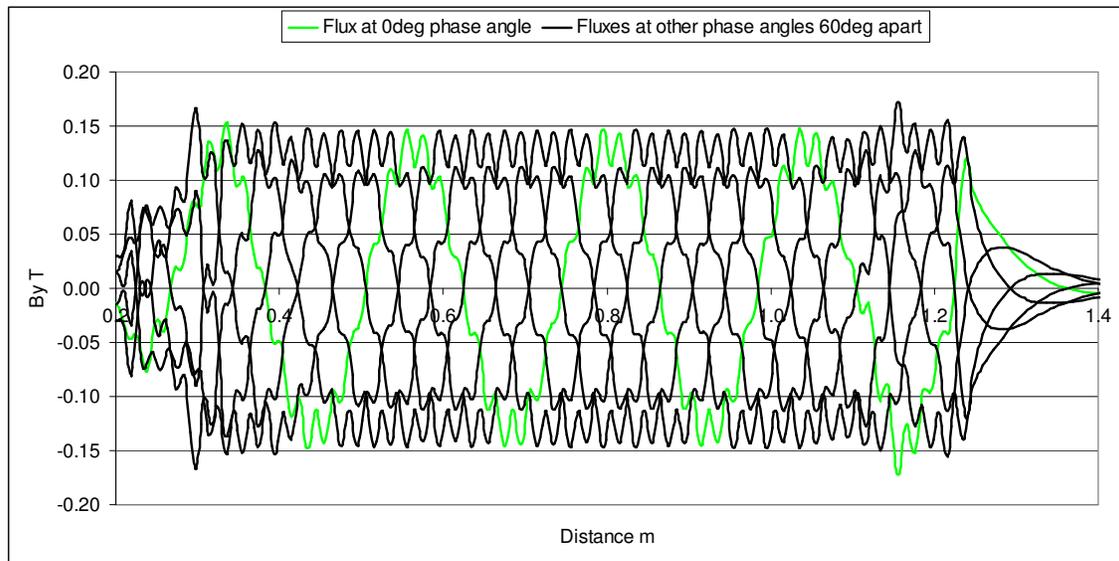


Fig 6 Flux distribution with flux forcing by parallel winding connections

This is at the expense of large currents at the input and output edges as shown in (Fig 7). These currents are necessary to force the flux to be constant despite the edge transients. The current imbalances can generally be tolerated in machines which are short time rated; for example in electromagnetic launch.

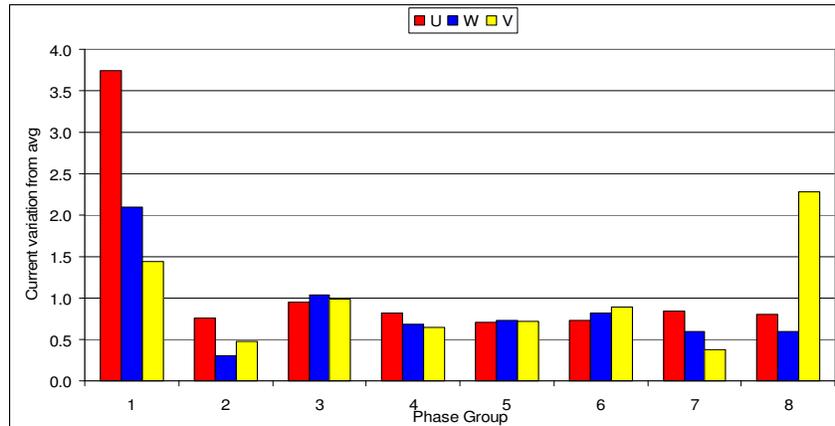


Fig 7 Phase group currents

The effect of the parallel connection on the force can be seen in (Fig 8). It can be observed that the perturbations in force produced by the series winding are corrected when the winding groups are paralleled.

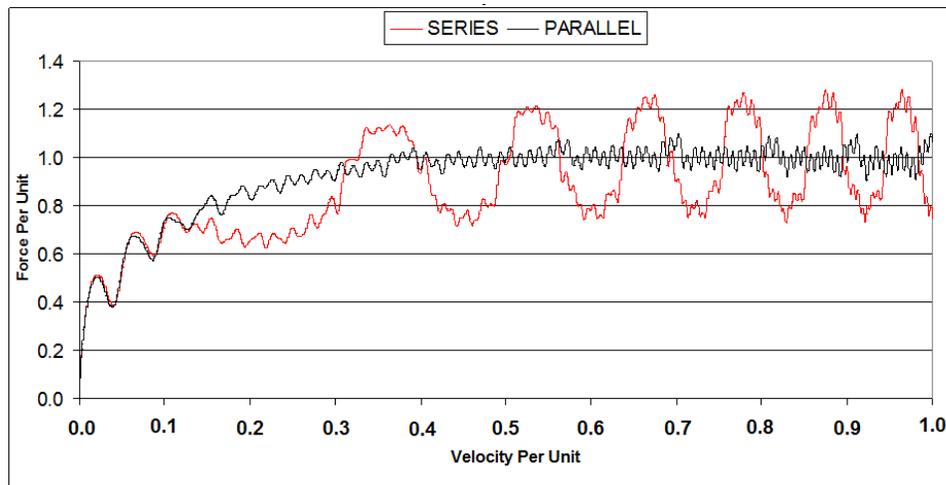


Fig 8 Comparison between force production in series and parallel connected machines

The effects of block connections on adjacent stators

With a standard double layer winding one side of a coil occupies the top half of a slot, whilst the other side occupies the bottom half of another slot separated from the first by the coil pitch as in (Fig 9). In discretely wound linear machines this configuration leads to half filled slots at the beginning and end of the stator (Fig 5). This means that the end slots carry reduced ampere turns compared to the rest of the winding and give a reduced performance compared to full slots. Another effect of the half filled end slots that may not be apparent is on the number of poles in the winding.

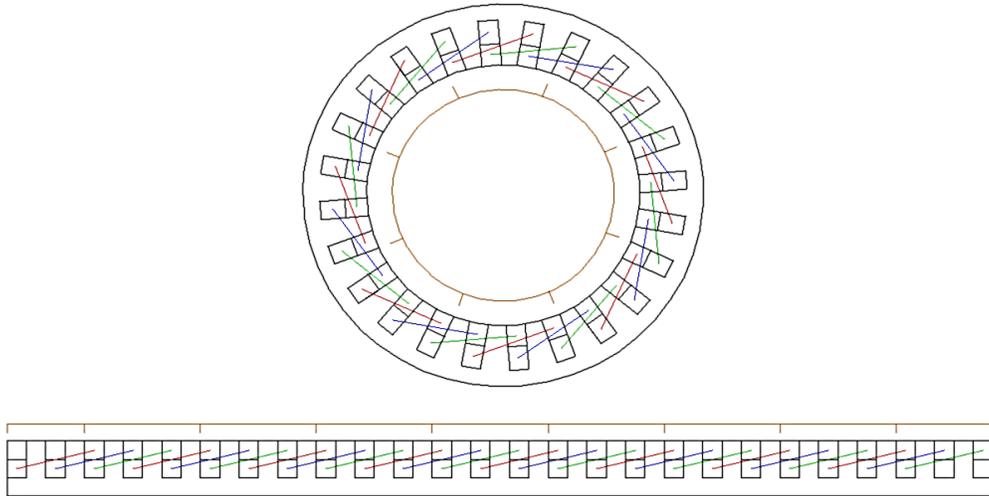


Fig. 9 Rotary and linear stator windings

The brown line in (Fig 9) shows the number of poles for each stator. For the rotary machine, It can be seen that we have 8 full poles whereas for the linear machine, it can be seen that we have 7 full poles plus a pole at each end of the machine where some slots are only half filled, giving 9 poles in total. In general, linear machines formed with double layer windings have a pole number of approximately $n+1$, where n is the number of poles in a single layer of the winding.

If a track of linear stators are used that are butted up closely to one another, the presence of an odd number of poles can significantly affect performance. If every stator has identical connections, both the first and last pole in each machine will have the same polarity, and when butted up together will introduce harmonics into the mmf. This will alter the thrust speed curve and degrade performance by forcing the machine to operate at a lower slip, lower efficiency and a higher current for a given thrust. To avoid this issue, alternate stators can be connected in a negative fashion i.e. the direction of current in all phase coils is reversed in adjacent stators. The difference in performance from the alternate connection method can be seen in (Fig 10).

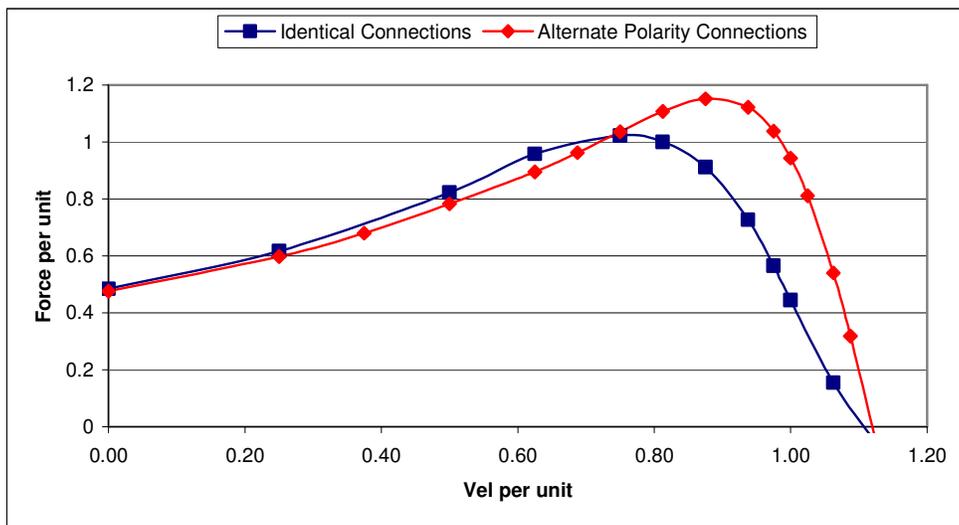


Fig 10 Thrust speed curve of a single stator in a track with identical and alternate phase polarities to its neighbours

The simple force speed curves are known to give a good approximation of short rotor dynamic behaviour¹⁴, and so the potential performance effects on a launcher may be significant.

Double-sided concentrated windings with harmonic cancellation

Commonly, linear induction machines use double layer windings as illustrated in (Fig 5). When such windings are used for launchers with discrete stator blocks, even when the blocks are butted closely together the excitation is perturbed by the half-filled slots at the stator ends. Single-layer planar concentrated windings of the type illustrated by (Fig 11) do not have this drawback and in addition are simpler and cheaper to construct, are more robust and have less bulky end-turns.

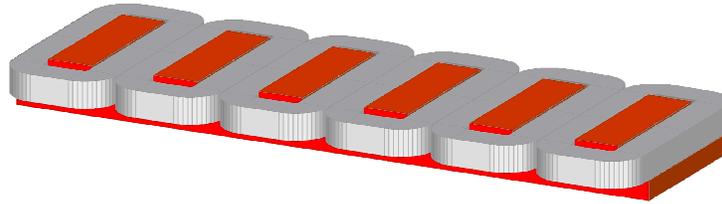


Fig 11 6 coil concentrated winding

However they produce multiple mmf harmonics travelling in opposite directions. This makes the arrangement unsuitable for induction motor use since all travelling fields produce forces which are oppositely directed and largely cancel leaving little net force. However, either of the two fields can be cancelled by use of a double sided concentrated winding with a physical offset of one of the stator blocks of with respect to the other in the direction of motion^{15,16}. Such arrangements produce simple and inexpensive block structures that have small end-turn regions and yield excitation with no perturbations when the blocks of a launcher are butted together. (Fig 12) shows a layout diagram of a system designed to launch an aircraft from a carrier using modular concentrated winding sections.



Fig 12 A track of modular short concentrated coil sections developed for aircraft carrier launch

The main advantage of the concentrated winding system is that the stators are modular, robust and inexpensive to build. Due to the use of few, concentrated coils a concentrated stator block is much more robust and less prone to faults than a distributed winding version due to a greatly reduced number of coils and connections. The concentrated winding is single layer, and so can use a longer pole pitch and lower frequency than a distributed 2 layer winding and so frequency may be reduced. Concentrated coils have extremely compact end turns, giving a larger active area for a given machine width than the equivalent two layer machine using standard end windings.

CONCLUSIONS

Three novel developments in linear machines have been described. The numerical method for calculation of airgap flux gives very good results when compared to FEA, and may be used to predict high speed end effects. The alternate connection method allows tracks of LIMs using two layer windings to be used without the significant detrimental harmonic effects that occur when a track of identically connected two layer windings is used. The offset concentrated winding design is a significant improvement on standard two layer distributed windings for aircraft launch, giving equal performance from a simple, inexpensive and robust modular stator design.

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APPENDIX 1

Development and types of Linear Machines

Linear machines can be developed by notionally cutting a cylindrical version along a radial plane and unrolling it. This is shown in (Fig A1) for the case of squirrel cage induction machine.

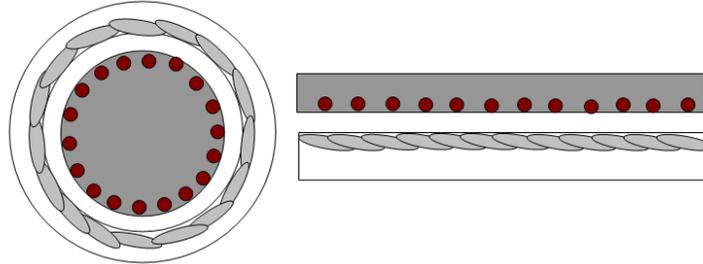


Fig A1 Development of linear machines from rotary types

If continuous force is to be produced then either the stator or the rotor must be shorter than the other member, as shown in (Fig A2). These figures also show that the squirrel cage can be replaced by a simple conducting plate.

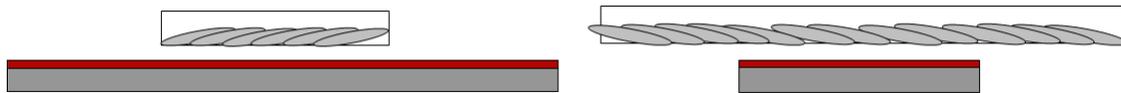


Fig A2 Left to right; Short stator linear motor; short rotor linear induction machines

For permanent magnet linear synchronous machines the conducting plate is replaced by an array of magnets in a 'North' 'South' sequence as shown at (Fig A3).

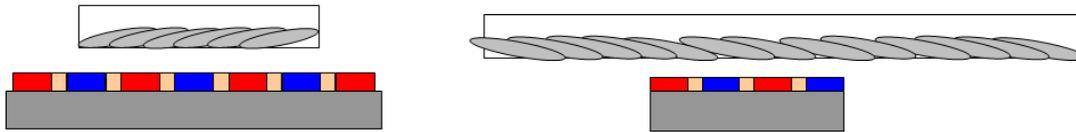


Fig A3 Left to right; Short stator and short rotor single-sided permanent magnet linear synchronous machines

The machines described above are single-sided. However in linear machines a 'double-sided' configuration, not usually used for cylindrical machines, is also available. This version, shown at (Fig A4) for the short stator induction machine case, uses a stator on each side of the secondary plate. From the illustrative flux lines on (Fig A4) it can be seen that each stator provides the return path for the stator on the opposite side. The corresponding double-sided short-rotor induction machine is shown at (Fig A5), along with double-sided short stator and rotor permanent magnet machines.

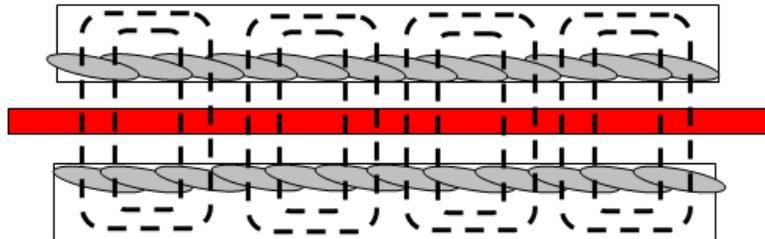


Fig A4 A short-stator double-sided induction machine showing flux paths

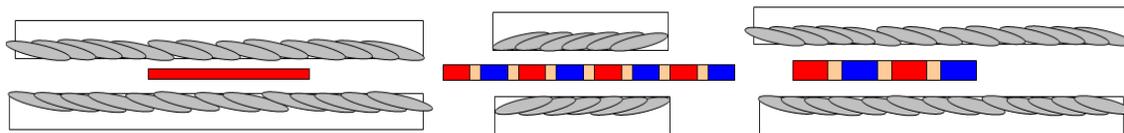


Fig A5 Double-sided linear machines. Left to right; Short Rotor Induction; Short Stator Permanent Magnet Synchronous; Short Rotor Permanent Magnet Synchronous