UK Magnetics Society

57 The Philog, Cardiff, CF14 1DZ, Wales, United Kingdom
T: +44 (0) 2920 626643 E: astewart@ukmagsoc.co.uk W: www.ukmagsoc.org

Extreme Machines

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Air Power: Achievements and Challenges in Electromagnetic Aircraft Launch

Tom Cox, Force Engineering tom@force.co.uk

***Abstract* - Aircraft launch using electromagnetic linear machines has been studied in various forms for over 60 years. Now, with the latest generation aircraft carriers on course to be equipped with electromagnetic catapults for aircraft launch, this long anticipated application of linear machines is finally close to being realised. Some of the significant challenges and technical choices that have shaped the design of linear motors for modern aircraft launch systems will be detailed: starting from the origins of assisted aircraft launch and the earliest systems developed in the 1940's, through to the current state of the art in aircraft launch using electromagnetic machines.**

I INTRODUCTION

Aircraft have been launched from ships for over 100 years. This has evolved from unassisted takeoff and early spring and compressed air systems through to steam catapults and finally to the latest generation of electromagnetic launchers.

A working electromagnetic launch system was developed in 1945 but was viewed as too costly and heavy and the steam catapult was used instead.

New advances in motor design and power electronics have lead to improved launcher configurations with significant advantages compared with steam catapults. There are currently major projects in electromagnetic aircraft launch for carrier systems in both the UK and The USA.

This paper explores some of the issues involved in linear machines design for high speed electromagnetic aircraft launch.

II 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. The aircraft carrier rapidly evolved, sometimes using compressed air or spring based launch systems, but more commonly with aircraft that could take off from a flight deck without assistance.

During the second world war, Westinghouse made the first known electromagnetic aircraft launch system, the 'Electropult' launcher shown in Fig. 1 for launching aircraft from short island runways.

The Electropult system used a short-stator single-sided induction machine. This had a stator that was fed through brushes and mounted on a wheeled vehicle, which could be linked to the aircraft to be launched.

The stationary track was in the form of linear conductive bars in iron slots. This enabled the secondary resistance and thrust characteristic of the motor system to be varied during launch in order to provide an improved launch performance.

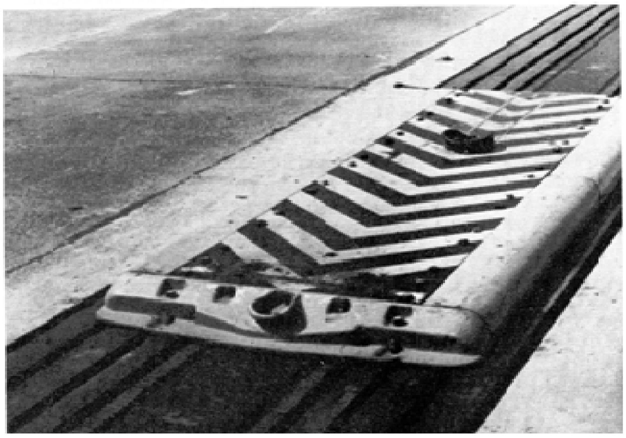

Fig. 1. The Westinghouse Electropult stator on track

This system was capable of reaching 100m/s max speed over a 420m range. It was powered by an 1100hp aircraft engine running a DC generator. This in turn powered a DC motor which drove an AC generator attached to a 24 ton flywheel.

While this system successfully test launched aircraft from a land based installation, it was never employed at sea due to significant cost and weight issues.

It was also overtaken by the invention of the steam catapult, which at the time was the superior technology. These however have significant issues including excessive size & weight, lack of feedback and fine control and the lack of steam subsystems on some modern ships.

III. NEW ELECTROMAGNETIC LAUNCHERS

Over the past twenty years electromagnetic aircraft launch technology has once again been under development in an effort to replace steam catapults.

Two key technological developments have contributed to the improvement of electromagnetic launchers compared to steam catapults.

Power electronics provide a high level of control over motor acceleration. Linear induction machines are supplied at increasing frequencies to give small slip conditions and high efficiencies.

Variations in linear motor topology and in particular the use of double-sided machines reduce unwanted attraction force between the secondary and the track and allow the use of a simple and robust conductive rotor. Linear machines also allow the stator to be constructed in a modular fashion, allowing for significant redundancy and easy repair and replacement.

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

Typical launch system specifications for both these systems, based on a modern carrier plane (F-35/JSF):

- 100m launch track – deck length
- 80m/s take off speed
- 35T payload
- 1MN force
- Failsafe in operation with some redundancy

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. 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 secondary conductive plate, as shown in Fig. 2.

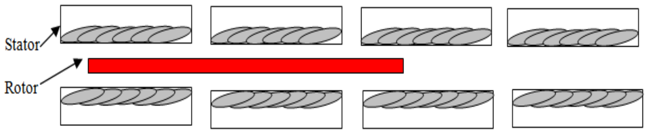

Fig. 2. Simplified layout of typical induction motor aircraft launch system.

Both systems also use double sided Linear Induction Motors. Issues with the use of synchronous rather than induction machines for electromagnetic aircraft launch include the need for high converter frequencies, challenges with high speed control and the need for precise speed feedback, a risk of permanent magnet demagnetization due to the high current loading and strong magnetic fields employed and supply and security issues with rare earth magnets.

The design of high speed LIMs is complex and time consuming. Some of the significant challenges are:

- Significant transient forces and currents in rotor
- Rapidly accelerating rotor
- Discontinuous stator blocks, each shorter than the rotor
- Discontinuous rotor, much shorter than the track
- The effect of entering unexcited stators at high speed can be significant
- Transient FEA usually required for accurate prediction of machine performance

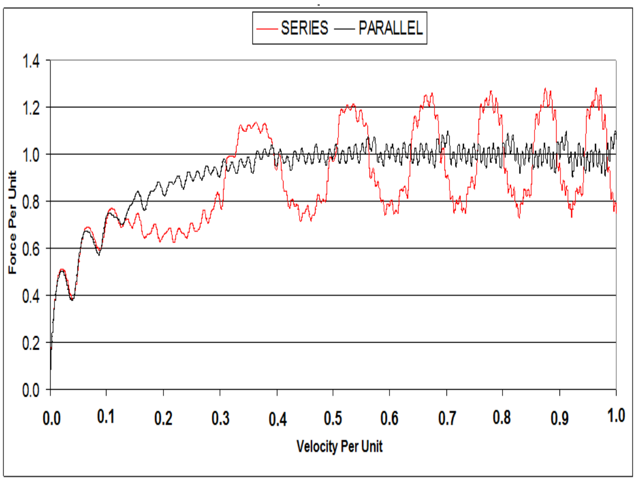

Fig. 4. Force perturbations from a series connected winding

A typical series connected stator has significant issues when used for high speed launch in a track such as seen in Fig. 2. The entry of a conductor at high speed into an excited series connected stator has the effect of reducing the airgap flux. The resultant flux envelope can be seen in Fig. 3. Using simple equations based on the rotor coupled time constant, the flux envelope can be plotted as shown in the red line on Fig. 3.

The reduced flux in the series case causes a severe ripple in the force developed on the rotor, as shown in Fig. 4. This force ripple could potentially cause significant performance and mechanical stress issues in an aircraft launch system.

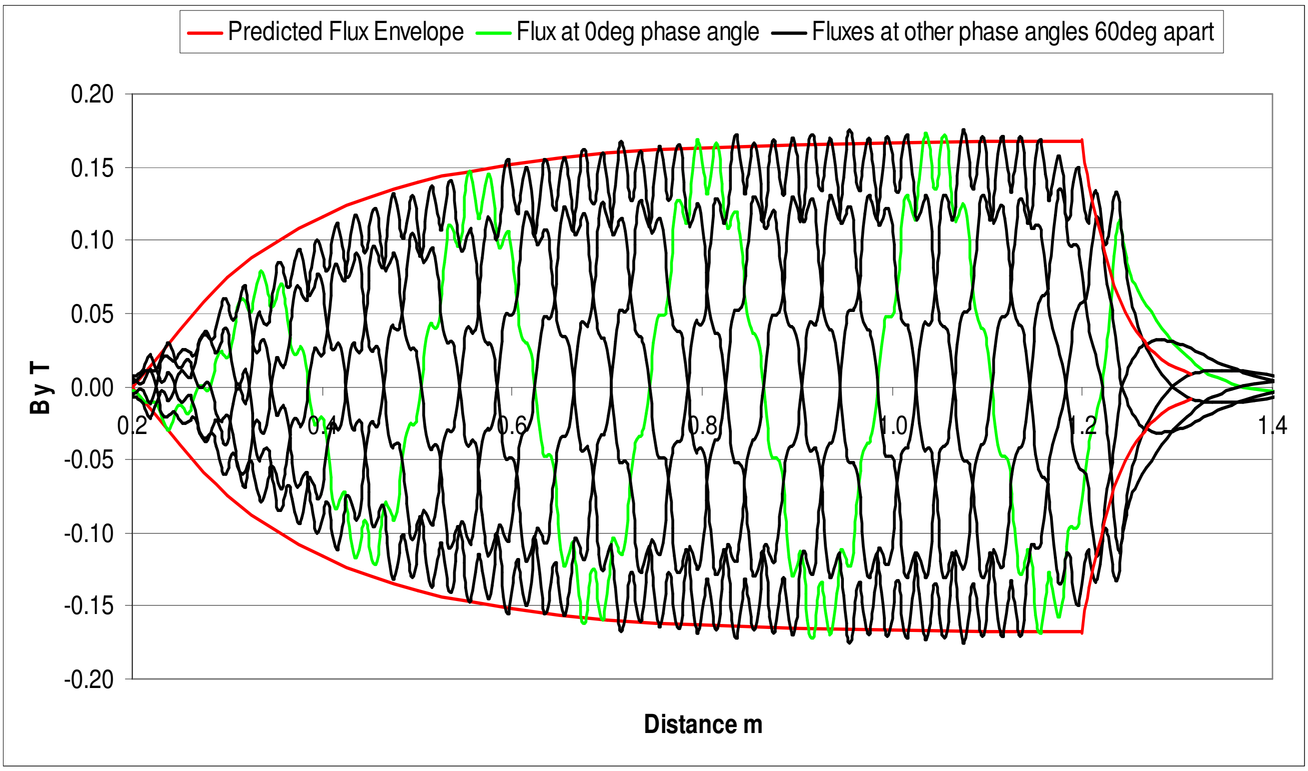

Fig. 3.Series connected stator flux envelope

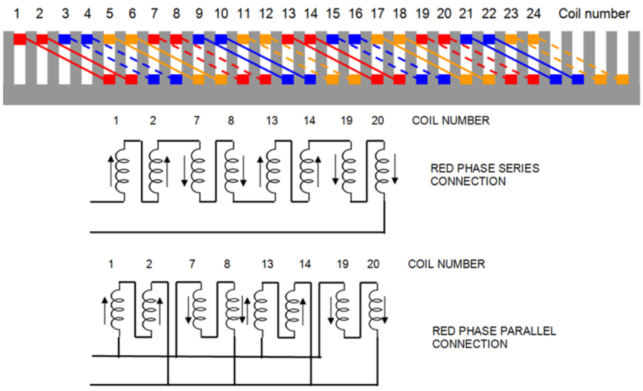

Fig 5. Parallel phase group connections

If the stator is connected in parallel phase groups as in Fig. 5, the situation is significantly improved. The voltage and hence flux is forced to be equal across all parallel phase groups, removing the flux perturbations found in the series case. This gives the stable Parallel trace shown in black in Fig. 4

In a rotating double-layer wound machine one side of a coil occupies the top half of a slot and the other side occupies the bottom half of another slot separated from the first by the coil pitch with all slots filled, as in Fig. 6.
In a double layer wound linear machine this configuration leads to half filled slots at the beginning and end of the stator Fig. 6. The end slots carry reduced ampere turns compared to the rest of the winding and give a reduced performance compared to full slots.

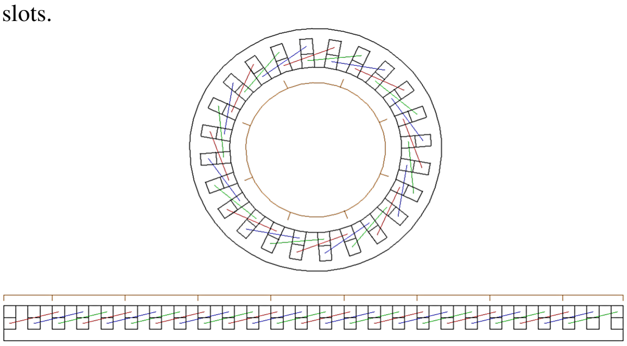

Fig. 6 Rotary and linear stator windings

The brown line in Fig. 6 shows the number of poles for each stator. The rotary machine has 8 full poles, while the linear machine has 7 full poles and a pole at each end of the machine with some half filled slots, giving 9 poles in total.
When linear stators are placed with their ends close to one another, as is the case in a launcher configuration with a track of discontinuous stators, the odd number of poles can significantly affect performance. With identical connections, the first and last pole in each machine has the same polarity and so when placed next to each other will introduce harmonics into the mmf and alter the thrust speed curve as seen in Fig 7.

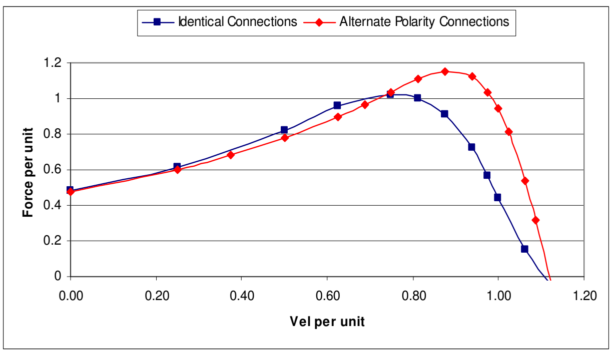

Fig. 7. LIM performance with identically and alternately connected stators

If alternate stators are connected in a negative fashion (reversing the direction of current in all phase coils) the performance of the machine is unaffected as shown in Fig. 7.

IV DOUBLE-SIDED CONCENTRATED WINDINGS WITH HARMONIC CANCELATION

Linear induction machines typically use double layer windings as discussed previously. Single-layer planar concentrated windings as shown in Fig. 8 can be butted up together without end effects, and are simpler and cheaper to construct, more robust and have a greater active area for a given surface area.

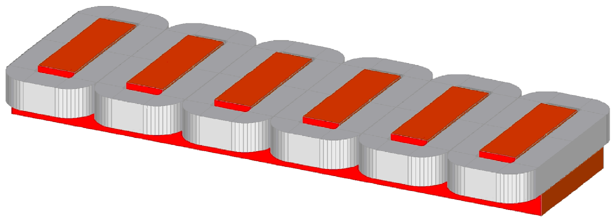

Fig. 8. Single layer planar concentrated winding

These windings produce multiple mmf harmonics travelling in opposite directions. One of these fields may be cancelled by use of an offset double sided concentrated winding [1][2].
Such arrangements give a simple and inexpensive stator block structure with small end-turn regions that can be simply butted together with no loss of performance.
The principal benefits of this concentrated offset winding system are stators are modular, robust and inexpensive to build. The use of few, concentrated coils in a stator block significantly reduce the number of joints and connections making it less prone to faults than a distributed winding. Concentrated planar windings are single layer and can use a longer pole pitch and lower frequency than a distributed 2 layer winding, allowing a reduced frequency. The end windings of concentrated coils are extremely compact, giving a larger active area for a given machine width.

V CONCLUSIONS

The issues with series connections in high speed launch machines are explored and the results of a numerical method for calculating airgap flux effects are shown. Parallel connection can eliminate these issues.
The alternate connection of LIM stator blocks allows tracks of double-layer wound LIMs to be used without significant detrimental harmonic effects.
Offset concentrated winding launch systems offer significant benefits for aircraft launch, allowing the use of simple, inexpensive and robust modular stators.

REFERENCES

[1] J F Eastham, Force Engineering Patent, 'Improvements in and relating to Electromotive Machines,' International Patent Application No PCT/GB2007/003849
[2] Prof. J F Eastham, Dr. T Cox, J Proverbs, 'Application of Planar Concentrated Windings to Induction Motors,' *IET Electric Power Applications,* Vol. 4, No. 3, pp. 140-148, Mar. 2010