ELECTRO MAGNETIC KINETIC INTEGRATED TECHNOLOGY - DEVELOPMENT OF AN ADVANCED LINEAR INDUCTION MOTOR POWERED UAV LAUNCH DEMONSTRATOR

BY

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ABSTRACT

Electromagnetic launch technology is proceeding worldwide on a number of fronts. This paper covers the application of Linear Induction Motor (LIM) technology to the launch of Unmanned Aerial Vehicles (UAVs) from Royal Navy platforms and the development of a UK based technical demonstrator. The paper discusses the project background, development and analysis of the technical requirement and the evolution of LIM technology. The development of this technology with Variable Frequency Drive (VFD) as the proposed technical solution for the power system is then covered and future opportunities are presented.

Authors' Biographies

Mr Alan Foster attained a MEng (Hons) in Electrical Engineering in 1969 from the University of Sheffield and has extensive experience in the LIM design field. In 1979 he founded Force Engineering Limited who are responsible for the design and manufacture of the EMKIT ALIMs and to date he remains owner and managing director of the company.

Mr Eric Lewis attained a first class honours degree in Electrical Engineering from London University in 1965. He is a Senior Engineering Consultant in the Marine and Offshore business at ALSTOM Power Conversion and is technical lead for the EMKIT project. His major achievements include the instigation and design of ALSTOM's advanced induction motor drives, the IPS drive system for the Office of Naval Research in the USA and power converter design lead for the USCG Healey ice breaker.

Background

EM launch technology is proceeding worldwide with a number of potential applications, especially in the area of future all electric naval platforms. One area of exploitation is to provide an efficient UAV launch capability from maritime platforms with minimum platform impact.

The UK MoD, together with ALSTOM Power Conversion Limited and Force Engineering Limited have previously completed the development and de-risking of the core technology required to launch aircraft from a carrier using an Electromagnetic Catapult (EMCAT). This project was completed in March 2003 with simulation and stall testing of an Advanced Linear Induction Motor (ALIM) proving all of the essential components[1]. The results from this initial project were extremely successful and showed that the technology had real potential for wider exploitation and with scalability had broader application to any form of linear launch.

Although an exact requirement for a UK MoD electromagnetic UAV launch system does not yet exist, the wider electrification of naval systems is progressing on a number of fronts for future platforms[2]. One area of wider exploitation of this technology is the development of an ALIM powered UAV launch technical demonstrator project named Electro Magnetic Kinetic Integrated Technology (EMKIT). The EMKIT technical demonstrator aims to conduct full speed dynamic acceleration and arresting tests on a range of test masses, at a range of speeds, within a short launch length, in order to demonstrate the flexibility and scalability of the technology.

Many LIM accelerators have been supplied using a fixed frequency AC supply with variable winding pitch LIMs to accelerate and control the speed of the moving load. These LIMs generally have a high operating slip resulting in low power factor and high losses. ALIM development allows the EMKIT linear motors to be optimised for low slip, which has many benefits including improved sensorless speed control, lower LIM losses and a higher power factor.

Development of the Technical Requirement

At the start of the EMKIT project the precise design requirements were not defined since there was no clear MoD concept of use for UAVs in the maritime environment. A statement of requirements was developed and consideration was given to the following areas:

The launched body

Fortunately the exact nature of what was to be launched was not important to the demonstrator because the design had to be scalable.

Launch mass

Launch mass has a proportional effect on energy required and also the ability to launch from a naval platform. A number of available UAVs were considered. Clearly, the largest UAVs would be difficult to store and handle but the smallest UAVs would not stretch the technology envelope sufficiently. A maximum mass was agreed that would provide a launch technology for a number of UAVs that could be operated from a range of platforms.

Maximum launch speed

Launch speed is critical in relation to the energy requirement. However, by knowing the speed envelope of UAVs under consideration this was easy to select. Programme targets were to be demanding in order to give an indication of the launcher scalability and also encompass typical aircraft launch speeds.

Launch distance & acceleration

Launch distance is another key factor since it determines the acceleration requirement. Clearly, the smaller the platform, the shorter the launch length and the greater the acceleration required in order to reach take off speed. The actual 'g' required was not specified, being a function of launch distance and launch speed. Since most aircraft instruments are only designed to withstand around 10g, this was agreed to be the maximum acceleration required. However, the requirement for a controllable thrust profile yielding low jerk starts and minimising airframe stress was an additional factor.

Launch readiness & launch interval

The ability to achieve a rapid start up from cold is essential for operational readiness. The impact on a ships electrical system was also deemed critical.

Statement of requirements

The results of these investigations provided the following basis for a statement of the technical requirements:

- Controllable launch speed;
- Short launch length;
- Launch a range of masses at the highest speed;
- Controllable thrust profile for low jerk;
- Ability to start from cold in a short period;
- Minimal time between launches;
- Minimum impact on host platform;
- System to be generic and scalable.

The MoD considered this to be a challenging scope, which would explore the envelope of existing technology in the field of low voltage power conversion and LIM technology. In addition, the requirement would increase the Technology Readiness Level[3] to a stage where a trial of a full-scale system could be undertaken in order to prove the launch of a UAV from a naval platform.

Project Approach

EMKIT has benefited from previous MoD ALIM work undertaken in the EMCAT project, which designed and modelled an ALIM, which had been previously built and proven on a stall test rig. Results of these tests were fed into the EMKIT project.

The approach to EMKIT was to establish key user requirements; develop a cost effective test facility; and prove the dynamic application of the technology with Commercial Off The Shelf (COTS) equipment where possible. This ensures maximum de-risking for future systems.

The EMKIT Team

ALSTOM Power Conversion Limited are the electrical project lead, manufacturing converters and energy stores; control system; provision of test facilities and testing/proving the demonstrator.

Force Engineering Limited are responsible for the design and manufacture of the ALIMs. Force were part of the previous LIM stall test project and has a wide range of LIM accelerator experience.

WGH Limited are responsible for the design and manufacture of the mechanical track and braking systems and have in-depth experience of a wide range of mechanical systems.

INBIS Limited are responsible for requirements capture, integrated logistics support, risk and safety issues.

EMKIT Progress

The team initially validated the baseline design for the system and produced a series of studies to determine optimum track length, optimum braking option, and overall system design. The launcher design was completed in late 2005 and a full speed demonstrator is now being built to prove the overall system and validate launch control. It will be operated at a green field site at Bruntingthorpe aerodrome and proving ground, Leicestershire, UK.

Analysis of Requirements

By combining the analysis of the technical requirements with an analysis of a typical selection of available UAVs the capability of the launcher could be validated[4]. This has shown that the EMKIT design can launch a range of UAVs from the Hermes 180 up to the Predator A. A graphical representation is shown in (FIG. 1).

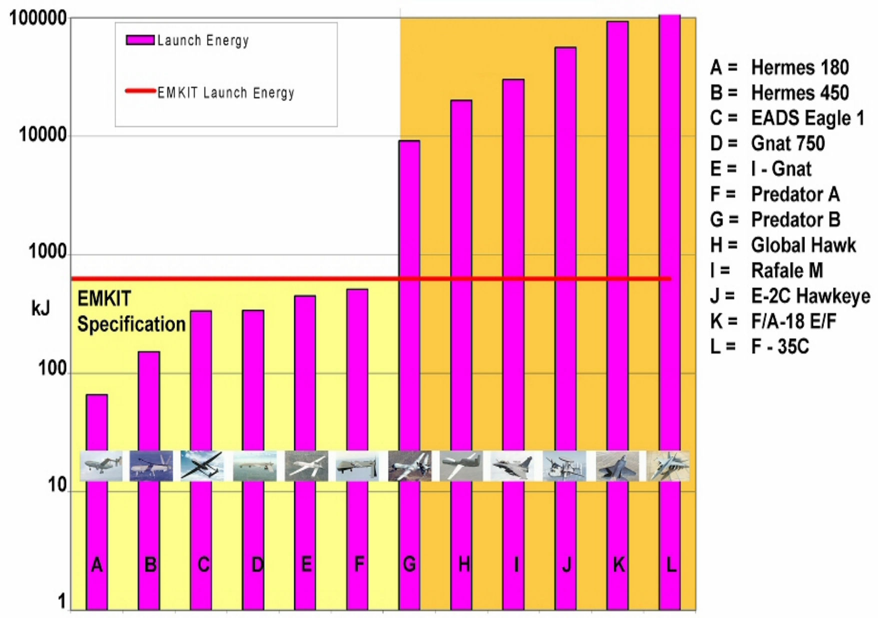

FIG.1 - TYPICAL TAKE OFF ENERGY DATA

Applying EMKIT technology to UAVs

To illustrate the application of the EMKIT technology (TABLE 1) gives the LIM launch design data for the Hermes 450 UAV shown in (FIG. 2).

Performance data for the Hermes 450 UAV is:

- Weight 450 kg;
- Maximum speed 95 knots (49 m/s);
- Cruise speed 70 knots (36 m/s);
- Stall speed 42 knots (21 m/s).

FIG.2 - THE HERMES 450

(TABLE 1) is based on achieving cruise speed at the launch point. The data is presented for a range of applied ‘g’ forces, which clearly shows the benefits of a high ‘g’ launch.

TABLE 1 - *Launch data for Hermes 450*

Launch Data	**Acceleration, ‘g’**				
	2 g	**4 g**	**6 g**	**8 g**	**10 g**
Time (sec)	1.8	0.91	0.61	0.45	0.36
Distance (m)	33	16	11	8	7
Force (kN)	9	18	26	35	44
Peak Power (kW)	318	635	953	1271	1588
Energy (kJ)	291	291	291	291	291

The forces required can be provided by the EMKIT ALIM technology. If a high ‘g’ launch is used the length of the launch becomes viable for a mobile system. The peak power required is available from a range of low voltage standard COTS converters and the energy required can be provided by a compact energy store.

Similar calculations can be carried out for a range of UAVs. (FIG.3) shows a smaller UAV - the Hermes 180.

FIG.3 - THE HERMES 180

(TABLE 2) shows similar data as (TABLE 1) but for the Hermes 180 UAV.

TABLE 2 - *Launch data for Hermes 180*

Launch Data	**Acceleration, 'g'**				
	2 g	**4 g**	**6 g**	**8 g**	**10 g**
Time (sec)	1.8	0.93	0.62	0.46	0.37
Distance (m)	34	17	11	8	7
Force (kN)	4	8	11	15	19
Peakpower (kW)	140	279	419	558	698
Energy (kJ)	130	130	130	130	130

EMKIT thrust can easily be varied over a large range to suit different UAVs so a common EMKIT design can easily be used for these UAVs. The same system could also launch any smaller UAVs. There are very large UAVs in service like the Global Hawk as shown at (FIG.4).

FIG. 4 - THE GLOBAL HAWK

Launch data for this UAV is given in (TABLE 3) for a mass of 11,600 kg and a launch speed of 108 knots (55.6 m/s).

TABLE 3 - *Launch data for Global Hawk*

Launch Data	**Acceleration, 'g'**				
	2 g	**4 g**	**6 g**	**8 g**	**10 g**
Time (sec)	2.8	1.4	0.94	0.71	0.56
Distance (m)	79	39	26	20	16
Force (kN)	228	456	683	911	1139
Peakpower (MW)	12.6	25.3	37.9	50.6	63.2
Energy (MJ)	17.9	17.9	17.9	17.9	17.9

This requirement is similar to a full size carrier based EM launch system, which could then launch conventional airframes and a wide range of UAVs such as the Global Hawk and Hermes.

Technical Aspects

Types of Linear Motor

For many years conventional LIMs have been used on fixed frequency supplies with good commercial success. Force Engineering has supplied 15 LIM accelerator launch systems for roller coasters and these have all proved to be extremely robust and reliable. They use utility frequency 3 phase supply with direct-on-line starting and were typically built to accelerate 7-8,000kg to 25-30m/s (2-3.5MJ) in about 60m at 1.3g peak.

For ease of manufacture, installation, and maintenance the LIM track is made up of a series of separate stator units. (FIG.5) shows how switches are used to energise the relevant stators.

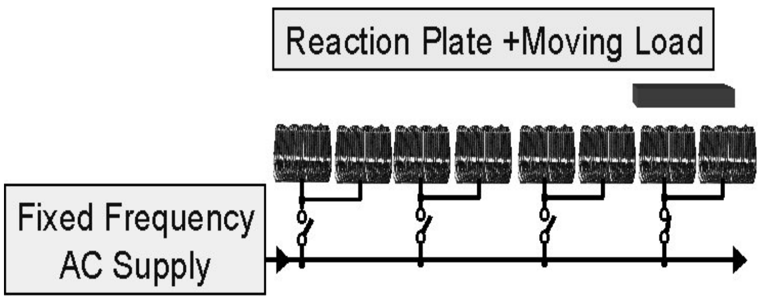

FIG.5 - CONVENTIONAL LIM SYSTEM

Linear motors can also be produced with permanent magnets on the moving load. These are called Linear Synchronous Motors (LSMs). For LIMs and LSMs the speed of rotation of the 3-phase voltage and the pitch of the windings determines the speed of the moving magnetic field.

Linear synchronous motors (LSMs)

LSMs use permanent magnets on the moving load and work like a rotary synchronous motor, with phase matching between the magnetic field and moving load. The position of the moving magnetic field must be synchronized precisely to the moving load using accurate position feedback sensors. LSMs have also been used successfully by ALSTOM and others for several roller coasters, including a 100mph (45m/s) launch. LSMs are more efficient than LIMs but require sophisticated control and measuring equipment.

For a LSM track the stator layout is similar to (FIG.5) except the reaction plate is replaced by a series of permanent magnets and the supply has a variable frequency. As the vehicle accelerates the supply frequency is increased, so all stator windings are identical. Unfortunately the supply must be matched precisely to the position of the secondary magnets and the complexity and reliability of the control and measuring system is challenging.

Conventional linear induction motors (LIMs)

Conventional LIMs use a conductive plate on the moving load and this passes freely between the stators as it accelerates along the track. Like a rotary induction motor, there is a slip between the speed of the magnetic field and that of the moving load. This slip induces voltage and current in the reaction plate, which then generates thrust.

The LIM synchronous speed must increase along the track to accelerate the load as it travels. If the supply frequency is fixed then this can only be achieved by increasing winding pitch, which means that all stators are not identical. See (FIG.6).

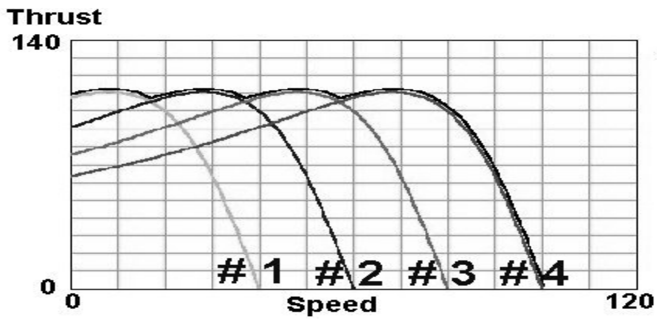

FIG.6 - THRUST AGAINST SPEED LIM CHARACTERISTICS

Previous work by ALSTOM and Force resulted in the design of an advanced linear induction motor (ALIM) which operates at low slips and high efficiency, approaching the performance of the LSM without its inherent control complexity.

Advanced linear induction motors (ALIMs)

Using this technology makes it possible to provide an aircraft launch system without sensors. This was achieved by the development from conventional LIMs to ALIMs[5] begun with EMCAT and further enhanced during the EMKIT project.

Removal of sensors eliminates the need for safety critical control software. The steep fronted thrust speed characteristic also provides for automatic speed recovery if an ALIM stator fails during launch, see (FIG.7). The ALIM efficiency has also been developed to be better than 80%.

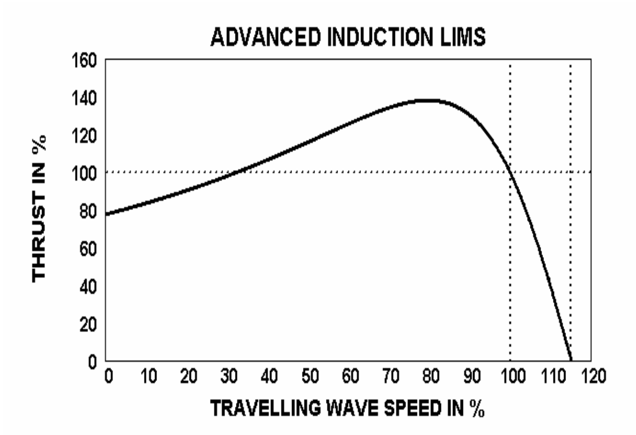

FIG.7 - THE LOW SLIP ALIM

Again for production and installation reasons the ALIM is made up of a set of stator units. To minimise the inverter current the thyristor switches are used to energise only those ALIM stators required as the reaction plate moves. See (FIG.8). For applications with a few ALIMs the thyristor switches can be omitted.

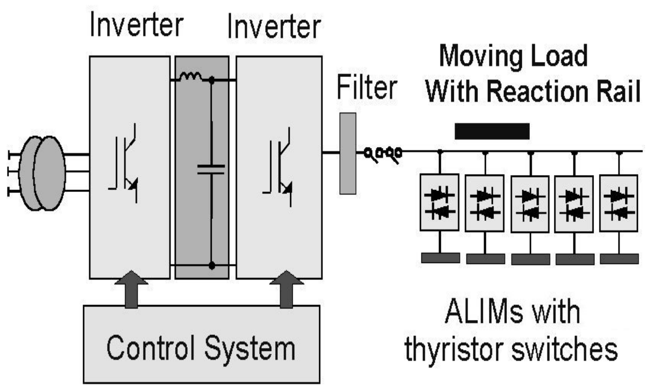

FIG.8 - THE ALIM SYSTEM.

With ALIMs the slip speed is lower, giving accurate open loop speed control. The winding pitch is fixed and the variable frequency is used to accelerate the load at constant thrust, as shown at (FIG.9).

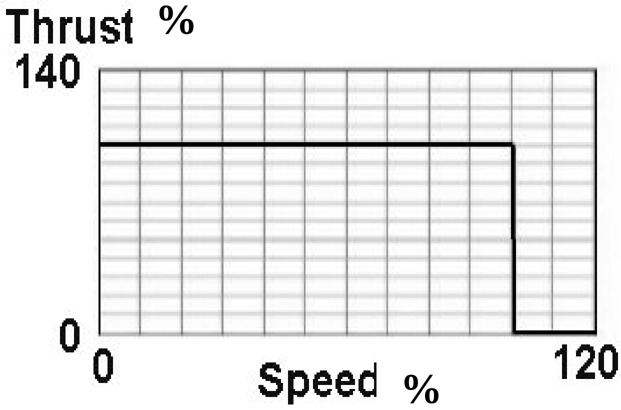

FIG.9 – ALIM THRUST / SPEED CURVE

The drive system has a fully reversing power flow; unity supply power factor; and very low harmonics.

Thyristor switches eliminate unnecessary motor currents and hence minimise inverter rating. ALIMs operate at low slip and the system has a high-speed open loop control accuracy without need for feedback sensors. The system also adapts to unexpected change of the moving mass with only a small speed error. See (FIG.10).

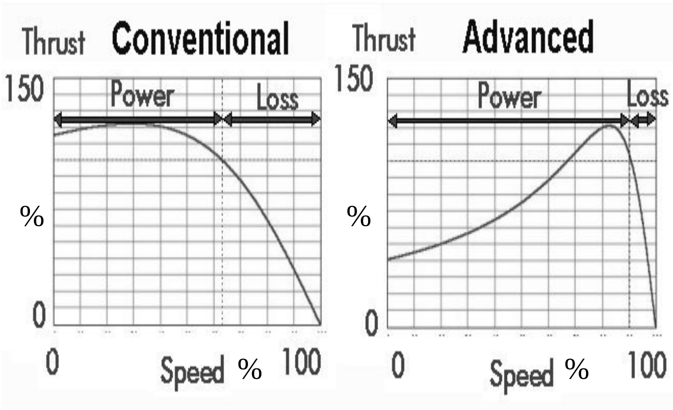

FIG.10 - ADVANTAGES OF LOW SLIP ALIMS

The EMKIT Linear Motor System

Based on the preceding arguments the variable frequency ALIM is the chosen solution for this technology demonstrator. All stator segments can be identical, switching is relatively simple, no position feedback is required, and the moving secondary is a simple lightweight aluminium plate. For manufacturing convenience and redundancy the system comprises two energy stores, two power converters, a set of ALIMs in a double sided configuration, with a single vertical aluminium reaction plate, motion control system, mechanical launch track and braking systems. See (FIG.11).

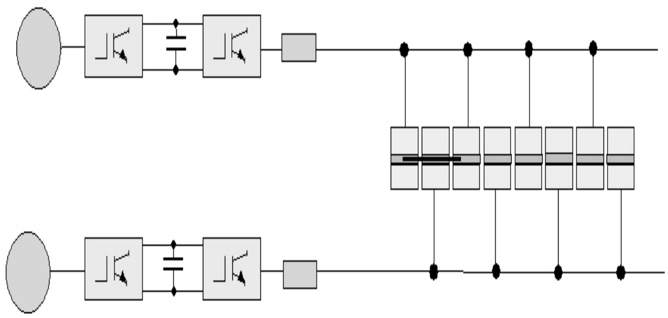

FIG.11 - THE EMKIT SYSTEM

The dual line system will prove all the control and redundancy requirements for all future ALIM designs. The development of the ALIM has already given many application benefits including:

- Reduction in converter size to 50% compared to conventional LIMs;
- Reduction in the AC supply current to 20% compared to conventional LIMs;
- Reduction in the AC supply voltage dip by 90% compared to conventional LIMs;
- Open loop speed control accuracy of better than 1% for a 10% load variation.

Benefits of EMKIT technology

The use of ALIM technology for launching UAVs has many benefits including:

- One design can launch many different UAVs;
- EMKIT technology automatically adapts to the mass or payload of different UAVs;
- Very low cost per launch;
- Eliminates risks of booster launching;
- Redundant design, such that a UAV will still launch with partial failures in the EMKIT system;
- Proven power electronic technologies and the experience of technicians;

- Fully automatic with minimum manning.

ALIM Development

A challenge with all linear motor systems is the classic 'end effect'. The end effects occur due to the need to produce the linear motor in sections. At the end of each section there is a disturbance in the magnetic fields that can produce thrust transients and extra losses. It is well known that as slip is reduced these end effects can generate large losses, resulting in severe thrust degradation. Because the stator is short compared to the number of poles per stator the problems of entry and exit end effects also arise. The present design effort has concentrated on minimising these for the ALIM solution. Analysis to date forecasts a successful outcome and that target speeds will be met within the available power supply limits. With EMKIT launch systems it is possible to:

- Apply constant thrust during launch;
- Apply minimum stress on the airframe;
- Preset launch speed to suit each type of mass;
- Automatically adapt to a range of launch masses.

The EMKIT technology makes possible to apply the optimum thrust profile to any given standard none modified UAV and to launch the UAV in the optimum distance. If a reinforced UAV is available extra thrust can be applied to achieve very short launch distances.

The EMKIT technology has also been developed to minimize the interface impact on the host platform. The technology can be mounted above deck as a temporary installation or fitted in a dedicated slot for a permanent installation as used by a carrier. The system is self contained versus cooling needs and the simple controls make it very easy to interface in to the platforms control system.

The key interface is the supply of the launch power and this can be provided by two different means:

- For systems with IFEP, like T45, the launch power can come, for certain ratings, directly from the main generators without the need for local energy stores. The required launch power is diverted from the main electric propulsion drives for the launch period. With this means the effect on the AC generation system is and ships speed are minimal;
- For all applications a dedicated energy store is used so that the launch energy demand is spread out evenly over the period between launches. The effects on the AC generation system can then be tailored to suit the available power level especially for none IFEP ships like T23.

For mobile land based application a dedicated diesel can be used to give a totally self sufficient system as used by the EMKIT demonstrator at Bruntingthorpe airfield.

Future Opportunities

The EMKIT system is a versatile launch system and has numerous applications including:

- Replacing steam catapults;
- Launching unmanned aerial vehicles or unmanned combat aerial vehicles. These could be launched from a wide variety of vessels or from areas with limited space like cliff tops;
- Torpedo launching;
- Missile boost;
- Ejector seat testing;
- Assisted satellite or space vehicle launching.

The high power interface technology, energy storage, pulse forming and switching is also applicable to any high power requirements such as high power weapons.

At present in addition to the previous UK EMCAT project and the present UK EMKIT project the USA have the Electromagnetic Launch System (EMALS) project which is the development of linear motors aimed at replacing steam catapults on carriers. The EMCAT, EMKIT and EMALS projects are all using the same essential concepts of energy stores, power converters and linear motors to provide an airframe launch system.

The UK EMKIT demonstrator is operating at a thrust density that will provide the proof of concept to move to a full scale UK carrier launch system if the need arises.

Conclusions

The EMKIT technology demonstrator has been designed for easy modification to suit the mechanical geometry of different UAVs.

One future naval platform that could benefit from EMKIT is the UK future carrier project (CVF) which may use an EM launcher at some future date.

EMKIT will significantly de-risk EM launch technology by proving the overall design; ALIM end effect design and the open loop control system.

EMKIT technology can also be developed into compact UAV launchers for naval platforms or land based sites. The technology is flexible and suitable for a wide variety of applications. It is based on proven designs, and can be brought into service in a realistic timeframe.

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