EMKIT - COMMISSIONING AND PERFORMANCE TESTING OF A TECHNICAL DEMONSTRATOR FOR THE ELECTROMAGNETIC CATAPULT LAUNCH OF UAV'S

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ABSTRACT

This paper forms the next in a series of papers covering the application of EM launch technology to the launch of Unmanned Aerial Vehicles (UAVs) from Royal Navy platforms. Fundamentally it covers the development of a UK based Electromagnetic Catapult technical demonstrator. The project background and requirements are discussed and an overview of the test facility, system and its present state of development are given. Design challenges, basic commissioning procedure and formulation of the testing program to demonstrate the technology is then discussed.

BACKGROUND

EM Launch technology is proceeding worldwide on a number of fronts with a number of future applications, especially in the area of future all electric naval platforms. One area of exploitation is to provide the capability to launch UAV's and manned aircraft from maritime platforms efficiently and with minimum platform impact. This is a key technology enabler towards the maritime contribution to a network enabled capability. The overall aim of which is to provide maritime patrol, surveillance, target designation, target illumination, weapon delivery and damage assessment.

The UK Ministry of Defence, together with Converteam Ltd. have previously completed a project on the development and de-risking of the core technology required to launch aircraft from an aircraft carrier using an Electromagnetic Catapult (EMCAT). This project was completed in March 2003, using simulation and stall testing of a linear motor to prove the thrust density and other essential components. The results from this 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 a specific requirement for a UK Electromagnetic (EM) UAV launch system does not yet exist, the wider electrification of naval systems is progressing on a number of fronts for future platforms. The need to ensure that EM launch technology is available, with the correct level of maturity, within the UK equipment supplier base is one of the keys to meeting UK future defence needs.

At present the only proven solution for marine aircraft launch is a steam catapult. It is difficult to envisage the use of steam launch technology for future Royal Navy applications. This view is supported by recent UK MoD work to qualify assisted launch of aircraft which concluded that EM launchers are the most attractive option for future aircraft launch.

The EMKIT UAV launch technical demonstrator project is part of the UK MoD above water effects research programme. The EMKIT project will demonstrate EM launch technology by the design, build and testing of a high - speed high-acceleration demonstrator. The test programme will include full speed dynamic acceleration and stopping 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.

TECHNICAL REQUIREMENT

To start the EMKIT project it was essential to have a clear set of design requirements. This was difficult to achieve, as a clear concept of use for UAVs in the maritime environment did not exist in the MoD at the time that the technical requirements were defined.

However, to explore the potential of EM launch within the boundaries of potential target platforms and UAVs a demanding set of requirements were formulated. These were such that the present commercially available power components required would be pushed to the limits and are deemed to be at the upper threshold for a LV topology.

These were as follows:

- Variable Launch Mass - 0 to 500kg at rated speed;
- Variable End Speed - 0 to 50m/s at rated mass;
- Short Launch Length - 15m travel;
- Maximum Acceleration - 10G;
- Controllable Thrust & Variable Launch Profile;
- Low Jerk Start and Low Jerk Characteristic;
- Duty of 5 launches per hour;
- Start up time from cold state < 2mins;
- System to be generic and scalable.

These requirements were deemed to be sufficiently demand to increase the technology readiness level to a stage where a trial of a full-scale system could be undertaken in order to prove the launch of a medium to large UAV from a naval platform.

PROJECT APPROACH

EMKIT has benefited from previous MoD Advanced Linear Induction Motor (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 DEMONSTRATOR SYSTEM

The EMKIT demonstrator system comprises of pulsed alternator energy stores, high power converters, advanced linear induction motors, a reaction plate and a catapult frame with friction brake. Additionally, the demonstrator system has a test vehicle and track, diesel generator, transformers, switchboard and a data logging system. See (FIG.1).

The catapult principle is based around the application of Advanced Linear Induction Motors (ALIMs).

The Linear Induction Motors work on the same basic principle as all induction motors except the motor is effectively unrolled to provide a linear stator and rotor. In this case the movement of the travelling electromagnetic stator field and hence the rotor is now linear not angular. This rotor is called the reaction plate. It is this reaction plate that is coupled to the UAV and then accelerated at a constant acceleration effectively pushing the UAV up to the required takeoff exit speed.

Because of the high pulsed energy demands and short duty cycle of the system, energy stores are used to provide the power requirements to the catapult. This maximises the system economy, reduces disturbances on any vessel or local supplies and provides a near self-contained system requiring minimum interface to prospective platforms.

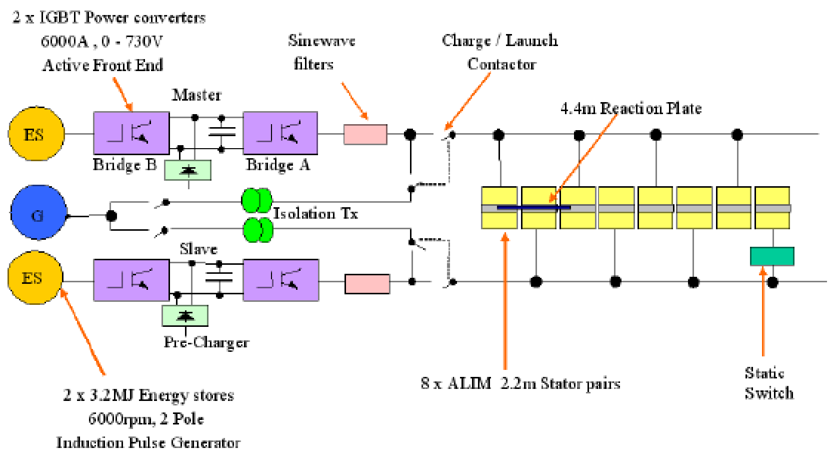

FIG.1 - SYSTEM TOPOLOGY

The converters perform several actions. Firstly, to drive the energy stores up to their rated speed by taking power slowly and at a low level from the local supply which in this case is the diesel generator. Secondly, once the energy stores are at rated speed the input / output contactors swap over and the converter's supply bridge (A) now effectively becomes the machine bridge and transfers the stored energy by a Variable Voltage Variable Frequency (VVVF) supply to the LIMs. The use of advanced low slip LIMs and suitable control algorithms allow the LIMs to be controlled open loop and apply constant thrust to the launch vehicle.

For rated condition, launching and braking occurs in less than one second. A typical launch profile showing the low jerk start is shown in (FIG.2).

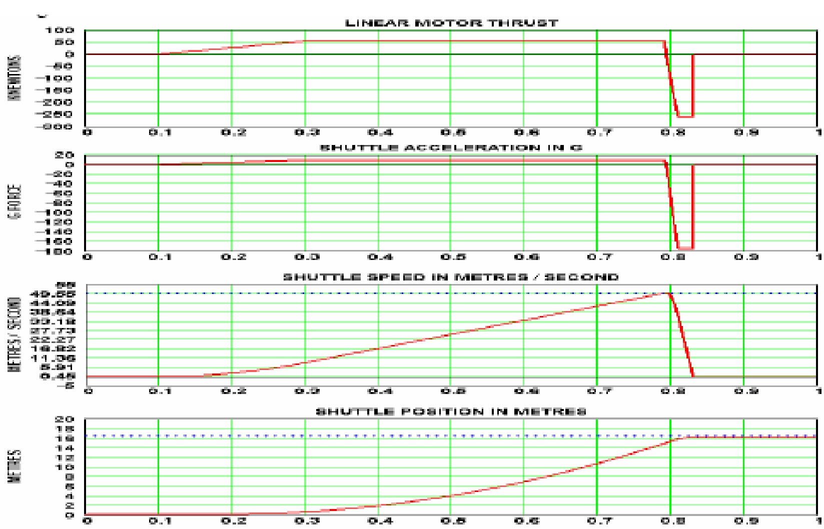

FIG.2 - TYPICAL LAUNCH PROFILE

Once the vehicle is launched the converters then retract the shuttle to the start position and automatically revert to their recharging configuration and bring the energy stores back up to their rated speed ready for any subsequent launches.

The mechanical arrangement of the launcher has the linear motor stators located in a U shaped support structure, with the reaction plate travelling down the centre. This arrangement can effectively be mounted above or below deck. A hook-up point protrudes through the launch deck in a central slot. The reaction plate itself is kept in line and guided by a set of wheel-less low friction slides. A mechanical friction braking system ultimately arrests the shuttle at the end of the track.

The demonstrator system also has an additional mechanical track system mounted on top of this deck structure to guide and support the UAV test mass in the form of a captive vehicle bogey arrangement. The additional test track provides an extended stopping distance with integral braking rail for the test vehicle.

Energy Stores

The energy storage (FIG.3) comes in the form of two pulsed alternator high-speed induction machines each of the following characteristics:

- Stored Energy = 3.2MJ	- Frequency = 100Hz
- Speed = 6000 rpm Power	- Power = 3.2MW peak
- Poles = 2 Current	- Current = 3800A at peak launch condition.

FIG.3 - 3.2MJ ENERGY STORE

Converters

The catapult has two Pulse Width Modulation (PWM) liquid cooled voltage source converters (FIG.4) in a Master, Slave arrangement. Each converter has the following characteristics:

- Rated Current = 6000A - Type = Voltage Source PWM IGBT
- Rated Voltage = 720V - Peak MVA = 7.5MVA
- Estore bridge B output: PWM - LIM bridge A output = Sinusoidal

FIG.4 - 7.5MVA EMKIT CONVERTER

The Master converter additionally provides all the plant automation for the test system and determines for both drives the optimum LIM control Voltage Frequency profile to apply for the desired thrust. Control of the drive and the complete test system is initiated by a touch screen HMI display where the operator can input the Mass / Speed and G Limits for the desired launch condition.

The master drive ultimately provides the VVVF supply to the first and alternate LIM pairs, where the slave drive powers all remaining LIMs. The slave drive follows the master drive profile and both drives are synchronised t o the PWM switching rate of 5kHz allowing open loop control to be implemented.

The LIM Bridge (A) also allows for a sinusoidal output to the LIMs by means of a sine wave filter.

This is essential to minimise EMI radiation from a catapult system that may be used in an environment with stringent EMI compliance needs. The sine wave filter gives more than a 50:1 reduction in all the output voltage and current harmonics and is essential to the correct operation of the static switches is these are required on larger systems. The use of the filter also provides minimum voltage to earth stresses seen by the motor, compared to conventional PWM voltages, resulting in extending the insulation life of the motor.

The final filter design was a technical challenge and complex design that was required to provide:

- Minimum Voltage Drop;

- High level attenuation of the high frequency PWM component;
- Minimum losses;
- Minimum current ripple to stay within the converter capability;
- Minimum voltage ripple to stay within the converter capability;
- Appropriate level of damping and a resonant frequency suitably away from any fundamental system frequencies.

FIG.5 - CAPACITOR MODULES OF SINEWAVE FILTER

A suitable LC filter design has been implemented to meet these needs. The capacitor modules of this filter are shown in (FIG.5).

Advanced Linear Induction Motors

Eight pairs of ALIMs provide the required thrust for the catapult accelerator section at 24kN of thrust in a 2.1m x 0.35m x .01m envelope. A total of 54kN of thrust is generated into the 4.4m plate given that two pairs of motors are on load at any one time. Each ALIM is epoxy potted and sealed within a stainless can to provide weather proofing and maximum shielding of stray voltage fields.

FIG.6 - LIM STATOR PAIR

A nominal synchronous frequency of 127Hz and speed of 60.8m/s is used for rated thrust condition with a slip of 0.18pu. Each LIM pair is designed to operate at 660V within the converter capability and demands 2600A at rated condition with an efficiency of <75%.

Previous validation from the EMCAT development and further thermal modelling has predicted very low temperature rises for the LIM stators of ΔT 4.2°C and ΔT 10.2°C for the reaction plate. As such thermal management issues are minimal and natural air-cooling is used for both LIM and Plate. The predicted temperature rises will be validated as part of the trials procedure.

Launcher Mechanical Arrangement

The mechanical needs of the EMKIT launcher demanded the following:

- Must locate and support the LIMs and maintain a constant air gap;
- React axial thrust into the ground;
- React the reversing transverse forces produced by the LIMs;
- Prevent reaction plate from contacting the LIMs during launch;
- Provide support and guidance to the reaction plate during a launch;
- Stop the reaction plate at the end of the launch;
- Meet maximum target weight for reaction plate assembly;
- Meet maximum reaction plate sliding resistance force requirement;
- Be an expandable design – modular;
- Allow for inclination of the launcher;
- Be transportable.

A trade off study was undertaken to investigate the possible reaction plate brake systems. This considered friction brakes, permanent magnet brakes, LIM brakes and a water brake. The main objective of the study was to minimise cost, maximise reliability and achieve a compact system. The selected solution was a hydraulic friction brake system.

The main frames were designed to locate the LIMs and maintain the air gap between them. They were made in identical modules, which are pre-aligned, and simply located on site using a tapered pin and hole before they are bolted together. There are four acceleration modules and one brake module. The frames see a reversing fatigue loading pushing the LIMs apart as the reaction plate passes through and pulling them together when there is no reaction plate present, much like a zip. This force is around four times the axial force produced on the reaction plate. The modules are all the same dimensions, apart from the brake section, which has deeper longitudinal beams to react the braking forces. The weight of each module is about 3.5 tonnes, making it possible to assemble on site using a fork lift truck (FIG.7).

FIG.7 - ACCELERATION MODULE

The design of the modules was optimised using Ansys finite element analysis. This showed that the major design restraint was the introduction of the capability to do an inclined launch at variable angles. This essentially made the design a bridge and required the end connections of the modules to be relatively thick and heavy. It was noted that this is unlikely to be a requirement for a launcher on an aircraft carrier. It is highly likely that the majority of the modules become part of the ship’s structure if an integrated build was required.

FIG.8 - ASSEMBLED LAUNCHER

The design does not use any wheels, this is to eliminate the problems of flat spotting wheels under high acceleration loads and bearing wear. The sliders run on a diamond shaped stainless steel track that supports and restrains the sliders. Low friction material pads are arranged on the four sides of the slider block (FIG.9) to ensure at least two are in contact with the rail at all times. As the aluminium reaction plate accelerates (FIG.10) or brakes the attitude or the sliding mechanism can change. The brake material surfaces are also attached to the top of the reaction plate and help provide stiffness to the structure.

FIG.9 - REACTION PLATE GUIDES

FIG.10 - REACTION PLATE

Due to safety needs at the test site it was decided that the test launch vehicle would be a trolley restrained on a track, like a roller coaster. The trolley incorporates brakes that run on a brake bar that is tapered out at the end of the launcher to stop the trolley. It also has provision for ballast weights to be added to vary the overall launch mass between 200kg and 1000kg. The trolley is pushed by the reaction plate, via a rubber buffer, which is incorporated to reduce any acceleration variations as the reaction plate moves between LIM pairs. The trolley mass is much greater than the reaction plate and therefore the track is 55m long to allow braking. Again the track supports are free to move axially to accommodate thermal expansion.

TESTING OBJECTIVES

Although many of the design tools and models have already been proven by the previous EMCAT contract, many elements can only be proven by test in a fully dynamic situation such as end effects, thrust control and system efficiency.

As such the key outcomes of the demonstrator testing phase is to validate existing models and by test:

- Prove the required forces and thrust can be achieved;
- Prove the speed, acceleration, g forces are as predicted and prove these can be varied as required;
- Prove the thermal effects are minimal and thermal profiles of the equipment are obtained;

- Prove the LIM end effects are as predicted;
- Prove the starting Jerk is low and can be varied;
- Prove the software and sensorless control system;
- Prove the self-compensation & adaptation to wrong mass setting;
- Prove the selected braking concept;
- Prove the performance of the energy store;
- Prove the recharge system;
- Prove the interfaces and interaction of all parts.

Commissioning & Testing Strategy

To achieve these objectives a fully defined testing philosophy has been applied to de-risk the equipment and the complete system. In summary this results in a phased approach as follows:

PHASE 1 - Factory Acceptance Testing (FAT)

PHASE 2 - Delivery & Installation

PHASE 3 - Unit Commissioning & Setting to Work

PHASE 4 - System Commissioning

PHASE 5 - Performance Testing

At the time of writing the project is in Phase 3 of the programme, with all equipment installed at the test site and being commissioned. All items of equipment have successfully passed their Factory acceptance tests. Phase 4 / 5 of testing will be completed between Autumn 06 and Spring 07 with a final technology report being produced in Summer 07. As can be seen from the phased approach to the testing the general approach to the demonstrator proving is to firstly test individual items of the system then bring them together, prove all interfaces and slowly build up trials in a controlled manner to the fully rated condition.

Data Acquisition & Measurement Systems

Due to the large amount of variables that need to be measured and the problems associated with capturing data over less than 1s launch duration; an autonomous measurement system has been installed. The demonstrator system has various built in and permanently connected transducers each monitoring variables needed to prove the performance objectives. (FIG.11) shows the transducer location and (FIG.12) its type and measurement purpose. These are logged via the drives built in data trending capability along with additional data loggers which allow sampling of up to 1MHz. This allows all trial result information to be captured automatically after each launch, logged and analysed either real-time or off line at a latter date.

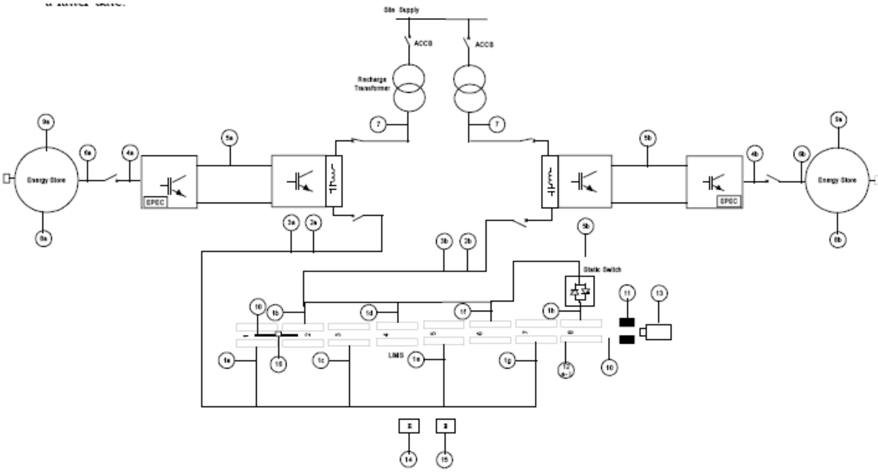

FIG.11 - TRANSDUCER TEST POINTS

TEST POINT	TRANSDUCER	MEASUREMENT PARAMETER
1a-b	Current transducer	Individual LIM Currents / End Effects / Efficiency
2a-b	Voltage transducer	Converter output / LIM volts / Frequency
3a-b	Current transducer	Converter output current
4a-b	Current transducer	Converter Input / Energy Store Current
5a-b	Voltage transducer	Drive DC Link Volts
6a	Voltage transducer	Energy Store Voltage / Frequency
7	Power Analyser	Recharge Current / Power / PF / Harmonics
8a	Embedded Winding Temperature Devices	Energy Store Winding Temperature / Temp Rise
9a	Vibration Monitors	Energy Store Vibration Levels
10a,b	Infra Red Temperature Transducer	Reaction Plate / Shuttle Temperature / Temp Rise
11	Resistive Temperature Devise	Brake Temperature / Temp Rise
12a-i	Embedded Winding Temperature Devices	LIM Stator Temperature / Temp Rise
13	Laser / Radar Speed Sensor	Shuttle / Launch Vehicle Speed
14	Electric Filed Antenna	Electric Field Strength
15	Flux Meter / Inductive Loop	Magnetic Field Strength
16	3 Plane Accelerometer	Thrust / Acceleration / Jerk / End Effects / Brake / Performance

FIG.12 - TRANSDUCERS & MEASUREMENT PARAMETERS

High Speed Low Power Trials

The pulsed nature of the catapult and the need for an energy store at the rated condition initially causes some problems when trying to commission this type of system.

How do you commission the basic mechanical system without first commissioning the energy stores? How do you commission the energy stores without first having a pulsed load? Ultimately this would mean trying to commission multiple items of equipment at the same time, these intrinsically interact with each other, ultimately increasing the complexity of the testing and the associated risks.

To overcome this problem an additional mode with a smaller direct energy source was engineered into the system. Diesel generator mode allows the energy store bridge to be configured as a conventional converter supply bridge with the converter used as a conventional VSD to the LIMs. This allows low power but relatively high speed launches with just the reaction plate up to 40m/s to be achieved.

During early trials stages this mode is used to prove mechanical systems, converter control and measurement system. It allows many tests at low levels with highly repetitive duties within the capability of the generator performance. Additionally it helps to prove the scalability of the system such that small, low energy launchers could be run directly from a vessel existing generation system.

This stage of testing will include the following trials:

- DC Link Bridge B Pre-Charging & Transformer Pre-Charging;
- Master Drive only 0 to 25m/s No Payload;
- Filter Performance Testing;
- Low Speed Retraction Tests;
- Launch Track Mechanical Proving Tests (including vibration and brake system proving);
- Both Drives 0 to 40m/s No Payload Tests.

High Speed Full Power Trials

Upon satisfactory completion of the low power trials, the system will be reconfigured into the principal energy store mode. Initially the energy store will be tested on no load before commencing full power build up trials. At this point the basic LIM / system control is already proven and concentration can be made on achieving full thrust, rated energy and profiling of the system. This period of testing will include the following trials:

- Energy Store No Load Tests 0 - 6000 rpm;
- Energy Store Vibration & Critical Speed Checks;
- Energy Store Acoustic Checks;
- Full System Launch 0 to 50m/s No Payload;
- Full System Launch 0 to 50m/s, 0 to 100% load;
- Electric / Magnetic Field Tests EMI Profile;

- Thermal Profiling, Temperature Rise Tests;
- System Efficiency Measurements;
- Supply Harmonic Measurements;
- Common Mode Voltage Measurements;
- Static Switch Tests;
- Fault Scenarios - Faulty LIM, Incorrect Setting.

FUTURE OPPORTUNITIES

One future naval platform that has the potential to benefit from EMKIT is the UK future carrier project (CVF) that may use an EM launcher (EMCAT system) in the future. EMKIT will significantly de-risk EM launch The EMKIT work so far is showing that the required thrust levels for an EMCAT system can be achieved by moving to HV LIM technology and associated converters and energy storage. A high power EMCAT system would be used with a similar topology to that of EMKIT but utilising a triple track system and tri-fin shuttle to achieve the required thrust and levels of redundancy required for a manned aircraft launch system.

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, from a wide variety of vessels;
- Torpedo launching;
- Missile boost;
- Ejector seat testing;
- Ship test tanks;
- Assisted satellite or space vehicle launching.

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

CONCLUSIONS

This EMKIT demonstrator is providing valuable information and de-risking via a real application of EM launch technology. The findings of the testing phase will improve greatly the technology readiness level for this size and larger EM launchers for manned aircraft launch. The EMKIT system has so far shown the potential to be flexible and suitable for a wide range of applications and has proven that this technology can be brought into service in a realistic timeframe.

ACKNOWLEDGEMENTS

The authors would like to thank the Ministry of Defence and Converteam Ltd. for supporting the EMKIT project and this paper. The views expressed are those of the authors and do not necessarily represent those of the Ministry of Defence of Her Majesty’s Government or Converteam Ltd.

AUTHORS' BIOGRAPHIES

Graham Bellamy joined Converteam (formally Alstom) after attaining an honours degree in Electrical Engineering from De-Montfort University in 1997. He is a Principal Applications Engineer in the Marine and Offshore business and Lead engineer for EMKIT. His previous experiences included lead project roles for major Naval and Offshore power and propulsion projects including Albion Class, Wave Class Naval Vessels and the previous EMCAT project.

Lt Mick Thomson RN joined the Royal Navy in 1997 as a Marine Engineer Officer having previously gained a first degree in Mechanical Engineering from UMIST. He was appointed to HMS MARLBOROUGH in 2000 as Deputy Marine Engineer Officer. On completion of a MSc from University College London in 2004 he was appointed to the Defence Logistics Organisation where he is involved with electrical propulsion development. He is the MoD project manager for EMKIT.