Final Report Summary - ELETAD (Electrical Tail Drive - Modelling, Simulation and Rig Prototype Development)

Executive Summary:
The Electrical Tail Drive-Modelling, Simulation and Rig Prototype Development (ELETAD) project has investigated the feasibility of powering the tail rotor of a helicopter with an electric drive, replacing the current mechanical system comprising high speed shafts and gearboxes. The electric tail rotor system comprises a lightweight and compact electric motor connected via cables to power electronic converters which act to condition and control the power feed to the electrical machine. The potential advantages include:

- Reduced future reliance on hydraulic and oil based systems;
- Low maintenance, high service life, with reduced repair and overhaul cycle impact;
Inherent torque control and power limiting directly inferred measurement of operating load;
Higher system integrity, and inbuilt fault tolerance;
Improved overall aircraft fuel efficiency when part of a ‘more electric’ power management system.

For the electrical drive alternative to be viable it will need to be shown to deliver the performance requirements, whilst satisfying the 10E-9 failures per flight hour integrity of a safety critical system. The integrity requirement dictates fault-tolerance and redundancy within the system design. Further the tail drive motor should be sufficiently compact to be mounted at the end of the tail boom together with the blade pitch mechanism and should therefore be weight-competitive with the existing mechanical transmission. Additionally the location and reliability requirement dictates air-cooling. All these challenges have been addressed within the ELETAD project, where the viability of a compact, fault-tolerant air-cooled electric tail rotor motor has been demonstrated.

The ELETAD project has centred on the use of high efficiency and performance permanent magnet brushless machines, requiring innovative use of modern materials and advanced design methods. Designs and prototypes of full-size axial-flux and radial-flux electric tail rotor motors have been delivered, accompanied by comprehensive test data and supporting analyses to enable a full performance assessment to be made. The characteristics of the double airgap axial-flux and the modular wound radial-flux topologies have been compared. It was found the axial-flux and radial-flux designs had near identical active weights, and the prototypes exhibited similar continuous output capabilities. However the radial-flux design proved to be overall more efficient and better suited to the tail rotor drive configuration. Importantly the work has identified areas where improvements in manufacture and materials would enhance performance and where future design and analysis effort should be focussed.

An innovative test capability for multi-phase fault-tolerant aircraft propulsion drives has been established, capable of dynamically characterising electrical drive systems with peak ratings up to 340 kW, 2000 Nm and 4500 rpm. A major element of this test rig is the complete functional representation of a redundant/fault-tolerant electrical supply and control system that would be needed for a safety-critical aircraft application. In the near term this ‘copper bird’ is to be used to support further developments development of electric tail rotor drive and additional research into fuel efficient more-electric helicopters.

Additionally the project has resulted in a new suite of validated software tools and techniques for predicting the loss, thermal behaviour and in-service life of high performance fault-tolerant electrical machines, over dynamic operating duties. These design tools and methods have widespread applicability, for example in developing electrical machine designs for other aircraft propulsion drive applications or for high torque wheel motors in electric vehicles. The new capabilities for modelling electrical machines offered by the software tools have been incorporated within commercially available design software marketed by one of the project partners.

The project has been undertaken by a pan-European consortium of two SMEs and two research institutes; The University of Bristol (Lead partner), Lucchi Rimini Elettromecanica, Motor Design Limited and the University Politehnica of Bucharest.

Project Context and Objectives:
The civil fixed wing aircraft is seeking to replace pneumatic, hydraulic and mechanical systems with electric equivalents wherever possible. Fuel efficiency and reduced maintenance have been the primary drivers of this disruptive technology change. As a result of this more electrification a significant pool of experience, research and available equipment has been amassed in the area of flight critical electrical generation and motor drives.

The rotary wing aircraft sector has traditionally had lower levels of installed electric power on board, primarily serving avionics and wing ice protection systems. However, there exists the potential to exploit the developments made in the fixed wing sector and use these to further advantage, provided an aircraft-wide approach is taken. Electrical systems can be used to replace a greater proportion of the installed equipment, extending to the drive of the tail rotor for medium sized aircraft and full propulsion for smaller aircraft and unmanned air vehicles. Over and above the efficiency savings, a significant benefit in terms of through life costs can be made if large mechanical, single function systems can be replaced by compact, reconfigurable and easily replaceable electric systems. This is reflected in the Clean Sky, Green Rotorcraft (GRC) ITD challenge statement, which states:

“The eventual elimination of noxious hydraulic fluids and the reduction of CO2 emission through efficiency and weight optimisation of on-board energy systems constitute the two crucial objectives pursued in this sub project. The emerging high performance electrical systems and equipment enable a range of new solutions but need to be adapted to the specific helicopter constraints”.

Traditionally, helicopter tail rotors are powered mechanically through a drive shaft that connects the tail rotor to the main transmission. The Electrical Tail Drive-Modelling, Simulation and Rig Prototype Development (ELETAD) project investigates the feasibility of replacing the mechanical drive system by an electric tail rotor (ETR) drive mounted at the rear of the helicopter. The ETR system comprises a lightweight and compact electric motor connected via cables to power electronic converters which act to condition and control the power feed to the electrical machine. The input to this power converter is derived from a generator driven off the main rotor gearbox. The potential advantages of the ETR system include:

• Reduced future reliance on hydraulic and oil based systems;
• Low maintenance, high service life, with reduced repair and overhaul cycle impact;
• Inherent torque control and power limiting directly inferred measurement of operating load;
• Higher system integrity, and inbuilt fault tolerance;
• Improved overall aircraft fuel efficiency when part of a ‘more electric’ power management system.

With the existing mechanical solution, the tail and main rotors are directly coupled through a series of high-speed shafts and gearboxes, where synchronous and closely-toleranced fixed tail rotor speed control avoids excitation of airframe and tail boom resonances. Mechanical malfunction of the tail rotor, which contains many critical parts and assemblies, and the resulting failure to provide main rotor torque reaction can lead to catastrophic loss of control of the aircraft. Consequently, the tail rotor drive is a safety critical component and its integrity is an overarching consideration. The integrity of 10E-9 failures per flight hour dictates a regular inspection, maintenance and replacement regime for the existing mechanical system, the frequency of which is based on a knowledge of the aircraft usage.
For the electrical drive alternative to be viable it will need to be shown to deliver the integrity and performance requirements whilst offering improved service life. Further the physical integration of the system poses several technical challenges:

• The tail drive motor should be sufficiently compact to be mounted at the end of the tail boom together with the blade pitch mechanism and should therefore be weight-competitive with the existing mechanical transmission;
• The location and reliability requirement dictates air-cooling. Air flow around the tail boom is, however, complex and unpredictable and the introduction of ducts to enhance simple and reliable air cooling could reduce the aerodynamic efficiency of the aircraft;
• Normal operation will expose the motor to high-velocity airborne water spray and dust, requiring an assembly that meets the IP66 standard whilst exposing the motor sufficiently to enable air cooling.

Compared to the established mechanical solutions, accelerated life testing and qualification process of substitute electrical drive systems are less well established. Failures in electrical components are dominated by thermal cycling rather than cyclic load accumulation. Based on reliability figures found in the literature and through correspondence with component suppliers it was concluded a quadruplex system comprising four separate electrical power channels would be needed to meet the safety critical availability target.

The electric tail rotor motor designs developed within the project were based around permanent magnetic brushless electric machines as these tend to have superior torque/power density and efficiency characteristics, and are particularly suited to highly dynamical load duty cycles. Candidate topologies were down-selected to the double airgap axial-flux and the modular wound radial-flux brushless permanent magnet motor topologies shown in Fig. 1.

The axial-flux arrangement comprises two wound stator assemblies stator located at either side of a central permanent magnet disc. The radial flux topology consists of an inner permanent magnet array surrounded by a single stator lamination carrying twelve magnetically independent coils. Whilst the manner of torque production differs, these two electrical machine topologies have a number of similarities:

• Both the axial-flux and radial-flux arrangements seek to maximise the available active area for force production and the radius at which this occurs within the constraints of a given housing volume and, as a result, these topologies have the highest specific torque.
• Open slot stator designs are possible which greatly simplify the winding process, leading to excellent copper utilisation, high electrical loading (ampere stream) for a given power loss and mechanical robustness. Importantly, this need not incur high levels of undesirable torque ripple. The lack of a tooth tip, however, means that the method employed to secure the winding within the slot can potentially introduce a thermal barrier, and a.c. loss effects in the winding and rotor are greater.

Fault tolerance is incorporated in a different manner for the axial- and radial-flux variants. In the case of the axial-flux topology, multiple machines can be stacked axially sharing a common shaft. In order to achieve a quadruplex system four rotor discs and eight stators were fabricated in a common housing. The radial-flux machine utilises a modular winding concept where each coil making up the stator has a dedicated slot and
magnetic circuit. Four independent electrical machines can be created by arranging the twelve coils into four sets of 3-phase windings. Whilst the designs ensure there is minimum electrical and magnetic interaction between the phases there is a degree of thermal coupling across the four independent motor channels.

The requirement for a weight-competitive solution will only be possible through the adoption of new high specific output permanent magnet motor technologies, state-of-art materials and manufacturing processes, and advanced design methods. The target specific outputs could not be met using traditionally conservative approaches to thermal design and rating and required the development of advanced thermal modelling and design tools. An important outcome of the modelling and testing activities was to provide robust, accurate data concerning the integrity of the tail rotor drive. Since the reliability of an electrical machine is primarily dependent upon electrical breakdown, resulting from degradation in electrical insulation materials, a significant part of the research activity has been the development of in-depth knowledge of the operational thermal and mechanical cycles to which the insulation system will be subjected. Ageing and reliability models were included within the developed design and simulation tools and validated through accelerated life ageing tests undertaken on representative winding coils and insulation systems.

Whilst the focus of the project is the evaluation of a compact and fault-tolerant electrical machine designed for an integrity target of 10E-9 failures per flight hour, this could not take place without consideration of the power electronic control and electrical generation system. The established 115 Vrms, 400 Hz nominal aircraft electrical standard was adopted as a basis for the project, although, in view of the high power levels, a 230 Vrms electrical system may be preferred in the future. A hardware emulation of the electrical supply system was developed to operationally characterise the prototypes, based on variable speed drive technologies with multiple power conversion elements to ensure fault-tolerance. Since the electrical supply would be positioned remotely from the drive motor located on the tail boom the electromagnetic interference implications of the relatively long cable run to the rotor were incorporated in the specification and test emulation.

The three principal software and hardware deliverables of the project are summarised below:

D1. A suite of validated software tools for modelling the electro-magnetic and thermal behaviour of the ETR motor, with a provision for assessing the impact of the resultant thermal cycling, over dynamic operating duties, integrated within a multi-physics design and optimisation environment;
D2. An automated dynamometer test facility capable of emulating tail rotor dynamic loads and the ambient cooling environment of a helicopter installation. A major element of this test rig is a functional representation of a redundant/fault-tolerant electrical supply and control system that would be needed for a safety-critical aircraft application;
D3. Fault-tolerant ETR motor prototypes and a comprehensive test characterisation supported with sufficiently detailed data to enable a full capability assessment.

The main objectives set for the ELETAD project were:

O1. To deliver the capability of accurately predicting the operating temperature and reliability of concept
ETR motor designs over the dynamic loads typical of a tail rotor;
O2. To evaluate an innovative electrical system architecture that is capable of meeting the integrity requirement of a safety-critical aircraft application;
O3. To evaluate the operation of a prototype ETR machine manufactured to standard that could be installed on an aircraft and which is weight-completive with the existing mechanical solution.

Each of these deliverables objectives has been addressed during the course of the project. The research and development program, supported through the EC JTI Clean Sky Rotorcraft (GRC) ITD, was undertaken by a pan European collaboration of two research institutes; the University of Bristol and the University Politechnica of Bucharest, and two SMEs, Lucchi R. Elettromeccanica and Motor Design Limited.

Project Results:
2.1 Overview of program structure

The program was structured around six technical work packages, WP1-WP6, as shown in Fig. 2. The project delivery was managed via WP7. Dissemination and exploitation outputs from the project were organised through a further work package, WP8. The following sections summarise the work package objectives and highlight research and development achievements.

The first phase of the research programme was concerned on the development of advanced thermal modelling and design tools. This was followed by a period of refinement and validation supported by focused experimental, computational and design trade studies to identify candidate technologies for development into full-scale prototypes. The second phase of the project comprised the development of the electric tail rotor motor designs, results of which were presented at preliminary and critical design reviews. Following the completion of the formal design review process prototype machines were constructed where the active elements were manufactured to a standard representative of an aircraft build. In parallel to the prototype manufacture a bespoke dynamometer test facility was established, capable of emulating the dynamic loads seen by a tail rotor over typical mission cycles. Within the facility commercial industrial motor-drive equipment was employed to provide a fully rated fault-tolerant electrical supply system with a functional and behavioural representation of an electrical system installation in an advanced more-electric aircraft. Finally comprehensive test characterisations of the prototype motors were undertaken under imposed air cooling conditions representative of the application.

2.2 Electrical and thermal software suite development (WP1)

Work package objectives: Within WP1 a suite of software models for fault-tolerant axial- and radial-flux electrical motors have been developed, with an emphasis on providing a parametric transient thermal model for candidate ETR motor designs. The principal objectives for the work package were:

O1.1 To develop and build parametric, scalable lumped-parameter thermal networks for candidate fault-tolerant topologies of axial-flux and radial-flux permanent magnet machines;
O1.2 To implement the insulation ageing model developed in WP2 to allow motor life-expectancy to be forecast under normal duty cycle load and fault conditions;
O1.3 To validate these thermal models against test data taken from previous prototype electrical machines developed by the project partners;
O1.4 To support the application of the modelling environment to tail rotor outline design and sizing studies across a range of operating scenarios.

Summary of achievement and research highlights: The motor design software suite developed in the project comprised two modelling suites; the Electric Tail Rotor Motor Design Software (ETR-MDS) and the Electric Tail Rotor Evaluation Software (ETR-ES), Fig. 3. The ETR-MDS software suite integrated four principal elements under an umbrella parameter and data exchange interface; an analytical electrical operating point and loss model, a lumped-parameter thermal model, electromagnetic and thermal finite element analyses and insulation life and reliability models.

An existing lumped-parameter thermal modelling tool (MOTORCAD) was extended, Fig.4a to cater for the fault-tolerant radial flux machine topologies. Furthermore a new bespoke modelling tool for axial-flux machines, Fig. 4b, was developed within the project, (O1.1).

A methodology was established for extracting and condensing the detailed data generated by the motor design suite into a computationally efficient behavioural model for the electric tail rotor machine, and this lead to the ETR-ES software deliverable, (O1.2). ETR-ES, was built as a reduced order MATLAB/Simulink based model which could be used to assess the performance of electric tail drive concepts as part of a larger rotorcraft system.

The modelling suite has been validated against a legacy fault-tolerant electrical machine and against the electrical machine prototypes developed and tested within the project, (O1.3). For example Fig.5 compares the model predictions against test measurements from a rotary wing UAV propulsion motor designed at the University of Bristol. The work undertaken within WP1 has resulted in new capabilities in thermal and loss analysis of redundant, fault-tolerant radial- and axial flux electrical machines. The software suite has proved to be a highly valuable in the development of candidate electric tail rotor motor designs (O1.4) and is being exploited by the consortium outside the ELETAD project.

2.3 Heat transfer, insulation reliability and component validation (WP2)

Work package objectives: The role of WP2 in the project was to undertake a series of focused computational and experimental studies that could be used to enhance the capabilities, and provide data for, the design and analysis tool developed in WP1. The following principal topics were originally envisaged:

O2.1 A model for insulation electrochemical degradation and ageing validated through tests on representative winding layouts (motorettes);
O2.2 Computational analyses and supporting experiments to determine accurate values for convective heat transfer via air cooling and radiation;
O2.3 Analyses and measurement of equivalent lumped thermal properties of composite materials used in the construction of candidate motor designs;
O2.4 Validation of complete thermal model against test data from representative legacy electrical machines.
Summary of achievement and research highlights: A major achievement of the project has been the work on the electrochemical degradation and thermal ageing of electrical machine windings. The focus has been to develop tools and methods that can be used to assess the reliability of insulation system when subjected to dynamic loading cycles seen in a real-world helicopter tail rotor drive. Accelerated ageing testing, based on representative motorette winding sub-assemblies, Fig. 6a, has yielded important data on the robustness of modern high temperature class insulation systems, and has identified measurable properties that can be used to diagnose approaching end-of-life, (O2.1) Fig. 6b. The outcome has been a test validated insulation life model for the wire and insulation systems used in the prototype electrical machines. Further the work has shown how, for example by operating for short periods at higher temperatures, it may be possible to extend the operating envelope of electrical machines.

Computational fluid dynamic (CFD) analyses have led to a more accurate understanding of the heat transfer across the air regions of the two motor topologies, Fig. 7a. Further CFD analyses, illustrated in Fig. 7b, have been used to gain insight into the external cooling environment of the tail region and to optimise the geometry of the cooling fins on the casing, (O2.2).

Extensive analytical, numerical finite element modelling and experimentation on the conductive heat through bundles of varnish impregnated multi-stranded wire has resulted in enhanced methods for modelling the heat transfer between the winding coils and the surrounding stator slot, (O2.3). A bespoke calorimetric based test bench was established which allowed accurate measurement of bulk thermal properties and interface thermal resistance, shown in Fig. 8. The modelled winding heat transfer estimates have been benchmarked against data obtained from sub-assembly ‘motorette’ testing and results from the performance characterisation of the full electrical machine prototypes, (O2.4).

The heat transfer and insulation ageing analyses undertaken in WP2 have provided improved confidence in the assumptions employed in the design of the full scale prototypes. Importantly the work package has established a large body of expertise within the consortium in the modelling and testing of the thermal behaviour of electrical machine windings, and in the understanding of how the electrochemical and thermal properties of high performance insulation systems degrade with thermal and vibration cycling. The knowledge gained is being exploited in follow-on developments in compact electrical drives for automotive and marine applications, in addition to other more electric aircraft systems.

2.4 Electric tail rotor motor design optimisation (WP3)

Work package objectives: The detailed design of the electric tail rotor motor demonstrators was undertaken within this work package. Both axial-flux and radial-flux motor formats were developed and compared.

O3.1 Develop candidate motor designs, with the best candidate configurations downselected following the outcome of trade-off studies to be presented at the preliminary design review;

O3.2 The motor designs to be further optimised and presented at the critical design review.

Summary of achievement and research highlights: Optimised designs for full scale axial- and radial-flux electric tail rotor motors were established within this work package. The modelling suite established in
WP1 and the supporting ‘deep dive’ analyses undertaken in WP2 proven to be highly valuable in the development of these designs, and as a means of assessing the performance of each design against pertinent real aircraft requirements. For example, Fig. 9 presents comparisons of motor temperature and loss over a flight mission using the development thermal and loss modelling tool. Fig. 10 illustrates some of the detailed finite element electromagnetic modelling undertaken during the development of the radial-flux electric tail rotor motor.

Permanent magnetic brushless AC machine formats were selected as these have superior torque/power density and efficiency characteristics, and are particularly suited to highly dynamical load duty cycles. The double airgap axial-flux and the modular wound radial-flux topologies were identified as preferred solutions due to their low losses and inherent fault-tolerance. The required four channel redundancy is implemented in the axial-flux design by incorporating four rotor discs and eight stators on a common shaft within in a single housing. The radial flux machine utilises a modular winding concept comprising twelve coils, each with a dedicated slot and magnetic circuit, which share a common stator housing, stator lamination pack and rotor. The twelve coils are configured as four independent star connected three phase motor modules.

The Preliminary Design Review (O3.1) confirmed the feasibility of both the axial- and radial-flux concepts. The axial-flux design was a development of prior machines of similar construction, whereas the radial-flux was a relatively new topology. As a result it was decided to take forward detailed design analysis of both machine formats to offset risk. The review was also used to highlight further design work priorities and supporting analyses to be undertaken in program. At the Critical Design Review (CDR), (O3.2) final designs for the axial flux and final radial flux prototype were presented that addressed the actions raised in the preliminary design phase. A main outcome of the CDR was to establish manufacture routes for both machine concepts. Fig. 11 shows CAD images from the axial-flux and radial-flux ETR motor designs.

The total weights of the electromagnetically active materials which made up the final designs were almost identical; however the relative contributions to the total active weight differed. The four stacked stator core and winding assemblies that make up the axial flux machine are heavier than the radial flux core back and windings. However the double-sided disc structure of the axial-flux eliminates the need for a back iron to return the rotor flux and is correspondingly lighter. The final active weights of the designs were 18% greater than the original targets. Readily available grades of permanent magnets and silicon iron laminations were used for the prototypes and there would be scope for weight reduction in using higher performance materials.

2.5 Prototype tail rotor motor manufacture (WP4)

Work package objectives: The manufacture of the prototype electric tail rotor motors was performed within this work package.

Summary of achievement and research highlights: The detailed designs generated in WP3 indicated axial-flux and radial-flux electric tail rotor machine with comparable performances and similar overall weights. The axial-flux design was a more mature design being based on previous machines of similar construction whereas the radial-flux design was a new concept and therefore carried greater development risk. As a result it was decided to manufacture prototypes of both machines. Whilst this represented an addition to
the statement of work, where the manufacture of only a single prototype was originally envisaged, the prototyping of two machines would mitigate program delivery and technological risks. It was agreed Lucchi Elettromeccanica would build the axial-flux tail rotor motor prototype, and this would be the first machine to be delivered any characterised. Whereas the University of Bristol would take over responsibility for the radial-flux prototype build, using local suppliers. Photographs of the manufactured electric tail rotor prototype machines and sub components are shown in Figs. 12 and 13.

The mounting and shaft arrangements of the prototypes were selected to suit the dynamometer test setup and are not representative of the final aircraft installation. Compared to the axial flux machine, the radial-flux prototype had a slightly smaller outer diameter (365 mm versus 375 mm) but a longer total length (314 mm versus 290 mm).

2.6 Integrated electric tail rotor test rig (WP5)

Work package objectives: The work package undertook the design, installation and commissioning of a bespoke integrated test rig with the capability of testing the 12-phase fault-tolerant electrical machines developed in the project.

Summary of achievement and research highlights: The project has delivered an innovative test facility for multi-phase fault-tolerant aircraft propulsion drives, capable of dynamically characterising electrical drive systems with peak ratings up to 340 kW, 2000 Nm and 4500 rpm. A schematic of the integrated test rig electrical power supply and dynamometer system is illustrated in Fig. 14; a summary specification of the electrical supply and dynamometer equipment is also given. An automated supervisory experimental control system provides co-ordinated operation of the numerous items of test equipment and a central data acquisition system is used to record the various test data. The facility has been realised using commercial “off-the-shelf” industrial systems as far as is appropriate, as this was a cost-effective means of providing a test-bed that is both reliable and safe.

The integrated test rig is designed to be capable of subjecting the electric tail rotor motor being tested to fully rated load duties under representative electrical supply and cooling conditions. In addition to a 300 kW rated dynamometer loading system four identical 3-phase electrical supply channels, each rated at a minimum of 75 kW and 115 Vrms, are provided to drive the four independent sub machine modules that make up the motor under test. The rig is designed to be flexible enabling significant reconfiguration so that different fault-tolerant supply architectures may be investigated. Through Independent control of each electrical supply channel, the arrangement is able to emulate either an open-circuit or a short-circuit fault in one or more of the motor sub modules.

The integrated test rig installation is shown in Fig. 15 and comprises five major sub-systems. The equipment is installed in a dedicated laboratory where it is has been necessary to upgrade the mechanical test bed, test cell cooling infrastructure and electrical supplies to provide the required capabilities. The system is designed to locally recirculate energy with only the losses in the various system elements being drawn from the incoming electrical supply.

Dynamometer: The dynamometer is based on a 4-quadrant industrial AC electrical drive system and an
inverter rated induction machine to act as a load to the prototype under test. The load and test machines are mounted on a customised cast iron bed-plate and coupled using a precisely aligned mechanical assembly, instrumented with torque and speed measurement. Supervised by a master digital controller, the dynamometer system is fully programmable to emulate machine loads over realistic flight mission cycles.

Local Electrical Power Conversion Emulation: The proposed electrical system architecture comprises four independent supply channels, one for each 3-phase module of the fault-tolerant tail rotor drive. This is realised in the integrated test rig installation using four industrial variable-frequency electrical drives, each rated at a minimum of 200 Arms continuous output and powered from a 270 V - 350 V DC input supply.

Aircraft AC Supply Emulation: A high power 300 kW 270-350 V DC bus has been installed to provide power to each of the four driving power electronic converters. A motor generator set is used for this purpose as it proven to be a robust and cost effective solution. Further equipment has been installed to provide high speed shafts to drive aircraft generators to allow testing of the complete electrical generation and supply system.

Thermal environment emulation: The ETR motor is designed to be air cooled and in-situ on the aircraft will subject to complex local air flows. An enclosure constructed around the prototype motor incorporates a speed controlled air-feed attempts to recreate these air flow conditions.

Instrumentation, data acquisition and control: A suite of high performance instrumentation has been acquired for the facility. These include: a precision inline torque transducer, high bandwidth power analysers, precision current and voltage transducers and a multi-channel data acquisition system. The instrumentation system is capable of monitoring simultaneously the mechanical output, the electrical conditions of all 12 motor phases and 80 temperature readings from thermocouples. The commercial electrical drives used in the test cell are all controllable through a serial bus connected to test cell control ‘dashboard’, Fig. 16. Using this capability the system operating point is controlled and monitored remotely, allowing dynamic control of the dynamometer and the inverter channels which power the machine under test.

2.7 Performance evaluation of prototype electric tail rotor system (WP6)

Work package objectives: The test characterisation of the prototype ETR motors was undertaken in WP6 and used the bespoke test facility developed in WP5. The objectives of the work package are:

O6.1 Determination of performance measures for systems under test;
O6.2 Development of test output requirements;
O6.3 Development of tools to facilitate interpretation of test data;
O6.4 Collation of test data and assessment of machine performance. and communication of results;
O6.5 Recommendation of optimum power conversion control strategies for efficient operation.

Summary of achievement and research highlights: The performance evaluations of the axial- and radial-flux electric tail rotor motor prototypes took place over the final period of the project. Initial characterisation
tests were undertaken alongside the commissioning of the test facility, followed by inverter driven tests when the integrated rig was fully operational. Typically each test point would be run over many hours, sufficient for operating temperatures to reach steady-state equilibrium or complete a prescribed duty.

A systematic test methodology for fault-tolerant machines was established, which is capable of identifying and separating principal electromagnetic and mechanical loss components in forensic detail, alongside the thermal behaviour of the prototype under test, (O6.1 O6.2). The test regime evolved continually with new measurements added where needed to explore particular observed characteristics. The test methodology has been structured to identify and separate the various no-load and load dependent losses, as well as establishing electromagnetic parameters. For example Fig. 17 contrasts the separated open circuit loss characteristics of the axial-flux and radial-flux prototypes, whereas Fig. 18 presents the recorded temperatures and loss analysis from a continuous load measurement.

The test regime developed in the project has shown how a limited number of no-load and inductive load tests can be effectively employed to separate out critical loss components and establish empirical relationships describing how these losses vary with frequency and temperature, (O6.3). This methodology has now been adopted as a test standard at the University of Bristol.

The emphasis of the prototype testing has been to validate the design process and understand in detail performance capabilities and limitations. Inverter driven operation of the radial-flux prototype has been demonstrated, benchmarking the continuous capabilities, transient endurance performance and operation over a representative mission cycle. Whilst faulted operation with open circuited motor windings was explored, time and test rig limitations did not permit a full test assessment of operation under short-circuited operation and unbalanced conditions, (O6.5). The testing of higher TRL tail rotor motor prototypes are planned to continue beyond the project. Fig. 19 shows the results of an inverter driven duty cycle test on the radial-flux machine, whilst Fig. 20 presents results from an investigation of operation of the machine with an open-circuit faults on two motor modules.

The experimental results have also been used to update and improve the models of the two prototypes. These calibrated loss and thermal models have been proven to accurately predict steady state and transient performances, Fig. 21. Importantly the empirical models provide a means of accurately validating the key assumptions used during the synthesis of the motor designs, and, in identifying variances, makes recommendations where future design and analysis effort should be focussed (O6.4 O6.5). Further the analyses have highlighted areas where the use of improved manufacture and materials would enhance performance.

Potential Impact:
The ELETAD project has delivered designs and prototypes of two full-size, high-integrity electric tail rotor motors, accompanied by comprehensive test data and supporting analyses to enable a full performance assessment. Importantly the work has clearly identified areas where improvements in manufacture and materials would enhance performance and where future design and analysis effort should be focussed. High power conversion efficiency, a benefit of more electric technologies, has been demonstrated.

The project has provided, for the air-framer, significant insight into the potential of air-cooled electric tail
rotor drives. The project findings have underpinned a higher TRL development of the electric tail rotor concept. Further is has contributed to a wider research and development advancement of a fully integrated fuel efficient ‘more electric’ helicopter. The adopted of electric tail rotor drive on an aircraft would require a substantial uprating of the installed electrical generation capacity. Given the intermittent peak power requirements of the tail rotor drive, the available excess capacity could be used to power other electrical equipment on an aircraft, such as de-icing, actuators, and cabin air conditioning. Consequently the holistic use of electrical systems for efficient power management has the potential to be a disruptive technology.

The research and development knowledge gained is highly relevant to future electric propulsion of fixed wing aircraft, and many other safety critical areas where electrical drives are being considered. Should electric propulsion be widely adopted new markets for electric motors, power electronic converters and generation systems will be created and will open up major new opportunities for existing and new aircraft generator and electrical system OEMs, the component supply-chain and research institutes. A direct benefit from the project is that it has exposed partner Lucchi R. Electromeccanica to more electric aircraft technologies and the consequent global market for high performance and integrity electrical machines. Over the project duration new capabilities and new businesses opportunities in the area have been acquired.

Additionally the project has resulted in a unique suite of validated software tools and techniques for predicting the loss, thermal behaviour and in-service life of high performance fault-tolerant electrical machines, over dynamic operating duties. These design tools and methods have widespread applicability, for example in developing electrical machine designs for other aircraft propulsion drive applications or for high torque wheel motors for fuel-efficient and low-noise ground operations. Furthermore the tools have applicability to the design of traction motors employed in hybrid/electric buses and local delivery vehicles or rapid transient systems. Training courses have been provided to the project industrial partners covering the use of the modelling suite to facilitate its more widespread application. Motor Design Limited has incorporated many of the design tool developments within their commercially available thermal modelling software, MOTOR-CAD. This has led to an expansion in the range of electrical machines catered for, to now include axial-flux topologies, and improvements in model accuracies. Over the course of the project they have seen a major growth in their software and consultancy business, which has resulted in the creation of several new skilled engineering jobs in the company.

The project has delivered an innovative test capability for multi-phase fault-tolerant aircraft propulsion drives, capable of dynamically characterising electrical drive systems with peak ratings up to 340 kW, 2000 Nm and 4500 rpm. A major element of this test rig is a complete functional representation of a redundant/fault-tolerant electrical supply and control system that would be needed for a safety-critical aircraft application. The University of Bristol plans to exploit this unique facility in the research of future aircraft propulsion. The rig is has been expanded to incorporate prime movers for high speed electrical generators to realise a hardware emulation of the complete electrical supply and generation system. In the near term this ‘copper bird’ is to be used to support the development of electric tail rotor drive and additional research into fuel efficient ‘more electric’ helicopters. Further the functional prototype electric drive system will be further characterised, and the associated models refined, to increase the background knowledge base in the operation and control of high-integrity systems.
The project has strengthened the relationship between the research and industrial partners, leading to follow on research collaborations. Close engagement with the air framer has promoted a greater understanding of the electrical systems and their exploitation potential amongst their engineers. The academic and conference publications arising from the project have raised the visibility of the University of Bristol and the University Politehnica of Bucharest within the research and industry community. This has seed-corned further research projects and grant proposals. Directly the project has led to new postdoctoral appointments and PhD opportunities, for example Motor Design Limited is sponsoring a 5-year Senior Research Fellowship at the University of Bristol. Indirectly the knowledge gained from the project has been incorporated into lecture material provided to undergraduates and postgraduates, thereby contributing to improving the skill set of the next generation of engineers.

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Related documents
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