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CAD for Electromagnetic Devices

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Practical Application of CAD in a High Power Density Motor for a Very Short Duty Aerospace Actuator

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***Abstract* – This paper describes how two popular CAD packages have been used to design a motor for a very short duty cycle in an aerospace application. The motor is the prime mover in an electrically actuated undercarriage suitable for the next generation of narrow body jets in the Airbus A320 / Boeing 737 size range. The undercarriage weighs several hundred kg and has to retract in less than 10s. The mechanism is entirely electromechanically actuated; there is no hydraulic assistance. Within the actuators, power from the motors is transferred via gearing and a rotary to linear device. Electro-Kinetic Designs Ltd is responsible for the thermal, electromagnetic and mechanical design of the motors. This paper focuses on the main retract motor, which is a permanent magnet, brushless DC motor operating from 540 V DC. It has dual windings and features to prevent fault propagation between the windings. The motor has high electrical and magnetic loading. The use of CAD for the electromagnetic and thermal design of the motor has enabled a high degree of optimization to be achieved, resulting in significant savings in size and weight, and has also brought other benefits to the programme.**

I. INTRODUCTION

A previous paper has highlighted the varying requirements for electric motors in the More Electric Aircraft. Primary flight control surfaces such as rudder, elevator and ailerons spend much of a flight making small, bidirectional movements, generally against static aerodynamic loads. Secondary flight controls such as flaps, slats and airbrakes are characterized by making relatively large single movements, often only at the beginning and end of a flight, and frequently using locks or brakes to enable the motor to be switched off when not actually moving the mechanism. The electrically retractable undercarriage falls into the category of secondary flight controls. Fig.1 shows the general arrangement of the undercarriage. Extension of the main actuator results in the undercarriage retracting. When the undercarriage is lowered, an over-centre mechanism locks it in position, and a small actuator is used to unlock the mechanism before retraction.

II. DESIGN DRIVERS

Because of the very short duty cycle and the need to minimize weight, the motor has been sized to meet the requirement that two consecutive cycles of lower and retract, totaling 48s of operation, should result in a temperature rise of 50°C per cycle.

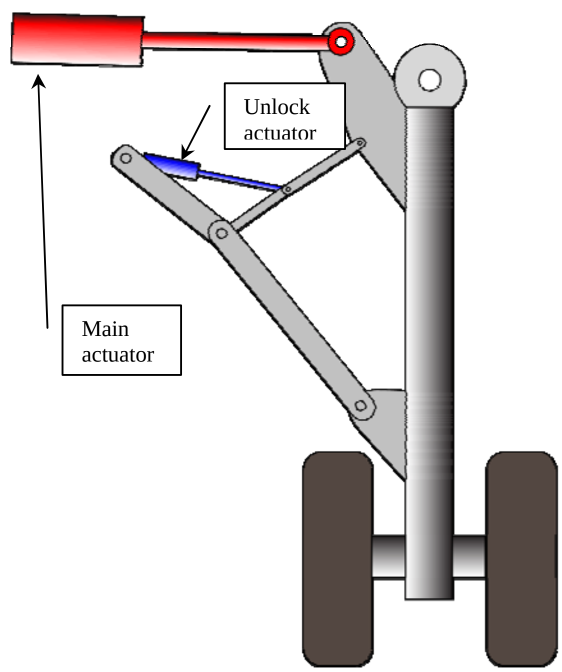

Fig.1. Schematic of undercarriage, showing actuators

Other important design drivers were:

- Operating point 7.74 Nm @ 17200 rpm
- No-load speed 23000 rpm
- Sinusoidal drive
- Low cogging torque

- High efficiency when operating at peak torque
- Current at peak torque not to exceed 40 A
- Redundant windings
- Low risk of fault propagation between windings
- Banded rotor and relatively large air gap

III. CAD SOFTWARE

EKD addressed the problem using SPEED software for the electromagnetic design, and Motor-CAD thermal analysis software for the thermal design. The two software packages are highly complementary and contain features to enable data to be readily exchanged, thus permitting an iterative approach and rapid convergence to the optimized design. Both applications are relatively easy for the non CAD specialist motor designer to use, whilst offering a high degree of versatility so as to enable a wide range of motor configurations and operating conditions to be analyzed.

IV. DESIGN PROCESS

The design process was as follows:

a) Define a baseline motor topography best suited to the requirement
b) Use established rules of thumb to estimate the initial dimensions
c) Create an electromagnetic model in SPEED, with all parameters defined at 20°C
d) Export the geometry, winding configuration and losses from SPEED to Motor-CAD
e) Set up the required torque vs. time profile in Motor-CAD
f) Determine the temperatures of winding, magnet, air gap and bearings using Motor-CAD
g) Update the temperatures in SPEED accordingly and re-run the model
h) Repeat steps c) to f) above until solution has converged (typically 3-4 runs).
i) Adjust the diameter and length of motor in SPEED, repeating steps c) to h) as necessary, until the winding temperature rise predicted by Motor-CAD is exactly 50°C.

V. MOTOR DESIGN

The motor topography is as shown in Fig.2. The winding configuration for a single winding is shown in Fig.3.

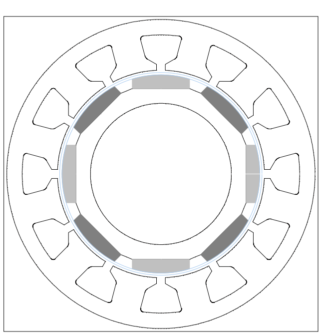

Fig.2. Motor cross section

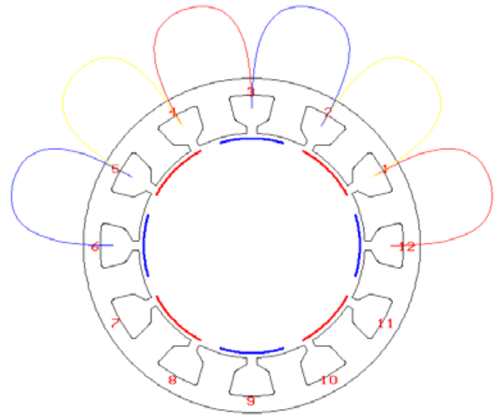

Fig.3. Insertion pattern for one winding

A tooth-wound configuration was chosen to avoid overlapping end-windings, to assist with minimizing fault propagation between windings. It also has the advantages of minimizing resistive losses and keeping as much of the winding as possible in close thermal contact with the stator iron. To achieve reasonable magnetic utilization, tooth-winding normally only works well when the number of magnet poles is similar to the number of stator teeth. In this case, because of the high speed of rotation, it was important to keep the number of poles to a minimum. At the same time a stator slot number that could contain both Prime and Redundant windings was required. The 12/8 configuration selected represented the best compromise between these requirements. Iron sections, slotting and tooth tip shape were determined using SPEEDs inbuilt FEA program, PC-FEA. A representation of the magnetic flux distribution under full-load conditions is shown in Fig.4.

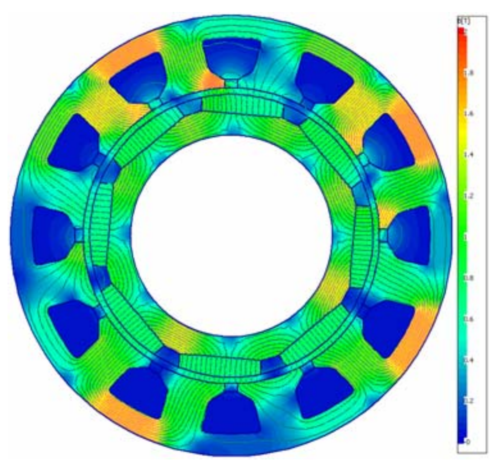

Fig.4.Flux distribution under full-load

The axial representation of the motor in Motor-CAD is as shown in Fig.5. (The Motor-CAD radial representation is similar to the SPEED model).

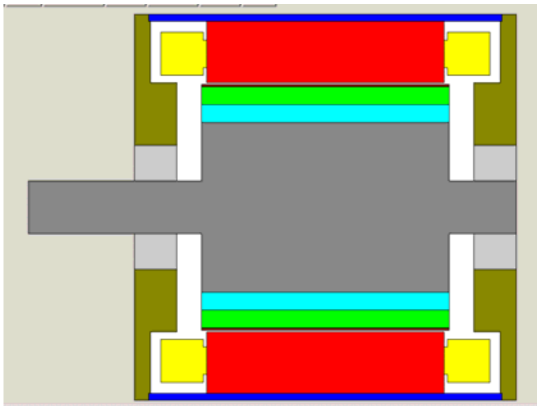

Fig.5. Motor-CAD axial cross-section

Fig.6 shows the Motor-CAD view of the non-overlapping stator winding, in which stator iron, slot insulation, winding wire, winding enamel and impregnation varnish are all represented. Copper losses, iron losses, rotor can losses, windage and bearing friction are all imported from SPEED, with sensible adjustments being made for distribution of losses where this is not already explicitly defined. In only one area did the data import require manual modification: Motor-CAD treats the copper losses as evenly distributed throughout the entire volume of copper, whereas in this particular design, the losses are concentrated in half of the winding. The problem was overcome by doubling the copper losses and applying this figure to the entire winding.

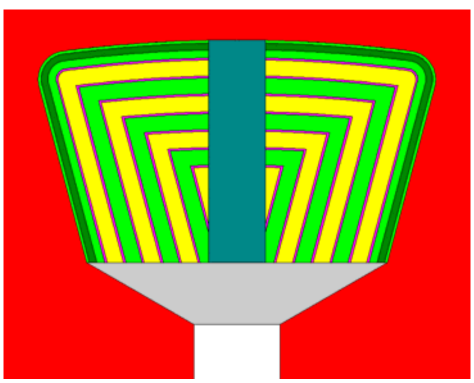

Fig.6. Motor-CAD representation of winding

VI. RESULTS OF ANALYSIS

In its transient analysis mode, Motor-CAD permits the user to enter a motor load torque vs. time profile. This was done using the data supplied for the undercarriage, suitably factored to take account of the effective gear ratios and mechanical losses. The resulting temperature profile in the motor is shown in Fig.7, in which the temperatures of the following critical areas of the motor have been tracked:

- Winding
- Magnet
- Rotor surface
- Stator surface
- Housing

The results shown are for the optimized design, in which it can be seen that the temperature rise per cycle is indeed 50°C as required.

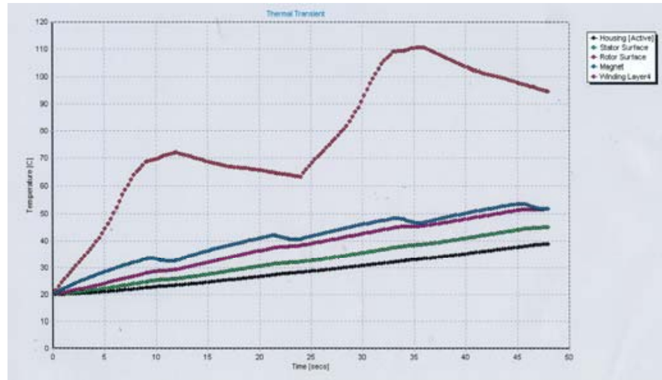

Fig.7. Temperature vs. time starting from 20°C ambient

Following on from this, it was then very easy to address the question of what the worst case winding temperature would be if starting from an ambient temperature of 70°C instead of 20°C, taking account of increased winding resistance and degraded magnet performance as a consequence of the higher temperature. Fig.8 shows that the winding reaches a peak of 180°C during the second cycle, which is a safe condition for the 200°C wire in use.

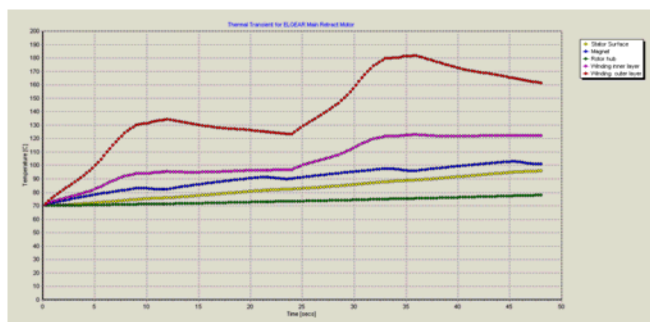

Fig.8. Temperature vs. time starting from 70°C ambient

During ground testing, it is planned that many thousands of cycles of extend and retract are to be performed. In order to evaluate how long this would take, further use was made of the model to define a safe duty cycle for ground testing. Fig.9 shows that, starting from 20°C ambient, a test duty consisting of one cycle of extend and retract followed by 7 minutes off resulted in the peak winding temperature stabilizing at about 175°C.

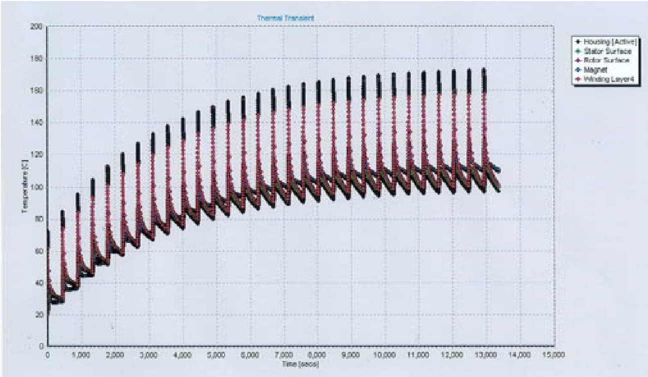

Fig.9. Temperatures resulting from many repetitions of a reduced duty cycle

VII. CONCLUSIONS

The evident design benefits brought by CAD optimization are a significant reduction in motor size and weight.

Parameter	**Unit**	**Before optimization**	**After optimization**
Stator diameter	mm	110	105
Stator length	mm	100	67
Effective volume	cm^3	950	580
Active mass	kg	5.45	3.75

Design optimization through application of CAD has resulted in a reduction in motor volume of 39% and a reduction in motor weight of 31%. Power density is 3.7 kW/kg when operating from either of the redundant windings. The high speed of calculation and rapid exchange of data between the SPEED and Motor-CAD software have been critical in keeping the cost of this complex analysis within limits acceptable to the client. Other advantages which flow from creation of the CAD models include a better understanding of the effects of worst-case conditions, and an evaluation of the time required for operational life testing.