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HIGH EFFICIENCY AND HIGH SPEED PM MOTORS FOR THE MORE ELECTRIC AIRCRAFT

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Abstract: More electric aircraft has been a subject of increasing discussions and research for more than ten years now, both in Europe and in North America. These efforts follow the growing realisation of the benefits that are likely to emerge from the future growth of the more electric aircraft technology. This is evident from the sizes and numbers of research and development programmes currently undertaken on the subject by both aerospace industry and academic institutions. High speed permanent magnet motors, excited by rare-earth magnetic materials, are used extensively in majority of these research programmes. The applications, on more electric aircrafts, often demand motor drives that have very high reliability, energy efficiency and high power density. One of the factors that require significant design consideration is the effect of high speed on the operational performance of the motor. High rotational speed impacts heavily on the rotational losses whilst the high peripheral speed influences the mechanical construction of the rotor. Iron and windage losses can become dominating factors in determining the overall rating and efficiency of the motor. The other important considerations relate to the ability of the motor to generate high torque at low speed, a feature that is very essential in actuation drive systems on the aircraft.

1. Introduction

In the last decade, there have been a number of research and development initiatives on electrical machines and systems for the future generation of more electric aircraft. In the main, most of this work has been collaborative, involving academic institutions and aerospace industry [1,2]. In the UK, some of this work has been supported through the DTI's Civil Aircraft Research and Technology Demonstration Programme (CARAD). Much effort, in the UK and world-wide, is going into wider use of electric power on aircraft. Innovative forms of electric or electromechanical actuation drive systems for applications such as flaps/slats control, electrical power generation systems with features of redundancy using high energy product

permanent magnet designs, a typical example of this type of machine is the permanent magnet fan shaft driven generator that is mounted at the back of the aircraft engine [3-8]. The real advantages are not dissimilar for military aircraft but the requirements are very different.

The brushless permanent magnet dc motor technology has been developing fast in this area in the last ten years. More and more high- efficiency high-speed pm brushless motors are becoming more favourable for a wide range of high speed drives in aerospace and defence applications. The physical, environmental and operational requirements of most of these applications are very difficult to meet and changes in technical requirements are frequent due to the continuous demands that emerge from the advances in technology. Up until recently,

majority of electrical machines, for aerospace applications, were designed using classical methods of lumped circuits and analytical calculations. The problems with classical methods are that they rely heavily on derived formulae, empirical factors and above all, they need to be aided by experimental data and vast amount of design experience. As such, design processes took long to complete and in some cases several errors were made and prototype machines had to be modified several times before final designs were established. The increasing demand for both higher power density and short design and development time meant that more and more accurate design techniques and powerful computational simulations were required to cope with the demand. Finite element was one of the computational techniques considered for modelling, with a high degree of accuracy, complicated electromagnetic geometries [9,10].

More electric aircraft drive systems do impose strict limits and requirements as regards to weight, physical size, efficiency and reliability. One of the ways in which a design approach can be made is by considering a high-speed drive design. Since the power output of a permanent magnet brushless dc motor is directly proportional to the volume of its active magnetic materials and the speed, increasing the operational speed results into a small size motor with less weight. The actual power rating of the motor is largely dictated by the method of cooling and the motor steady-state temperature rise. To achieve the necessary improvements in motor performance, brushless dc motors are excited by high-energy product materials such as samarium cobalt or neodymium iron boron magnet materials.

The use of high-energy magnets creates high flux densities in the machines. The

combination of high operational flux densities and high speed can give rise to excessive iron losses. It is essential, therefore, to be able to calculate and account for the iron losses more accurately. Windage losses are also equally important particularly with motors that have high peripheral speed [11]. This paper looks at novel ideas and innovative geometries of high-energy density permanent magnet brushless dc motor designs that lend themselves more favourably to these new aerospace requirements. Simpler methods of estimating both iron and windage losses are presented and ways in which these methods are incorporated in the design process are suggested. The paper also discusses the novel features of the rotor design which has been the instrumental to the success of this class of machine. The results of a case study from a typical high speed brushless dc motor for an aircraft application, rated at 500W at a speed of 24000 r/min are presented. This design considered the use of both samarium cobalt and neodymium iron boron magnets for making direct comparison between the two types of rare-earth magnetic materials. The comparative results of these two prototype motors show the advantage of NdFeB over the SmCo materials [12,13].

2. Motor Design

In order to achieve significant improvement in motor performance over and above that is possible so far, one needs to look at substantial changes of the ways in which the geometry of the motor can allow for significant improvements in performance. Various attempts have been made in the past by many researchers who looked at the techniques of flux focusing that are able to result in higher flux densities in the radial airgap than in the magnets themselves. A

typical example is a design that was suggested by Prof K Binns in the early 1970s, shown in Figs 1 and 2 below. This design shows a 4-pole, 3-phase synchronous motor with samarium cobalt magnets barred in the rotor core. The rotor core is laminated and employs rotor slots for forming a cage construction. The design uses non-magnetic aluminium for creating magnetic reluctance path in the rotor in order to force the flux into the airgap. The design combines both features of an induction motor and of a synchronous motor. The ends of the rotor are shorted by aluminium end-rings. The motor starts from rest as an induction motor and when it reaches the pull-in torque, it synchronises itself and continues to run as a synchronous motor.

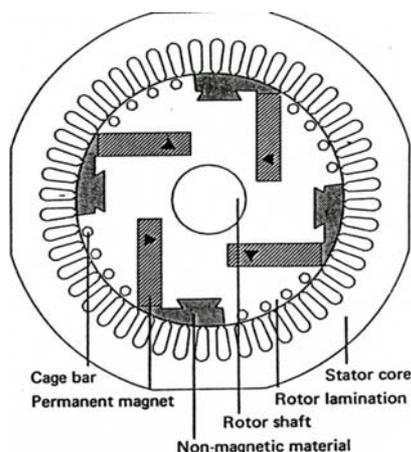


Figure 1

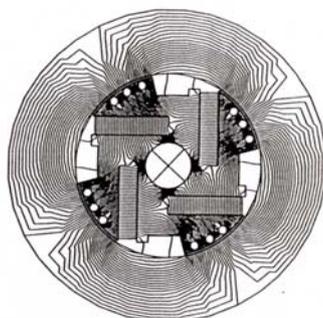


Figure 2

This was a wonderful invention and this design outclassed both the permanent magnet motor and the induction motor designs at the time. The design did achieve having higher flux density in the airgap than in the magnet. The motor developed very high torque capability even at low speed and its efficiency was higher than that of the conventional designs. Both Prof K Binns and Prof L M C Mhango, spent many years developing this design. The main practical disadvantages of this design are clearly seen from the structure of the rotor construction. First, the mechanical construction of the rotor is very complicated to manufacture and to guarantee consistency in quality and in performance. The rotor is made up of several components that require to be put together with significant amount of skill. Second, the total cost of materials, components and labour results in very high prime cost. As a result, not many motors, of this design, appeared on commercial market. Similar rotor design constructions, without rotor bars and end-rings, were experimented on for brushless dc motor applications. The results were that due to high cost of the rotor assembly, many researchers abandoned this rotor geometry.

The authors have since developed new novel rotor geometries that are also based on flux focusing. An example of this type of design is an experimental 4-pole, 3-phase permanent magnet brushless dc motor shown in Figs 3 and 4. The motor used hall sensors for sensing the position of the rotor magnet. The rating of the motor was 500W at the speed of 24000 r/min. The motor excitation system used both SmCO and NdFeB magnets. The rotor design comprised of the laminated core and four magnet segments. The rotor lamination had four inner slots arranged in a symmetrical position around the rotor and corresponding to the number of poles. The slots are in

direct radial axis with the magnets, creating minimum iron core depth in the direct axis of the pole and maximum iron depth in the quadrature axis of the pole. There are two reasons for matching the slot and the pole numbers of the motor. First, the core depth in the inter-polar region, see Fig. 5, is designed to carry the useful flux generated by one half of the magnet pole within the desired level of core flux density. Second, the core depth in the polar region, shown in Fig.6, is intended to minimise the effect of armature reaction flux; hence in this region the iron is saturated. The level of saturation is critical and it requires to be optimised such that it does not affect the operational performance of the machine especially at low speed. The shape of the rotor slots forms flux barriers in the inter-polar region, forcing the useful flux into the airgap under the pole area, thereby increasing the airgap flux density to be above that in the magnet itself. It was found that by using this design concept, airgap flux density could be increased substantially to equal that of Prof Binn's design described earlier and gave an improvement of between 10 and 15% of flux density; this takes the value to close to remanence value of the magnet.

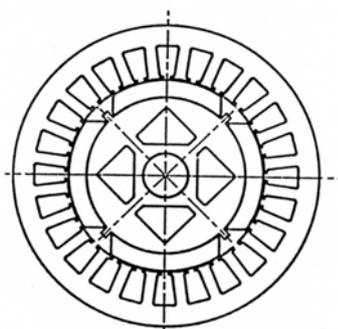


Figure 3

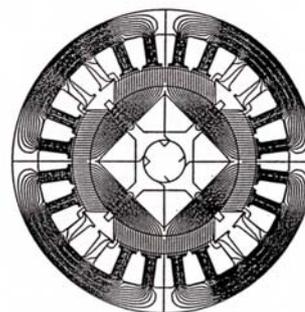


Figure 4

This is good news because it enables the design to open up the mechanical airgap without significant loss of performance. The typical airgap length for the size of machine reported in this paper is 0.7mm in total. Another important feature of this novel design is the inclusion of the four notches on the rotor lamination, as can be seen in Fig.5, that are used for easy assembly of the already magnetised magnets.

The layout of the stator winding was designed to eliminate some low order harmonics and also to provide at least a skew angle of 0.85 slot pitch. However, the inclusion of the skew angle presents some complications in the calculation routine for the iron losses. The effect of skewing was to minimise torque ripple, noise and cogging.

The magnets were secured on the laminated iron core and on the outside, they were protected by a thin tube that is made of non-magnetic steel. The thickness of the tube was designed to achieve optimum mechanical strength for protection against centrifugal forces whilst at the same time minimise the core losses in the tube that were caused by the airgap flux pulsation. High-speed operation of the rotor, inevitably, required effective protection of the magnets.

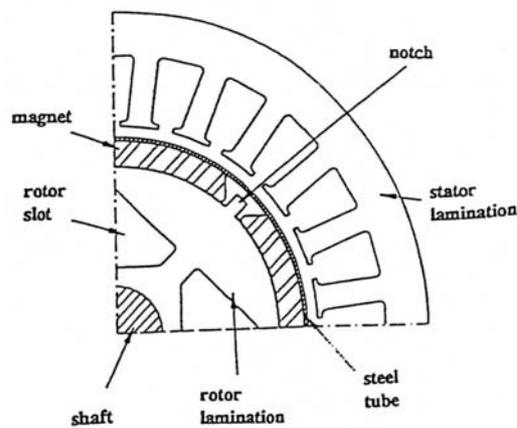


Figure 5

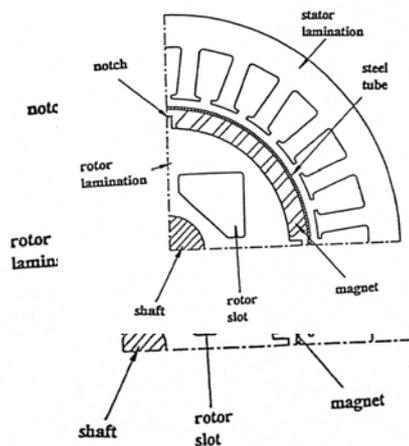


Figure 6

This means that in the process of iron loss calculations, losses in the tube also required careful assessment. However, since the magnets exert attractive forces towards the centre of the rotor core, the magnitudes of the centrifugal forces are minimal. Hence, thinner tubes can be used and this would also lower the core loss developed in the retaining tube.

Other configurations of rotor geometries for 4-pole, 6-pole and 8-pole, using the same flux focusing techniques are shown in Fig. 7. These configurations can accommodate any number of poles although in practice limits are imposed by both physical size of the machine and performance requirement of the application. High number of poles is ideal for low speed and high torque applications as would normally be required from a torque motor. Equally, higher number of poles allows the core length of the machine to be reduced. The ratings of the experimental rotors of high-speed high-energy density brushless dc motors shown in Fig.7 are (A) 2.75kW at 45000r/min, (B) 5kW at 45000r/min and (C) 20kW at 50000r/min.

3. Prediction of Iron Loss

Although the design of a motor that is excited by high-energy permanent magnets and operated at high speed offers benefits of minimising the physical size of the motor as well as increasing the motor power density, it also creates two notable problems. First, the operating flux density in the machine increases due to the limited space available in the iron and second the operational frequency of the flux-wave also increases due to increase in rotor speed. The combined effect of these two factors produces high iron loss that can become a significant portion of the total loss and can affect the overall performance of the motor. Iron losses or core losses as they are commonly known, occur in the magnetic circuits in which flux is changing. Traditionally, iron losses are known to comprise of hysteresis and eddy current losses. The eddy current loss has two components. The classical eddy current loss and the anomalous loss also known as excess loss. The excess loss is associated with the movement of the domain wall

across the grain boundaries in the magnetic material. The expressions that show the composition of all the three components of the iron losses have been previously presented in references {14,15}. The difficulties often encountered in the calculation of iron losses for a high-fluxed and high-speed motor design are due to the

fact that there are many influencing factors, some of which can be difficult to guarantee accuracy. The type and grade of lamination material, the method of production and heat treatment, the type and method of insulation, and the nature of supply waveform all have influence on the outcome of iron loss prediction.

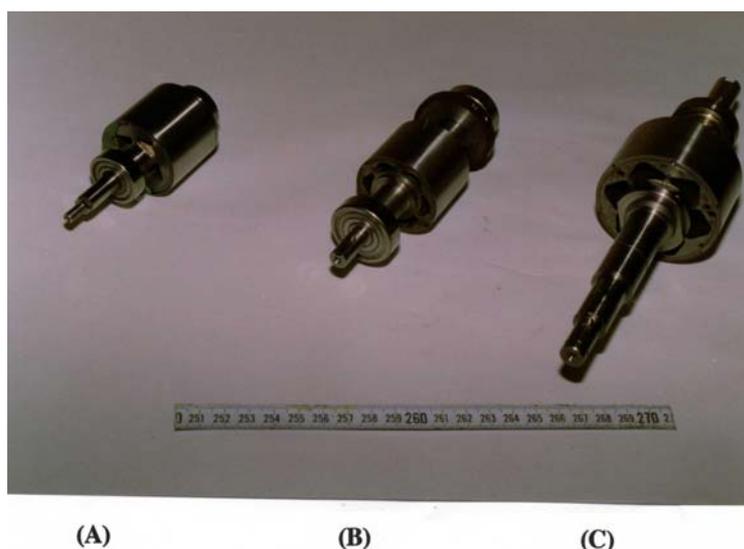


Figure 7

Over the years, there have been several attempts, in many applications, to calculate iron losses with better precision. One of the common approaches involves resolving the flux distribution into harmonic components.

By using the information of iron loss density provided by the material supplier. Losses are calculated for each harmonic and then by applying the principle of superposition, total iron loss is calculated. An alternative method uses loss curves from lamination data that give the total iron loss per unit weight of iron plotted against the maximum flux density for a respective value of fundamental frequency of the flux wave. This data is provided by the manufacturer of the lamination material is often quoted using sinusoidal supply and is not valid for non-

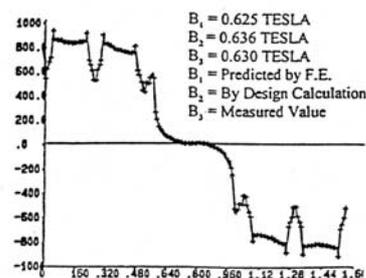


Figure 8

sinusoidal waveform. Consideration is needed to account for non-sinusoidal waveform and for saturation.

The calculations are performed by separating the magnetic circuit of the machine into smaller sections and then by calculating the flux density in each section separately. In order to simplify the

calculation, each section is assumed to yield constant flux density for each rotor position with respect to the stator. The process is then repeated for the whole 180 degrees electrical. To speed up the process and to obtain satisfactory results, finite element methods can be used to compute the flux densities in all sections of the magnetic circuit of the motor.

Fig.4 shows the 2D finite element flux analysis of the experimental motor shown in Fig.3. As can be seen, in Fig.4, saturation is clearly visible in the yoke of the stator lamination and in the stator teeth of the polar region. One notable feature of this flux distribution is the perfect symmetry of the flux around the machine and the way in which the flux is focused into the polar region of the airgap. This feature boosts the flux density of the airgap.

The results of the radial flux density in the airgap as a function of the rotor angular position are shown in Fig. 8 and are used to estimate the total iron loss of the motor. The comparison of test and experimental values of the airgap flux density show reasonable agreement. The results of the variation of iron loss with fundamental supply frequency for given values of airgap are illustrated in Fig. 9. Points on this figure denote calculated values and solid lines denote experimental measurements. As can be seen, the correlation is very good at lower frequencies but the error increases with frequency. It is also evident that as the airgap increases, the error remains small throughout a wider frequency range. This means that leakage flux plays a large part in contributing to the error with small airgaps. The results also show that iron loss on the whole increases much more rapidly with frequency for the motors that have small airgaps.

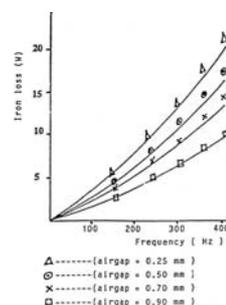


Figure 9

Iron losses were seen to increase by square of flux density; the results that were similar to those obtained in references [14,15]. The method of predicting the core losses in the stainless steel tube was covered in the previous papers [9,10].

4. Comparison of Performance of experimental Motors

A case study was undertaken in which the experimental motor described in Fig.3 was built for experimental comparison between the use of SmCO and NdFeB magnetic materials. The physical sizes of the two motors were essentially the same but the motor that was fitted with SmCo material was slightly bigger due to the lower energy product of SmCo in comparison with that of NdFeB. Both motors were designed to satisfy the same rating and to meet the same operational conditions.

Each motor was intended to drive a mixed flow fan used for electronic cooling in an aircraft application. The rating of the motor was 500W at 24000 r/min. The electronic controller was an integral part of the fan unit and was fitted at the back of the motor. The fan forced the air over the motor casing and the integral controller as well. This arrangement allowed both the motor and the controller to be provided with effective cooling during the operation. In view of the difference in maximum energy product,

coercivity and remanence between SmCO and NdFeB, the difference in the physical design of the two rotors was in the thickness of the magnet segments and thickness of the magnet retaining tubes.

Item	Motor NdFeB	Motor SmCO
Rating kW	0.50	0.50
Speed rpm	24,000	24,000
Weight p.u	1	1.4
Inertia p.u	1	1.35
Size p.u	1	1.28
Efficiency %	96.0	91.00
P/W ratio p.u	1	0.71
Cost p.u	1	1.18
Wdg temp rise, °C	34	41

Table 1

Both motors used the same magnetic airgap, hence this resulted in differences in useful fluxes in the airgap with NdFeB motor achieving higher flux. The comparative results are illustrated in Table1. Significant advantages of using NdFeB material are evident from these results. The main benefits being 5% improvement in efficiency, 18% reduction in cost, 40% reduction in weight, 28% reduction inertia and 29% improvement in power/weight ratio. These improvements are essential and are particularly suitable to most of the more electric aircraft applications identified for CARAD programme described earlier in the introduction of this paper.

5. Conclusions

This paper has described the benefits of new rotor design that shows the geometry that focuses the flux into the airgap and achieves higher airgap flux density than can be achieved in the conventional designs. The new rotor geometry has the benefit of reducing iron losses and rotor inertia whilst improving the symmetry of flux distribution in the machine. Larger airgaps prove to be essential and the use of non-magnetic steel tube for retaining the magnet segments against centrifugal forces is recommended.

The degree of correlation that has been achieved between experimental and calculated results is acceptable for most practical aerospace applications. This has given confidence in the design approach and in the method of calculations that have been described. For complicated designs, these techniques need to be backed up by comprehensive experimental tests. Clearly, there is a requirement for an improved mathematical model that is capable of handling high flux densities, high frequency and saturation conditions; these being outside the data that are readily available from the suppliers of lamination materials.

It has also been illustrated that there is good future for NdFeB material for new design requirements that require high efficiency and high speeds. At present, NdFeB magnet material offers the highest energy product and unlike SmCO, it is not radioactive. It is, therefore, suitable for both civil and military applications.

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