Feasibility study of a superconducting motor for electrical helicopter propulsion

C A B A E Simons[1], C Sanabria-Walter[2], H Polinder[3]

[1,3] Delft University of technology, 2628 CD Delft, the Netherlands
[2] EADS Innovation Works, 81663 Munich, Germany

E-mail: [1] c.a.b.a.e.simons@student.tudelft.nl
[2] christian.sanabria-walter@eads.net
[3] H.Polinder@tudelft.nl

Abstract. During the past decades, superconducting electrical machines have become more suitable to replace conventional iron based designs, because of their lower weight and higher torque density. These properties make them good candidates for use in More Electric Aircraft (MEA). Especially helicopter propulsion systems could benefit from the increased performance. This paper describes the feasibility study of a superconducting motor to be used for helicopter propulsion as part of a More Electric Aircraft (MEA). For this, the armature, field windings and cryostat are designed, aiming at meeting the difficult specifications. Since superconductors have virtually no electrical resistance when cooled down below a certain critical temperature, they can be used to build high field and low weight coils for electrical machines. Especially the possibility to not use iron can make the superconducting motor lighter with a higher power density compared with conventional Permanent Magnet (PM) motors.

1. Introduction

Increasing the efficiency and therefore lowering the environmental impact of aircraft is becoming an increasingly important goal of the aerospace industry. One effective way to reduce the environmental impact of aircraft is to utilize a hybrid drivetrain, more efficient and reliable when compared to conventional solutions. By combining the advantages of electrical motors and high efficient diesel engines, a hybrid solution is currently considered [1]. An essential part of this solution is the main propulsion direct-drive electrical motor, which greatly determines the feasibility of the concept itself. Such a motor has to provide a very high torque and power density, and a high reliability.

In aerospace it is common to use Permanent Magnet (PM) machines, operating at high rotational speeds [1]. When considering direct drive propulsion for helicopters, no conventional machine can suffice and new topologies have to be considered, an example being a new concept machine in [1].

In this paper a superconducting machine is proposed that could offer the high torque densities required. This first study is to research the possibility of such a machine and therefore only the technical feasibility is considered. Up to now not much work has been done on superconducting propulsion motors for aerospace, with the exception of [4] and [5]. These motors are designed for high speed operation and much less on high torque properties.

In the following sections a machine design for this purpose is developed. First the machine setup is described. Then, the armature is designed, together with superconducting field windings and cryostat. Finally the machine performance is analyzed and a conclusion with recommendations are given.

2. Machine Setup

In this section the machine parameters are given and the major design choices are described. The specifications for the propulsion motor are based on an average civilian helicopter with a payload of 7 to 8 persons, 1.5 tons of empty weight and 3 tons of maximum take-off weight [1]. Technical and operational specifications and machine dimensions are presented in table 1. Based on them; the following design choices were made:

- Partially superconducting: Conventional aluminium armature coils are used together with superconducting field windings placed in a cryostat to avoid high AC losses.

- Rotating armature: A rotating armature using slip rings is adopted while the field windings remain stationary, avoiding a heavy failure-prone cryogenic rotating coupling [6].

- Air core: Since HTS coils produce a larger MMF without active iron, a lighter air core machine can be made [7], as low weight is essential to the design.

Table 1. Machine Specifications.

Property	Value	Property	Value
Nominal power (kW)	600	Airgap radius (cm)	51.25
Nominal rotation speed (rpm)	350	Mechanical airgap (cm)	0.5
Nominal torque (kNm)	16.4	Electromagnetic airgap (cm)	2.5
Axial length (cm)	25	Rotor radius (cm)	50
Expected weight (kg)	150	Machine radius (cm)	70
Operating temperature HTS (K)	65	Inner rotor radius (cm)	45

3. Armature Design

In this section the non-superconducting aluminum armature coils are proposed. The choice of the armature configuration for superconducting machines is usually distributed because of the significantly lower space harmonics. However, in aerospace it is preferred to choose Fractional Slot Concentrated Windings (FSCW) [9] for certain performance advantages as mentioned in [10].

A full pitch distributed winding, the “least distributed”, is then compared to a 3/2 FSCW configuration, “the least concentrated”, for use in an HTS machine (see figure 1). The decision criteria for the armature configuration choice are the severity of the space harmonics seen at the superconducting side and the losses induced in a 1cm thick aluminum EM shield. The rotating armature uses the mechanical parameters given in the previous section with 72 slots, 60% slot space and a fill factor of 0.4 for the distributed configuration and 0.7 for the concentrated one (5A/mm^2).

A Comsol FEM simulation of the space harmonics, normalized to the fundamental with and without the EM shield is shown in figure 3. The effectiveness of the shield in reducing harmonics is proven, and the eddy current loss is of 120W and 2.9kW for the distributed and concentrated windings respectively. The increased cooling needed for the concentrated windings means that for any given cooling capacity, the distributed configuration can operate at a higher current density compared to the concentrated configuration. Because of this advantage the distributed winding configuration is used.

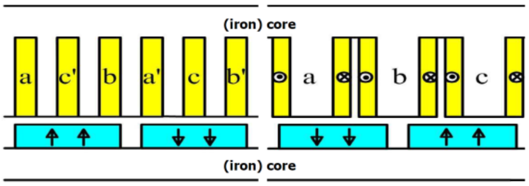

Figure 1. Full pitch distributed (left) and 3/2 fractional slot concentrated (right) windings [10]

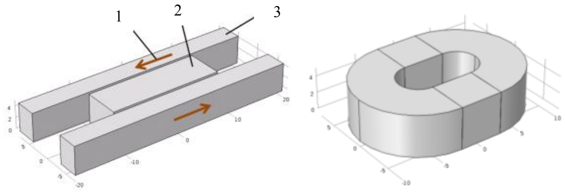

Figure 2. Model of bulk concentrating flux setup with current direction (1), HTS bulk (2) and HTS windings (3) (left), and model of the racetrack coil setup (right)

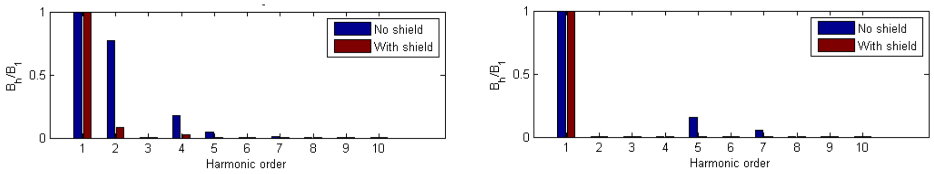

Figure 3. Space harmonics with and without EM shield for 3/2 concentrated (left) and full pitch distributed (right) winding configurations.

4. Field Winding Design

Using the methodology below, the superconducting field windings are designed in this section.

4.1. *Superconducting topology selection*

Two inductor topologies were considered for the field windings: the synchronous machine with superconducting racetrack coils shown in figure 2, the most popular and with very good performance, and the bulk concentrating flux topology shown also in figure 2, proposed in [4] and [5] and specifically developed for aerospace applications.

A comparison of the airgap field using Comsol for both designs using models of comparable size and weight is shown in figure 4. The resulting waveforms have peak values of 0.25T and 0.75T for the bulk concentrating flux and racetrack coil configuration respectively. It is evident that with three times better performance, race track coils are more appropriate for the ongoing design.

4.2. *Superconducting topology selection*

The racetrack coils consist of 12 stacked pancakes, each with 375 windings of 4mm YBCO tape from Superpower [12] and aluminum support material. Of interest are the parameters examined below.

4.2.1. Critical values. The critical current according to the *maximum normal and parallel magnetic field* are calculated using Comsol FEM simulations. The resulting critical current density is 144A/mm^2 and with a fill factor of 0.7, the critical current becomes 58A, incorporating a safety factor of 0.8. The corresponding maxima are 2.3T and 1.1T for the parallel and normal fields respectively.

4.2.2. Effective airgap field. Although the field inside the coil is as high as 2.3T, it decays rather fast further away from the coils due to the lack of iron to contain the flux, and due to the large airgap. Because of this, the average airgap field seen by the armature is taken: 0.8T.

4.2.3. Effective stack length. Also because of the absence of iron, air core machines suffer from large end-effects. These end-effects are taken into account by defining the effective stack length, which amounts to only 65% of the actual stack length.

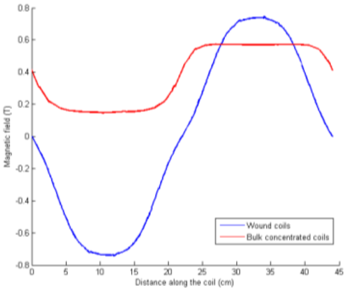

Figure 4. Magnetic field along the coil for bulk concentrating flux setup and race track coils.

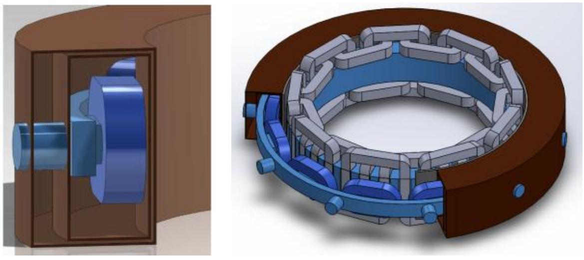

Figure 5. SolidWorks model of the cryostat (left) and of complete machine (right)

4.3. *Cryostat design*

The field coils are placed in a cryostat to keep them at 65K. Important design parts of a cryostat are the vacuum insulation and the cryostat mounting. Vacuum insulation is part of the airgap, therefore as thin as possible, and consists of two glass fiber reinforced plastic (GFRP) walls 3mm thick. The Multi-Layer Insulation (MLI) space between the walls is 4mm long for a total thickness of 1cm.

By using 10 GFRP rods for mounting, a thermally insulating and mechanically strong support is proposed. A thorough mechanical analysis, beyond the scope of this paper, must still be performed.

With the cryostat structure defined (see figure 5), the main heat losses inside the cryostat are calculated (see table 2): HTS conduction losses, mounting and support conduction losses, radiation losses from the outer to the inner cryostat wall, and current lead losses. For a thorough explanation on these calculations, see [13]. For cooling the cryostat the use of the cryo-coolers is preferred, since it will result in a much lighter cooling system. Using pulse tube cryo-coolers designed for aerospace made by Lockheed Martin [14], 15W can be removed at 65K, with 7kg of weight and consuming 600W. Using 5 cryo-coolers for redundancy the total weight amounts 35kg. The required input power is 3kW, which is only 0.5 percent of the target power.

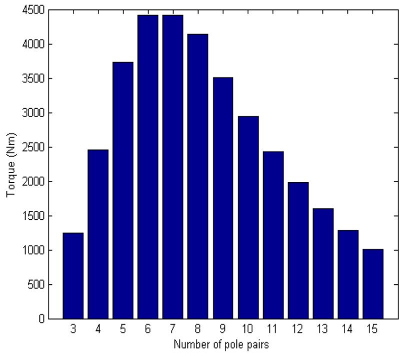

Figure 6. Torque as function of the number of pole pairs

Table 2. Cryostat heat sources.

Heat source	Losses [W]
Electrical conduction	0.07
Thermal conduction	39
Thermal radiation	0.7
Current leads	3.7
Total	**43.07**

Table 3. Specification comparison.

Property	Target	Acquired
Nominal power (kW)	600	251
Normal torque (kNm)	16.4	7.1
Power-to-weight ratio (kW/kg)	4-5	0.65
Torque-to-weight ratio (N/kg)	110-130	18.4
Torque volumetric density (kNm/m^3)	43-51	17.6
Expected weight (kg)	150	386

5. Machine Performance

In this section the armature, field windings and cryostat designs are combined to calculate the torque, torque density and efficiency of the final design.

5.1. Torque Calculation

The torque is calculated using FEM simulations on Comsol as function of the number of pole pairs and the results presented in figure 6. From the results it is concluded that the optimum torque of 4.4kNm occurs with 6 pole pairs, using an armature current density of 5A/mm^2.

The optimum is explained as follows: with a pole pair number lower than six, the field coils are too large compared to the machine and the excitation flux becomes less effectively linked to the armature coils. On the other hand, with a pole pair number higher than six, the field coils become smaller. Due to the lack of iron and the large airgap, the flux leakage is dominant and the torque decreases.

5.2. Weight Estimation

A very important aspect of the design is the total weight of the machine. Summing up the weight of the different components, the total weight is 386kg, including cooling system.

5.3. Performance of Final Design

In table 3 the results obtained are presented together with the target values (for an armature current density of 8A/mm^2). The main power losses are 3kW from the cryo-coolers and 12.3kW of resistive losses in the aluminum windings. With a machine power of 251kW, the efficiency becomes 94%.

From table 4, 42% of the targets are met with a weight 2.5 times higher. The main reasons behind these low values are explained below.

5.3.1. Operating temperature of superconductors. The operation at 65K limits the performance of the superconductors resulting in a low critical current of 60A, and in a low airgap field of 0.8T.

5.3.2. No iron use. Without the use of iron the machine weight was kept as low as possible, but at the same time no flux path could be designed, resulting in dominance of airgap leakage flux. The weight decrease is partly counteracted by the higher amount of superconductor material needed.

5.3.3. Large airgap. The airgap length, characteristic of a superconducting design, is 5% of the airgap radius and 17% of the active axial length, making it more advantageous to design larger machines.

6. Conclusions

A first technical feasibility study on a superconducting motor for helicopter propulsion has been made. The armature, superconducting field windings and cryostat were designed adopting a radial flux topology with an inner rotating armature removing the need for a cryogenic rotating coupling.

For the armature design, a comparison between a distributed winding configuration and a FSCW configuration yields unacceptable losses for the concentrated configuration, and favoring the choice of the distributed configuration. Regarding the superconducting field windings, a comparison between the bulk flux concentrating and the wound racetrack coil topology showed that the latter has much higher torque capabilities, favoring its choice. A tentative cryostat design was given. The heat load, estimated at 43W, is removed most effectively with high-power-density pulse tube cryo-coolers.

Finally the machine parameters were calculated. The result was that only 42% of the targets were met with a weight 2.5 times higher. According to these figures is estimated that a superconducting electrical propulsion motor may not be feasible with current technology and specifications.

7. Recommendations

Although the superconducting electrical propulsion motor may not be feasible under the current set of constraints, it is expected that the machine performance can be improved with future work.

The most important recommendation is to consider liquid hydrogen (LH2) for cooling, which is not unrealistic in aerospace, since it is also considered as a potential replacement for kerosene in the near future. This would bring the operating temperature from 65K down to 20K, resulting in significantly higher operating currents and a potential performance increase of 3 to 4 times, but also in a need to redesign the cooling scheme. This would bring the machine performance closer to the target values.

References

[1] P Jänker, J Stuhlberger, F Hoffmann, G Niesl and V Kloeppel 2010 The Hybrid Helicopter Drive – A Step to New Horizons of Efficiency and Flexibility, *36th European Rotorcraft Forum*
[2] E D Ganev 2007 *Power Engineering Society General Meeting* **1** 771-778
[3] C Sanabria-Walter, H Polinder, J A Ferreira, P Jänker and M Hofmann 2012 *Proc. of the XX conference on electrical machines (ICEM)* 2583-2590
[4] P Masson and C Luongo 2005 *IEEE Trans. App. Superconductivity* **15** 2226-2229
[5] C Luongo, P Masson and T Nam 2009 *IEEE Trans. App. Superconductivity* **19** 1055-1068
[6] R Flitney 2007 *Seals and Sealing Handbook* (Elsevier)
[7] J Frauenhofer et all 2008 *Journal of Physics: Conference Series* **97** 012189
[8] A Parviainen 2005 *Design of axial-flux permanent-magnet low-speed machines and performance comparison between radial-flux and axial-flux machines* PhD Thesis, Lappeenranta University of Technology, Finland
[9] E Tsampouris, M Beniakar and A Kladas 2012 *IEEE Trans. Magnetics* **48** 943-946
[10] A EL-Refaie 2010 *IEEE Trans. Ind. Electronics* **1** 107-121
[11] H Polinder, M J Hoeijmakers and M Scuotto 2007 *Electric Machines & Drives Conf.* **1** 652-657
[12] SuperPower 2012 [Online]. Available: http://www.superpowerinc. com/content/products.
[13] S S Kalsi 2011 Applications of High Temperature Superconductors to Electric Power Equipment (John Wiley & Sons, IEEE Press)
[14] J R Olson, P Champagne, E Roth and T Nast 2012 AIP Conf. Proc. **1434** 161-167