High-output density partial superconducting motors for aviation systems

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Abstract. This paper describes electromagnetic design of partial superconducting motors (PSCMs) using YBCO field coils and copper armature windings. It has simpler structure than that of fully superconducting motors (FSCMs), which have superconducting field/armature windings. The target output density is set over 16 kW/kg. For the first step, we designed the 3.0-, 5.0- and 9.0-MW superconducting motors by means of analytical equations. We used genetic algorithm to find the proper conditions, including magnetic flux density amplitude, machine diameter and rotation speed, for our optimal machine structure. The results show that the 5.0- and 9.0-MW PSCMs could reach over 16 kW/kg and in some 9.0-MW cases, we recognized that the output density of 26 kW/kg had been almost attained. After the optimal design, FEM analysis was conducted for some design results of the 5.0- and 9.0-MW PSCMs, in order to evaluate motor losses, copper and iron loss, as well as maximum magnetic flux density and motor output. The motor efficiency could reach over 98% in all the FEM design cases. Also, the output density values were almost the same as those in the design cases with analytical equations. These analytical and FEM design results refer that over 16 kW/kg is possible with PSCMs; if we should obtain the output density of over 20 kW/kg with the PSCM structure, however, the 9.0-MW PSCMs are indispensable.

1. Introduction
The aircraft market has been expanding continuously today. Some stats show that an airplane takes off every several seconds all over the world. However, the increase of aircraft operation has brought some problems, such as the increase of greenhouse gas emission from turbo-fan engines mounted on both wings. Therefore, the future aircraft propulsion systems are demanded to realize such high efficiency as decreasing the greenhouse gas emission.

The electrified aircraft propulsion system is one of the effective solutions to realize the higher efficiency systems. The blade fan of the electrified aircraft propulsion system will be activated by electrical motors with higher output density in comparison with the state-of-the-art motors. An aircraft for over 200 passengers, like B737, needs the 16 kW/kg motors and generators, to realize its propulsion systems [1]; in case of the aircraft for several hundred passengers, like A380, over 20 kW/kg with MW class machines will be required [2]. In spite of such a high requirement, the output density of the latest permanent magnet machines for aircraft has merely attained the level of 5 kW/kg with 250 kW, so far [3]; under such circumstances, the only answer we could get is “reducing each motor weight while keeping its output power”.


Superconductivity is one of the attracting technologies for realizing high output density rotating machines; motor coils made of superconducting wires have several hundred times higher current density than that of copper motor windings; moreover, higher magnetic flux density generation with less quantity of motor windings is available. It means that such problems as the reduction of the iron-core percentage and as the motor-weight reduction can be solved simultaneously.

Due to these advantages, superconducting motors have been studied in many groups in the world [4]-[10]. Figure 1 shows an example of superconducting aircraft propulsion system, which is called turbofan electric system: in the system, the electric power is generated by the gas turbine engine and generator; after the conversion from AC to DC power, the DC power is distributed to the whole aircraft systems. At a take-off, the DC power is converted to AC power via inverters, and the superconducting motors connected to fans are activated. The combination of the gas turbine engine and the generator can control the power generation efficiently during the flight missions even against the load fluctuation. This system structure has been quite popular in the electrified aircrafts using superconducting motors and generators [7, 9]. Some groups focus on fully superconducting motors (FSCMs) made of superconducting field/armature windings [6]-[10]. These structures are expected to realize high output density machines because they have higher current density coils and smaller air gap in comparison with partial superconducting motors (PSCMs) using superconducting field coils and copper armature windings; this is because the field and armature windings of the FSCMs are put into the same cryostat and the mechanical distance among the two windings can be shortened; the FSCM structure, however, tends to be complicated because both superconducting coils should be cooled at ultra-low temperature. On the other hand, PSCMs have superconducting field coils at only rotor part and their stator parts are made of non-superconducting components. NASA has been studying the PSCM structures and achieved the output density of over 16 kW/kg at active material part [4]. This result shows the PSCMs also have potential to realize high output density motors for future electrified aircraft propulsion systems.

This paper focuses on the electromagnetic characteristics of the PSCM structures obtained through analytical equations and FEM analysis. The design using genetic algorithm is carried out for PSCMs with different output and output density of the machines is evaluated. After the evaluation, FEM is applied to the evaluation of maximal magnetic flux density at field coils and motor losses to discuss the efficiency of the PSCMs.

2. Partial superconducting motor structure

The conceptual illustration of the PSCMs is as shown in Figure 2. The armature winding at the stator part is made of copper wires; the wire is cooled by liquid to increase armature coil current density. On the other hand, the rotor part made of cryostat is evacuated for cooling the superconducting field coils made of high-temperature superconducting wires. Also, the copper electromagnetic (EM) shield and the torque tube are installed near the superconducting field coils. The coolant for field windings, for example liquid nitrogen and liquid hydrogen, is supplied from rotor shaft. The superconducting field coils are additionally excited by a field coil exciter mounted behind the cryostat [6].

![Figure 1 Example of turbofan electric system](image1)

![Figure 2 Partial superconducting motor structure](image2)
3. Partial superconducting motor design

3.1. Motor diameter

The motor diameter is decided from tip speed of the fan blade. Figure 3 shows the geometrical relationship between the fan blade and the PSCMs, whose diameter $D_{motor}$ is assumed half as much as the fan blade diameter $2R$. The equation (1) describes that the tip speed $v = R \omega$ is less than or equal to 500 m/s and the motor speed $N_{rot}$ in the equation (2) is chosen from 5000 rpm or 7000 rpm.

\[
v = R \omega \leq 500 \text{ m/s} \tag{1}
\]

\[
\omega = \frac{2\pi N_{rot}}{60} \tag{2}
\]

As a result, the maximum $D_{motor}$ values under the conditions of $N_{rot} = 5000$ rpm or 7000 rpm are less than or equal to 954 mm or 682 mm, respectively (Table 1).

![Figure 3 Relationship between fan blade and a motor](image)

Table 1 Relationship among the fan-blade tip speed, the motor speed and the motor diameter

| Tip speed $v$ (m/s) | Motor speed $N_{rot}$ (rpm) | PSCM diameter $R$ (mm) |
|---------------------|-------------------------------|------------------------|
| 500                 | 5000                          | $\leq 954$             |
|                     | 7000                          | $\leq 682$             |

3.2. Motor design conditions

Table 2 shows the specifications of the PSCMs; we assumed the aircraft as one for around 200 passengers and the total output power for take-off as 45-MW, respectively. Three output-power ranges, 3.0-, 5.0- and 9.0-MW, were chosen to investigate the total take-off power; accordingly, the combinations of 3 MW×15, 5.0 MW×9 and 9.0 MW×5 could be chosen for the superconducting propulsion systems.

Number of poles $p$ was chosen from the range between 6 and 16. The range $p$ is fortunately wider than that of fully superconducting motors; in the PSCMs using the copper armature windings, there is no need to consider AC losses, which affect the motor frequency. Also, the gap magnetic flux density amplitude $B_{max}$ was chosen from the range between 0.4 T and 3.0 T. On the contrast, the FSCMs employed the range between 0.4 T and 1.0 T [10]. In comparison with the FSCMs, it is also a great merit for the PSCMs to have a wide range in choosing the value $B_{max}$.

The operating temperature of the PSCMs was set to either 20 K or 65 K. The coolants used under the environments were liquid hydrogen and liquid nitrogen, respectively.

The maximum magnetic flux density at the superconducting field coils was less than or equal to 2.5 T. As for the electrical load $A_e$, 120 kA/m was chosen. This value is higher than that of usual motors with air cooled armature windings because we considered to employ liquid cooled copper wire with 30 A/mm$^2$ [11].
How to choose the voltage values of aircraft propulsion system was quite important. Some research groups employed kV order motor voltage and we set the motor line voltage to 1.41 kV in this research [12].

| Parameters                          | Values                  |
|-------------------------------------|-------------------------|
| Output power $P$                    | 3.0, 5.0, 9.0 MW        |
| Power factor                        | 1.0                     |
| Number of poles $p$                 | $6 \leq p \leq 16$      |
| Gap magnetic flux density amplitude $B_{\text{max}}$ | $0.4 \text{T} \leq B_{\text{max}} \leq 3.0 \text{T}$ |
| Operating Temperature               | 20, 65 K                |
| Max. magnetic flux density at field coils | $\leq 2.5 \text{T}$   |
| Electrical load $A_s$               | 120 kA/m                |
| Motor speed $N_{\text{rot}}$        | 5000, 7000 rpm          |
| Line voltage                        | 1410 V                  |

4. Analysis results

4.1. Motor design by means of analytical equations

Based on the values in Table 2, we derived our optimal design with the following equation (3):

$$
P = \frac{\pi^2}{\sqrt{2}} k_w B_{\text{max}} A_s D^2 L_{\text{eff}} \frac{N_{\text{rot}}}{60} \tag{3}
$$

In the equation, the symbols of $k_w$ ($= 0.95$), $D$ and $L$ stand for the winding coefficient, the armature part diameter and the motor effective length, respectively. We used the solver “Evolutionary” mounted on Microsoft Excel® for this optimal design.

Figure 4 shows the output density of the PSCMs as a function of number of poles. On the three graphs, the border line of 16 kW/kg is also shown. All the design cases of the (a), (b) and (c), in Figure 4, show the same tendencies that the order of output density is 20K_7000 rpm, 20 K_5000 rpm, 65 K_7000 rpm and 65 K_5000 rpm. The results reveal that the choice of operating temperature, $T$, is more effective for the PSCM design to obtain higher output density in comparison with the motor speed $N_{\text{rot}}$. The lower $T$ makes current density higher, leading to the reduction of the superconducting wire amount in the field coils. Also, peak values of the output density are found in all the design cases.

No case of the 3.0 MW-PSCM designs had attained 16 kW/kg despite $T = 20$ K and higher $N_{\text{rot}} = 7000$ rpm, as shown in the Figure 4 (a); however, the case of 20 K_7000 rpm has a potential to reach or exceed 16 kW/kg with some improvement in its design. On the other hand, there were some high output density motors over 16 kW/kg in the PSCM design cases of 5.0 MW (Figure 4 (b)) and 9.0 MW (Figure 4 (c)); among the 5.0 MW-PSCMs, the motors operated at 20 K exceeded 16 kW/kg and the Motor A reached 20 kW/kg. However, the 5.0 MW-PSCM with 65 K_7000 rpm also reached nearly 16 kW/kg line. As for the 9.0 MW design cases in the Figure 4 (c), we recognized many cases exceeding the16 kW/kg; both the Motors C and D cleared the 20 kW/kg line, and it should be mentioned that the output density of the Motor C was 25.6 kW/kg. While the two motors exceeded 20 kW/kg were operated at 20 K, the Motor E operated at 65 K also reached 19.8 kW/kg; it was the only case that the motor was operated at 65 K, and we could say, in other words, liquid nitrogen is usable in the Motor E.

The motor design cases over 16 kW/kg of peak values are summarized in Table 3; two 5.0 MW and three 9.0 MW motors are picked up in this table. The “Weight” in the table includes all the motor components in Figure 2. 12 poles were used in most of the cases, and the $B_{\text{max}}$ was ranging from 0.80 T to 0.97 T. These values are slightly higher than those of the FSCMs [10]. All the motor diameter $D_{\text{motor}}$ was defined less than 682 mm, which is lower than the design condition values, as shown in the Table.
1. The values for the motor effective length \( L_{\text{eff}} \), in Table 3, are lower than those of the \( D_{\text{motor}} \) and we can find that the PSCM structures will be pancake structure.

![Graph showing output density vs. number of poles for 3.0 MW, 5.0 MW, and 9.0 MW motors.](image)

Figure 4 Motor output density as a function of number of poles

| Table 3 Partial superconducting motors over 16 kW/kg |
|-----------------------------------------------|
| Motor | A | B | C | D | E |
| \( P \) (MW) | 5.0 | 5.0 | 9.0 | 9.0 | 9.0 |
| \( T \) (K) | 20 | 20 | 20 | 20 | 65 |
| \( N_{\text{rot}} \) (rpm) | 7000 | 5000 | 7000 | 5000 | 7000 |
| Number of poles | 12 | 12 | 12 | 12 | 10 |
| \( B_{\text{max}} \) (T) | 0.80 | 0.80 | 0.89 | 0.89 | 0.97 |
| \( D_{\text{motor}} \) (mm) | 614 | 614 | 675 | 675 | 627 |
| \( L_{\text{eff}} \) (mm) | 197 | 275 | 267 | 373 | 292 |
| Weight (kg) | 247 | 302 | 352 | 441 | 455 |
| Output Density (kW/kg) | 20.2 | 16.6 | 25.6 | 20.4 | 19.8 |

4.2. Motor design with FEM analysis

We evaluated the motor losses and the maximal magnetic flux density at field coils by utilizing JMAG-Designer®. The three PSCMs over 20 kW/kg in the Table 3 were chosen for this analysis. Figure 5 shows the magnetic flux distribution of the Motor A (5.0 MW). The maximal magnetic flux density at the field coil was 2.55 T according to the analysis result. The difference between this value and the specification value in the Table 2 was only 2.0%. Also, the maximal magnetic flux density values of the Motor C and the Motor E were 2.56 T and 2.59 T, respectively. In both motors, the differences against
the specifications were less than 3.0%. These results show that the designed motors satisfy the initial design specifications.

Figure 6 shows the losses of the three PSCMs; both the iron loss, including hysteresis loss and eddy current loss, and the copper loss were evaluated. We did not consider the loss at EM shield because it was several W orders according to the previous results [9]. It is obvious from the graph that the eddy current loss is much higher than the copper loss and hysteresis loss. When we evaluated the motor efficiency from these values, all the efficiency was estimated as 98.9%.

Table 4 shows the comparison of the motor output density calculated by two methods. We could find no critical difference between the motor output density values and the values gained from the two design methods: the optimal design and the FEM analysis.

The above results show that not only the FSCMs but also the PSCMs could be good candidates for the future electrified aircraft propulsion systems; however, we should confess that the realization of the over 9.0 MW-grade superconducting motor is indispensable to achieve the output density exceeding 20 kW/kg with the PSCM structures.

### Table 4 Comparison of motor output density calculated by two methods

| Motors          | Output density based on analytical equations | Output density based on FEM analysis |
|-----------------|---------------------------------------------|-------------------------------------|
| A (5.0 MW)      | 20.2 kW/kg                                  | 19.0 kW/kg                          |
| C (9.0 MW)      | 25.6 kW/kg                                  | 26.4 kW/kg                          |
| E (9.0 MW)      | 19.8 kW/kg                                  | 18.4 kW/kg                          |

### 5. Conclusions

We have designed and analyzed the PSCMs for electrified aircraft propulsion systems. The 5.0-MW motor with the output density over 16 kW/kg is available with the PSCM structures, while the over 9.0-MW motor is required to achieve over 20 kW/kg in order to realize the PSCM structures.

However, further system analyses, including the transient state analysis, will be required for the feasibility evaluation of the superconducting electrified aircraft propulsion systems.

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