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Cylindrical double air gap motor for aerial applications

***Abstract**. The authors describe various constructions of high torque density motors for electrical drive system to small airplane. There were also proposed projects of motors with dual stator and dual rotor for aerial applications. Further, there was also presented the comparison of parameters between motors with dual air-gap, with inner stator and with outer stator.*

***Streszczenie.** Autorzy opisują konstrukcje silników o wysokej gęstości momentu dla elektrycznego systemu napędu do małego samolotu. Zamieszczono przykładowe projekty silników z podwójnym statorem i podwójnym rotorem dla zastosowań lotniczych. Porównano parametry silników z podówjną szczeliną z silnikami w wykonaniu z zewnętrznym oraz wewnętrznym stojanem. (**Silnik elektryczny z podwójną szczeliną powietrzną do zastosowań lotniczych**).*

Keywords: high-torque motor, fault-tolerant motor, permanent magnet motor, motor with double air gap.
Słowa kluczowe: silnik elektryczny o wysokim momencie obrotowym, silnik elektryczny o wysokiej niezawodności, silnik elektryczny z magnesami trwałymi, silnik z podwójną szczeliną powietrzną.

Introduction

With regard for continuously increasing oil price, use of electric drive for vehicles becomes more profitable each year. Therefore, electric motors have begun to be used not only in cars but also in aerial industry. Some producers offer self-launching electric gliders to sale and some prototypes of hybrid or solar planes have been created nowadays.

The electric motors have many advantages over the combustion engines when it comes to aviation applications. The first and most important is reliability. The mechanical construction of electric motor is easier. For that reason, the time between overhauls is significantly longer. The devices with high failure risk like for example control electronics can be implemented without problem in fault-tolerant technology. Also the maintenance of electric motor is easier. Practically, in a brushless motor there exists necessity of lubrication of bearings only. Also the electric motor has a significantly longer useful life. Moreover, the electric motor is easier to restart in air than combustion engine and it can work in dusty environment. Furthermore, the electric motor has significantly higher efficiency (often higher than 90%) than internal combustion engine (often lower than 25%). And important advantage is that the electric motor does not emit any exhaust gases. Also produced noisy and vibration are significantly lower in electric propulsion. However, the electric drives have also disadvantages. Firstly, the petrol has still significantly high power density among the methods of storage energy. Secondly, the petrol is burnt during a flight in a combustion engine, so an airplane becomes increasingly lighter and thus the lift force to balanced weight can be lower. And thirdly, the necessary time for recharging battery is significantly longer than time for refilling petrol tank.

Aircraft motors require a high power density (high power with a minimum weight of motor), a high efficiency and a high reliability and fault-tolerant work (safe landing in case of occurrence of failure). The output rotational speed of drive is strictly imposed by relation of speed to propeller efficiency, so high-torque density is more convenient parameter. The requirement of low weight is dictated by limit of lift force and weight balance of an airplane. Moreover, the motor must have compact dimension because often into fuselage is limited space for motor. Whereas the motor is mounted outside of fuselage then air drag is increased with increment of motor outer diameter, so the small dimensions of motor are desired. Also the condition of small torque ripple must be fulfilled due to silent work of motor and extension of useful life. With regard for requirements of high power density and high efficiency, only motors with permanent magnet were taken into considerations for aerial drive.

The constructions of high – torque motors.

The most popular method for improving torque density is the use of high-speed outer-rotor motor with mechanical gear. This method is used by almost all producers of motor gliders nowadays. However the use of mechanical gear causes reduction of drive efficiency and generates additional problems with lubrication, cooling and maintenance mechanical gear. So the use of direct drive is more convenient. First preposition of direct drive can be the application of two motors mounted on common shaft proposed in article [1]. This construction has the highest reliability due to the use of two redundant motors and power converters. But the power density is the same as for a single motor. The next solution is the multi-phase motor described in article [2,3]. The multi-phase motor has higher power density as typical 3-phase motor but requires more complicated power electronic system and needs more space.

The combination of these two techniques can be the motor with dual air-gap. The motor with double air-gap can be dividing on two groups: motor with dual stator (described in article [4,5,6]) and motor with dual rotor (described in article [7,8]). This motor seems to be very convenient for aircraft drive. It has high power density and torque density. Furthermore, the two stators improve reliability and fail-safe work. Application of 3-phase winding for both stators enables to use typical 3-phase power converter. In addition, the two stators enable more techniques of torque ripple reduction.

Also very promising solution of high power density machine is pseudo-direct drive ([9,10,11]). It is the motor with integrated magnetic gear inside. It offers all advantages of drive with mechanical gear but magnetic gear has not mechanical connection between rotating elements. So the useful life of magnetic gear is longer and the vibration and noise during work is lower. However magnetic gear reduces efficiency due to eddy current losses in additional magnet rings, so this article described only direct drive constructions.

The motor with double stator.

The motor with dual stator is built with two stators - inner and outer. Between the stators there is a rotor made of permanent magnets and titanium separators between magnets. The exemplary construction of motor with double stator is depicted in Fig.1.

The researched construction has 36 slots in inner stator, 40 poles and also 36 slots in outer stator. In motor is applied fractional-slot concentrated winding because this type of winding can significantly reduce the weight of end-winding. The flux flows out from magnet. Next it closes by tooth and ends in adjacent magnet. The flux paths in inner stator and outer stator are symmetric relative to rotor. This is presented in Fig. 2.

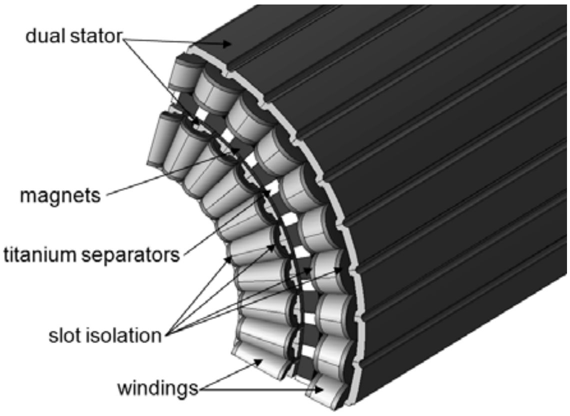

Fig.1. The structure of motor with dual rotor

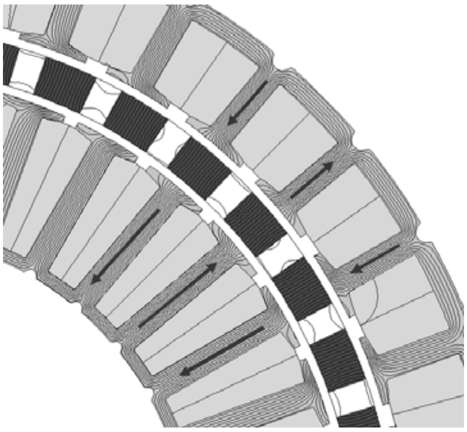

Fig.2. The magnetic flux paths in dual-stator motor. The arrows show the direction of flux

The comparison motors with inner, outer and double stator.

In order to compare parameters of dual-stator motor to parameters of motors with single rotor, there were prepared analysis of work all these machines. The program which makes calculations on the basis of Finite Element Method was used for test of parameters of machines. For all construction there were taken the same requirements of axial length, number of slots, number of poles, length of air-gap, area of slots and current density. Moreover, all constructions have the same radius of air-gap. In Table 1 there are collected the values of common parameters for all motors.

Table 1. The motor requirements

Number of slots	36
Number of poles	40
Rotational speed	1875 rpm
Current density (with assumed slot-fill factor 50%)	10 Arms\mm^2
Stack length	165 mm
Number of turns per phase	36
Air-gap radius	The same for all construction
Size of air-gap	1 mm
Size of magnets	The same for all construction
Maximal outer diameter	150 mm

Results of simulations prove that the motor with dual-stator has the highest torque density among researched constructions. The torque of double-stator motor is almost two times more than other motors (the torque is lower than two times more with regard of higher reluctance of air-gap in motor with dual-stator) but weight is only one and half times more higher. The reduction of mass in double stator motor in comparison to two single stator motors is caused by eliminating necessity of using a back-iron in rotor.

The motor with internal stator has almost the same torque density as motor with external stator but its outer diameter is lower. The detailed results are presented in Table 2.

Table 2.The results of comparison three motor types

	Internal stator	External stator	Double stator
Torque [Nm]	90.05	90.05	164.7
Weight of active parts [kg]	10.653	10.81	14.292
Torque density [Nm\kg]	8.453	8.332	11.52
Outer diameter [mm]	132.8	150	150

The choice combinations number slots and poles.

In order to better optimization of construction and achievement higher torque density factor were prepared some models of machine with various combinations of number slots and poles. The simulations were proceeding for conditions which are collected in Table 3.

Table 3. The motor requirements

Rotational speed	1500 rpm
Current density (with assumed slot-fill factor 50%)	10 Arms\mm^2
Stack length	160 mm
Number of turns per coil	3
Air-gap radius	The same for all construction
Size of air-gap	1 mm
Outer diameter	150 mm

The results of simulations are gathered in Table 4. It can be noticed that the most optimal construction for stators is 36 slots. In spite of fact that value of back EMF is lower than in stator with 45 slots with regards of lower turns per phase and lower winding factor, slots have bigger area and therefore the current amplitude can be higher with achievement assumed current density. However excessive increasing of area slots leads to reduction of torque density as it can be noticed in construction with 27 slots. The higher number of poles leads to abbreviation of flux paths and higher flux value in result. Nevertheless, the higher number of poles causes increase frequency and iron losses.

The efficiency.

The construction with 36 slots in each stator and 40 poles in rotor was chosen to further optimisation in order to fulfil the requirements of a motor to an airship. The requirements were presented in Table 5. For achievement of 32 kW, the stack length of motor was increased to 165 mm and speed was increasing to 1875 rpm. Then the motor achieved torque density 11.707 Nm/kg what is very good result in comparison to motors used for driving of airships nowadays. The more particular parameters of the motor are shown in Table 8.

The simulations prove that this motor has also very good efficiency (about 95%). The power losses were estimated basing on FEM analysis. The results of estimation were presented in Table 6.

Table 4. The dual-stator motors comparison with various combinations of slots/poles number

Construction	36-40-36	45-40-45	36-40-45	27-30-27	36-42-36	45-42-45	45-44-45
Parameters							
Average torque [Nm]	160.2	154.34	147.7	146.795	163.288	155.314	157.003
Output power [kW]	25.16	24.1	23.2	23.06	25.65	24.397	24.662
Area of slot in inner stator [mm^2]	82.3	60.7	72.5	139.534	82.3	60.7	60.7
Area of slot in outer stator [mm^2]	82.3	63.5	66	128.03	82.3	63.5	63.5
Current amplitude in inner stator [A]	96.6	73	84.4	164.4	96.6	73	73
Current amplitude in outer stator [A]	96.6	73	77.8	150.848	96.6	73	73
Back EMF voltage - RMS value - inner stator [V]	62.38	78.784	61.8141	35.6305	63.15	82.0473	82.61
Back EMF voltage - RMS value - outer stator [V]	63.66	81.387	77.5133	35.6057	64.4	84.8959	85.71
Weight of active parts[kg]	13.89	14.146	13.749	13.593	13.903	14.16	14.174
Torque density[Nm\kg]	**11.533**	**10.84**	**10.744**	**10.799**	**11.745**	**10.969**	**11.0768**
Number of turn per phase	36	45	36/45	27	36	45	45
Winding factor for 1st component	0.945	0.953	0.945/0.953	0.945	0.933	0.951	0.955

Table 5. The motor requirements for airship

Power [kW]	32
Speed of motor [rpm]	1500
Outer diameter [mm]	150
Current density (with assumed slot-fill factor 50%)	10 Arms\mm^2
Weight of active parts	Less than 15 kg

Table 6. The estimation of efficiency

Power output	**32 476 W**
Losses in winding (for temp. 150 deg C)	1475.5 W
Iron losses in stator	227 W
Joule losses in magnets*	50 W
Joule losses in titanium separator	20 W
Input power	34 249W
Efficiency	**94.8 %**

* For magnet divided on four parts in axial direction

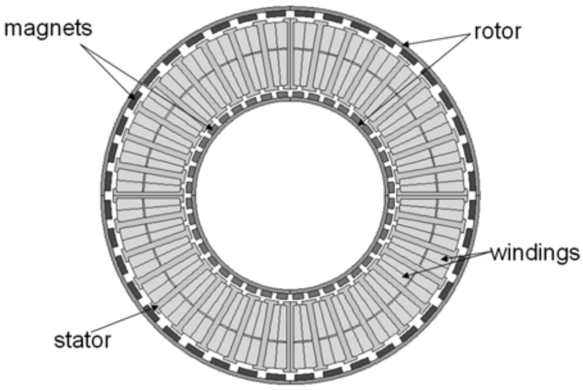

Fig.3. The construction of dual-rotor motor

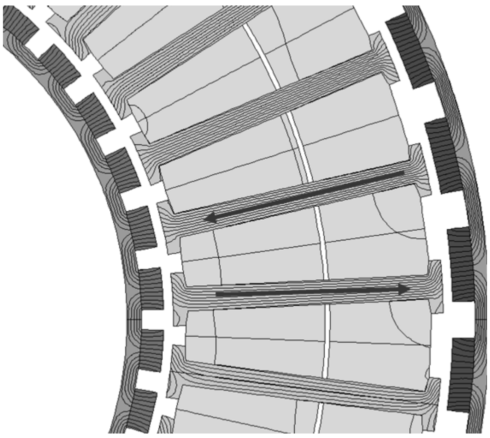

Fig.4. The magnetic flux paths in dual-rotor motor. The arrows show the direction of flux

The motor with double rotor.

The motor with double rotor have two rotors - inner and outer - which are built with permanent magnet and soft magnetic material yoke. Between rotors there is a stator with the sets of windings for each rotor. The construction of motor with dual rotor is presented in Figure 3.

The stator yoke between the teeth is useless from electromagnetic point of view, but from mechanical point of view is necessary. Moreover, in researched construction these back-irons are made of non-conducting magnetic flux material. Then magnetic flux flows from magnets of first rotor to the magnets of second rotor through teeth. The flux path is presented in Figure 4.

Comparison of two motors with dual air-gap.

Both models have the same number of slots and poles, axial length of motor, outer diameter, current density, rotational speed and number of turns per coil.

Table 7. The motor requirements

Motor with dual rotor	40poles-36slots-40 poles
Motor with dual stator	36 slots-40 poles-36 slots
Rotational speed	1875 rpm
Current density (with assumed slot-fill factor 50%)	10 Arms\mm^2
Stack length	165 mm
Number of turns per phase	36
Size of air-gap	1 mm
Outer diameter	150 mm

Table 8. The comparison of parameters for two motors with dual air gap

Construction	Dual stator	Dual rotor
Parameters		
Average torque [Nm]	165.432	158.397
Output power [kW]	32.482	31.101
Area of slot in inner stator [mm^2]	82.3	90.5
Area of slot in outer stator [mm^2]	82.3	90.5
Current amplitude in inner stator [A]	96.6637	106.6552
Current amplitude in outer stator [A]	96.6637	106.6552
Back EMF voltage - RMS value - inner stator [V]	79.4522	67.5806
Back EMF voltage - RMS value - outer stator [V]	83.4381	77.5443
Weight [kg]	14.131	13.537
Torque density[Nm\kg]	11.707	11.701

The Table 8 presents the parameters of motor with double rotor and with dual stator. Both motors have almost the same torque density. However the motor with dual rotor achieved lower torque and did not achieve required power, but its weight is lower. Moreover, the mechanical construction of dual rotor motor is more difficult to realization with regard to two moving parts. Furthermore, the dual stator motor has better mechanical and electrical isolation between windings of both stators, what leads to better reliability. What is more, the cooling system is easier to implement in motors with a dual stator. Therefore, this issue is very important, for in stator there are the highest losses, and therefore, this part will have the highest temperature. Then, when the stator is located between two rotors, it will be very difficult to remove heat from it. On this basis, it can be concluded that the motor with dual stator seems to be a better solution for aerial applications.

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