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Pseudo-direct drive for aerial applications

***Abstract**. The authors describe possibility of the motor with magnetic gear usage in drive system of small aircraft. They present basic requirements for motor to aviation application. Furthermore, they discuss operation principles of magnetic gear and compare several constructions of pseudo-direct drives. An exemplary project of pseudo-direct drive was included in this article.*

***Streszczenie.** Autorzy opisują możliwość użycia silnika elektrycznego z przekładnią magnetyczną do napędu statku powietrznego. Prezentują podstawowe wymagania dla silnika elektrycznego do zastosowań lotniczych. Opisują zasadę działania przekładni magnetycznej oraz porownują kilka konstrukcji. Podany został przykładowy projekt silnika elektrycznego z* pseudo-bezpośrednim układem przenoszenia napędu. *(**Silnik elektryczny** z **pseudo-bezpośrednim układem przenoszenia napędu do zastosowań lotniczych**).*

Keywords: high-torque motor, permanent magnet motor, magnetic gear, pseudo-direct drive.
Słowa kluczowe: silnik elektryczny o wysokim momencie obrotowym, silnik elektryczny z magnesami trwałymi, przekładnia magnetyczna, silnik elektryczny z pseudo-bezpośrednim układem przenoszenia napędu.

Introduction

The main requirement (excluding security issue) for electric motor to aerial application is high power density. A rotational speed is not very high in propeller drives due to propeller efficiency. Therefore, there are used high-torque machines or motors with gearbox. Gearbox enables mounting a high-speed motor, which has lower mass and lower dimensions than a high-torque motor. However, drive system with mechanical gear has some disadvantages such as worse efficiency, higher noise, additional cooling system and lubrication system. Moreover, mechanical gearbox increases the failure risk and causes necessity of frequent overhauls.

Given these reasons, it can be seen why the conception of substitution mechanic gear for magnetic gear was born. The works on the design of magnetic gear have been carried out for thirty years. Some constructions of magnetic gears, which try to imitate constructions of mechanical gears were created during this period of time [1,2]. Currently, the most promising is co-axial magnetic gear construction [2,3]. According to [3], the transmitted torque density exceeds 100 kNm\m^3. The construction of the co-axial magnetic gear was shown in figure 1. The gear was built with two rings which are made of permanent magnets and ferromagnetic materials (back-iron). Between these rings is implemented ring with iron pole-pieces which modulates magnetic fields of magnets. The high-speed rotor is always the inner magnets ring. The low-speed high-torque rotor can be outer magnets ring or iron pole-pieces ring.

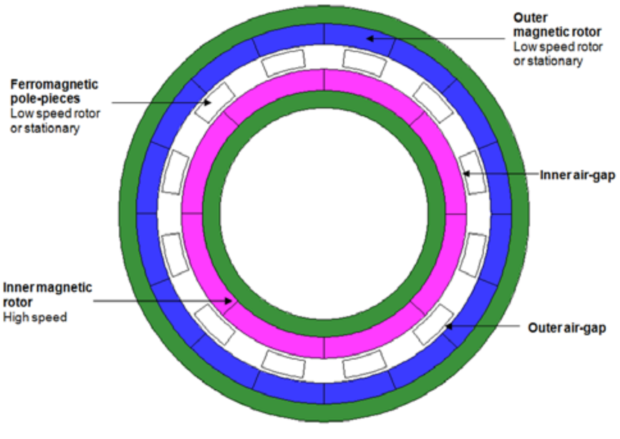

Fig.1. The structure of magnetic gear

The principle of operation magnetic gear

The distribution of magnetic field in air-gap for permanent magnet motor.

The key principle of work for synchronous motor is synchronism between magnetic field produced by rotor and magnetic field produced by stator. Magnetic fields must have the same number of poles and the same rotational speed for achievement constant torque. The distribution of magnetic field in air-gap around moving rotor with permanent magnet can be described by the following equations:

$$B_r(r,\theta) = b_r(r)\cos(p\theta - p\omega t - p\theta_0) \tag{1}$$

$$B_\theta(r,\theta) = b_\theta(r)\sin(p\theta - p\omega t - p\theta_0) \tag{2}$$

where: $b_r(r)$ and $b_\theta(r)$ – amplitude of magnetic field density for radial and circumferential components, p – number of pole pair, ω – rotational speed, θ_0 – initial phase.

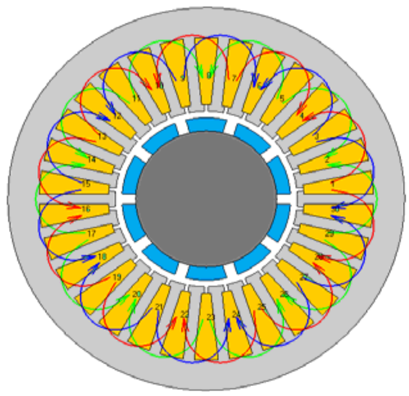

Fig.2. The electric motor with permanent magnet and distributed winding

The stator construction must enable generation of magnetic field, which will be synchronized with rotor magnetic field. For achievement of non-zero value of torque, vectors of magnetic fields must have different angle.

Figure 3 presents distribution of magnetic field density in air-gap for surface permanent magnet motor (30slots – 10magnets). It can be noticed that number of poles is the same for both magnetic fields and current frequency was selected for achievement of the assumed rotational speed of rotor. This example is analogical for two magnetic rings with the same number of poles rotating with the same rotational speed.

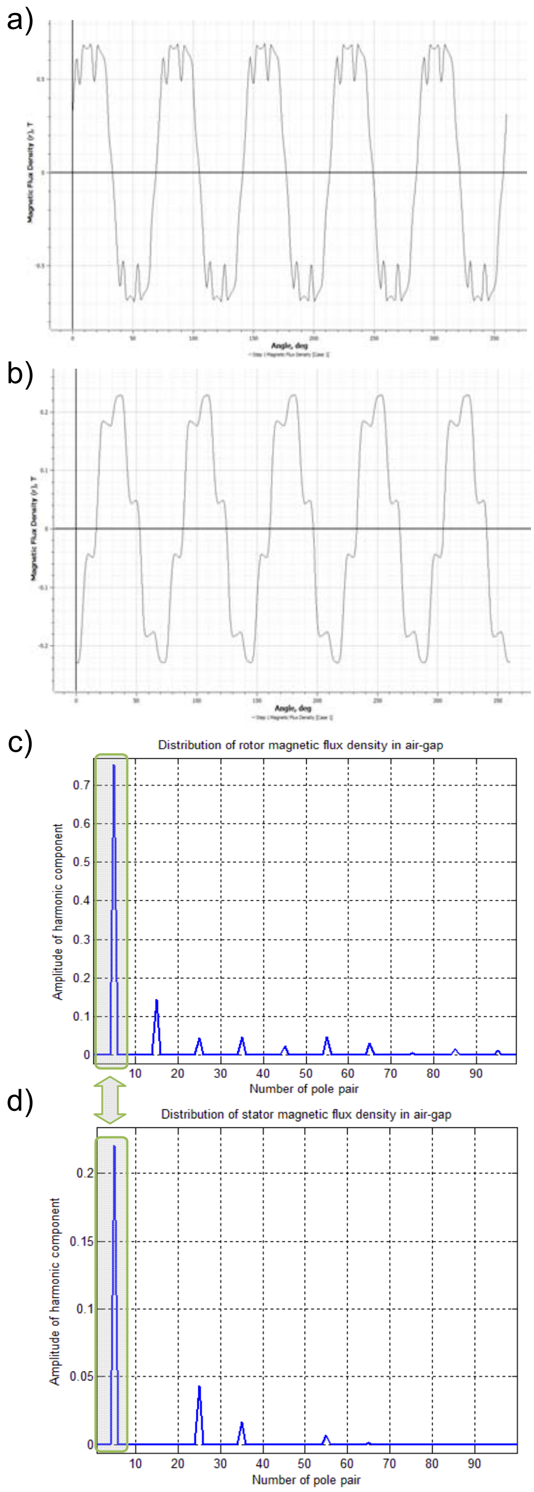

Fig.3. The distribution of magnetic field density in air-gap: a) from rotor; b) from stator; c) FFT of rotor magnetic field density; d) FFT of stator magnetic field density

The distribution of magnetic field in air-gaps of magnetic gear.

The transmission of speed and torque between two magnets rings can take place only in case when magnetic fields have the same number of poles and equal rotational speeds. Therefore, the simplest magnetic gear is two non-coaxial magnets rings with various numbers of poles and various rotational speeds. Then, gear ratio depends on radiuses of rings and numbers of poles in both rings. However this kind of magnetic gear has low efficiency and low transmitted torque density especially with high gear ratio [2,6].

The key element for correct working of co-axial magnetic gear is ferromagnetic pole-pieces ring. This ring modulates the magnetic fields from magnets and enables cooperation between the two rings of magnets with different numbers of poles. Co-axial magnetic gear uses the phenomena of slotted air gap effect which was described in articles [4,5]. In general this effect can be described by the following equation:

(3)
$$B_s = B_{sl}\lambda^*$$

where: B_s – magnetic flux density in slotted air gap, B_{sl} – magnetic flux density in slotless air gap, λ – complex relative air-gap permeance.

Components of air-gap permeance λ_r, λ_θ can be expressed as Fourier series:

(4)
$$\lambda_r(r,\theta) = \lambda_0(r) + \sum_{n=1}^{\infty} \lambda_{nr}(r)\cos\left(nQ_s(\theta-\omega_s t)\right)$$

(5)
$$\lambda_\theta(r,\theta) = \sum_{n=1}^{\infty} \lambda_{n\theta}(r)\sin\left(nQ_s(\theta-\omega_s t)\right)$$

where: λ_{nr}, $\lambda_{n\theta}$ – amplitude of permeance components for n-th Fourier component, Q_S – number of iron pole-pieces, ω_S – rotational speed of ring with ferromagnetic pole-pieces.

If equations (1,2,4,5) put to equation (3) and make some mathematical transformations, then equations describing distribution of magnetic field density in air-gap are defined as follows:

(6)
$$B_{sr}(r,\theta) = \sum_{m=1,3,5,\ldots} b_{mr}(r)\lambda_0(r)\cos\left(mp(\theta-\omega_r t)+mp\theta_0\right)$$
$$+\sum_{k=\pm1}\ \sum_{m=1,3,5,\ldots}\ \sum_{n=1}^{\infty} c_{k,m,n}\cos\left(\left(p_{k,m,n}\right)\left(\theta-\omega_{k,m,n}t\right)+mp\theta_0\right)$$

(7)
$$B_{s\theta}(r,\theta) = \sum_{m=1,3,5,\ldots} b_{m\theta}(r)\lambda_0(r)\sin\left(mp(\theta-\omega_r t)+mp\theta_0\right)$$
$$+\sum_{k=\pm1}\ \sum_{m=1,3,5,\ldots}\ \sum_{n=1}^{\infty} d_{k,m,n}\sin\left(\left(p_{k,m,n}\right)\left(\theta-\omega_{k,m,n}t\right)+mp\theta_0\right)$$

where: $c_{k,m,n}$, $d_{k,m,n}$ are amplitudes of particular harmonic components.

From equations (6) and (7) can be noticed that distribution of magnetic field density includes harmonic components resulting from number of poles in magnets ring and harmonic components resulting from modulation by pole-pieces ring. The number of poles and rotational speed of harmonic components of magnetic field density resulting from modulation can be represented by the following equations:

(8)
$$p_{k,m,n} = \left|mp + knQ_s\right|$$

(9)
$$\omega_{k,m,n} = \frac{mp\omega_r + knQ_s\omega_s}{mp + knQ_s}$$

where: p - number of poles in magnet ring, Q_S – number of iron pole-pieces, ω_S – rotational speed of ring with ferromagnetic pole-pieces, ω_r – rotational speed of ring with magnets, k – factor which differs from which magnet ring are produced harmonics in space, m – number of Fourier harmonic component magnetic field density, n – number of Fourier harmonic component air-gap permeance.

From equation (8) results that if requirement of the same number of poles for magnetic field from magnets ring and magnetic field from other magnets ring after modulation must be achieved, then following identity must be fulfilled:

(10)
$$p_{lr} = p_{hr} + Q_s$$

Where: Q_S – number of iron pole-pieces, p_{lr} – number of poles for output magnets ring, p_{hr} – number of poles for input magnets ring.

The gear ratio can be calculated from equation (9) taking into consideration the requirement of the same rotational speed of magnetic fields. Accordingly, gear ratio for non-moving output magnet ring and gear ratio for moving output magnet ring are presented below:

(11)
$$G = \frac{Q_S}{p_{hr}}$$

(12)
$$G = \frac{p_{lr}}{p_{hr}}$$

The more detailed information and mathematical model of work for magnetic gear are included in articles [6,7,8,9].

An example of magnetic gear is presented for better explanation. The sketches of magnetic flux density distribution in air-gap were made on the basis of a simulation in program with FEA method. An exemplary construction is presented in figure 1. The number of pole pairs of high speed rotor is equaled 4, the number of pole pairs of low speed rotor is equaled 8 and the number of pole-pieces is equaled 12. According to theory presented above, the pole-pieces ring modulates magnetic field of one magnet ring and causes formation of additional harmonic component which correspond with basic harmonic component (resulting from number of poles) generated by second magnet ring.

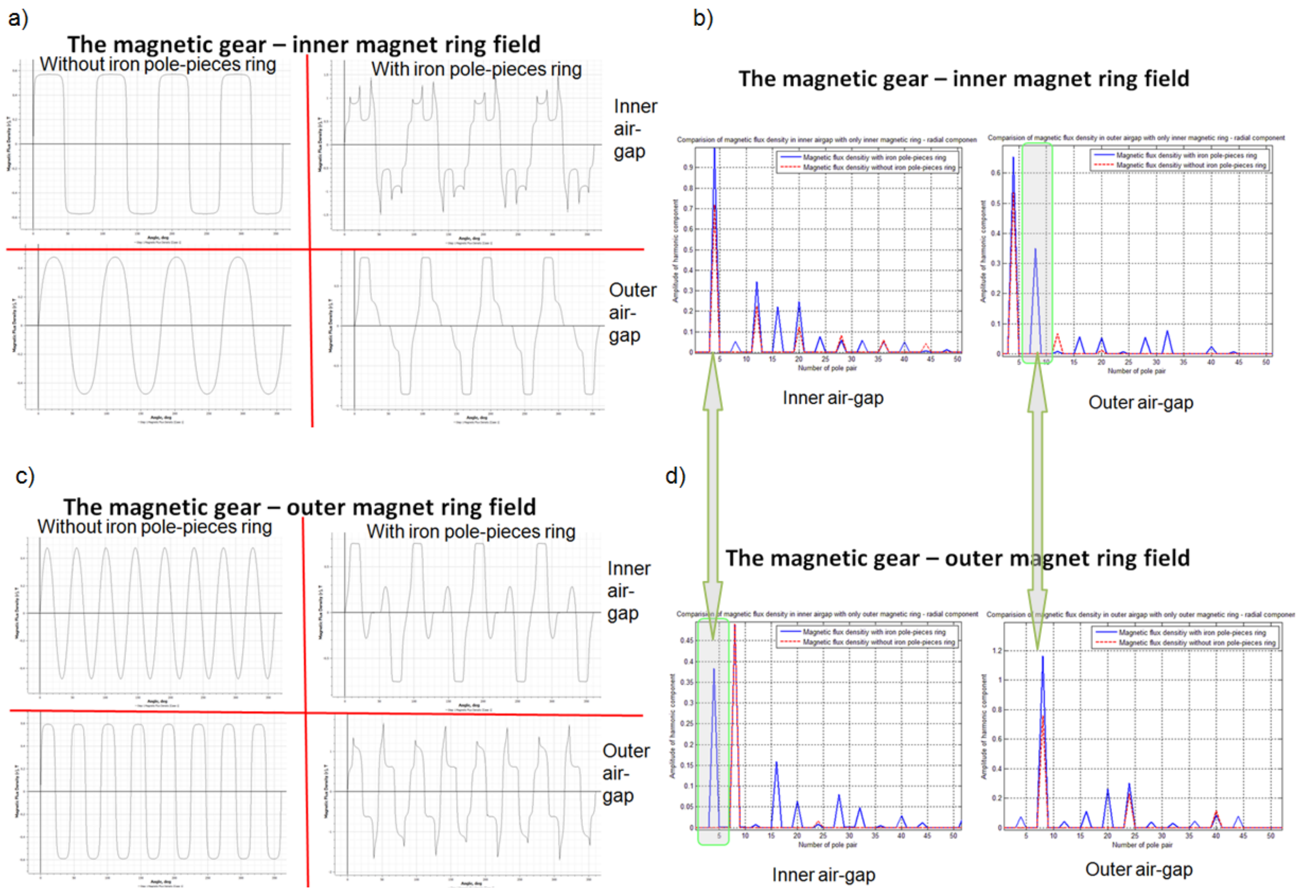

Fig.4. The distribution of magnetic field density in air-gap: a) from inner magnetic ring; b) FFT of curves from (a); c) from outer magnetic ring; d) FFT of curves from (c)

The proposed construction of pseudo-direct drive.

The requirements for designed motor.

The aircraft drive is a very specific application. Therefore motor must fulfil a lot of very strict requirements which were described in the introduction of this article. The detailed requirements for proposed motor for air-vehicle were presented in table 1. The maximal outer diameter is dictated by limited space for mounting motor and the value of air-drag, because motor will be mounted outside of a fuselage.

These requirements are very difficult to fulfil for low-speed direct drive. Therefore, the application of pseudo-direct drive was proposed. The idea of pseudo-direct drive was presented in article [10].

Table 1. 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
Voltage in DC-link	210 V
Max. RMS phase voltage	$210/\sqrt{3}/\sqrt{2} = 85.7$ V

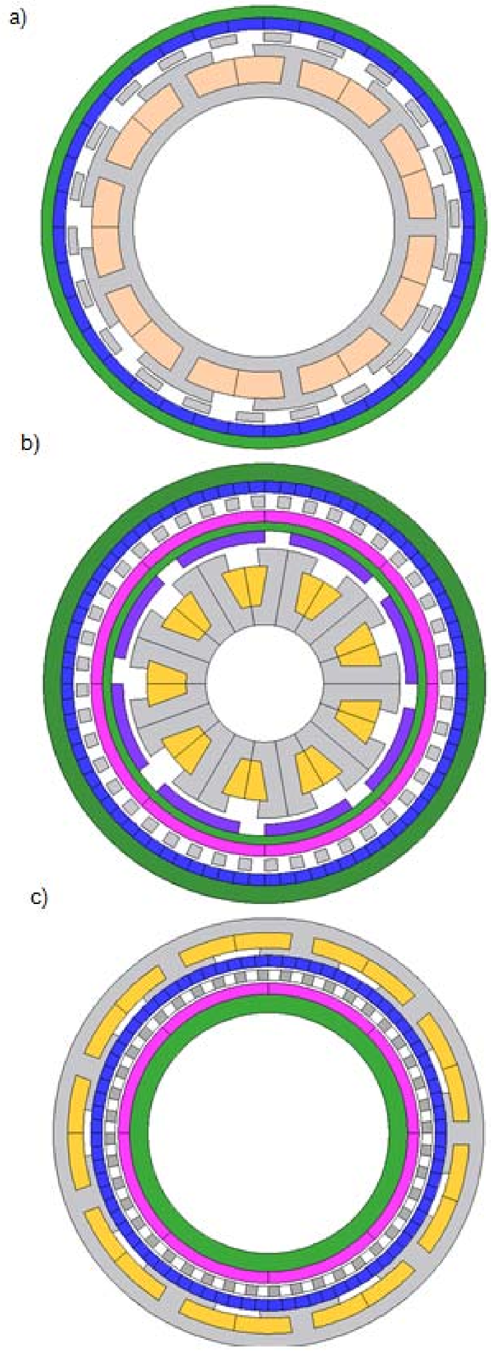

Fig.5. The researched models of pseudo-drives: a) with only one rotor; b) with two rotors – outer stator; c) with two rotors – inner stator

The comparison a various constructions of pseudo-direct drives.

The driving unit consists of motor with integrated magnetic gear inside. Three constructions of pseudo-direct drive were taken into consideration. These constructions are presented in figure 5.

In the first construction, the inner high-speed rotor was replaced by a stator with windings (figure 5a). This solution is described in articles [11, 12]. One of the considerable advantages of it is lack of one magnet ring what makes construction lighter and cheaper. Moreover, only one moving part makes mechanical construction easier. Unfortunately, with regards for lower magnetic field strength generated by stator with windings than permanent magnets ring, the transmitted torque density is lower. Furthermore, the value of leakage flux is significant with regards on lower diameter of stator and high width of air-gap. Because of these reasons, attempts achieving of required parameters with this construction failed.

The second researched construction is presented in figure 5b. Stator is inside of construction and high-speed rotor has two rings of magnet. The internal magnets are put in order to reduce width of air-gap and reduce leakage flux. A significant disadvantage is cooperation of stator with high speed rotor. It is very difficult to achieve sinusoidal distribution of magnetic field in air-gap with very small air-gap width and with small number of magnets. The increase number of magnets results to increase frequency and that cause to increase losses in motor.

The last construction (in figure 5c) is similar for second construction, but stator is mounted outside and cooperates with high-speed rotor which has only one ring of magnets. This construction has higher width of air-gap, so magnetic field density in stator is lower and it is easier to achieve sinusoidal back EMF.

The simulation results of Model 1.

The structure of proposed motor is shown in figure 6. This drive must reduce rotational speed and increase torque, so the inner magnet ring will be an input and what follows, the stator must act on it. The output rotor of drive will be the ferromagnetic pole-pieces ring for achievement of higher gear ratio and simplification the construction. Then, outer magnet ring is not moving and can be mounted with stator. The combination of 8 poles in inner magnet ring, 80 poles in outer magnet ring and 9 slots in stator was chosen with regard for achievement of high gear ratio and sinusoidal shape of back EMF. The construction data of proposed pseudo-direct drive are collected in table 2.

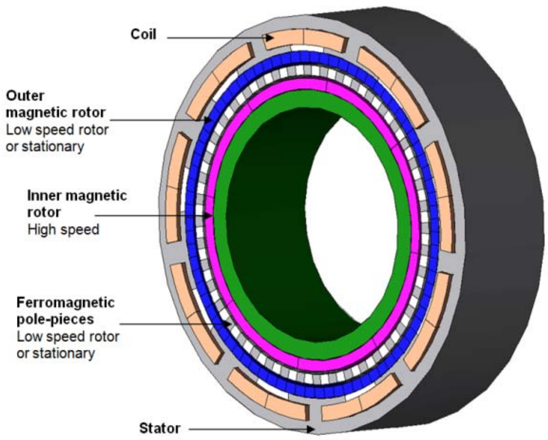

Fig.6. The structure of model 1

Table 2. The motor requirements for airship

Number of pole pair in inner rotor	4
Number of pole-pieces	44
Number of pole pair in outer rotor	40
Number of slot	9
Rotational speed inner rotor (input)	16500 rpm
Rotational speed pole-pieces ring (output)	1500 rpm
Rotational speed outer magnet ring (stopped)	0 rpm
Gear ratio	11

Table 3. The simulation results of model 1

Outer diameter	150 mm
Axial length	165 mm
Air-gap between rings	1 mm
Number of turns per coil	3
Current frequency	1100 Hz
Current amplitude	250 A

Current density (with assumed slot fill factor 50%)	10 Arms\mm^2
Voltage for no-load state Amplitude \ RMS	110 V \ 80 Vrms
Voltage for load state Amplitude \ RMS	121.5 V \ 83 Vrms
Output torque	243.35 Nm
Mechanical power	38.225 kW
Estimated weight of active parts	13.87 kg
Torque density	**17.54 Nm\kg**
Power density	**2.76 kW\kg**

Table 4. The power losses of pseudo-direct drive model 1

Joule loss in winding	W	416.25
Iron losses in stator	W	233.5
Iron losses in pole pieces	W	105
Joule losses in inner magnets*	W	1309.15
Joule losses in outer magnets*	W	1630.08
Iron losses in rotor	W	7.5
Total losses	**W**	**3701.48**
Power output	**W**	**38225**
Efficiency	**%**	**91.17**

* Magnets divided by 4 parts in axial direction.

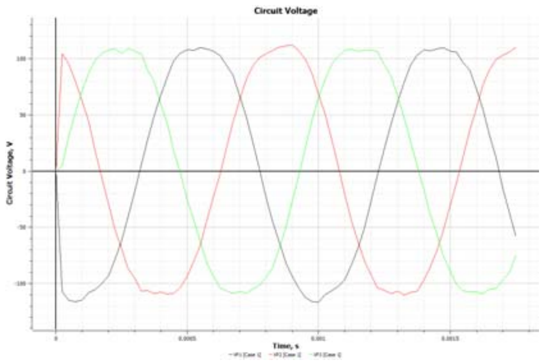

Fig.7. The back EMF of model 1

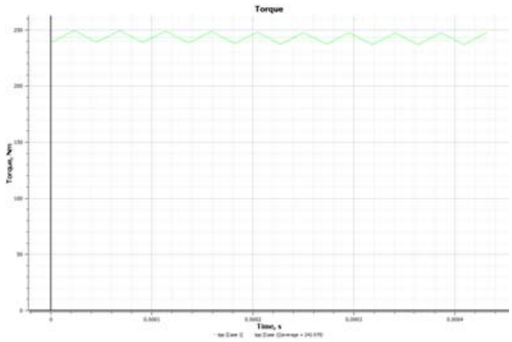

Fig.8. The output torque of model 1

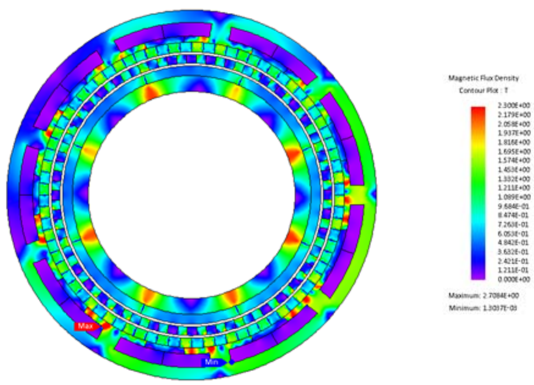

Fig.9. The distribution of magnetic field density in model 1

The simulation of motor work was prepared with the help of program with Finite Element Analysis. The results of analysis were presented in table 3. In table 4 there were presented the estimated power losses.

Proposed drive fulfils all previously assumed requirements. Moreover, the torque density is very high 17.54 Nm\kg with very good efficiency about 91%. Moreover, as it can be noticed from the distribution of magnetic field density (Fig.9), weight can be reduced by removal of those places where magnetic flux density is low.

The simulation results of Model 2.

The structure of model 2 was presented in figure 10. The number of magnets and pole-pieces are the same as in Model 1. Moreover, the low-speed rotor is pole-pieces ring as well. Then, model 2 has the same gear ratio as model 1.

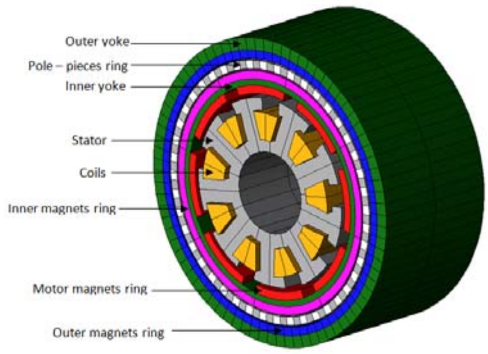

Fig.10. The structure of model 2

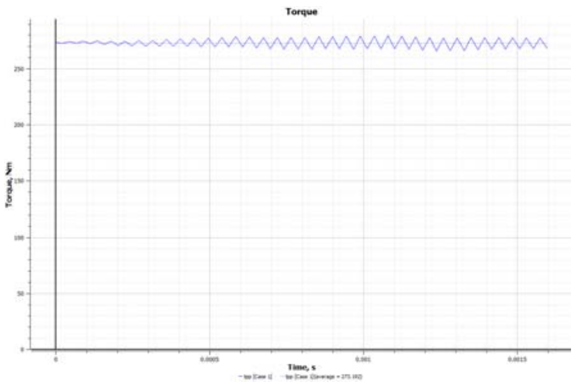

Fig.11. The output torque of model 2

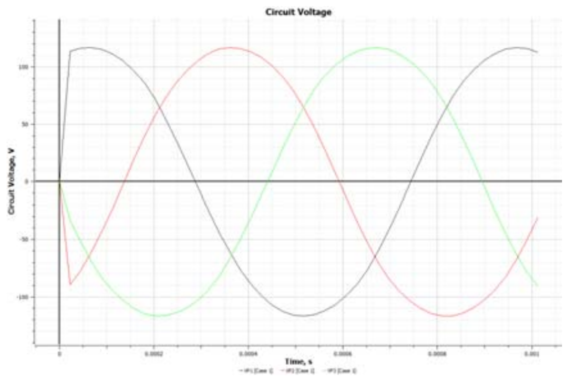

Fig.12. The back EMF of model 2

Table 5. The results of simulation of model 2

Outer diameter	150 mm
Axial length	135 mm
Air-gap between rings	1 mm
Number of turns per coil	2
Current frequency	1100 Hz
Current amplitude	260 A

Current density (with assumed slot fill factor 50%)	10 Arms\mm^2
Voltage for no-load state Amplitude \ RMS	117 V \ 83 Vrms
Voltage for load state Amplitude \ RMS	126 V \ 91 Vrms
Output torque	273.192 Nm
Mechanical power	42. 913 kW
Estimated weight of active parts	14.65 kg
Torque density	**18.648 Nm\kg**
Power density	**2.93 kW\kg**

Table 6. The power losses of pseudo-direct drive model 2

Joule loss in winding	W	202.8
Iron losses in stator	W	307.7
Iron losses in pole pieces	W	99
Joule losses in inner magnets*	W	711
Joule losses in outer magnets*	W	1924.6
Joule losses in motor magnets*	W	5102
Iron losses in rotor	W	123.3
Total losses	**W**	**8486**
Power output	**W**	**42913**
Efficiency	**%**	**83.5**

* Magnets divided by 4 parts in axial direction.

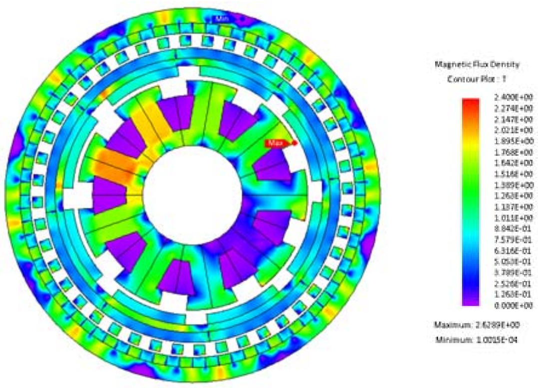

Fig.13. The distribution of magnetic field density in model 2

The comparison of simulation results for model 1 and model 2 leads to the conclusion that the use of additional magnet ring and inner stator improve performance of drive unit. With regards for higher magnetic flux density in stator, the width of teeth must be higher but this fact enables to reduce number of turns per coil and axial length of motor. In spite of the fact that additional magnets and ferromagnetic rotor increase the mass of motor, the torque density and power density are higher. Unfortunately, eddy current losses are very high in magnets ring cooperating with stator due to high magnetic field density and high frequency. From this reason, efficiency is about 83%.

Conclusion

The pseudo-direct drive seems to be a very promising solution for aviation. Its torque density significantly exceeds parameters of motors used in the produced electric glider for example motor in Antares 20E – torque density 8.1 Nm/kg, Silent 2 Targa Electro – 5.46 Nm/kg, AE-1 Silent 4.3 Nm/kg (the data from websites of producers). Also the efficiency of motor with magnetic gear is quite high. However, the mechanical construction is very difficult. The drive has two rotating rings including one high speed ring and one ring consisting of small pieces of ferromagnetic material. Model 1 (despite of presenting a little worse performance of motor) seems to be more convenient to apply as far as mechanical and heat removal are considered. Furthermore, the efficiency of model 1 is higher.

The future work can improve torque density by removing of some places in stator and rotor where magnetic field density is low. Moreover, the use Halbach array (articles [7, 13]) should reduce mass of machine and reduce losses in magnets as well. Next interesting improvement can be designing a dual stator motor with magnetic gear. That construction is described in article [14], however, the implementation can be difficult in regard to the requirement of low outer diameter. The next step should be also improvement of efficiency. Both models have significant eddy current losses in magnets resulting from modulation of fields. Fortunately, this kind of losses can be easily reduced by magnets segmentation.

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