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DEVELOPMENT EXPERIENCE OF BRUSHLESS DC MOTOR WITH VARIOUS METHODS OF PERMANENT MAGNETS PRODUCTION

ABSTRACT *In the paper estimation of machining influence of samarium-cobalt permanent magnets on the aircraft brushless DC electric motor parameters is carried out. As a result of machining of permanent magnets in magnetized state, the experimental confirmation of deteriorating of the brushless DC electric motor parameters was received.*

Keywords: *AEA - all electric aircraft, aircraft systems, permanent-magnet machine, brushless DC electric motor, samarium-cobalt permanent magnet, machining*

1. INTRODUCTION

One of the perspective directions of development in aircraft engineering is called "All Electric Aircraft" (AEA). AEA suggests to use only electrical energy for support of aircraft systems functioning and their actuators instead of three types of energy which are used now: hydraulic, pneumatic and electrical.

Today aircraft designers, both in Russia and abroad, consider the concept of incomplete electrification of the aircraft "More Electric Aircraft" (MEA).

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In the control system of AEA, for deviation of elevator, ailerons, rudder, etc. it should be developed high dynamic drives (with high cutoff frequency, small phase lag in bandwidth up to 4-5 Hz for passenger planes and above for maneuverable aircrafts, high speed of reverse and minimum nonlinear distortions at small input signal amplitudes).

High dynamic behavior can be reached at usage of the independent electric drive with "hydraulic gear", i.e. electro-hydrostatic actuator (EHA) on the basis of reverse controlled brushless DC motors (BLDC) instead of traditionally used mechanical-hydraulic drives with supply from central hydraulic system [1, 2].

2. INFORMATION ABOUT THE ELECTRIC MOTOR

JSC "Electroprivod" (Kirov) has developed the mechatronic unit consisting of BLDC and control unit intended for the EHA prototype unit (Fig. 1). BLDC DB120-22000-12 is developed taking into account the given bandwidth of electric drive frequencies of 4.5 Hz. The electric motor appearance is shown in Figure 2. The main characteristics of BLDC are resulted in Table 1.

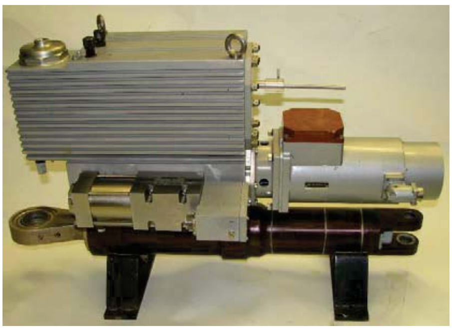


Fig. 1. Experimental model of the electro-hydrostatic actuator

Fig. 2. Brushless electric motor DB120-22000-12

TABLE 1
Specifications of DB120-22000-12

Parameter	Value
Power, kW	21
Rotary speed, rpm	11000
Rated torque, Nm	18
Mass, kg	9.5
Duty	intermittent
Cooling	natural

Generally the requirements of BLDC response speed are provided with the value of induction and effective magnetic flux in air gap which can be increased at the expense of permanent magnets application with higher maximum specific magnetic field energy. Efficiency of specific magnetic field energy of permanent magnets can be raised owing to the core construction allowing at the same volume of the rotor to provide magnification of the magnetic flux in working air gap [3].

There are many core constructions of magnetoelectric machines with various forms of permanent magnets. In high-speed electric machines for supporting of high response speed and improving mass and overall indexes the assembled core with radial magnetization of permanent magnets having the segmental form (Fig. 3) is more spread. This core provides simplicity and workability, small inductive resistances and, hence, high rigidity of the mechanical characteristic, possibility of compliance of motor and generating modes in wide range of rotary speed [4].

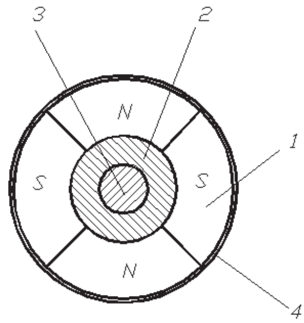


Fig. 3. Assembled core of BLDC rotor with radial magnetization of permanent magnets. Where:
1 – segmental permanent magnet; 2 – magnetically yoke; 3 – shaft; 4 – band

3. TEST OF PERMANENT MAGNETS PARAMETERS

JSC "Electroprivod" develops and issues the special-purpose BLDC (power range of 0.01 – 8.0 kW) with usage of assembled core of rotors in the volumes required for customers.

A series of standard sizes of segmental permanent magnets for BLDC rotors is fabricated by JSC "Electroprivod" together with manufacturer of permanent magnets. Required permanent magnets are bought in the magnetized state from the manufacturer and exposed total incoming inspection on technical compliance.

Heterogeneity of permanent magnets properties leads to space asymmetry of an external magnetic field of the rotor. For obtaining the BLDC magnetic systems balanced according to the magnetic flux there is used a selection of permanent magnets when completing an assembled rotor. The complete set is led by the procedure developed in JSC "Electroprivod" [5] with preliminary measurement of average value of the magnetic flux of separate magnets. Magnetic flux measurement is carried out in the working gap of closed symmetric control magnetic system by means of the measuring winding and fluxmeter.

Selection and batching of permanent magnets of magnetic rotor systems is a compulsory component of manufacture of BLDC at JSC "Electroprivod".

At development of the brushless electric motor DB120-22000-12 with power of 20 kW for the experimental sample of EHA the new magnetic rotor system with radial magnetization of permanent magnets has been designed.

The one of the major requirements presented to the aircraft magnetoelectric machines is a high stability of magnetic properties in wide range of temperatures. That is the reason that permanent magnets on the basis of Sm_2Co_{17} have been applied in DB120-22000-12.

The manufacturer of permanent magnets made a set of prismatic billets of permanent magnets on the basis of Sm_2Co_{17} (hereinafter referred to as the set N1). Permanent magnets have arrived in magnetized state and magnetic parameters of prismatic permanent magnets have been guaranteed by the supplier.

The demanded segment form of magnets has been received by means of machining by an electroerosion cutting method in the liquid medium theoretically eliminating the excessive magnet heating during handling. The permanent magnet billet is shown in Figure 4.

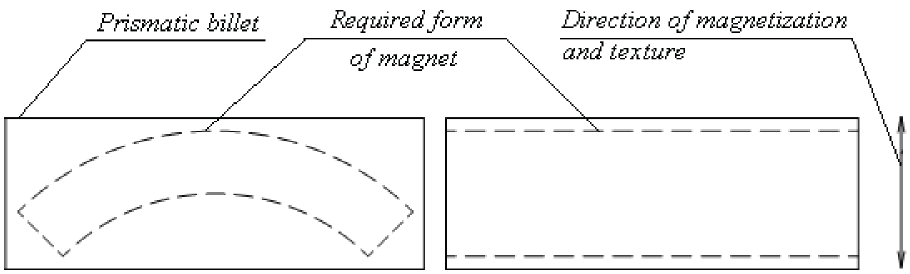


Fig. 4. Permanent magnet billet

The electric motor with permanent magnets received in such way has been made and tested. Test results have shown that the electric motor doesn't provide the characteristics prescribed in the draft proposal. The analysis of test results follows.

It is known that rare-earth alloys on the basis of Sm_2Co_{17} are not monophase and can contain microheterogeneities in accordance with chemical composition. These microheterogeneities are eliminated by long high-temperature annealing [6]. Thus quality of permanent magnets is influenced also by various impurities, distribution of particles, conditions of pressing, etc. [7]. Experience of manufacturers of magnetic systems shows that, as a result, rare-earth magnets can have appreciable heterogeneity of properties in volume and it is necessary to consider at magnet parcelling or at change of shape with considerable reduction of volume. Besides, at magnet machining, the permanent magnets can lose a magnetic flux owing to influence of various adverse factors.

The electric motor hasn't provided the prescribed characteristics because of reduction of magnetic flux at the expense of machining in magnetized condition, and also due to removal of the considerable part of magnetic material volume at processing.

In this connection the new complete set of permanent magnets (hereinafter referred to as the set N2) processed up to required sizes in the degaussed condition and magnetized after machining, was ordered.

4. TESTS OF THE ELECTRIC MOTOR

Two rotors and experimental researches of the electric motor with each rotor (including tests in EHA structure) have been carried out. Notice that the electric motor was subjected to the equal tests in the identical operating modes specified in the draft proposal.

The magnetic induction values on the rotor surface over each pole have been measured. Measurement of magnetic induction was carried out with magnetometer in five points along a surface of each pole of the rotor in the open magnetic system. Average values of magnetic induction on the rotor surface are shown in Figure 5.

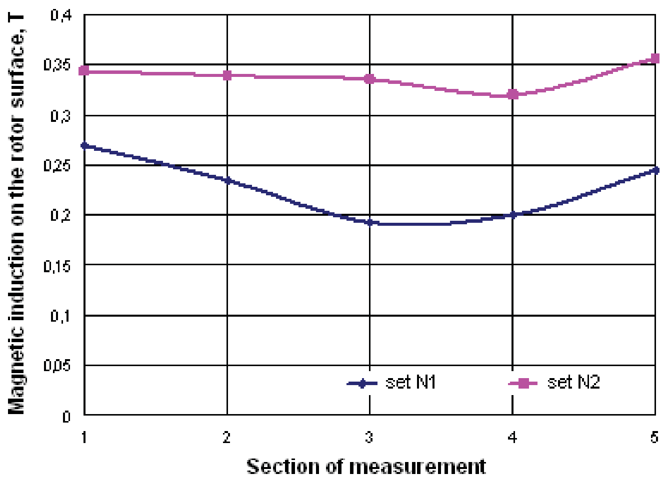


Fig. 5. Average value of magnetic induction on the rotor surface of electric motor with various complete sets of permanent magnets

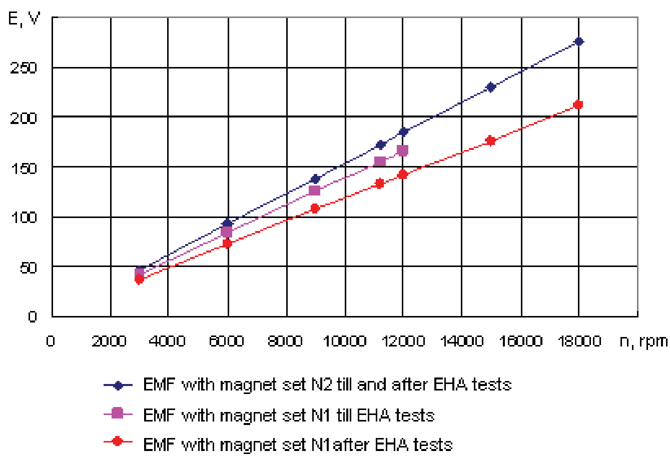


Fig. 6. Dependence of effective linear EMF from rotary speed

Average value of magnetic induction on the rotor surface with magnets of the set N2 is higher by 48.5% than with magnets of the set N1.

In the electric motor with each rotor the effective linear EMF (hereinafter referred to as EMF) has been measured in generating mode. Results of measurements have shown that the electric motor with the magnet set N1 at rated rotary speed of 12000 rpm has EMF less by 11% than with the magnet set N2 (Fig. 6).

During electric motor tests with the set N1 the dependences shown in Figure 7 have been investigated.

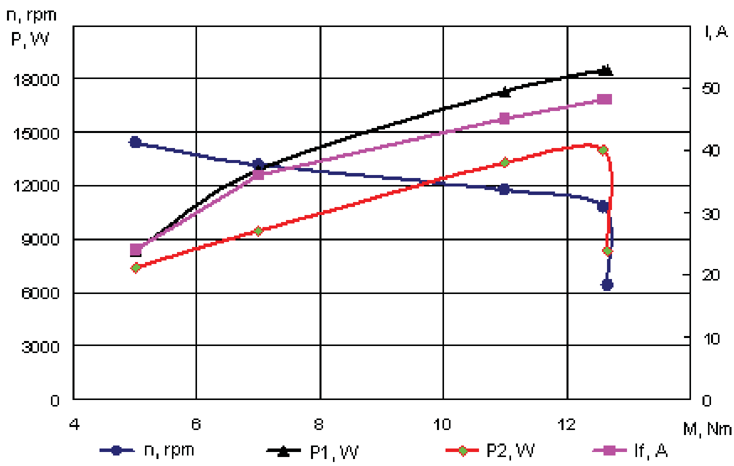


Fig. 7. Dependences n, P1, P2, If = f(M) of the electric motor DB120-22000-12 with the magnet set N1. Where:
n – rotary speed, rpm; P1 – input power at the converter, W; P2 – power consumption, W; If – effective phase current, A; M – output torque, Nm

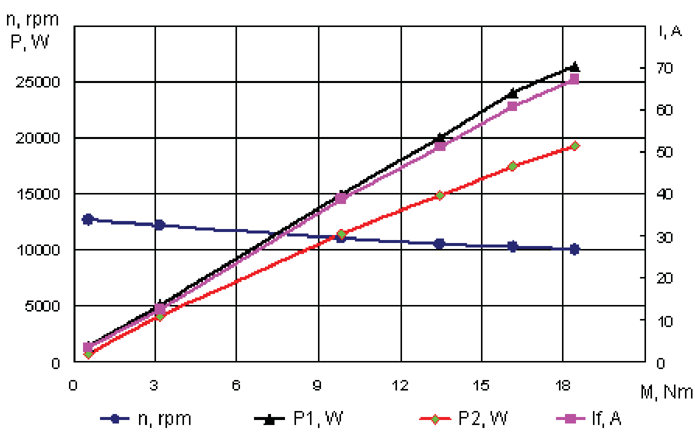


Fig. 8. Dependences n, P1, P2, If = f(M) of the electric motor DB120-22000-12 with the magnet set N2

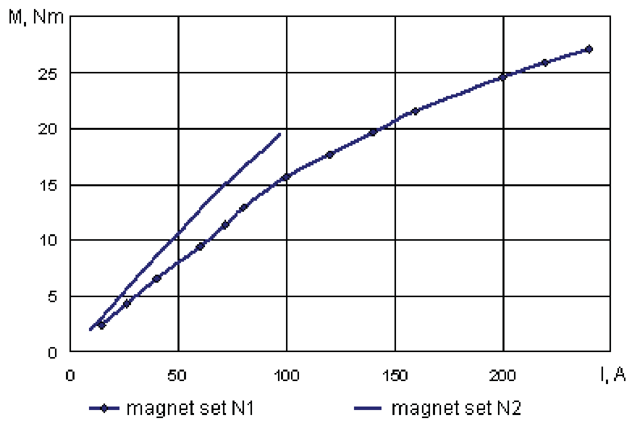
Dependences represented in Figure 7 shows that the electric motor sharply reduces rotary speed and stops at the torque of 12.7 Nm. After electric motor testing under loading in the specified modes of operation, EMF value has decreased by 17% in comparison with initial value (Fig. 6). That testifies to irreversible decreasing of magnetic induction of permanent magnets in connection with complex influence of temperature and degaussing field of armature interference.

During electric motor testing with the magnet set N2 the dependences shown in Figure 8 have been received.

The analysis of the experimentally received dependences shows that the electric motor with the magnet set N2 has developed the nominal torque of 18 Nm at the rotary speed of 10000 rpm. Electric motor power is 19 kW. After testing EMF value of the electric motor remains constant that confirms stability of permanent magnets properties.

For definition of maximum torque of the electric motor in short circuit mode the dependence $M = f(I)$ shown in Figure 9 has been received.

Fig. 9. Dependence M = f(I) of the electric motor DB120-22000-12



Measurements results $M = f(I)$ have shown that the nominal torque of DB120-22000-12 with the magnet set N2 is provided at smaller value of consumption current.

The generalized results received at experimental researches of the brushless electric motor DB120-22000-12 with various technologies of permanent magnet shaping are resulted in Table 2.

TABLE 2
Comparison of the experimental results

Parameter	**Magnet set N1**	**Magnet set N2**	**Percentage of indexes of the set N1 to ones of set N2, %**
Average value of magnetic induction on the rotor surface in the open magnetic system, T	0.228	0.339	48.5
Effective linear EMF of the stator winding at rotary speed 11200 rpm, V	133	170	27.8
Torque, Nm	12.7	18.3	44.1
Effective stator phase current at nominal torque 18 Nm and zero rotary speed, A	125	89	-40.4

5. CONCLUSIONS

1) For development work and researches of the electric motor DB120-22000-12 have been made two complete sets of permanent magnets. The demanded segment form of permanent magnets is received by means of machining. The first magnet set is processed in magnetized condition, the second magnet set is processed in degaussed condition and is magnetized after machining.

2) Experimental researches of the electric motor DB120-22000-12 with both magnet sets on the rotor are executed.

3) The analysis of experimental researches results has shown that machining of permanent magnets in magnetized condition leads to loss of magnetic flux and, as consequence, to degradation of magnetoelectric machine characteristics.

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DOŚWIADCZENIA Z RÓŻNYCH METOD WYTWARZANIA BEZSZCZOTKOWYCH SILNIKÓW PRĄDU STAŁEGO O MAGNESACH TRWAŁYCH

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STRESZCZENIE: *Przedstawiono wyniki analizy i badań dwóch egzemplarzy takiego samego bezszczotkowego silnika prądu stałego wykorzystywanego w technice lotniczej. W pierwszym z nich wirnik z magnesami był poddawany obróbce mechanicznej po namagnesowaniu. W drugim – magnesowanie nastąpiło dopiero po obróbce mechanicznej. Wyniki analizy i badań wskazują na znaczne osłabienie strumienia magnetycznego w wyniku obróbki, a więc w konsekwencji znaczne pogorszenie właściwości i charakterystyk silnika.*

Słowa kluczowe: *lotnicze elektryczne systemy pokładowe, maszyny o magnesach trwałych, bezszczotkowy silnik elektryczny prądu stałego, magnesy samar-kobalt, obróbka skrawaniem*

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