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CONSTRUCTION AND CONTROL OF AMBs HIGH SPEED FLYWHEEL

The paper reports on investigation and development of a flywheel device intended for an energy storage prototype. The goal was to design and experimentally verify the concept of self-integrated flywheel with smart control of energy flow and accumulation. The Flywheel Energy Storage System (FESS) must has high energy efficiency and structural robustness. Investigation on structural dynamics of the composite flywheel connected with outer type rotor was carried out using Finite Element Method. The FESS is designed to run in vacuum and is supported on low-energy, controlled, active magnetic bearings (AMBs). The flywheel device of 10 MJ energy density and a weight of 150 kg with two integrated rotors/generators of 50 kW power density each is intended to operate up to 40 000 rpm.

1. Introduction

Many conventional power backup or energy storage systems have been developed over the last decade. Several of them are modern, and are characterized by immediate delivery of energy and high power density. The fast progress of material science offers advanced technologies, such as composite flywheels, superconductors, supercooled electromagnets, hybrid-fuel cells, hydraulic and pneumatic energy storages and electrochemical batteries. The high energy density lead electric batteries are commonly used in many devices/applications, and the number of such applications is still increasing. However, this type of energy storage is not “clean”, and causes environmental problems.

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The alternative solution of the "clean energy storage system" are flywheels [1-4]. The traditional (low-speed) Flywheel Energy Storage System (FESS) has a steel wheel supported by mechanical contact bearings and is coupled with a motor/generator, which itself increases rotary inertia moment and limits rotational speed. The traditional FESS are capable of delivering approximately 70% of the flywheel's energy as the usable energy. Thus, they have many disadvantages such as low power density, high friction and aerodynamic losses and noise.

The modern compact high-speed flywheels, where magnetically (non-contact) supported rotor with composite wheel and bearingless motor are located in a vacuum chamber may have a high storage energy capacity, high power density, low current and aerodynamics losses and they take advantage of modern materials, electronics technologies and optimal control strategies [5-6]. The main disadvantage of the active magnetic bearings (AMBs) flywheel systems is that they require additional control and supply units.

The purpose of this research is development of a high-speed flywheel energy storage system, which can replace the conventional battery without maintenance and environment degradation. The flywheel is supported magnetically in the radial and axial directions. The position control of the 5 DOF (degree of freedom) flywheel is realized by active magnetic bearings in the closed-loop configuration. The low bias-current PD control algorithm is used. Thus, the energy-saving AMBs flywheel is developed and presented via simulation and experimental investigations.

2. Flywheel description

A composite glass-fibre flywheel assembled on a high-strength steel rotor is used as the electromechanical energy accumulator. The total kinetics energy storage capacity is ~10 MJ, where the maximal power is equal to 100 kW at the maximal rotational speed of 40 000 rpm. The flywheel outer diameter is 0.47 m and the main shaft length is 1.12 m. The total mass of the flywheel with the rotor is over 150 kg. The energy-absorbing composite rotor is driven by two motors/generators of 50 kW power each. The synchronous motors (3 pole pairs, 3 phases) are made of laminate sheets and permanent magnets mounted on the outer rotor. The motors/generators are controlled by electronic inverters. Two radial and one axial active magnetic bearings are applied to realize 5 DOF rotor position control. The axial bearing (thrust bearing) carriers the weight of the rotor. The force disturbances in axial direction in the thrust bearing are small, while the radial disturbing forces (mainly due to unbalance) are quite strong. Each of the radial magnetic bearing has

8 electromagnets, which are connected to 4 pairs in serial configuration (see Fig. 1). The magnetic bearing parameters are presented in Tab. 1.

Table 1.

Parameters of the AMBs

radial AMBs		axial AMB
nominal air gap	0.4 mm	0.7 mm
bias current	5 A	5 A
maximal current	10 A	10 A
number of coils	8	2
displacement stiffness	2.6e6 N/m	9.1e6 N/m
current stiffness	208 N/A	1.2e3 N/A

Radial and axial displacements of the rotor are measured by using 5 eddy-current proximity sensors. The radial and axial AMBs are supplied by controlled 10-chanells current PWM amplifiers.

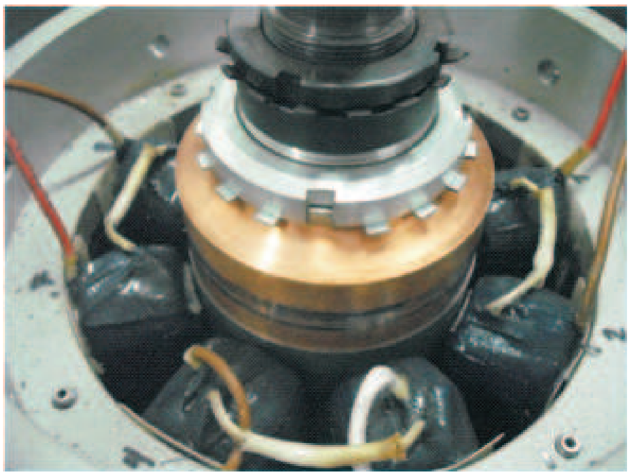

Fig. 1. Heteropolar radial active magnetic bearing

The maximal current is equal to 10 A for each of the active magnetic bearing electromagnets. The control of the rotor/flywheel position is fully digital, and performed in real time. The control algorithm is implemented in a digital signal processor (DSP). The sampling frequency of the AMBs controller equals 10 kHz. To ensure a stable operation at high rotor speed, the PWM amplifiers must have a wide bandwidth of 2 kHz. The diagram of flywheel set-up configuration is presented in Fig. 2. The ratio of the moments of inertia I_z/I_x is <<1 (equals 2.28/5.75 kgm^2), thus the influence of the gyroscopic effects is quite strong and can cause stability problems.

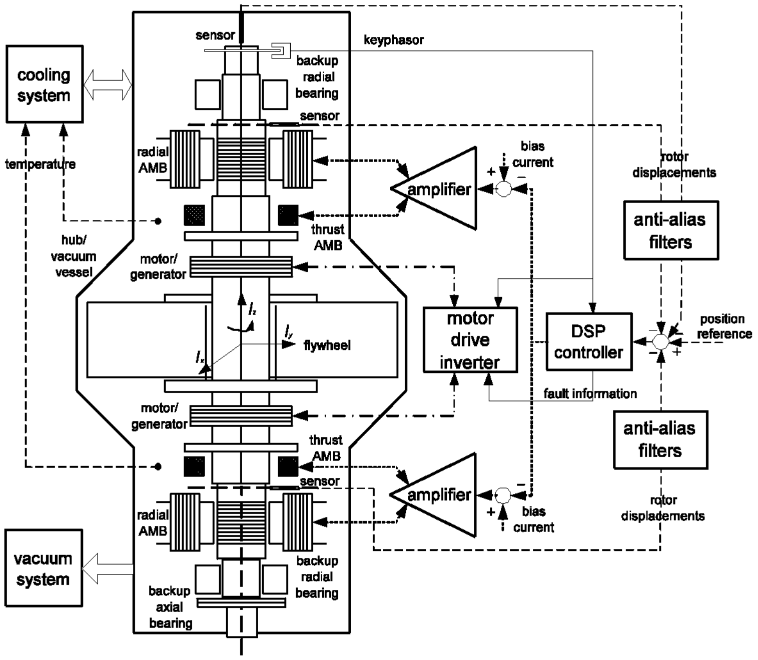

Fig. 2. Flywheel with control, cooling and vacuum system

It is important for the flywheel system to maintain electric power for many hours, so all energy losses should be taken into account. Therefore, the flywheel is suspended without mechanical contact by AMBs and is located in a vacuum chamber. The low-pressure system (underpressure of 1 Pa) is used to reduce aerodynamic friction losses and the overhead power consumption. The fluid-cooling system is applied to reduce the temperature of the motor and AMBs. For the case of current supply failure or AMBs stability loss, the critical touch-down (backup) radial and axial bearings are designed, which can be used to ensure the rotor's emergency slow down and stop controlled by electromagnetic brake mode of electric motors. Finally, the flywheel construction is characterized by high energy density, low maintenance, wide operating temperature range and very long cycle life (see Fig. 3).

3. Structural strength calculation

The goal of the structural calculations is to determine the highest safe circumferential velocity of the flywheel. In the case of failure, the stored energy of 10 MJ can completely damage the flywheel system. So that, structural strength calculations of the glass-fibre flywheel and steel rotor are necessary.

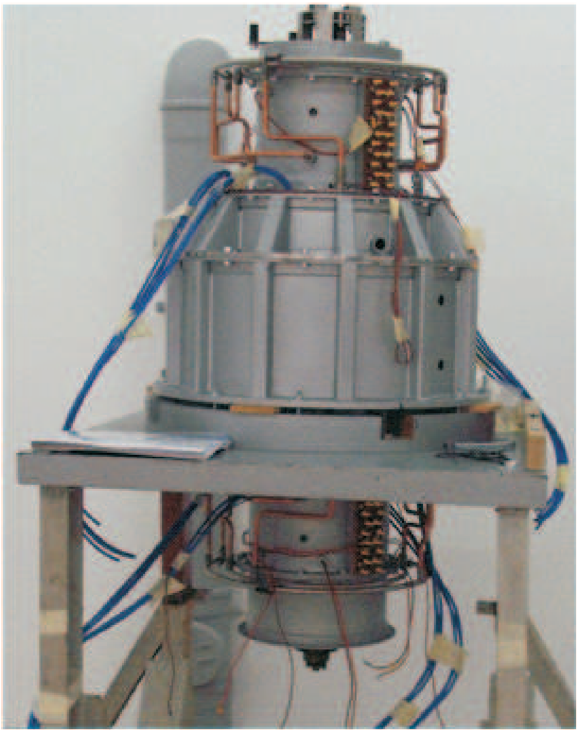

Fig. 3. Flywheel supported by active magnetic bearings

In the flywheel test setup, there are the following structural hot-spots: composite flywheel attachment, shrink fits, laminations of AC motors and AMBs, magnetic pull phenomena, influence of the bearing support, etc. The first hot-spot is the connection between the composite flywheels and the steel rotor. The composite flywheel rim is made of fibre layers. The glass-fibre composite flywheel with a steel band is attached with screws to the outer rotor (see Fig. 4).

Next, the results of the flywheel structural strength calculations are presented. The most critical one, the tangential stress of the flywheel at rotational speed of 10 000 rpm is presented in Fig. 5. The highest stress values occur at the inner boundaries of the rotor (composite-steel boundary).

Another important hot-spots are the radial magnetic bearings. The magnetic bearing lamination core is mounted on the rotor with shrink fits. The outer diameter of AMBs laminated core is 0.204 m. The stator is also made of transformer sheets. The diagram of total tangential stress in the air gap of the radial magnetic bearing (between the laminated rotor and the stator) at 21 000 rpm is presented in Fig. 6. Numerous lab experiments have been performed. Rotor speeds of up to 340 m/s in the bearing area can be reached

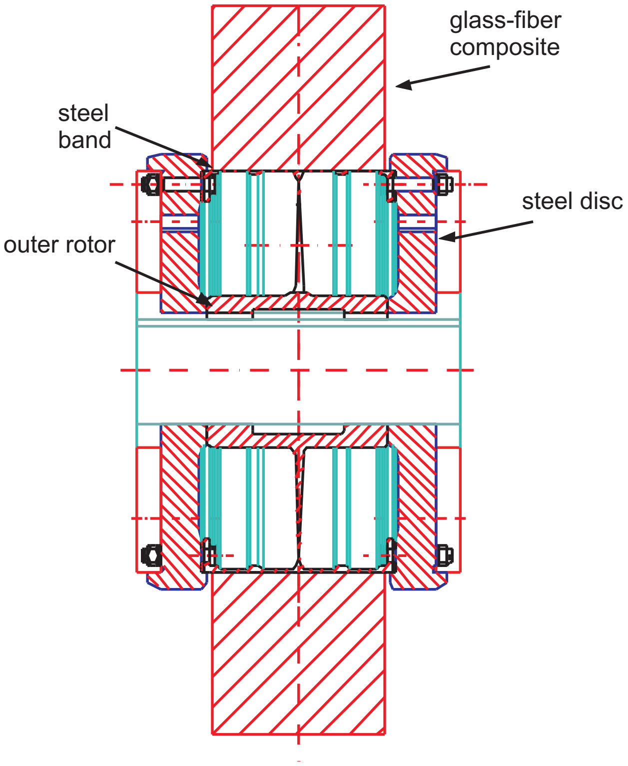

Fig. 4. Cross-section of the flywheel

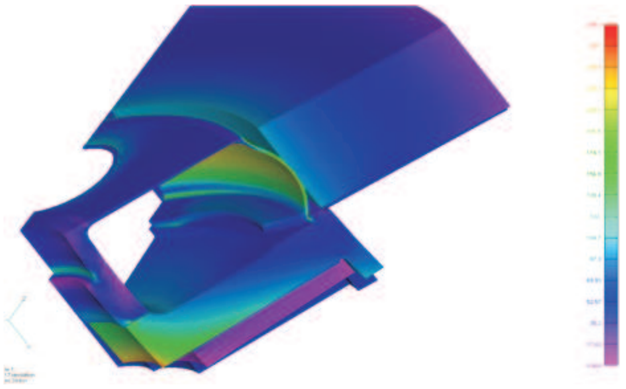

Fig. 5. Flywheel total tangential stress

when iron sheets made of an amorphous metal (metallic glass) having good magnetic and mechanical properties are used [7].

The structural flexible investigations are performed to define the failure criteria for the flywheel operation. As far as strength is concerned, the flywheel can sately operate with circumferential velocity up to 314 m/s, which

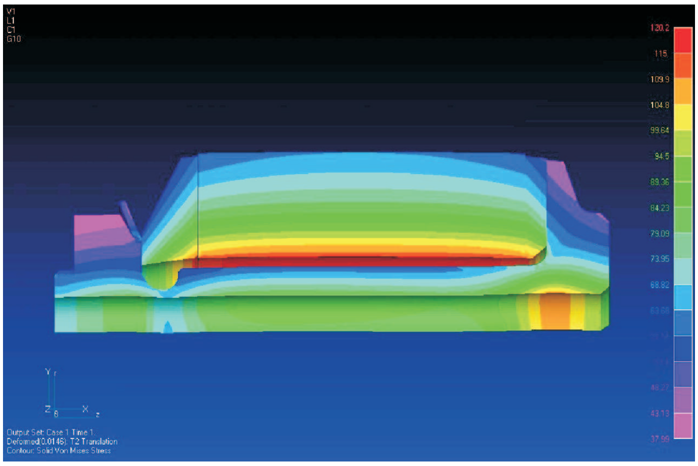

Fig. 6. Total tangential stress in the radial AMB cross-section

is about 25 000 rpm. This speed is limited by rotor laminations, glass-fibre transverse tensile strength, flywheel material nonlinearity, and some other hot-spots.

4. Optimal control challenge and energy losses

Many conventional magnetic bearings systems are controlled by a control current or magnetic flux with a bias current. This method is much easier than the control without a bias, but has many disadvantages. Firstly, the bias current causes a negative stiffness of AMBs, which must be compensated by the control current. Secondly, the AMBs controlled by the method based on the bias current consume energy even if the rotor is controlled at the equilibrium point. Thirdly, the control with both bias and control currents often requires an additional feedback loop for the bias current control. Finally, at high rotational speed, the bias current causes eddy current losses. Several nonlinear methods have been investigated to solve the zero-bias AMB problem. Input-output linearization was studied in [8-11]. Sliding mode controllers were investigated in [12]. Stable position of the rotating flywheel is controlled by the AMBs. In order to save energy, the low bias-current control method is used [13-14].

The reduction of energy losses is very important, especially in energy storage AMBs flywheel systems. In order to eliminate eddy-current losses, the synchronous motors and magnetic bearings are made of thin laminate sheets. The control energy of the AMBs must compensate any disturbances, e.g. rotating unbalance forces and losses, e.g. hysteresis, eddy-current, etc. In the electromagnetic AMBs circuit, the losses can be divided into: the ohmic loss ($\approx I^2$), the rotating hysteresis loss ($\approx I$) and the eddy current loss ($\approx I^2$). Then, the energy is used to fix the bias point, to stabilize the unstable rotor, and to increase the level of vibration damping. The reduction of magnetic flux in the magnetic bearing circuits can be made by both control/software and hardware optimization [15-16].

In our application, the bias-current was limited to reduce the negative stiffness of the bearings by the robust control system. In this approach, the control current is switched between two opposite magnetic actuators generating the attractive electromagnetic forces in each of two perpendicular directions. Thus, at any moment, only one coil is activated in each of the two control axes. The coil current of the activated AMBs is calculated according to the PD control law,

$$i = k_p x + k_d dx/dt, \tag{1}$$

where x is rotor displacement within the air gap. The electromagnetic force of AMBs is controlled by a singular control function of flux density, where the force produced by each electromagnet is

$$F_i = \phi_1^2/\mu_0 A \tag{2}$$

where: ϕ is electromagnet flux, μ_0 is the permeability of free space, and A is the cross-sectional area of the air gap. The value and sign of the control law function depend on the system conditions. These conditions mainly depend on the rotor position. Thus, the control law is given by

$$u = -sgn(\gamma) \tag{3}$$

where γ is the switching function due to control conditions (description omitted for the sake of conciseness).

The measured power consumption of the 10 channel PWM electronic amplifiers equals 300 W, while the AMBs need about 420 W to compensate the flywheel weight and unbalance forces. Thus, the whole flywheel system consumes 720 W. Moreover, the energy losses during loading/unloading could arise. The preliminary investigations show that the following task should be realized in future:

- further reduction of power consumption of the AMB by using attractive force of a permanent magnet to compensate, first of all, the rotor weight,
- development of an optimal (zero power) non-linear/linear robust control algorithm [17-18].

5. Experimental tests

A stable levitation of the FESS rotor was achieved successfully. The results of total current measurement are shown in Fig. 7. The mean value of the total current supplied to the radial AMBs was about 0.604 A, while for the axial AMB it equalled to 5.36 A.

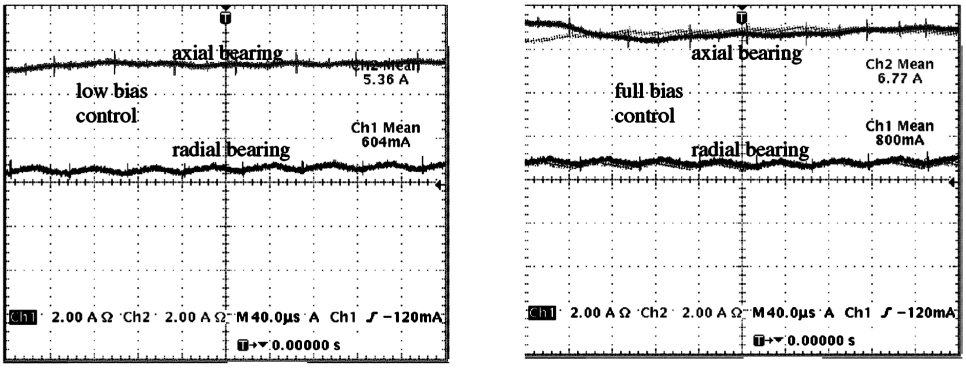

Fig. 7. Results of current measurements

The investigated low-bias control approach was verified during experimental rotational tests. The main goals of the preliminary rotational tests were met, and confirmed:

- stable rotor operation at rotational speeds up to 3 000 rpm,
- fast compensation of the external and internal disturbances,
- low hysteresis losses of the motor by suitable inverter control technique,
- stiffness of construction of the rotor (high first flexible mode of the rotor),
- reduction of power consumption of the AMBs owing to the use of control with low bias-current technique.

Further, critically important task for the rotational tests will be verification of the control algorithm, which should ensure a robust stability irrespective of unstable phenomena that could occur at higher rotational speeds.

6. Conclusions and outlook

We have designed and built a long-lifetime flywheel with a minimal need for maintenance and high energy density, supported by radial and axial magnetic bearings of low energy consumption. The flywheel design, configuration, structural calculation results and experimental setup has been presented. Decentralized feedback control of low energy consumption is proposed. The lab investigations on the flywheel with high gyroscopic effects operating at low speed indicate that it meets control and energy requirements.

In future, we plan to investigate loading/unloading behaviour and perform unbalance measurements for high rotational speeds. The task is to optimize energy balance and analyse rotor displacement signals and the behaviour of flywheel with vibration-isolated vacuum hub. It is expected that these actions should lead to optimization of the flywheel dimensions and mass.

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Konstrukcja i sterowanie wysokoobrotowym łożyskowanym magnetycznie magazynem energii kinetycznej

Streszczenie

W pracy przedstawiono konstrukcję wykonanego prototypu wysokoobrotowego zasobnika energii kinetycznej łożyskowanego magnetycznie. Prototyp został zrealizowany w ramach projektu badawczego realizowanego przez konsorcjum, w którego skład wchodzą: Akademia Górniczo-Hutnicza, Instytut Lotnictwa, Politechnika Warszawska i Politechnika Białostocka. Projekt obejmował wykonanie analizwytrzymałościowo-sztywnościowych krytycznych elementów zasobnika, projekty techniczne zespołu i poszczególnych podzespołów w tym łożysk magnetycznych, bezszczotkowych silników elektrycznych, wirnika kompozytowego oraz przeprowadzenie prób funkcjonalnych. Zasobnik został przystosowany do pracy w próżni (ciśnienie 1 Pa). Zewnętrzne układy sterowania napędem oraz położeniem wału zasobnika za pomocą silników tarczowych i aktywnych łożysk magnetycznych zostały zaprojektowane, wykonane i opisane w pracy. Prototyp zasobnika energii kinetycznej posiada następujące parametry pracy: użytkowa wartość gromadzonej energii do 10 MJ, masa elementów wirujących 150 kg, moc silników/generatorów 50 kW każdy oraz zakładana maksymalna prędkość obrotowa pracy do 40 000 obr/min.