Energy Save Robust Control of Active Magnetic Bearings in Flywheel

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Abstract: The paper reports on the investigation and developed of flywheel device as energy storage prototype. The FESS is designed to run in vacuum and is supported on low energy controlled active magnetic bearings (AMBs). The goal was to design and experimental verification of the self integrated flywheel conception with smart control of energy flow and accumulation. The low power control, with reduced bias current, approach of the flywheel active magnetic bearings is used. The weighting functions are designed in order to meet robust control conditions. The laboratory investigations of the flywheel with high gyroscopic effects operated at low speed meet the control and energy performances requirements.

Keywords: Flywheel, Active Magnetic Bearings, Weighting Functions, Singular Control

Introduction

Many conventional power backup or energy storage systems have been developed over the last decade. A 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 as composite flywheels, superconductors, supercooled electromagnets, hybridfuel cells, hydraulic and pneumatic energy storages and electrochemical batteries. The high energy density lead electric batteries are common used in many devices/applications and their number is still increasing. But this type of storage energy is not “clean”, and causes environmental problems.

The alternative solution of the “clean energy storage system” are flywheels [1-4]. The traditional (low speed) Flywheel Energy Storage System (FESS) has steel wheel supported by mechanical contact bearings and coupled with motor/generator, such that increases rotary inertia moment and itself limits rotational speed. The traditional FESS are capable to delivering approximately 70% of the flywheel’s energy as usable. 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 located in vacuum chamber, achieve a high storage energy capacity, high power density, low current and aerodynamics losses and take advantages of modern materials, electronics technologies and optimal control strategies [5-6]. The main disadvantage of the active magnetic bearings (AMBs) flywheel systems are demanding additional control and supply units.

A purpose of this research is development of the 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 non-linear control algorithm is used. Thus, the energy-saving AMBs flywheel is developed and presented via simulation and experimental investigations.

Energy-save approach

Many conventional magnetic bearings systems are controlled by control current or flux with a bias current. This method is much easier than control without a bias, but has many disadvantages. First, the bias current causes a negative stiffness of AMBs, which has to be compensate by control current. Second, the AMBs with control method based on the bias current consume energy even if the rotor is controlled at the equilibrium point. Third, the control with both bias and control currents often requires a additional feedback loop for bias current control. Finally, in high rotational speed the bias current causes an eddy current losses. Several nonlinear methods have been investigated for the zero-bias AMB problem. Input-output linearization has been studied in [7-11]. Sliding mode controllers have been investigated in [12]. The rotating flywheel stable position is controlled by the AMBs. In order to energy save, 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 performed with thin lamination 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 are divided into: ohmic loss ($\approx I^2$), rotating hysteresis loss ($\approx I$) and eddy current loss ($\approx I^2$). So the energy is used to fix the bias point, to stabilize the unstable rotor, and to increase the level of the vibration damping. The reduction of the magnetic flux in the magnetic bearing circuits can be done by both control/software and hardware optimization [15-16].

In the paper, the displacement control of the vertical 5-DoF (degree of freedom) flywheel supported magnetically with low bias current based on a optimal nonlinear robust control is proposed. The optimal robust controller has been designed using weighting functions to optimize the energy consumptions and signals limits with respect to the desirable performances of closed-loop system. Thus, the optimal (low power) non-linear control algorithm was established [17-18]. The bias-current was limited to reduce the negative stiffness of the bearings by robust control system. In this approach, the control current is switched between two opposite magnetic actuators generating the attraction electromagnetic forces in each of two perpendicular directions. Thus, at any time only the one coil is activated in each of two control axes. The rotor displacement (x) control law is given by:

$$u = -\mathbf{sgn}(K)x \tag{1}$$

The control algorithm function K is operated in negative feedback loop. From optimal energy control point of view the rotor displacement and control signals have to be limited. The output displacement signal is limited by robustness weighting function W_y which was selected based on the complementary sensitivity function given by transfer function:

$$T(s) = L(s)S(s) \tag{2}$$

where L – open-loop function, S – sensitivity function $S = (1+L)^{-1}$.

The control signal u is limited by control weighting function W_u which was assigned based on the control function given by:

$$R(s) = K(s)(I + L(s))^{-1} \tag{3}$$

The performances of the closed-loop system strongly depend on properly chosen weighting functions. The signal limits have to pass the stability conditions given by inequality:

$$\left\| \begin{matrix} R(s)W_u(s) \\ T(s)W_y(s) \end{matrix} \right\|_\infty \le 1. \tag{4}$$

If the influence of the power amplifier dynamics is slightly (flat Bode plot), then the electromagnetic coil control current depends only of the coils dynamics (R-L curve) $i_s = u \times$(coil dynamics). The total current in upper and lower coils equals:

$$i_{1,2} = i_0 \pm i_s \tag{5}$$

The static bias current i_0 is limited due to pass performance given by (4). Additional bias and control currents control sequence was used due to over-ranged signals. Therefore, the singular switching control function was used. The value and sign of the control law function depends on the system conditions described above. These one degree of freedom AMB control system is presented in Fig. 1.

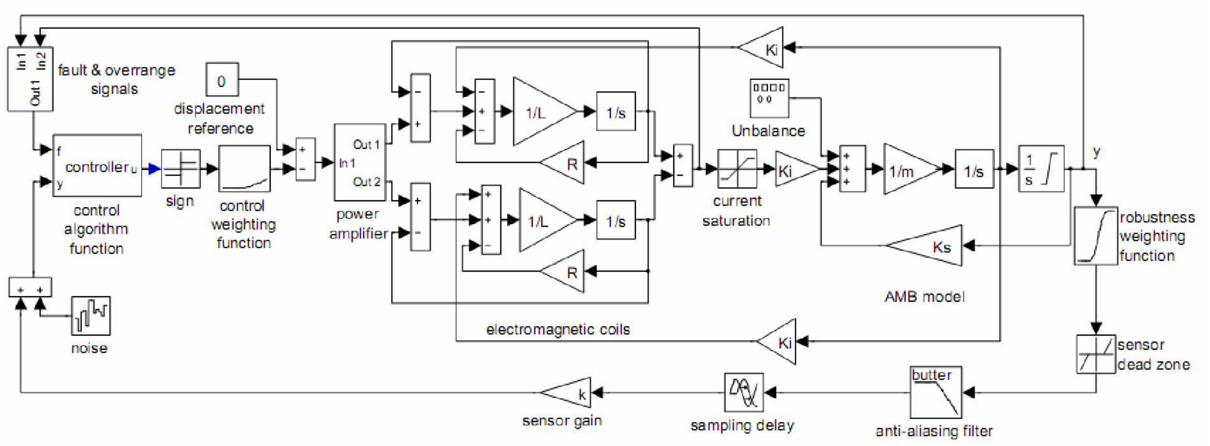

Fig. 1. Single degree of freedom AMB control system

The measured power consumption of the 10 channels PWM amplifiers electronic equals 300 W and reduction need a hardware optimization. The two radial and one axial AMBs need about 480 W to compensate the flywheel weight and unbalance forces. By using optimal singular control, the power consumption was reduced to 380 W. Moreover, the other energy losses could arise during flywheel loading/unloading.

Experimental set-up

The composite glass-fibre flywheel assembled on the high strength steel rotor is used as electromechanical energy accumulator. The total kinetics energy storage capacity is ~10 MJ, where the maximal power is equal 100 kW at the maximal rotational speed of 40 000 rpm. The flywheel outer diameter is 0.47 m and main shaft length is 1.12 m. The total mass of the flywheel with 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 performed with lamination sheets and permanent magnets mounted on outer rotor. The motors/generators are controlled by electronic inverters. The two radial and one axial active magnetic bearings are applied to 5 DOF rotor position control. The axial bearing (thrust bearing) carriers the weight of the rotor. The force disturbances in axial direction for the thrust bearing are small, where 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. 2). The magnetic bearings parameters are presented in Tab. 1.

Tab. 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	0.2e3 N/m
current stiffness	9.1e6 N/A	1.2e3 N/A

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

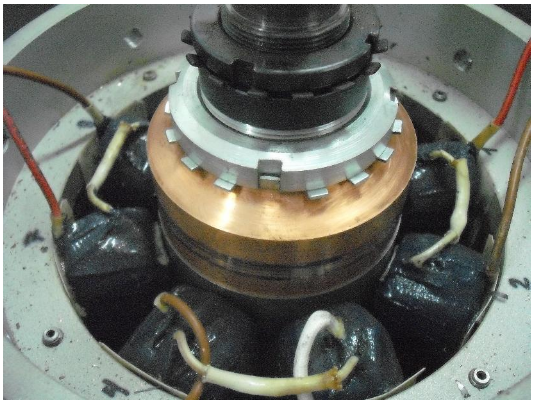

Fig. 2. Heteropolar radial active magnetic bearing

The maximal current is equal 10 A for each of the active magnetic bearing electromagnet. The control of the rotor/flywheel position is fully digital in real time. The control algorithm was implemented in digital signal processor (DSP). The sampling frequency of the AMBs controller equal 10 kHz. To ensure a stable operation at high rotor speed, the PWM amplifiers must have a wide bandwidth of 2 kHz. The flywheel set-up configuration picture is presented in Fig. 3. The ratio of the moments of inertia I_z/I_x is <<1 (equal 2.28/5.75 kgm^2), thus the influence of the gyroscopic effects is quite strong and could case stability problems.

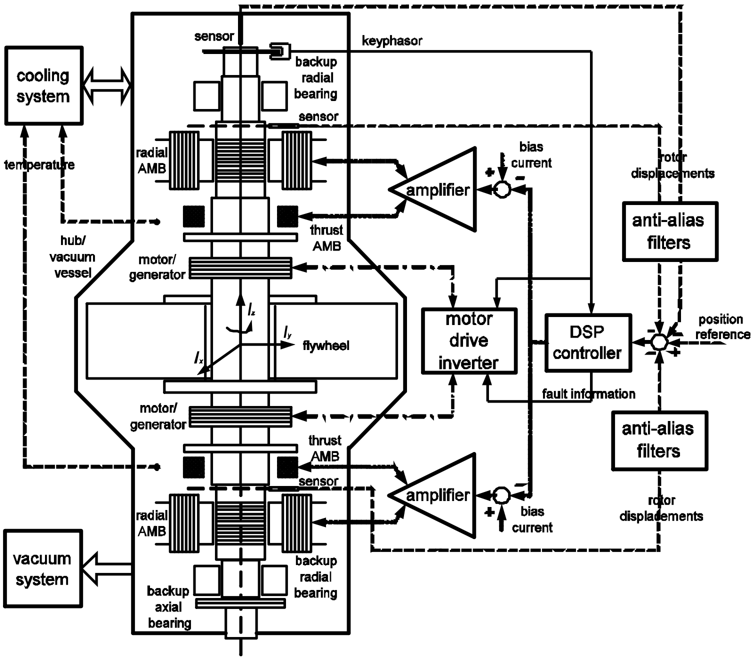

Fig. 3. Flywheel with control, cooling and vacuum system

It is important for the flywheel system to keep electrical power for many hours, thus any 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 overhead power consumption. The fluid cooling system is applied to reduce a temperature of the motor and AMBs. In 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 rotor 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. 4).

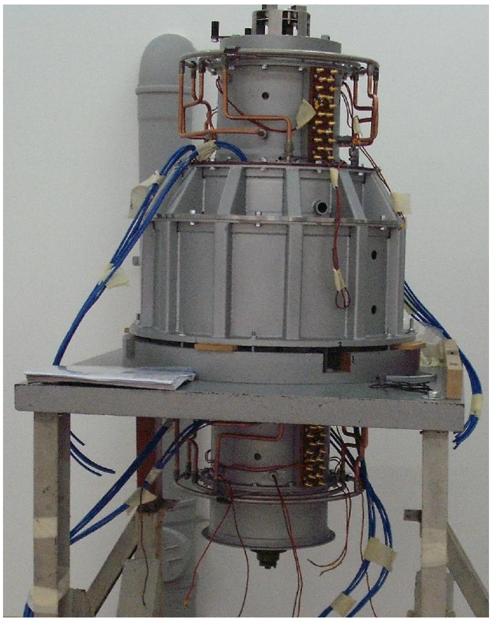

Fig. 4. Flywheel supported by active magnetic bearings

Experimental tests

A stable levitation of the FESS rotor was achieved successfully. For example, the measured results of total currents are shown in Fig. 5 at rotor speed 1000 rpm. The mean value of the radial AMBs currents was below 2 A, where for the axial AMB upper coil was over 5 A.

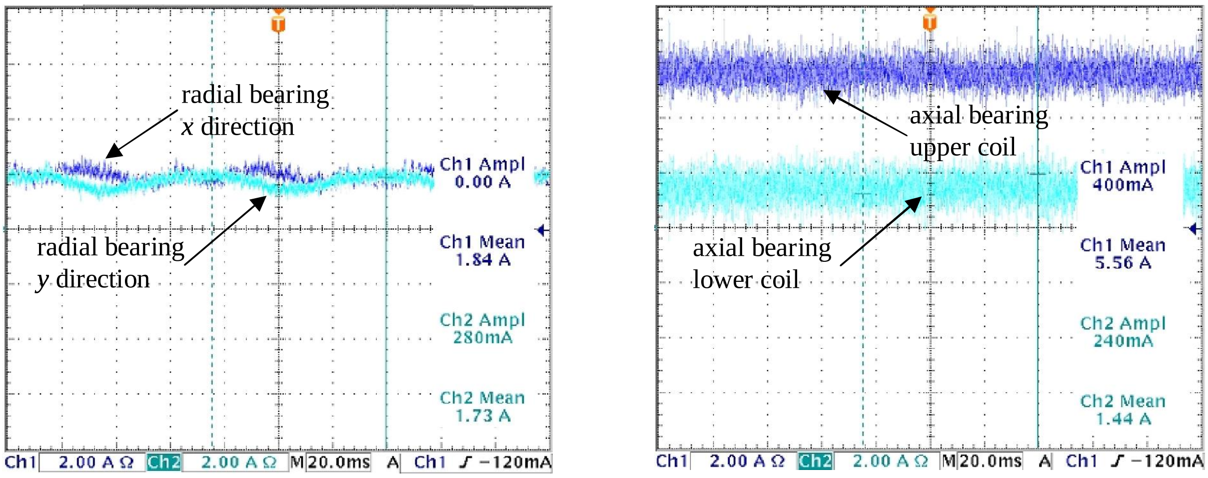

Fig. 5. Measured results of currents for low energy control

The investigated low bias control approach is verified during experimental rotational tests. The main goals of the initial rotational tests confirm that:

§ by using optimal control algorithm, the AMBs currents are lower (about 15%) than in case of full bias standard control (not presented here),

§ stable rotor operation and fast compensation of the external disturbances was achieved by using limited control signal,

§ future reduction of AMBs power consumption need a hardware optimization.

The critically important further task of the rotational tests will be verification of the control algorithm which should ensure the robust stability in spite of unstable phenomenon which could occurs at higher rotational speeds.

Summary

We have designed, built and experimental investigated a long lifetimes with minimal maintenance high energy density flywheel supported by low energy consumption radial and axial magnetic bearings. The decentralized feedback control with low energy consumption is proposed. The low bias control approach to stabilize rotor supported magnetically are presented via simulation and experimental investigations. The energy saving active magnetic bearing systems controlled by the non-linear control algorithm with low bias current was carried out and applied in the flywheel. The laboratory investigations of the flywheel with high gyroscopic effects operated at low speed meet the control and energy performances requirements.

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