ENERGY SAVING ROBUST CONTROL OF ACTIVE MAGNETIC BEARINGS IN FLYWHEEL

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Abstract: The paper reports on the investigation and development of the flywheel device as a energy storage system (FESS). The FESS is designed to operate in a vacuum and is supported on a low energy controlled active magnetic bearings (AMBs). The goal was to design and experimentally test the self integrated flywheel conception with a smart control of the flywheel rotor magnetic suspension. The low power control approach, with the reduced bias current, 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 effect operated at low speed met the control and energy performances requirements.

Key words: Flywheel, Active Magnetic Bearings, Weighting Functions, Singular Control

1. 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 [5], superconductors, supercooled electromagnets, hybrid-fuel cells, hydraulic and pneumatic energy storages and electrochemical batteries. The wide overview of flywheel technology, its applications and resent development is presented in the work Bolund et al., (2007).The high energy density lead electric batteries are commonly 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 (Kameno et al., 2003; Nathan and Jeremiah, 2002; Norman, 2002; Ward, 2005). The traditional (low speed) Flywheel Energy Storage System (FESS) has a steel wheel supported by the mechanical contact bearings and coupled with motor/generator, such that they increase moment of inertia and limit rotational speed. The traditional FESS are capable of delivering approximately 70% of the flywheel’s energy as usable. Thus, they have many disadvantages such as low power density, high mechanical friction and aerodynamic losses and noise. The power consumption is optimized by hardware and software development. In many applications the IGBTs power control technology are used. The IGBT is a switch device with ability to handle voltages up to 6.7 kV, currents up to 1.2 kA and most important high switching frequencies (www.igbt-driver.com/ english/news/scale _hvi.shtml, www.pwrx.com).

The modern compact high speed flywheels have a rotor supported magnetically (non-contact) with composite wheel and bearingless motor. These rotating parts are located in a vacuum chamber. Therefore, the applications achieve a high storage energy capacity, high power density, low current and aerodynamics losses. These systems take advantages of a modern materials, electronics technologies and optimal control strategies (Charara et al., 1996; Kubo, 2003; Larsonneor, 1990; Lottin et al., 1994). The active or passive magnetic bearings is a way to stabilize the end of the flywheel axle, possible since the configuration of the electromagnetic coils or permanent magnet levitates the flywheel, and thus, reduce the mechanical friction (Fremery, 1992; Swedish patent Nr 508 442, 1998).The main disadvantage of the active magnetic bearings (AMBs) flywheels are demanding additional control and supply units. Also the active magnetic bearings are nonlinear systems itself, therefore their modelling is complicated (Gosiewski and Mystkowski, 2006, 2008; Tomczuk et al., 2011; Tomczuk and Zimon, 2009).

A purpose of this research is development of the 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 feedback configuration. The low-bias current and non-linear control algorithms are used. Thus, the energy saving AMBs flywheel is developed and presented via calculations and experimental investigations.

2. ENERGY SAVE APPROACH

Many conventional magnetic bearings systems are controlled by the 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 compensated by the 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 (Sivrioglu et al., 2003; Zhang and

Nonami, 2002). Input-output linearization has been studied in Charara and Caron (1992); Fremery (1992); Larsonneur (1990); Lottin et al. (1994); Smith and Weldon (1995). Sliding mode controllers have been investigated in Torries et al., (1999). The rotating flywheel stable position is controlled by the AMBs. In order to save energy, the low-bias current control method is used (Hu et al., 2004; Sivrioglu and Nonami; 2003; Sivrioglu et al., 2003).

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 (Maslen et al., 1989; Schweitzer, 2002).

In the paper, the displacement control of the vertical 5-DoF (degree of freedom) rotor flywheel supported magnetically with low-bias current control based on the optimal nonlinear robust control strategy 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 (Gosiewski and Mystkowski, 2006, 2008). The bias current was limited to reduce the negative stiffness of the bearings controlled 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 time only the one coil is activated in each of two control axes. The rotor displacement (x) control law is given by (see Fig. 1):

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

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 (Zhou and Doyle, 1998):

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

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

The control signal u is limited by the control weighting function W_u which was assigned based on the control function given by Zhou and Doyle (1998):

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

The performances of the closed-loop system strongly depend on the properties of chosen weighting functions (Zhou and Doyle, 1998). The signal limits have to pass the stability conditions given by inequality (Zhou and Doyle, 1998):

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

If the influence of the power amplifier dynamics can be neglected (flat Bode plot), then the electromagnetic coil control current depends only of the coils dynamics (R-L curve) i_s=u×(coil dynamics) [6, 7]. The total current in upper and lower coils equals:

$$i_{1,2} = i_0 \pm i_{s1,2} \tag{5}$$

The static bias current i_0 is limited due to 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.

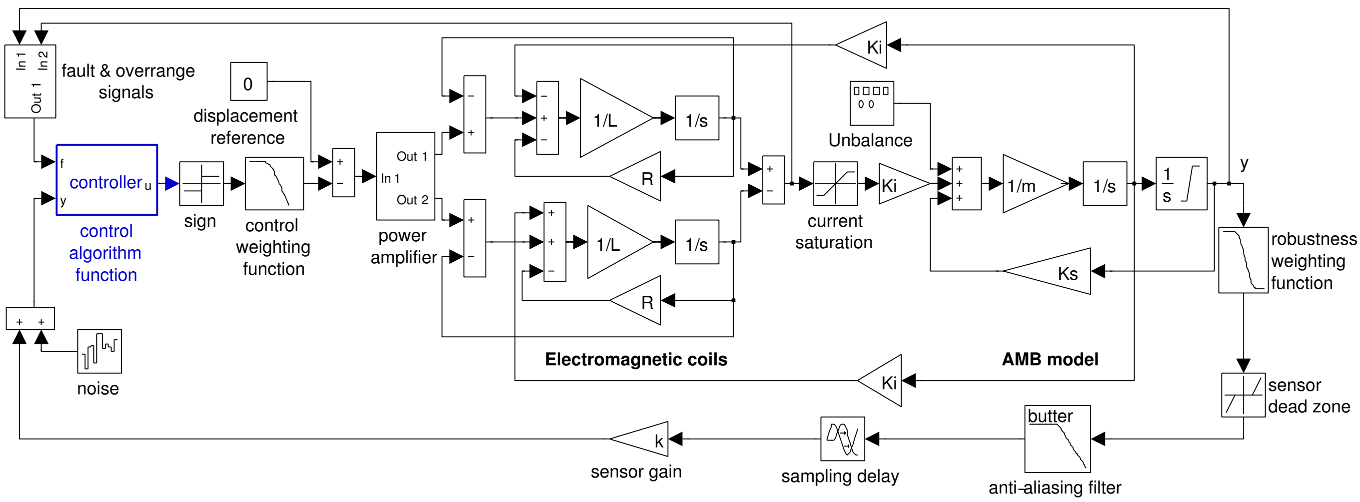

Fig. 1. Single degree of freedom AMB control system

In this application actively controlled digital power amplifiers are used based on the pulse width modulation (PWM) technology. The PWM amplifiers are bipolar, where the switching frequency equals to 18 kHz, voltage ±180 V and a maximal current is up to 10 A. The measured power consumption of the magnetic suspension of the flywheel system, where the radial and axial magnetic bearings are supplied by the 10 channels of the PWM amplifiers, equals to 480 W. The 480 W is a nominal power to compensate the flywheel weight, unbalance forces and other external/internal disturbances, in case of PID control. By using optimal singular control, the power consumption was reduced to 380W. Moreover, the other energy losses could arise during flywheel loading/unloading. The position controller bandwidth is over 4kHz. Meanwhile, the bandwidth of the whole closed-loop system is limited by the power amplifier to 1kHz.

3. EXPERIMENTAL SET-UP

The composite steel flywheel assembled on the high strength steel rotor is used as electromechanical energy accumulator. The total kinetic energy storage capacity is ~10 MJ, where the maximal power equals to 100 kW at the maximal rotational speed of 40 000 rpm. Meanwhile, for presented system the maximal achieved rotational speed was limited to 2000 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 AMB	axial AMB
nominal air gap	$0.4{\cdot}10^{-3}$ m	$0.7{\cdot}10^{-3}$ m
bias current	5 A	5 A
maximal current	10 A	10 A
number of coils	8	2
displacement stiffness	$2.6{\cdot}10^{6}$ N/m	$9.1{\cdot}10^{6}$ N/m
current stiffness	$0.2{\cdot}10^{3}$ N/A	$1.2{\cdot}10^{3}$ 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

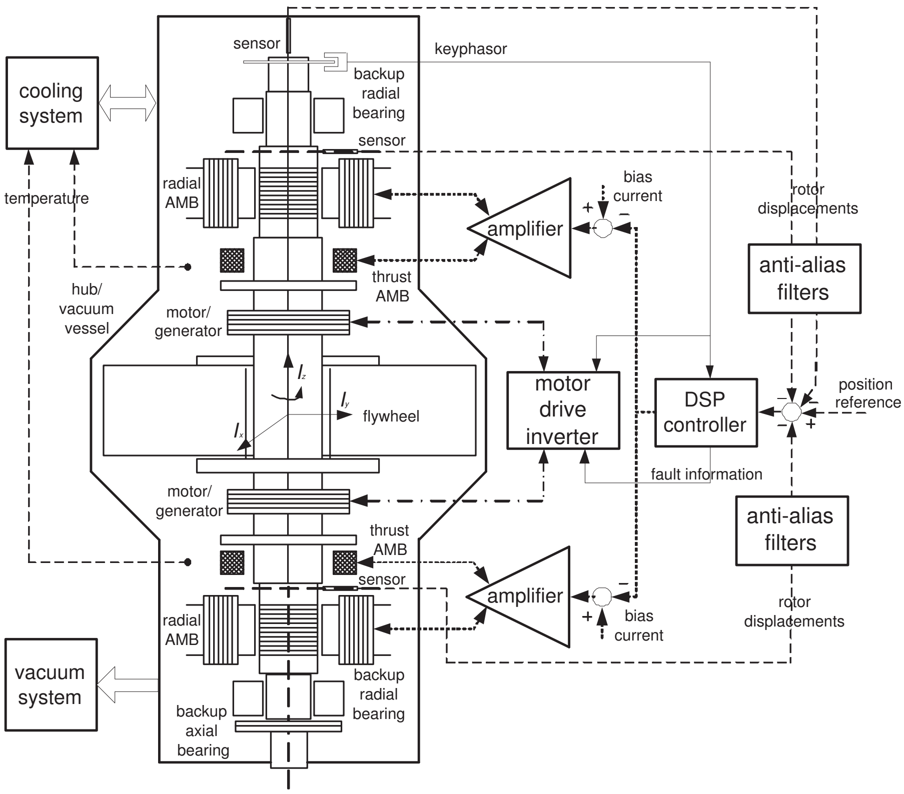

Fig. 3. Flywheel with control, cooling and vacuum system

The maximum current does not exceed 10 A for each of the active magnetic bearing electromagnets. The control of the rotor/flywheel position is fully digital in the real time. The control algorithm was implemented in digital signal processor (DSP). The sampling frequency of the AMBs controller equals to 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 is presented in Fig. 3. The ratio of the moments of inertia I_z/I_x is 2.28/5.75 kgm^2, thus the influence of the gyroscopic effect is quite strong and could case stability problems.

Fig. 4. Flywheel supported by active magnetic bearings during assembling

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 (under-pressure of about 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 the AMBs stability loss, the critical touch-down (backup) radial and axial bearings are designed. The backup bearings are used to rotor emergency slow down and stop in a controlled way. Finally, the flywheel construction is characterized by high energy density, low maintenance, wide operating temperature range and very long cycle life (see Fig. 4).

4. SPEED TESTS

A stable levitation and low control current of the FESS rotor was achieved. For example, the measured results of total currents and rotor displacements are shown in Fig. 5 and Fig. 6.

The rotor speed equals to 1 000 rpm, the mean value of the radial AMB currents was below 2 A, where for the axial AMB upper coil was over 5 A. Thus, these values do not extend 50 % of amplifiers ability. The rotor displacements in radial directions (x-y) do not extend $0.08 \cdot 10^{-3}$ m. The investigated low-bias control approach is verified during experimental rotational tests. The initial rotational tests confirmed that:

- by using optimal control algorithm, the AMB 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.

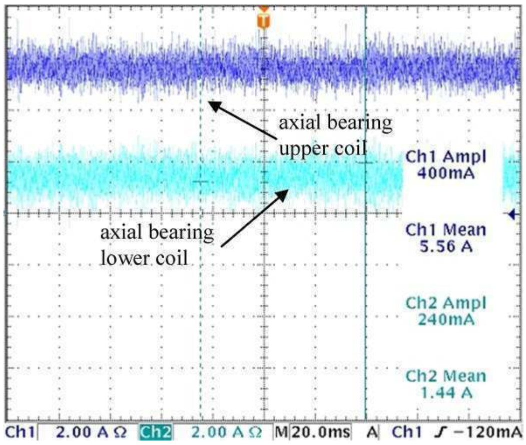

Fig. 5. Measured results of currents for low energy control

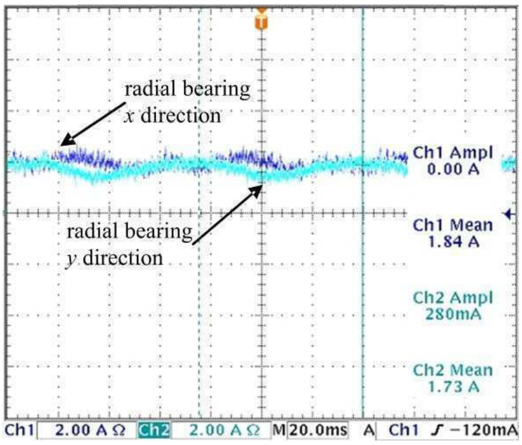

Fig. 6. Measured results of rotor displacements for low energy control

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 phenomena which could occurs at higher rotational speeds.

5. SUMMARY

The magnetic bearings FESS prototype was described and the optimal robust feedback control law with the low energy consumption was proposed. The low-bias control approach to stabilize the rotor supported by active radial/thrust magnetic bearings are presented via experimental investigations. The parameters of the magnetic bearings flywheel and test rig setup were described. The speed test results were presented. The energy saving active magnetic bearings controlled by the nonlinear control algorithm with the low-bias control current was successfully applied in the flywheel.

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