Compact AMB-Flywheel Structure Design and Support Control System

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Abstract: In this paper, an AMB-flywheel energy storage system with 3-electromagnets is developed for minimizing flywheel size and reducing the production cost. The system description and dynamics characteristic of the AMB-flywheel system are discussed. Based on analyzing the dynamic model of the magnetic flywheel disc, the digital control system based on TMS320F2812 via using integral-separated PID control algorithm is designed, which realize the stable suspension of magnetic suspension platform.

Keywords: Energy Storage, Flywheel, Integral-Separated PID Control

I. Introduction

Now many of the worldwide famous automobile manufacturers are seeking to research and develop energy-efficient hybrid cars and pollution-free electric vehicles，the main constraining factor is the battery. Flywheel energy storage has become one of the most promising power batteries of the electric vehicle, for its characteristics with high specific energy, high specific power, small size, fast charging, long working life, no exhaust and pollution-free. The contact-free flywheel is realized by magnetic bearing. The paper shows the design and test results of the AMB-flywheel.

According to the reference, traditional active magnetic bearings usually use control system of five degrees of freedom (DOF) active control. In the system, controlled object is discoid steel, magnetic flywheel disc suspension device has 3 electromagnets for controlling three DOF of the flywheel disc, and other two DOF are constrained by the centripetal effect of magnetic field.

II. System description

Experimental prototype of vehicle flywheel battery has been machining, and this prototype includes the following components (Fig.1): flywheel, integrated generator / motor, support bearings, power electronics and control systems, auxiliary bearings and accidents shielded flask. Flywheel disc and the outer rotor-type integrated motor / generator rotor assembly as a whole stator installed in the flywheel battery shell. According to the principle of three points defining a plane, three electromagnets and three sensors are used to achieve suspension of the flywheel rotor. The electrical appliances positioning plate on the top of flywheel rotor is used to install sensors and solenoid. The three sensors and three electromagnets alternate uniform are arranged on the same circle (the angle between them is 60 degrees), and the installation way can minimize the interference of magnetic field between electromagnets and sensors. The mounted flywheel battery, three electromagnets and three sensors are shown in Fig.2.

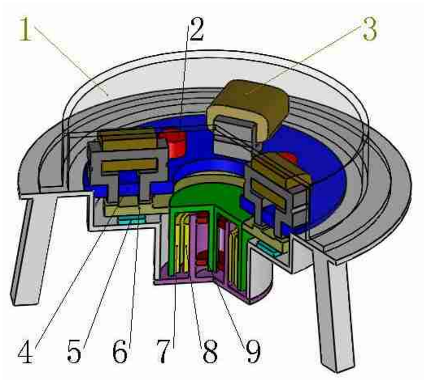

Fig.1 Structure scheme of AMB-flywheel
1-enclosure, 2-sensor, 3-electro-magnet, 4-electrical appliances positioning plate, 5-flywheel disc, 6-axial auxiliary bearing, 7-motor/generator stator, 8-radial auxiliary bearing 9-motor/generator rotor

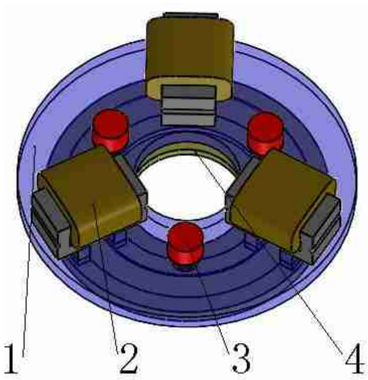

Fig.2 Schematic diagram of AMB-flywheel
1-electrical appliances positioning plate,
2- electro-magnet, 3-sensor, 4-flywheel disc

Radial protecting bearings are installed in the two ends of the motor shaft. There is a small air gap between radial protecting bearings and the central axis of flywheel when the flywheel is suspended stably. The air gap is smaller than that between motor stator and rotor, so the radial protecting bearings will protect the integrated motor of AMB-flywheel when encounter power failure or accidence.

On the flywheel disc, there are two bumped circular rings (The cross-section is U type). Displacement sensor probes detect the inner circle of the two bump rings. When flywheel is working stably, the two raised rings are corresponding to the two ends of the U-magnet core surface. If the edge of suspended object is close to the edge of the electromagnet, when the suspended object deviates, the magnetic flux on the suspended objects changes significantly [1]. Therefore, the convex structure of flywheel can enhance centripetal effect of the magnetic field.

In order to calculate the magnetic flux density distribution of the actual AMB-flywheel and electromagnetic force, ANSYS is used for simulation. Due to the symmetric structures, two-bit plane model is adopted for analyzing. Fig.3 shows the magnetic flux intensity distribution in the magnetic circuit when the current is 1.8A, It shows that the whole magnetic circuit is still within the material linear interval, and with less magnetic flux leakage.

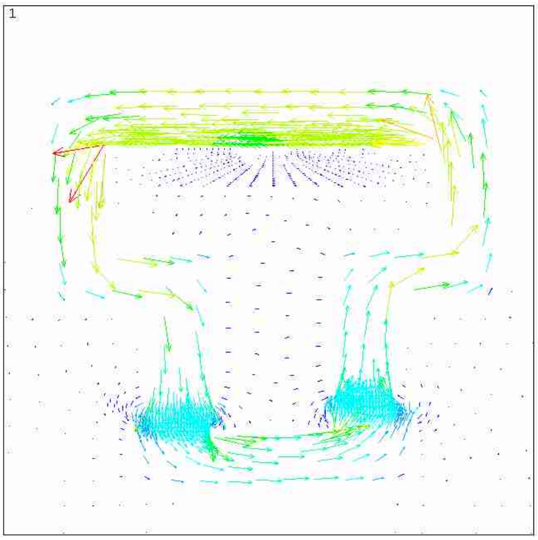

Fig.3 Magnetic flux intensity distribution

III. Mathematical model of the flywheel energy storage system

Active magnetic levitation systems are generally composed of sensors, controllers, power amplifier and electromagnets. In order to simplify flywheel structure and reduce the axial size of flywheel battery, flywheel disc is selected as the controlled object. In the magnetic disc device, three electromagnets on the electrical locator are used to support flywheel and constrain three DOF of the disc: vertical displacement, the x-axis rotation and y-axis rotation. Other DOF of the flywheel battery disc are constrained by the centripetal effect of magnetic. Forced diagram of magnetic flywheel disc by magnetic bearings supporting is shown as Fig.4.

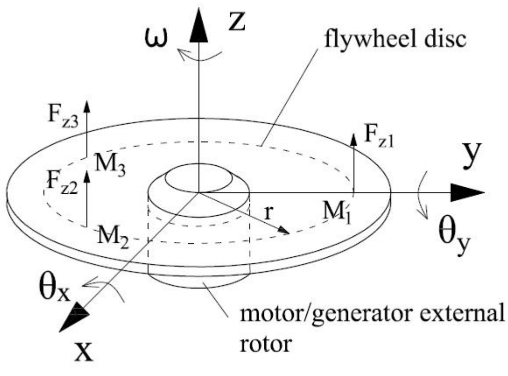

Fig.4 Schematic diagram of the flywheel disc force

The main parts of the model are selected for completeness, the horizontal displacements of x-axis and y-axis directions are ignored. Three angles of three electromagnets relative to the flywheel disc center are all 120 degrees. For the sake of reducing or eliminating the mutual influence between electromagnets and sensors, it needs to ensure that the distance between electromagnets and sensors is the largest at the work time. Accordingly, the sensors and electromagnets relative to the flywheel disc centre are symmetrically laid on the same plane, and the sensor measuring center and the electromagnets relative to the disc center are in the same circle. According to Newton's laws of motion and moment of momentum theorem, the available dynamical equations are as follows:

$$[M]\begin{bmatrix}\ddot{z}\\ \ddot{\theta}_x\\ \ddot{\theta}_y\end{bmatrix}=\begin{bmatrix}1 & 1 & 1\\ 0 & r\sin 60^o\cos\theta_x & -r\sin 60^o\cos\theta_x\\ r & -r\cos 60^o\cos\theta_y & r\cos 60^o\cos\theta_y\end{bmatrix}\begin{bmatrix}F_{z1}\\ F_{z2}\\ F_{z3}\end{bmatrix}-\begin{bmatrix}mg\\ 0\\ 0\end{bmatrix} \tag{1}$$

Where, M=diag(m, J_x, J_y); m is flywheel disc mass; r is the distance between disc centre and the sensor centre. Usually θ_x,θ_y is very small, so $\cos\theta_x \cong \cos\theta_y \cong 1$. The system dynamic equation is as follows:

$$[M]\begin{bmatrix}\ddot{z}\\ \ddot{\theta}_x\\ \ddot{\theta}_y\end{bmatrix}=\begin{bmatrix}1 & 1 & 1\\ 0 & r\sin 60^o & -r\sin 60^o\\ r & -r\cos 60^o & r\cos 60^o\end{bmatrix}\begin{bmatrix}F_{z1}\\ F_{z2}\\ F_{z3}\end{bmatrix}-\begin{bmatrix}mg\\ 0\\ 0\end{bmatrix} \tag{2}$$

The electromagnet gap is needed to transform into displacement signals of the magnets respectively, thus the decoupling relationship between the gap and the center coordinates of displacement sensor can be obtained from the simplification (the gap is the distance between the electromagnets and the flywheel disc), and the relationship is as follows:

$$\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix}=\begin{bmatrix}\frac{2}{3} & \frac{2}{3} & \frac{-1}{3}\\ \frac{-1}{3} & \frac{2}{3} & \frac{2}{3}\\ \frac{2}{3} & \frac{-1}{3} & \frac{2}{3}\end{bmatrix}\begin{bmatrix}z_1\\ z_2\\ z_3\end{bmatrix} \tag{3}$$

z_1, z_2, z_3 are distance between the sensor and the flywheel disc respectively, x_1, x_2, x_3 are distance between electromagnets and the flywheel disc respectively. The distribution of electromagnets and displacement sensors is shown in Fig.2.

IV. Controller designing

The AMB-flywheel test-rig is a three-channel multiple input and output system. The coil current of each electromagnet is controlled on the basis of local information at the corresponding position[2]. These force requirements corresponding currents must be calculated. This can be done independently for each bearing. Each electromagnet of the AMB-flywheel can be analyzed as the single DOF system. The force involved in the system dynamic equation is modeled by the standard static relation between bearing currents and air gap lengths (j $\in$ {1, 2, 3}in this section):

$$F_{z,j}=\frac{1}{4}N^2\mu_0 A\frac{(i_0-i_{c,j})^2}{(x_0-x_j)^2} \tag{4}$$

$$F_{z,j}=k_i i_{c,j}+k_x x_j \tag{5}$$

Where, N is the coil turns; A is area of magnet poles; μ_0 is the air permeability; $i_{c,j}$ is the control currents; x_j is the deviation of the gap between electromagnets and flywheel disc; i_0 is the bias current; x_0 is the balance position. $k_x=\frac{\mu_0 A_0 N^2 i_0^2}{x_0^3}$, $k_i=\frac{\mu_0 A_0 N^2 i_0^2}{x_0^2}$

Formula (3) shows the decoupling relationship of the two distances, and one distance is between the sensor and the disc and the other distance is between the electromagnet with the disc. But the relationship between displacement x_j and $i_{c,j}$ is determined by the control strategy. For Fig.3, make the interference power p(t) = 0. Magnetic bearing makes the displacement X as the output and current I as the input at single DOF, that the transfer function model is:

$$G(s)=\frac{X(s)}{I_x(s)}=\frac{k_i}{ms^2-k_x} \tag{6}$$

The conclusion is that this object is an unstable second-order object from formula (6), and only through closed-loop control can make it work stable. Supposing digital controller transfer function is $G_c(S)$, for simple, assuming that power amplifier and the displacement sensors are proportional components, the gains are k_1 and k_2 respectively. About the power amplification circuit and sensors will be detailed in the sequel. Closed-loop transfer function of system temporality is:

$$\phi(s)=\frac{k_1G_c(s)G(s)}{1+k_1k_2G_c(s)G(s)} \tag{7}$$

In this paper, integral-separated PID control algorithm is used in the magnetic suspension control scheme. Although integral action of the regulator can eliminate static deviation of the called amounts, the system oscillations will increase with the unstable factors of the regulating system increase[3,4]. For making use of advantages of integral action and overcoming its drawbacks, integration separation control arithmetic is used commonly in digital control. According to the basic idea of integration separation controlling, integration separation control arithmetic can be expressed as [5]:

$$u(k)=k_p error(k)+\beta k_i\sum_{j}^{k} error(j)T+k_d[error(k)-error(k-1)]/T \tag{8}$$

Where, T is sampling time, β is switching coefficient of the integral terms.

$$\beta=\begin{cases}1 \, |error(k)|\le\varepsilon \\ 0 \, |error(k)|>\varepsilon\end{cases} \tag{9}$$

Transform formula (8) indicates that the integral-separated PID into transfer function form, which with formula (6) are substituted in formula (7), then system closed-loop transfer function is available:

$$\phi(s)=\frac{k_1k_ik_p(1+\beta\frac{1}{T_Is}+T_Ds)}{ms^2-k_x+k_1k_2k_i(1+\beta\frac{1}{T_Is}+T_Ds)} \tag{10}$$

IV Control system configuration

As it is hard to satisfy the requirement of rapid response of AMB-flywheels system, DSP (TMS320F2812) is selected for the core processor of the controller.

The CPU is a low-cost 32-bit fixed-point digital signal processor, which has abundant peripherals (CAN, SCI, SPI, ADC) and has 128K Flash and 18K SRAM on chip. It is the most important feature of the CPU that the special module of motor control in various modes becomes very simple. The core clock of the CUP which has several advantages in speed, accuracy, performance, expansion, is up to 150MHz. Therefore complex algorithm can be achieved in limited time. The ADC module has 16 channels, configurable as two independent 8-channel modules. Thus two channel current signals can be sampled simultaneously. Therefore, exploiting TMS320F2812 as the core chip controls some of the hardware circuits. The expansion circuit includes: anti-aliasing filter collection of sensor signal; no phase difference A/D conversion of the input signal, D/A conversion output module and power amplifier.

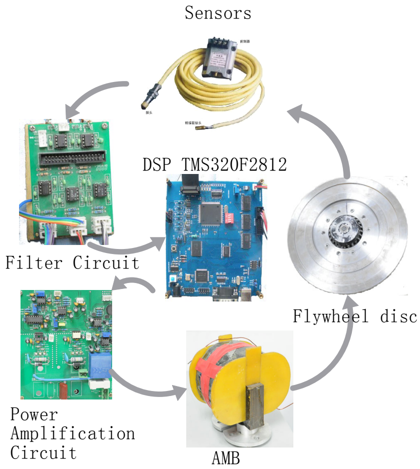

Fig.5 Frame of DSP control system

The laboratory device which is used as test-rig is composed by an AMB system, a DSP based controller is shown in Fig.5.

Sensors: Taking into account the need of a smaller air gap, the CWY-DO-810802 model eddy current sensor is selected, and the response of sensors is given by:

$$V_{sensorj} = 2.5V/mmD_j - 1.272\text{, } j=1, 2, 3 \qquad (10)$$

Power Amplifier: This power amplifier uses the switching power amplifier of PI-type current controller and PWM-type form of pulse generating, transform 110 V AC into 155 V DC, filtered by capacitor then supply power for magnetic bearings. The dynamics of amplifier is given by:

$$i_j = 0.6A/V \times C_{controlj}\text{, } j=1, 2, 3 \qquad (11)$$

The whole system works as follows: firstly, displacement sensor detects the location of suspended flywheel disc, and give the feedback to the DSP, secondly, the signals flow between DSP and flywheel test-rig is provided by Anti-aliasing filter circuits and A/D converters, thirdly, the DSP produces control signals based on feedback signals, and the signals flow between DSP and AMB test-bench is provided through power amplification circuits and D/A converters. The power amplifier converts the control signals into control currents which controls the coils actively, thus the magnetic flywheel disc can be suspended.

V. Experiments and discussions

Based on the above analysis, MATLAB is used to establish integral-separated PID control system simulation model. The flywheel disc is suspended at the position which is 1mm off-center. The response curves of the integral-separated PID parameters on-line adjustment are shown in Fig.6. The results show that integral-separated PID control is faster rising speed, small overshoot and shorter adjusting time compared with the traditional PID control.

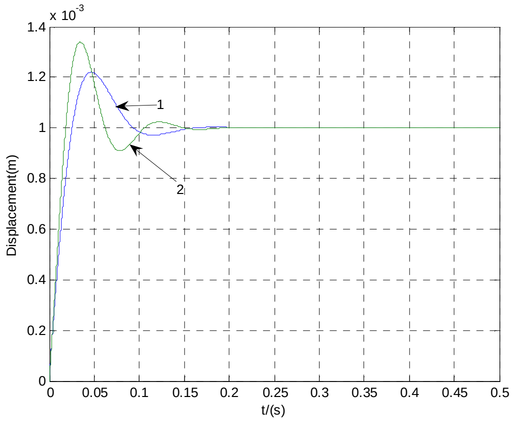

Fig.6 Response curves of simulation

The electromagnetic structure and electrical parameters of the magnetic levitation vehicle flywheel are as follows: weight of the flywheel rotor is 9 kg, pole area is 960mm^2, single-pole turns is 800, bias current is 1.5 A, offset position (air gap) is 1mm. The half-bridge structure switching power amplifier is selected, and control voltage of 5V is converted into control current of 3A. The strong electricity supply and DC voltage of 150 V is selected, eddy current displacement sensor is selected.

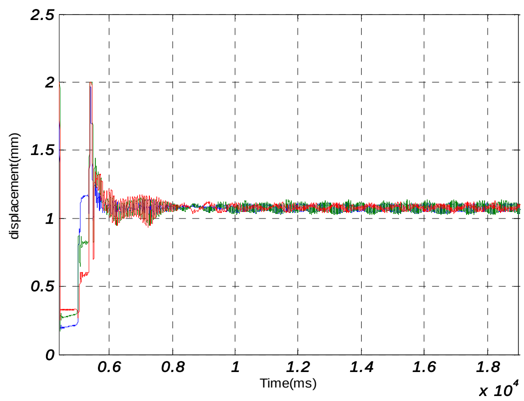

Fig.7 Response curves by integral-separated PID control

The magnetic levitation flywheel battery control system is based on DSP processor and integral-separated PID control, and the controller system is used in completing suspended experiment of the flywheel battery disc(fig.7). The experiments confirms that the control system can achieve a stable suspension. Those results enforce the idea that it is feasible for the AMB-flywheel system with three electromagnets structure. Similar conclusions and numerical data are obtained by carrying out this approach with PID controller.

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