Zero-Power Control for Magnetic Bearings in Artificial Heart Pumps

Shuqin Liu[a], Zhongguo Bian[a], Youpeng Fan[b], Yunpeng Zhang[a]

[a] School of electrical engineering, Shandong university, Jinan, China, lshuqin@sdu.edu.cn bzhongguo@sdu.edu.cn
[b] State grid of China technology college, Jinan, China

Abstract—Artificial heart pump is a new approach to the treatment of heart failure, and the main representative of the third generation of pump is the application of the magnetic suspension or other suspension technology. Energy saving operation of artificial heart pump is very important. This paper studies the application of zero power control in the artificial heart pump. The model of zero power controller and operation theory is presented, and the stiffness characteristic of rotor under zero power control is analyzed. The control method to change equivalent stiffness of rotor system is given according to suspension position, verifying the results.

I INTRODUCTION

According to the survey of WHO, the cardiovascular disease and heart disease accounted for about 30% of all diseases. Various types of heart disease turns to heart failure at last, and about 1/5 of people will eventually become the heart failure patients according to statistics. The rapid developments of drugs and interventional techniques have saved a lot of acute myocardial infarction patients' life. However, the current treatment of heart failure is mainly depends on drugs , whose effects are limited. Effective therapy of heart failure disease is heart transplant. Due to the impact of donor and cost, the treatment is not widely applied. The majority of heart failure patients are dead in waiting for donor heart!

In recent years, ventricular assist device (VAD), artificial heart pump shows its unique advantage in clinical treatment, and has been increasingly applied in clinical so that it plays an important role in medicine and surgery of heart. VAD can compensate or replace heart function, and decrease the after-loading at the same time, in favor of myocardial metabolism and the recovery and balance of nutritional. Also, VAD can promote the recovery of cardiac function. For those heart that can't recovery heart function completely, VAD can replace the natural heart and exert physiological blood pumping function in a long term, which can extend the life of patients and improve their quality of life. Artificial heart has good application prospect and it's a new way for the treatment of heart failure. The countries all over the world have invested a lot of manpower and material resources for its development. Artificial heart pump has been developed to the third generation, and the main symbol is the application of the magnetic suspension technology or other suspension technology. More and more evidence shows that the third generation of the blood pump is better than the first two generation products in performance. The third generation of the blood pump uses the suspension technology, without the problem of bearing wear, improving the using durability of the blood pump. As a result, it's more suitable for long-term circulatory support. The impeller is suspended in the pump body, having no friction and extrusion and decreasing hemolysis significantly, so that the incidence rate of thrombosis reduced significantly. Because of avoiding energy consumption and temperature increase caused by mechanical friction, the third generation of the heart pump has higher energy efficiency ratio and it's more conducive to long-term assistance. The third generation of the heart pump attracts more research and development personnel.

Energy saving operation of artificial heart pump is very important! How to realize stable suspension in the rotor and have low power consumption is a key problem in maglev artificial heart pump. At first, zero power control mainly uses permanent magnet to provide levitation force, but it doesn't always save energy with the permanent magnet. In order to improve the utilization rate of permanent magnets, we need to search how to set quiescent operation point to make the system have stronger robustness and larger stability range. In view of the above problems, this paper mainly studies the zero power control system of Maglev artificial heart pump.

Ⅱ THE PRINCIPLE OF MAGNETIC BEARING ZERO POWER CONTROLLER

A. The principle of the zero power control

Zero power control strategy makes the electromagnetic coil current is near to zero when rotor is suspended stably. When subjected to static force within the allowable range, the system can always keep the coil current in small vibration around zero by adjusting the suspension gap, therefore it can reduce power consumption. But zero power controller has low stiffness and when subjected to strong disturbance, it is easy to make the collision between rotor and stator lose stability. Therefore, it's particularly important to research on high stiffness control of zero power control. Zero power control also should have strong adaptability to interference. In order to solve the anti-interference problem of zero power control, the mirror-image current integral feedback is added to achieve zero power control.

B. Mirror-image current integral feedback

The zero power control block diagram of mirror-image current integral feedback is shown in Figure 1.

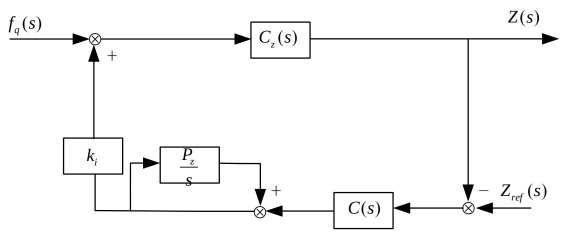

Figure1. Zero power control block diagram

Where $C_z(s) = \dfrac{1}{ms^2 + k_x}$, $C(s) = P_d + P_v s$.

Taking the disturbance force as input, the coil current as output, the transfer function of the system is

$$I(s) = \frac{-\left(P_v s^2 + P_d s\right)}{ms^3 + \left(k_i P_v - P_z\right)s^2 + \left(k_i P_d + k_x\right)s - k_x P_z} F_q(s) \tag{1}$$

When the disturbance force is a step force, that is $F_q(s) = \dfrac{F_0}{s}$. According to final value theorem

$$\lim_{t\to\infty} i(t) = \lim_{s\to 0} sI(s) = 0 \tag{2}$$

Equation (2) shows when the magnetic bearing is in the steady state, the coil current is 0. The rotor relies on the balance between axial force generated by radial bearing and axial magnetic force by balance to achieve the rotor suspension, indicating that zero power control can be achieved.

When rotor is suspended stably, axial displacement can be expressed as

$$\lim_{z\to\infty} z(t) = \lim_{s\to 0} sZ(s) = \frac{F_0}{k_x} \tag{3}$$

Equation (3) shows that when the system is in a steady state, the rotor will deviate from the equilibrium position. The degree of deviation is related to disturbance force and force displacement stiffness coefficient, at the same time it shows that stiffness parameter is very important for zero power control.

Ⅲ RESEARCH ONSTIFFNESSOFZEROPOWERCONTROLLER

Equivalent stiffness and equivalent damping of rotor have the same meaning as ordinary magnetic suspension system. Equivalent stiffness and equivalent damping of rotor shown as:

$$\begin{cases} K = k_x - \mathrm{Re}\left(\dfrac{K_i(k_d s^2 + k_p s)}{P_z - s}\right) = k_x + \dfrac{K_i \omega^2 (P_z k_d + k_p)}{P_z^2 + \omega^2} \\[2ex] d = \dfrac{k_i \bullet \mathrm{Im}\left(-\dfrac{K_i(k_d s^2 + k_p s)}{P_z - s}\right)}{\omega} = -k_i \dfrac{k_p P_z - k_d \omega^2}{P_z^2 + \omega^2} \end{cases} \tag{4}$$

Dynamic stiffness characteristics of the rotor is

$$\frac{F_q(s)}{Z(s)} = K_{dy} = \left| \frac{(ms^2 + k_x)(P_z - s) - K_i(k_d s^2 + k_p s)}{P_z - s} \right| \tag{5}$$

Equation (4) shows that the displacement of the rotor static offset rotor is related to the axial open-loop stiffness and the amplitude of disturbance force.

The rotor's dynamic stiffness and damping ratio under zero power control of changes with the integral parameters as shown in figure 2. In Figure 2, the black line shows stiffness damping characteristics when the mirror-image integral feedback coefficient is 0, and it's the common PD control at this time. Green line, blue line and red line respectively correspond to pz=50, pz=100, pz=150. In general, in the low frequency band, compared to common PD control, the value of dynamic stiffness of zero power control decreases, indicating that the sensitivity of the rotor to static load is increased. That is, when the rotor is suffered by external interference, the balance position of the rotor will be changed, while the damping is decreased. At high frequency band, zero power control is the same with PD control. For different mirror-image integral feedback coefficient, the changes of dynamic stiffness and damping ratio is also different. The smaller mirror-image integral feedback coefficient is, the more quickly dynamic stiffness and damping ratio increases with the frequency change.

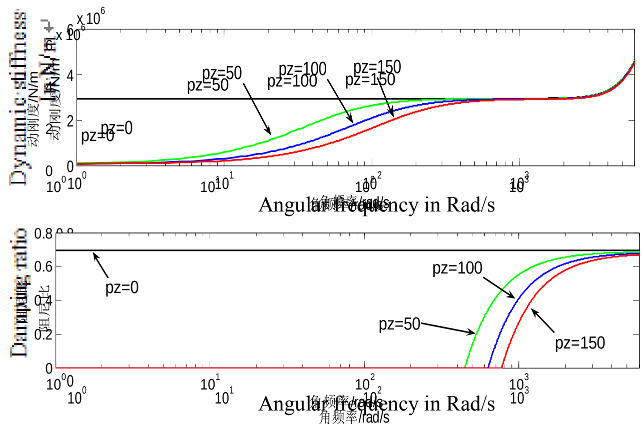

Fig2. Stiffness and damping characteristics with different image integral feedback coefficient

Ⅳ IMPROVED ZERO POWER CONTROLSTRATERY

In order to improve the stiffness of zero power control, we can introduce a small displacement feedback to the current terminal to increase the axial stiffness. The structure diagram is shown in figure 3.

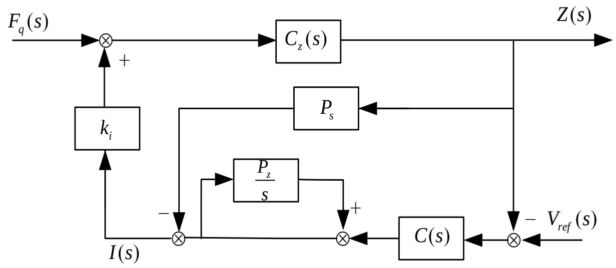

Figure 3. Diagram of improved zero power control

We can list the transfer function of disturbance force and output current by same method, which is shown in equation (6)

$$I(s) = \frac{-[k_d s^2 + (k_p + P_s)s - P_s P_z]}{ms^3 + (k_i k_d - mP_z)s^2 + (k_i k_p + k_i P_s + k_x)s - P_z(k_i P_s + k_x)} F_q(s) \tag{6}$$

When the disturbance force is a step force, that is, $F_q(s) = \frac{F_0}{s}$, According to final value theorem

$$\lim_{t\to\infty} i(t) = \lim_{s\to 0} sI(s) = \frac{P_s F_0}{k_i P_s + k_x} \tag{7}$$

At this time when the current is in steady state, the coil current is not zero, but the constant., whose numerical value is related with the amplitude of interference force, force current stiffness coefficient and $\frac{P_s}{k_x}$. And the current of rotor is

$$Z(s) = \frac{-(P_z - s)}{ms^3 + (k_i k_d - mP_z)s^2 + (k_i k_p + k_i P_s + k_x)s - P_z(k_i P_s + k_x)} F_q(s) \tag{8}$$

By simplification

$$Z(s) = \frac{P_z - s}{(ms^2 + k_x)(P_z - s) - K_i[k_d s^2 + (k_p + P_s)s - P_z P_s]} F_q(s) \tag{9}$$

The axial displacement after rotor is suspended steadily

$$\lim_{z\to\infty} z(t) = \lim_{s\to 0} sZ(s) = \frac{F_0}{k_x + k_i P_s} \tag{10}$$

Compared to equation (3), $k_i P_s$ is added to the denominator, that is, we can increase axial stuffiness by adjusting P_s.

V EXPERIMENTALRESULTS

Based on the above analysis and research, we design and fabricate a maglev artificial heart pump prototype, as shown in figure 4.

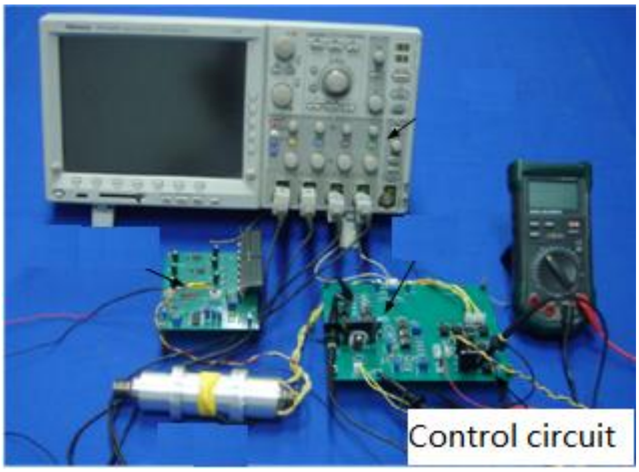

Figure 4. Maglev artificial heart pump prototype

Among them, Hall sensor UGN3503 is used to measure the rotor displacement. The sensor gain becomes 20V/mm and the amplifier gain becomes 0.03A/V after the signal conditioning circuit. The closed-loop control of coil current can be achieved by sampling resistor. By changing the position of the prototype, the load is changed. Figure 5 is the current curve after the change of load.

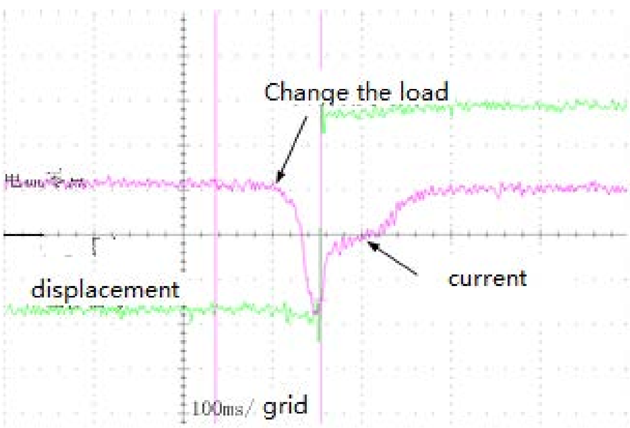

Figure 5. Zero power control curve when load changes

From Figure 5 we can know that the coil current is zero under the initial state, and the displacement of rotor deviates from the zero position because permanent magnetic force is not equal to radial force. When the load is changed, the coil current becomes reverse 0.3V, and then gradually decays to zero. The displacement of rotor turns to another equilibrium state, achieving zero power control.

Acknowledgment

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