Force Free Control in Active Magnetic Bearing Systems for the Magnetically Suspended Compound Molecule Pump

Pingfan Liu[a], Lei Zhao[a], Ying He[a], Kai Zhang[b]

[a] Institute of Nuclear and New Energy Technology
[a] The key laboratory of advanced reactor engineering and safety, Ministry of Education
[b] Department of Engineering Physics
Tsinghua University
Beijing, 100084
PR China
Email: lpfhit@163.com

***Abstract*—A force free control method is studied based on the active magnetic bearings (AMBs) system of the magnetically suspended compound molecule pump. This method uses the feed-forward strategy. The output signals generated with the least mean square (LMS) algorithm are the same as synchronous disturbances, which are caused by unbalance forces. So through this approaches, the controller need not respond to synchronous disturbances. This method can let the rotor rotate around its inertia axis and eliminate the synchronous disturbances of the currents in the electromagnet windings to significantly attenuate the mechanical vibration of the shell. The experimental results verify that the proposed approach is significantly minimized the amplitude of the shell vibration of the magnetically suspended compound molecule pump, which will provide good experience and design references for the future application of the AMBs in the molecule pump.**

I. INTRODUCTION

It is well known that the active magnetic bearings (AMBs) system have many advantages including no contact, no lubrication, low vibration and efficient operation at high speed. So it has been widely used in high-speed turbines such as the magnetically suspended compound molecule pump[1], [2]. Because of the existence of unbalanced masses, unbalance vibrations are generated when the shafts are rotating. They are also referred to as synchronous disturbances. With the rotating speed increasing, synchronous disturbances are more and more significant. Therefore, how to attenuate synchronous disturbances and increase system stability is of extreme importance in the AMBs design[3], [4]. To attenuate synchronous disturbances in AMBs, a number of techniques have been applied[5], [6], [7], including both feed-forward and feedback techniques. A force free control method can be used to reduce the unbalance vibrations by reducing the synchronous disturbances of the currents, which is physically equivalent to the shaft rotating about its principal axis of inertia. In this paper the force free control technique is applied in the magnetically suspended compound molecule pump. This method uses the feed-forward strategy. The output signals generated with the least mean square (LMS) algorithm are the same as synchronous disturbances[8], which are caused by unbalanced masses. So through this approaches, the controller need not respond to synchronous disturbances. This method can let the rotor rotate around its inertia axis and eliminate the synchronous disturbances of the currents in the electromagnet windings to significantly attenuate the mechanical vibration of the shell. The experimental results verify that the proposed approach is significantly minimized the amplitude of the shell vibration of the magnetically suspended compound molecule pump, which will provide good experience and design references for the future application of the AMBs in the molecule pump.

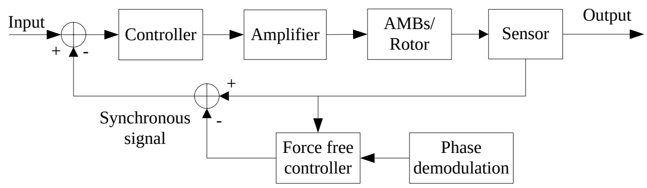

Figure 1. Block diagram of the force free control method

II. FORCE FREE CONTROL

A. General Description

In order to attenuate the mechanical vibration of the shell of the magnetically suspended compound molecule pump, a force free control method is to prevent the controller from saturate by subtracting the synchronous component from input of controller. The block diagram is shown in Fig. 1.

Figure 1 shows the proposed the force free controller block for the minimization of unbalance vibrations in AMBs. A controller is used for stabilizing AMBs, while the force free controller is used to generate compensating signals to minimize synchronous disturbances. The output of the force free controller is injected at the summing junction of the magnetic bearing feedback control loop.

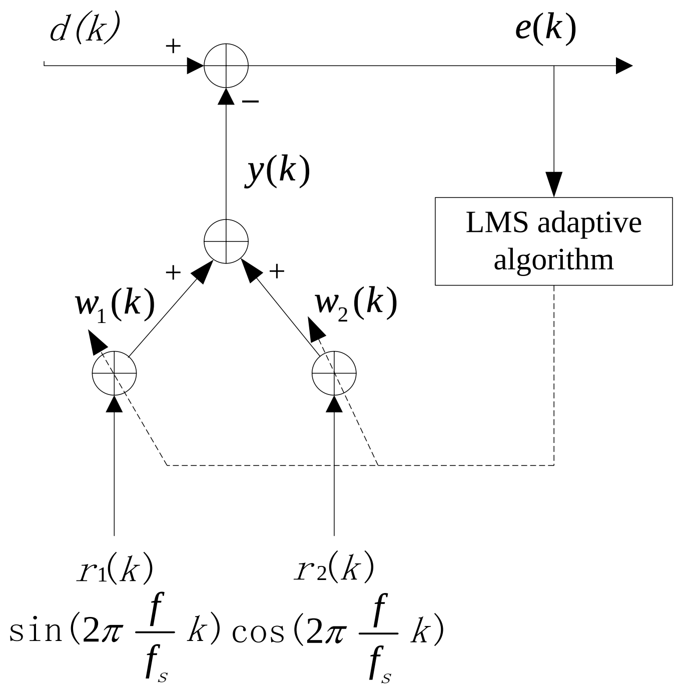

Figure 2. Structure of the force free controller

The basic idea of force free control is to generate a compensate signal with the same amplitude and phase of the synchronous disturbances signal, which is used for offsetting rotor vibration signals of the rotor displacements. And then controller need not respond to synchronous disturbances. So the core issue of force free control is how to get the compensation signal. In other words, the problem is how to extract the synchronous disturbances from the vibration signals.

B. LMS Algorithm

A detailed structure of the force free controller is shown in Fig. 2. Where f represents the rotational frequency in Hz, f_s represents the sampling frequency, and T is the sampling period, ie. $f_s = 1/T$. $d(k)$ is the input displacement signal, $y(k)$ is the compensation signal, and $e(k)$ is the error signal after compensation. Two reference signals $r_1(k)$ and $r_2(k)$ are adjusted by two weighting functions $w_1(k)$ and $w_2(k)$ to generate an estimation of the synchronous disturbance signal in $d(k)$.

These weighting functions are to be updated using the LMS algorithm derived below. LMS algorithm has a very simple structure, it modifies the gain parameter every sample time. It uses a momentary gradient method, and has the advantage of simple structure of algorithm. Assume that the input displacement signal to the force free controller is:

$$d(k) = sin(2\pi \frac{f}{f_s} k + \varphi) \tag{1}$$

Assume that the vector form of the two reference signals is:

$$X(k) = \begin{bmatrix} r_1(k) \\ r_2(k) \end{bmatrix} = \begin{bmatrix} \sin(2\pi \frac{f}{f_s} k) \\ \cos(2\pi \frac{f}{f_s} k) \end{bmatrix} \tag{2}$$

And the vector form of the two weighting functions also is:

$$W(k) = \begin{bmatrix} w_1(k) \\ w_2(k) \end{bmatrix} \tag{3}$$

So the compensation signal from the force free controller is:

$$y(k) = W'(k)X(k) \tag{4}$$

The objective of the adaptation algorithm is to seek parameters vector $y(k)$ so as to minimize mean squared vibration performance cost function:

$$J(W) = e^2(k) \tag{5}$$

where the error signal is:

$$e(k) = d(k) - y(k) = d(k) - W'(k)X(k) \tag{6}$$

And now the LMS algorithm is used to update the weighting functions. The basis for the LMS algorithm is the momentary quadratic error. The momentary gradient is calculated by:

$$\nabla_W \{J(W)\} = -2e(k)X(k) \tag{7}$$

The weight coefficient is updated by using the momentary gradient:

$$W(k+1) = W(k) - c\nabla_W \{J(W)\} = W(k) + 2ce(k)X(k) \tag{8}$$

where c is the adjustment factor. When c is small, the adaptive process is not fast and not sensitive to the change of the signal amplitude. But when c is too large the process is sensitive to noise and tends to unstable. The force free control method requires a relatively small c for it uses a momentary gradient.

III. EXPERIMENTS RESULTS

Experiments have been carried out in the AMBs system of the magnetically suspended compound molecule pump. The force free control method has been tested and investigated. Because the performances of the upper and lower radial AMBs are similar, so only the lower radial AMB is discussed, which is represented by AMB1.The force free controller is injected at the summing junction of the feedback control loop at the rotating speed of 200 Hz.

The measured actuator current in the x-direction of the AMB1 is represented by i_x . Fig. 3 shows i_x time response with and without the force free controller. Fig. 4 and Fig. 5 show the frequency response. It will be noted that the amplitude of the actuator current is significantly reduced when implementing the force free controller, and even no synchronous disturbances are observed. As a consequence the unbalance forces at the synchronous speed are negligible. Therefore the amount of improvement achieved in reduction of the shell vibration of the magnetically suspended compound molecule pump is more than 15dB.

Furthermore, the effects of the force free controller on the displacement of the AMB1 are also analyzed. Fig. 6 shows the shaft centerline orbits at the AMB1 without the force free

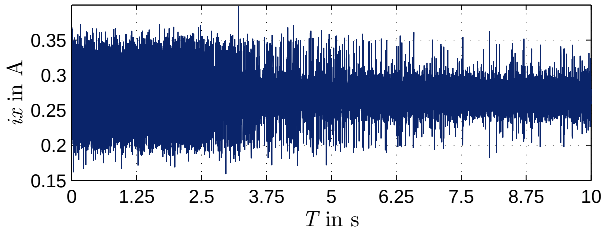

Figure 3. i_x time response with and without the force free controller

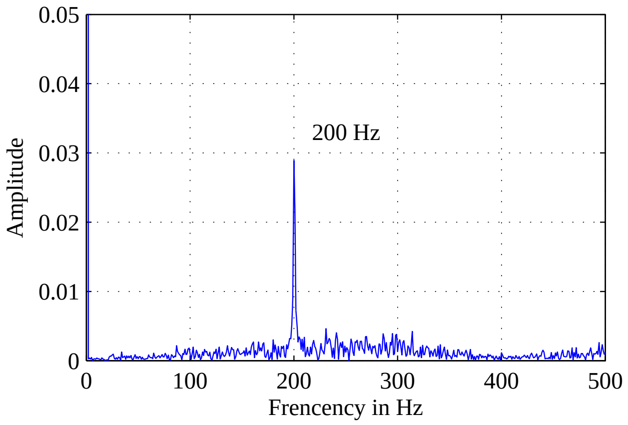

Figure 4. i_x frequency response without the force free controller

controller. The shaft centerline orbits at the AMB1 with the force free controller are shown in Fig. 7. Fig. 8 and Fig. 9 show the frequency response of the displacement in the x-direction of the AMB1. The comparison of them indicates that the size of the orbits is slightly big with the use of the force free controller at the rotating speed of 200 Hz. The amplitude of the rotor displacement is increased from 16 μm to 20 μm. But it is also much smaller than the protection gap of the magnetically suspended compound molecule pump. So the performance of the magnetically suspended compound molecule pump is not affected.

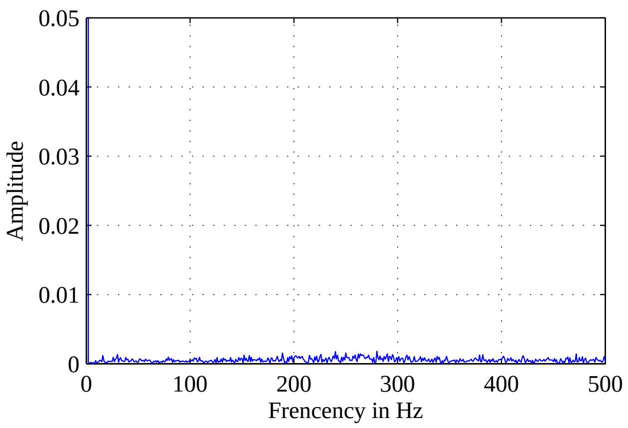

Figure 5. i_x frequency response with the force free controller

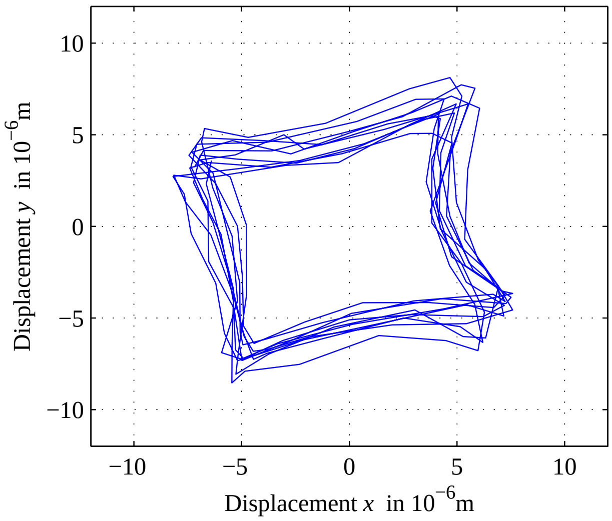

Figure 6. Shaft centerline orbits at the AMB1 without the force free controller

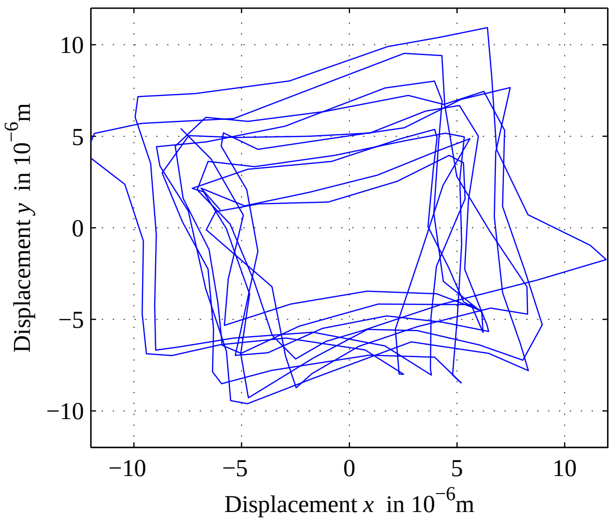

Figure 7. Shaft centerline orbits at the AMB1 with the force free controller

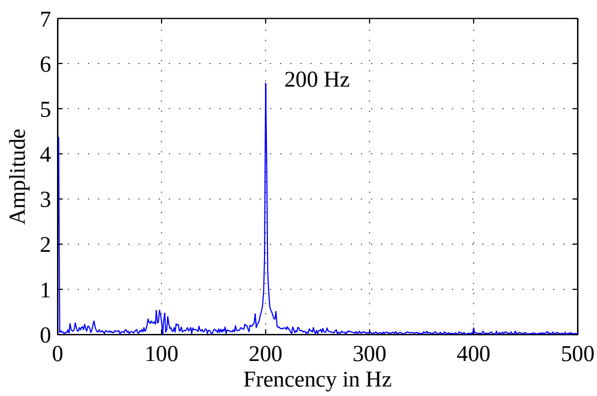

Figure 8. Displacement x frequency response without the force free controller

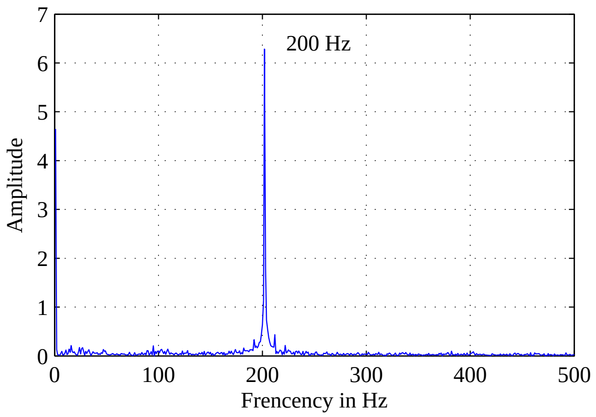

Figure 9. Displacement x frequency response with the force free controller

IV. CONCLUSIONS

In this paper, we have investigated the force free control method in the AMBs system of the magnetically suspended compound molecule pump. The LMS algorithm is proposed to get the compensation signal. The synchronous disturbances of the currents in the electromagnet windings have been eliminated. So the rotor has rotated around its inertia axis, and finally the machine vibration has been restrained. The force free control method has been successfully implemented in real time operation using the magnetically suspended compound molecule pump at Tsinghua University and this technique prove to be significantly practical and it achieved good results.

V. ACKNOWLEDGMENT

Thanks go to Lei Zhao for his constant encouragement and guidance. I also would like to express my thanks to Kai Zhang who have instructed and helped me a lot. This paper is financially supported by the National Science and Technology Major Project of China (2011ZX069).

REFERENCES

[1] G. Schweitzer, H. Bleuler, and A. Traxler, "Active magnetic bearings-basics, properties and application of active magnetic bearings," *ETH, Switzerland*, 1994.

[2] K. Wada, T. Inohara, M. Yoshida, Y. Yamato, T. Nakayasu, M. Iguchi, Y. Hikichi, N. Ogiwara, and K. Mio, "Development of the radiation-hardened magnetically suspended compound molecular pump," *Vacuum*, vol. 84, no. 5, pp. 699–704, 2009.

[3] K. Zhang and X. Zhang, "A review of unbalance control technology of active magnetic bearings," *China Mechanical Engineering*, vol. 21, no. 8, pp. 897–903, 2010.

[4] C. R. Knospe, R. W. Hope, S. J. Fedigan, and R. D. Williams, "Experiments in the control of unbalance response using magnetic bearings," *Mechatronics*, vol. 5, no. 4, pp. 385–400, 1995.

[5] K. Zhang, J. Dong, X. Dai, and X. Zhang, "Vibration control of a turbo molecular pump suspended by active magnetic bearings," in *Proceedings of ASME Turbo Expo 2011*. ASME, 2011.

[6] J. Shi, R. Zmood, and L. Qin, "The indirect adaptive feed-forward control in magnetic bearing systems for minimizing selected vibration performance measures," in *Proceedings of the Eighth International Symposium on Magnetic Bearings*, 2002.

[7] C. Hui, L. Shi, J. Wang, and S. Yu, "Adaptive unbalance vibration control of active magnetic bearing systems for the htr-10gt," in *Proceedings of the 18th International Conference on Nuclear Engineering*, 2010, pp. 793–802.

[8] Z. Dekui, J. Wei, and Z. Hongbin, "Unbalance vibration control methods for active magnetic bearings system," *Journal of Tsinghua University*, vol. 10, p. 008, 2000.