Experiment Study on a High Speed Motor Supported by Active Magnetic Bearings

Kai Zhang, Xingjian Dai and Xiaozhang Zhang
Dep. of Engineering Physics
Tsinghua University
Beijing, 100084, China
zhangkai@mail.tsinghua.edu.cn

Xingjian Jiang
Dept. of Electrical Engineering
Tsinghua University
Beijing, 100084, China

***Abstract* –In a high speed motor system suspended by active magnetic bearings, the bearing load capability is limited, the bias force from the motor rotor produced by permanent magnets is large compared with the bearing load capability and the influence of the residual unbalance in the rotor is obvious. So the active magnetic bearings have to work with nonlinearity conditions and high speed running is hard to be achieved. To deal with the marked nonlinearity of the active magnetic bearing system, a global linearization method is used to linearize the magnetic forces produced by active magnetic bearings. Meanwhile, controller designs are improved. A gain schedule method is used to make the rotor running stable across its rigid critical speed. Through using a zero-pole pair shaping method, the gain of the controller in the frequency domain near the running frequency of the rotor is effectively decreased and the rotor runs almost about its mass centre. The saturation of the magnetic forces of the active magnetic bearings is avoided and stable running of the motor system at high rotation speeds is achieved.**

***Index Terms* –Active magnetic bearing Nonlinearity High speed motor**

I. INTRODUCTION

In some industry applications, there are urgent needs for high speed motors. For examples, in design of high speed spindles, the increase of rotation speeds and output power of the spindles help to enhance production efficiency and production quality. For turbine machines, such as generator rotors, compressors and blowers, the motors with high working speeds and a compact space design are attractive and highly required. Such a motor can vary the rotation speed of the rotor directly and large gear systems for speed control in traditional machines can be discarded. With a compact system structures, the total weight of production decreases rapidly, system efficiency is improved and system produce cost and maintain cost is reduced effectively [1].

Recently, with the rapid development of power electronics technology, permanent magnet materials , electrical steels with low iron loss, computer simulation and analysis, magnetic bearings and other advanced bearing technologies, high speed and super high speed motors are developed quickly.

The high speed motor discussed here is a permanent synchronous motor and it is suspended by 5-DOF active magnetic bearings. The AMBs work with strong nonlinearity for various reasons and the nonlinearity makes the AMB controller design difficult.

In the motor system, the size of the active magnetic bearings is restricted by space availability. So the load capacity is limited. The motor rotor is produced by a permanent magnet. After assembling the motor system, the magnet attracts the motor stator which is made of ferromagnet and the attraction produces a bias force. Compared with the load capacity of the AMBs, the bias force is large; it greatly influences the running of the rotor and makes the radial AMBs working with a nonlinear condition.

Because of the assembling mode of the rotor system, the residual unbalance of the rotor is large; the AMBs have to compensate the unbalance force when the rotor runs at high rotation speeds. The linearity of the AMBs is decreased further. On the other hand, the large unbalance force makes the vibration large especially when the rotor runs across its rigid critical speeds. When a controller with a large gain used, the vibration of the rotor at the rigid critical speeds is too large and makes the system unstable. But when a controller with a small gain used, the AMBs can’t compensate the bias force from the motor at low rotational speeds.

To deal with the strong nonlinearity in the system, a global linearization method is used to linearize the magnetic forces of the AMBs. Meanwhile, the controller designs are improved. A gain-scheduled control method is used to achieve a stable running of the rotor near its rigid critical speeds. With a zero-pole pair shaping method used, the controller gain in the frequency domain nearby the working speed of the rotor is decreased effectively to make the rotor run almost about its mass centre and the saturation of magnetic forces is avoided.

The experiment results are provided and they prove that the methods used are effective and the motor system with large nonlinearity and unbalance can run stable at high rotational speeds.

II. ROTOR SYSTEM

The motor is a high speed permanent motor with 5-DOF AMBs and its design speed is 30,000 rpm. It has a vertical rotor which is shown in Fig. 1. The weight of the rotor is supported by an axial AMB.

Fig. 1 Motor rotor.

The parameters of the rotor are shown in Table I.

TABLE I
ROTOR PARAMETERS

AMB rotor diameter of the fore bearing (mm)	20
AMB rotor diameter of the rear bearing (mm)	20
Gap of the fore bearing (mm)	0.4
Gap of the rear bearing (mm)	0.4
Gap of the backup bearing (mm)	0.2
Weight of the rotor (kg)	0.3

The parameters of the radial AMBs are shown in Table II.

TABLE II
RADIAL AMB PARAMETERS

Pole number	8
Area of one pole (cm^2)	0.65
Coil number of a pair of poles	50
Bias current (A)	0.73
Force current parameter (N/A)	0.93
Force displacement parameter (N/m)	1700

III. SIMULATION STUDY ON THE IDEAL MODEL

A theory model of the system is built according to the theoretical parameters and a simulation study is carried out with the model. The diagram of the simulation is shown in Fig. 2.

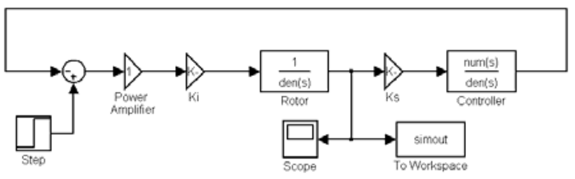

Fig. 2 Simulation diagram.

Because the coupling among the different DOFs of AMBs is not obvious, a 1-DOF model is used for the system [2]. The following discussion is based on the fore radial DOF of the AMBs.

The open loop bode plot is shown in Fig. 3.

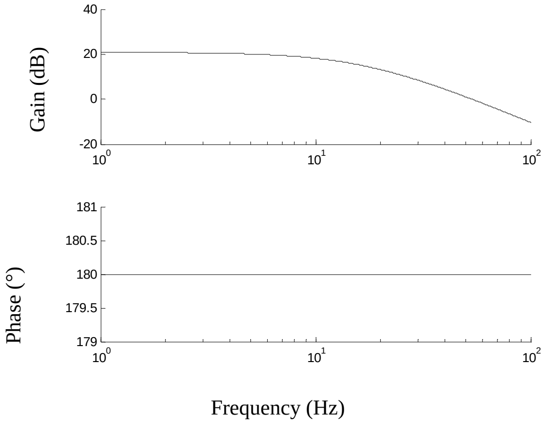

Fig. 3 Open loop bode plot of the system.

In Fig. 2, a PD controller is used and its bode plot is shown in Fig. 4. The corresponding simulation result of step response is shown in Fig. 5.

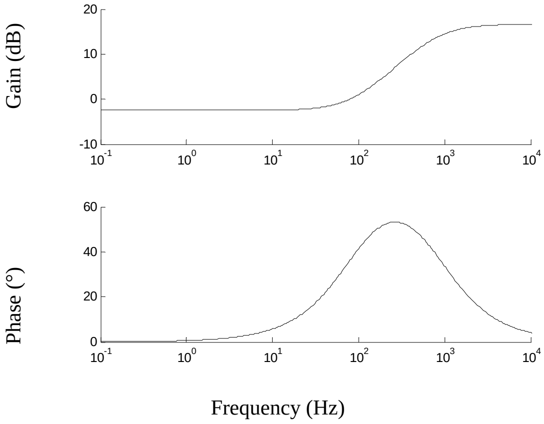

Fig. 4 Open loop bode plot of the PD controller.

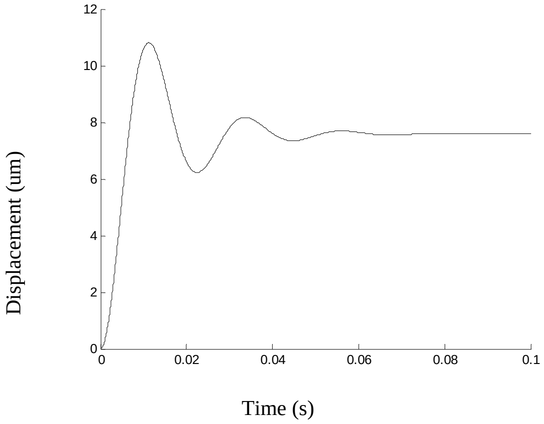

Fig. 5 System step response.

In the simulation, it is shown that good system performance can be achieved with the PD controller for the ideal model. But in the real system, the model is very complex and a simple PD controller is not enough.

IV. SYSTEM NONLINEARITY AND CONTROLLER DESIGN

A. *Coupling from the Motor*

The motor rotor is composed of permanent magnet. The magnetic field of the rotor is very strong. The motor stator is produced by ferromagnetic material. When the rotor is assembled in the stator, they attract each other and a bias force for the rotor is produced. The bias force greatly influences static suspension of the radial AMBs. In fact, it increases negative stiffness of the radial AMBs, causes serious nonlinearity and makes it difficult to increase the system performance.

System identification is performed to obtain the real system parameters. Because the AMBs are open loop unstable, a small gain PD controller is used to achieve a stable static suspension. Then a non-parameter method is used to identify the system open loop model [3]. The bode plot from the identification is shown in Fig. 6.

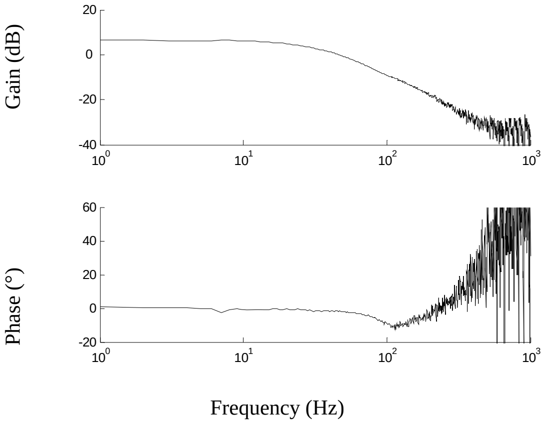

Fig. 6 Identification result of the open loop system.

In Fig. 6, it is seen that the system open loop gain in the low frequency range is about 2.0. In Fig. 3, the corresponding result is about 10, which is much greater than the identification result. It proves that the increment of the negative stiffness coming from the motor is very serious. It is also illustrated by the recorded static working currents flowing in the coils of the radial AMBs as shown in Table III.

TABLE III
STATIC WORKING CURRENTS OF THE RADIAL AMBS

Magnets	Current (A)
Up magnet of the front bearing	1.27
Down magnet of the front bearing	0.15
Left magnet of the front bearing	0.87
Right magnet of the front bearing	0.54
Up magnet of the rear bearing	2.00
Down magnet of the rear bearing	0.00
Left magnet of the rear bearing	0.38
Right magnet of the rear bearing	1.04

It is shown that the currents in the coils belonging to the same pair of magnets are unbalance. Sometimes, one current is 2.0 A, while the other one is only 0.0 A as in the rear AMBs. Obvious nonlinearity exists in such a system. According to linearization condition, the difference between the two coil currents in the same pair of magnets should be small [2].

The experiments showed that the force capacity of the radial AMBs was limited and the bias force from the motor couldn't be neglected. The bias force, as a disturbance, will do harm to the AMB performance, especially in a low rotation speed range. Actually, the experiment results showed that a stiff suspension was needed to compensate the bias force and to achieve a stable running in the low speed range. Otherwise, the rotor collided to the backup bearings.

B. *Influence of the Rotor Unbalance*

The unbalance of the rotor produces synchronous disturbance forces for the system. The forces are proportional to the square of the rotation speed of the rotor. The unbalance vibration is critical for the stability of the high speed system.

In the test setup, the high speed motor rotor is assembled in a not so firm way and brings a large unbalance. When the rotation speed rises, unbalance force increases continually and the system performance is greatly influenced. Especially when the rotor tries to run across its rigid critical speeds, the unbalance causes the saturation of the power amplifiers and the system stability is damaged.

Decreasing the unbalance of the rotor is a way to deal with the problem. But considering that the unbalance distribution is somewhat uncertain and it is interesting to test the ability of the AMBs in dealing with unbalance disturbance in a high rotation speed, controller design methods are used to solve the problem.

Because of limited bearing load capacity, it is attractive to decrease the rigid critical speeds of the rotor and make the rotor run across its critical speeds at a low speed. After the rotor running at supercritical speeds, by further decreasing the gain of the controller nearby the rotation frequency, the rotor can rotate almost about its mass centre and the vibration from the rotor to the housing can be decreased dramatically.

C. *Controller Design*

To deal with the problem of the strong nonlinearity, the disturbance forces from the motor, the residual unbalance of the rotor and so on, special controller design methods are used. The performance of the controller based on a PD controller is increased.

The strong nonlinearity mainly comes from the relationship among the magnetic forces, the coil currents and the displacements. The forces are proportional to the square of the currents and the square of inverse of the displacements. It can be solved by a global linearization method [4]. It makes use of the square relationship to deal with the large difference between the gains of the two currents flowing in a pair of magnets. Then linear controller design methods can be used to design a controller for the AMBs.

To restrain disturbance forces in the low speed range, the controller gain should be large enough. But a large bearing stiffness is not good for the supercritical operation. With a large stiffness, the corresponding rigid critical speeds will be increased and it will be hard for the magnets to provide enough magnetic forces to restrain the synchronous vibration of the rotor. As discussed in 3.2, it is possible to restrain the rigid critical vibration by decreasing the controller gain and the rigid critical speeds. But it is a contradiction for the high stiffness command in the low speed range.

The problem can be solved by using a gain-scheduled method. A high gain controller is used at low rotation speeds. When the rotor runs to a speed at which the influence of the disturbance force from the rotor is not so large, the high gain controller is switched to a controller with a much lower gain. Then the rigid critical speeds of the rotor will be decreased obviously and be much lower than the synchronous speed of the rotor. Then, the rotor can run at a supercritical speed and a stable running with a higher speed can be achieved.

After the speed of the rotor is increased further, it is necessary to make the rotor run almost about its mass centre to avoid the saturation of the magnetic forces and decrease the vibration transmitted to the housing. It is achieved by decreasing the controller gain in a special frequency range. A zero-pole pair shaping method can be used to shape the gain and phase of the controller in the frequency range [5].

The final controller diagram is shown in Fig. 7.

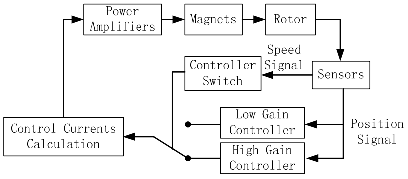

Fig. 7 Controller diagram.

In the figure, the linear controller outputs a control force command, and the corresponding currents needed are calculated according to the nonlinear relationship among the magnetic forces, the currents and the displacements. The switching between the high gain controller and the low gain controller is trigged by a rotation speed signal. When the rotor runs from a low speed to a high speed, the controller is switched form the high gain controller to the low gain controller and vice versa.

The bode plots of the low gain controller and the high gain controller are shown in Fig. 8 respectively. In Fig. 8, it is shown that the gains of the two controllers are obviously different and the distance between their rigid critical speeds is large. When the rotor runs near the rigid critical speeds of the high gain controller (at about 140 Hz), the synchronous vibration becomes large. If the speed increases continually, the system becomes unstable. The rotation speed of 140 Hz is much higher than the rigid critical speed of the low gain controller (less than 100 Hz). So through the controller switching, a stable supercritical operation can be achieved. The corresponding experimental results will be provided below.

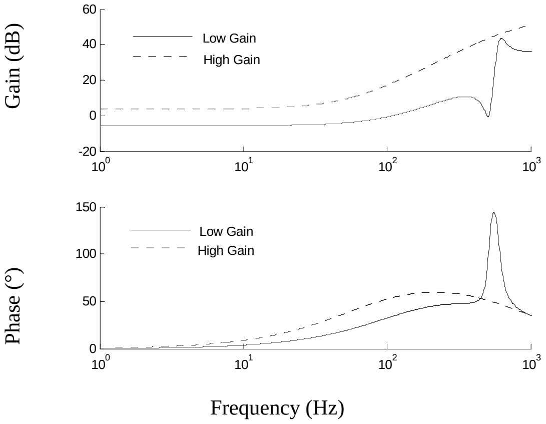

Fig. 8 Bode plot of the linear controller.

Furthermore, in Fig. 8, it is seen that the gain and phase characters of the controller near the working rotation frequency of the rotor change obviously with a zero-pole pair added in the controller. The gain is decrease largely and the phase is increased effectively. Such a controller can guarantee that the rotor keeping stable when its rotation speed is nearby the working frequency of the rotor and rotating almost about its mass centre.

V. EXPERIMENT RESULTS

Unless specifically stated otherwise, the data provided below is from *x* DOF of the front AMB.

With the global linearization method used in producing the magnetic force, the experimental results of the suspension when the rotor runs at the speed of 117 Hz is shown in Fig. 9.

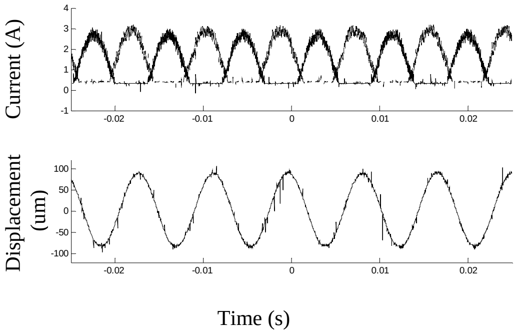

Fig. 9 Experimental results at the speed of 117 Hz.

The top of Fig. 9 shows the currents flowing into the coils of the two magnets of the AMB. The bottom of Fig. 9 shows the displacement of the rotor. The currents are calculated according to the global linearization method and they can produce linear magnetic forces

The displacement curve during the controller switching is shown in Fig. 10. It is recorded during the switching from high gain controller to the low gain controller at the speed of 140 Hz. It is shown that the switching is successful. In the figure, x_1, y_1, x_2, y_2 are the displacements at the front x radial DOF, the front y radial DOF, the rear x radial DOF and the rear y radial DOF respectively. In experiments, without the switching, the vibration of the rotor will rise dramatically. After the switching, the rotation speed of the rotor has been far above its rigid critical speeds which are less than 100 Hz. The rotation speed of the rotor can be increased further.

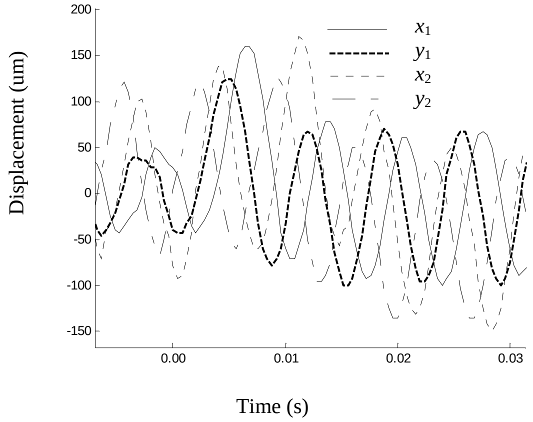

Fig. 10 Switching from the high gain controller to the low gain controller.

The working currents in a magnet at x_1 DOF at the speed of 400 Hz and 500 Hz respectively are shown in Fig. 11. As we known, the unbalance force of the rotor is proportional to the square of the rotation speed. But in Fig. 11, there is no obvious difference between the current gains at the two rotation speeds, and the signal recorded by acceleration sensors from the housing showed little difference in amplitude. It means that the rotor has almost rotated about its mass centre in the frequency range.

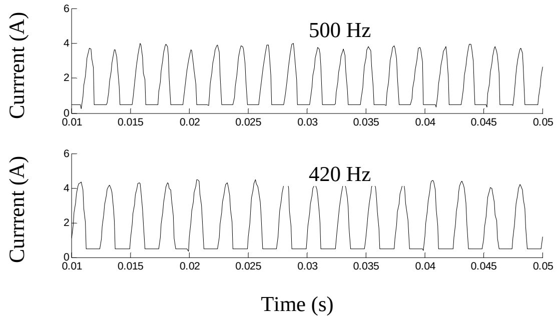

Fig. 11 Currents in a magnet at the speed of 500 Hz and 420 Hz.

In the experiments, the highest rotation speed achieved for the motor is 530 Hz. The rotor orbits at the speed are shown in Fig. 12.

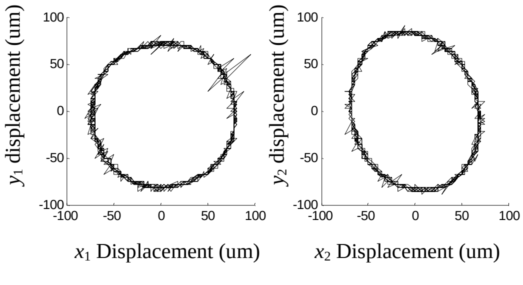

Fig. 12 Orbits of the rotor at the speed of 530 Hz.

The results show that the demand performance of the controller and the target speed of the motor are achieved.

VI. CONCLUSION

The bias force from the high speed permanent motor and the large residual unbalance of the rotor force the AMBs to work with a nonlinear condition. To achieve stable high speed running, the global linearization method is used to produce linear magnetic forces and the controller design method is improved. The gain-scheduled method is used to ensure that the rotor can run stable across its rigid critical speeds. The zero-pole pair shaping method is used to shape the local characters of the controller, decrease the controller gain in the frequency domain near the working frequency of the rotor and make the rotor running almost about its mass centre. The saturation of the magnetic forces of AMBs is avoided and the synchronous vibration transmitted from the rotor to the housing is decreased. At last, the high speed stable running of the AMB motor with the high nonlinearity condition is achieved.

REFERENCES

[1] M. A. Rahman, A. Chiba and T. Fukao, “Super high speed electrical machines – summary,” IEEE Xplore: Power Engineering Society General Meeting, Denver, USA, 2004, pp. 1272-1275.

[2] G. Schweitzer, H. Bleuler and A. Traxler, “Active magnetic bearings — basics, properties and application of active magnetic bearings,” Zurich, Switzerland: Hochschulverlag AG, 1994.

[3] H. J. Ahn, S. W. Lee, H. S. Lee and et al, “Frequency domain control-relevant identification of MIMO AMB rigid rotor,” Automatica, 39(2), pp. 299-307.

[4] L. Li, T. Shinshi and A. Shimokohbe, “Asymptotically exact linearizations for active magnetic bearing actuators in voltage control configuration,” IEEE Trans. on Control System Technology, 2003, 11(2), pp. 185-195.

[5] K. Zhang, L. Zhao, H. Zhao, “Low order gain schedule robust controller design of a magnetic-bearing-supported flywheel,” Chinese Journal of Mechanical Engineering, 2005, 41(9), pp. 198-201 (in Chinese).