Experimental Research on Unbalance Control of Active Magnetic Bearings

Zhang Kai[1,a], Zhang Xiaozhang[1,b]
[1]Department of Engineering Physics, Tsinghua University, Beijing, 100084, China
[a]zhangkai@ tsinghua.edu.cn, [b]zhangxzh@ tsinghua.edu.cn

Abstract: Two unbalance control methods, General Notch Filter (GNF) and LMS (least mean square), for active magnetic bearings (AMBs) were applied to a high speed rotor supported by AMBs. The rotor operation was greatly influenced by a large residual unbalance in the rotor and some low frequency vibration modes from the structure of the rotor system. GNF was used to help the rotor to increase its dynamic balance efficiency with two different methods. To achieve a better unbalance cancellation effect for the rotor in a large rotation speed range, GNF and LMS methods were combined in a single unbalance controller and performed in different speed ranges. A simple but effective method was used to achieve a smooth switching of the two methods. Corresponding experiment results are provided. GNF algorithm increased the balance efficiency. The smooth switching of GNF and LMS was successful and the unbalance control effects were improved.

Keywords: Active Magnetic Bearing, Unbalance Control, Dynamic Balance

Introduction

Active magnetic bearings are attractive for their special advantage compared with traditional ball bearings and fluid film bearings, such as contactless, no wear, no oil, low power consumption, low maintenance cost and controllability of bearing dynamic characteristics [1]. Another attractive character of AMBs is that they can be used to control synchronous vibration of a rotor.

Many researchers have devoted to the study of unbalance control of AMBs and achieved a lot of valuable theory and experiment results [2-6]. They are applied to different AMB rotor systems and prove their value. General Notch Filter (GNF) and LMS methods are both important developed methods about unbalance control of AMBs. GNF method can be used in almost all speed range for a rigid AMB rotor, but detail information about the close loop system is needed, whereas, LMS method can be used with little knowledge of model parameters of a system, but it can be used only at a supercritical speed range.

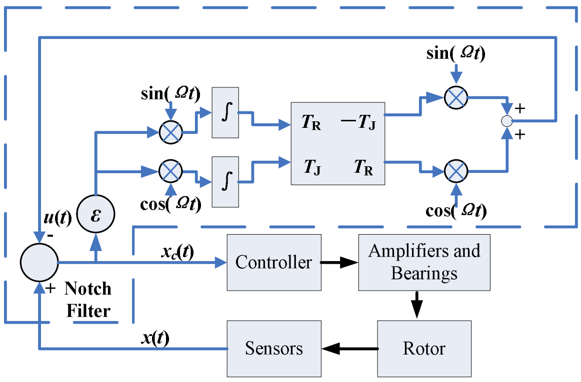

Fig. 1 Principle of the generalized notch filter

The structure of the GNF is shown in Fig. 1. Parameter values of ε, T_R and T_J are very important. The stability of the control loop would be decided by the parameter selection. The selection method is detailed presented by Herzog in [3]. For a MIMO system, it is a complex process and an accurate model of the original close loop system without GNF is needed.

Compared with GNF method LMS method is a much simpler feedforward unbalance control method [6]. It estimates parameters of a modeled system in real-time using an error object function. Its structure is very simple, it modifies its gain parameter every sample time by some special method. When LMS is used to achieve speed-synchronous current elimination, almost no system model parameter is needed. Its drawback is the white noise assumption about sensor noise $n(k)$. Further more, it is not suitable for a subcritical running AMB rotor. When applied to such a rotor, the stability of the system would be destroyed.

GNF and LMS are studied to work in a single unbalance controller to improve performance of a high speed rotor setup equipped with AMBs. The controller would switch its operation algorithm between GNF and LMS according to the rotor speed. The setup is a prototype of an industrial turbo molecular pump. It runs at a maximum speed of 27000 rpm. The rotor will be composed by a motor spindle and a large disk with blades. In the test stage, the rotor runs in the air without any vacuum equipment. For safety reason, and to decrease air resistance, the disk with blades is replaced with a simulation plate with similar gravity center position, polar moment of inertia and transverse moment of inertia with the real pump plate. The photo of the rotor is shown in Fig. 2. The rotor can be seen as a rigid rotor in the running speed range. To make the algorithm simple and easy to be implemented, GNF is simplified to a SISO structure and compared with SISO LMS algorithm. But they are tested in the MIMO rotor system.

Fig. 2 the rotor system with the simulation plate

The rotor operation was greatly influenced by a large residual unbalance in the rotor and some low frequency modes from the setup structure. In dynamic balance experiments, a general dynamic balance procedure was proved not suitable for the rotor. So GNF was used to help the rotor to run to a suitable balance speed, and then help do rotor dynamic balance with two different methods.

Using GNF to Identify Unbalance Distribution and Help Balancing a Rotor

Though balance control algorithms are helpful to decrease synchronous vibration of a rotor, a good balance is still a base for a high speed rotation machine to achieve a good performance. For a balance of an AMB rotor, field dynamic balance is suitable and necessary. In a rotor dynamic balance, Influence Coefficient Method is usually used. When the GNF algorithm has converged, its output factors multiplied with $\sin(\Omega t)$ and $\cos(\Omega t)$ converges to two constants. These two constants are related to unbalance distribution of a rotor. In a linear system, it is natural that one residual unbalance is corresponding to a pair of constants. This character can be used to identify and correct the mass distribution of a rotor, and obtain corresponding Influence Coefficients, namely help balancing the rotor. Detail steps are discussed below based on a SISO model [1].

At first, the rotor runs to a balance speed. When GNF works, its output $V_{c0}=a_0+j^*\, b_0$ after convergence is recorded as an initial unbalance vector. Then an unbalance $m_1=c^*\cos(\Phi)+j^*\, d^*\sin(\Phi)$ is added to a correction plane (the same plane as the measuring plane in the SISO model), at a special angular position. When the rotor runs to the same speed again, a new output $V_{c1}=a_1+j^*\, b_1$ is recorded. The coefficient of mass influence from the correction plane to the GNF output can be calculated by $(V_{c1}- V_{c0})/m_1$, and the initial unbalance mass can be calculated by $V_{c1}*m_1/(V_{c1}- V_{c0})$. The procedure can be extended to the real rotor system mentioned above.

Suppose two correction planes are used to do dynamic balance for the rotor, one plane on the upper part of the rotor and the other one on the down part. The radial displacement sensors in x plane or y plane (rotation axis is z) can be directly used to measure the vibration. Suppose x plane is used, after GNF convergence, the initial unbalance vector (corresponding GNF output) $V_{c0} =[\ a_{xu0}+j*b_{xu0}\ \ a_{xd0}+j*b_{xd0}]^T$ is obtained. "xu" is corresponded to the upper plane and "xd" to the down plane. Then a test mass $m_{xu1}=c_{xu}*\cos(\phi_{xu})+j*d_{xu}*\sin(\phi_{xu})$ is added to some angle in the upper plane. A new output $V_{c1}= [a_{xu1}+j*b_{xu1}\ \ a_{xd1}+j*b_{xd1}]^T$ is recorded. After that, mass $m_{xd1}=c_{xd}*\cos(\phi_{xd})+j*d_{xd}*\sin(\phi_{xd})$ is added to the down plane. A second output $V_{c2}=[a_{xu2}+j*b_{xu2}\ \ a_{xd2}+j*b_{xd2}]^T$ is recorded. The equation (4)、（5)、(6) are obtained:

$$\begin{bmatrix} a_{xu0}+j*b_{xu0} \\ a_{xd0}+j*b_{xd0} \end{bmatrix} = T \begin{bmatrix} m_{xu0} \\ m_{xd0} \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} a_{xu1}+j*b_{xu1} \\ a_{xd1}+j*b_{xd1} \end{bmatrix} = T \begin{bmatrix} m_{xu1}+m_{xu0} \\ m_{xd0} \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} a_{xu2}+j*b_{xu2} \\ a_{xd2}+j*b_{xd2} \end{bmatrix} = T \begin{bmatrix} m_{xu0} \\ m_{xd1}+m_{xd0} \end{bmatrix} \tag{6}$$

With equation (4)、(5) and (6), the coefficient matrix T can be obtained:

$$T = \begin{bmatrix} ((a_{xu1}-a_{xu0})+j*(b_{xu1}-b_{xu0}))/m_{xu1} & ((a_{xu2}-a_{xu0})+j*(b_{xu2}-b_{xu0}))/m_{xd1} \\ ((a_{xd1}-a_{xd0})+j*(b_{xd1}-b_{xd0}))/m_{xu1} & ((a_{xd2}-a_{xd0})+j*(b_{xd2}-b_{xd0}))/m_{xd1} \end{bmatrix} \tag{7}$$

Then the initial residual unbalance can be obtained as:

$$\begin{bmatrix} m_{xu0} \\ m_{xd0} \end{bmatrix} = T^{-1} \begin{bmatrix} a_{xu0}+j*b_{xu0} \\ a_{xd0}+j*b_{xd0} \end{bmatrix} \tag{8}$$

Using GNF to Restrain Unbalance Response when a Traditional Balance is Performed

Sometimes, to increase balance efficiency, it is necessary to reduce operation times in a balance procedure. But without any dynamic balance at low rotation speeds, it is often hard to run to a high speed. So an unbalance control algorithm, such as GNF, for an AMB rotor is helpful to its dynamic balance efficiency if the rotor can run directly to a higher speed to perform its first dynamic balance. The method introduced above can be used to identify rotor unbalance and so can help to balance a rotor according to unbalance distribution data obtained.

It is also possible to combine GNF with the traditional Influence Coefficient Method, namely the second method. The process implies that the behavior of a rotor system is linear. The balance procedure is very simple. First directly run a rotor to a designed speed with GNF working. Other steps are just the same as that in the Influence Coefficient Method. More detail will be introduced in a later example.

Using GNF in Dynamic Balance of the AMB Rotor

Because the residual unbalance of the setup rotor with the plate is large, to increase operation efficiency, GNF method is tried to be used for the dynamic balance of the AMB rotor. Generally, for such a rotor, it is hard to run it to a high rotation speed without several times of careful balance at different rotation speeds. The dynamic balance of the setup rotor is influenced by some vibration mode from the structure of the system. It can be seen in the identification plot of one DOF of the rotor in Fig. 3.. The plot is corresponding to a force to displacement transfer function corresponding to one radial bearing. In the plot, there is a marked peak around 20 Hz. The peak is caused by a structure mode. Without suitable dynamic balance, it is hard to run the rotor above 20 Hz, and the self-excited vibration will make it collide to the backup bearings when it runs nearby 20 Hz.

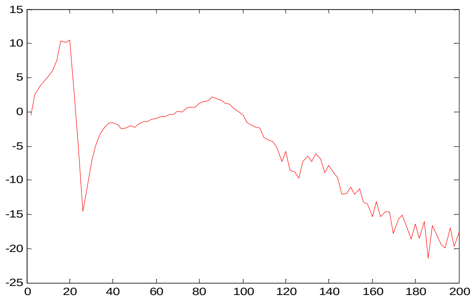

Fig. 3. the force to displacement transfer function of one radial bearing in the setup

But a careful dynamic balance below 20 Hz doesn't perform well when the rotor speed is increased. The low speed dynamic balance even deteriorates synchronous performance of the rotor at a higher speed. This had been proved by some field dynamic balance experiments when a high performance dynamic balance machine was used to balance the rotor. Running the rotor to a much higher speed than 20 Hz and decreasing the influence of the structure mode is an effective way to measure and reduce the real residual unbalance of the rotor.

Because GNF method can restrain the rotor synchronous vibration at a subcritical rotation speed, with the algorithm working, it is possible to directly run the rotor to a high rotation speed without careful dynamic balance. Then the dynamic balance times can be reduced and the balance efficiency can be improved. Unbalance information can be taken from sine and cosine coefficients of the algorithm after it converges as the first method discussed above. The correlative experiments are done at 1740 rpm, and the detail results are omitted to save space. The effect of the method is good. After only one balance procedure, the initial unbalance vector was reduced from $[-0.95+j*2.3\ \ 0.96+j*0.21]^T$ to $[0.11-j*0.075\ \ 0.06-j*0.012]^T$.

It is also attractive to use GNF algorithm to increase dynamic balance efficiency of the rotor by the second method discussed above. A dynamic balance exercise was performed to test this method at 2400 rpm. At first, the initial synchronous vibration measured by the displacement sensors of x-plane was recorded by a synchronous sampling system. Then a test mass was added to some special angle in the upper balance plane, and a new synchronous vibration was recorded. After that, a test mass was added to the down balance plane, and another synchronous vibration was recorded. With the data recorded, an influence coefficient matrix was calculated as what was done in a traditional Influence Coefficient Method. The experimental results were good and are omitted to save space.

Effective of GNF and LMS Methods

GNF method and LMS method were first tested separately in the high speed rotor system. Experiment results showed that they were suitable for different rotation speed range. With LMS method used, the synchronous currents of the AMBs could be reduced markedly when the rotor ran far above its rigid critical speed. But it couldn't be used when the rotor ran below or near its critical speed, or the AMB rotor would lose its stability.

GNF method can be used at both a subcritical and a supercritical speed. The plot in Fig. 4. shows a rotor trajectory recorded in the rotor's upper sensor plane at a subcritical rotation speed of 15 Hz. The dotted curve is corresponding to the controller without GNF working and the solid one to the controller with GNF working. It is clear that GNF was helpful to restrain the synchronous vibration of the rotor when it ran at a subcritical rotation speed.

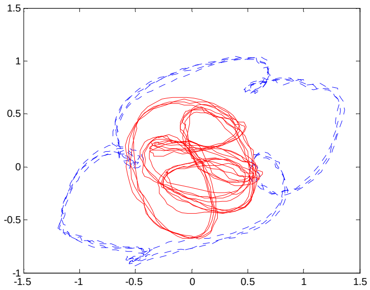

Fig. 4. rotor trajectory in the upper sensor plane at a rotation frequency of 15 Hz

But the GNF SISO algorithm's effect was not as good as that of LMS when the rotor ran at a supercritical speed for a model accuracy reason. So combining the two methods into a single controller and using them to deal with unbalance control problem at two different frequency ranges respectively was possible and valuable. The new unbalance controller was hoped to be helpful to achieve better performance compared with a controller with only one method used.

Combine GNF and LMS in an Unbalance Controller

For successful combination of the two methods, a suitable switching of the two algorithms at a special rotation speed is important. Simulation and experiment results showed that a direct switching without any transition consideration would make the rotor vibration increased markedly in a short time. It was harmful for the running of the rotor. A simple but suitable switching process control method was found and used for the switching of the two algorithms.

In fact, a vibration burst would possibly happen when an unbalance control algorithm begin to work. It is usually coming from the output discontinuity of the unbalance control algorithm. So a careful selection of the initial amplitudes of the sine and cosine components of the algorithm output is very important. Suppose the amplitude of the sine and cosine components of GNF is achieved before the algorithm switching, they would be very suitable initial values of the corresponding parameters in LMS. Then a good method for algorithm switching is obtained. When the rotor runs from a low speed to the designed switching speed of the two algorithms, the amplitude of the sine and cosine components of GNF can be recorded before the algorithm switching, and used as the initial values of $w_1(k)$ and $w_2(k)$ in LMS. With the suitable initial $w_1(k)$ and $w_2(k)$, a large vibration burst would not happen. On the contrary, when the rotor runs from a high speed to the designed switching speed, the recorded data could be restored in the GNF algorithm and a smooth switching could be achieved.

With the method used, GNF and LMS algorithm can be successfully combined into a single unbalance controller and can play their role at different rotation speed ranges respectively. Experiment results showed that good unbalance vibration suppression performance at the whole running process of the rotor system was obtained. In Fig. 5., the displacement of one DOF of the upper bearing and the corresponding current of one coil are shown. The rotor was running from a high speed to a switching speed of 300 Hz. It is seen that the synchronous displacement amplitude corresponding to LMS is obviously smaller than that of GNF as well as the corresponding bearing currents. When the algorithm switching was activated, no obvious vibration burst happened.

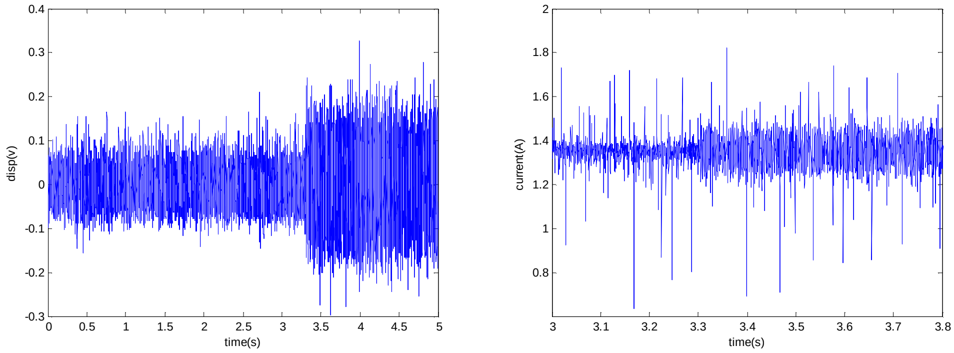

Fig. 5. displacement of one DOF of the upper bearing and the corresponding current of one coil

Summary

Because of the structure mode of the rotor system, a general dynamic balance procedure was not suitable for the rotor. GNF was used to help the rotor to run to a suitable balance speed and it increased the dynamic balance efficiency with two different methods. Experiment results showed, when GNF and LMS methods were applied to the high speed rotor supported by AMBs to decrease its unbalance response, they were suitable for different rotation speed ranges respectively. So GNF and LMS methods were combined in a single unbalance controller and performed in different speed ranges. To achieve a smooth switching of the two methods and avoid a vibration burst, the simple but effective method was used. A better unbalance cancellation effect for the rotor in a large rotation speed range was achieved.

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