A smooth switch between different unbalance control parameters in rotor systems with active magnetic bearings

Kai ZHANG*, JiuchaoYIN* and Xingjian Dai*
*Dept. of Engineering Physics, Tsinghua University
Beijing,100084, China
E-mail: zhangkai@mail.tsinghua.edu.cn

Abstract
Unbalance control is necessary for rotor systems with active magnetic bearings (AMBs), especially for vibration sensitive applications such as flywheels and turbo molecular pumps. When a special unbalance control method is used in an AMB rotor system, its key feedback parameters such as gain matrix parameters are usually closely related to the AMB model, which changes with the rotation speed of the rotor. For simplicity and convenience, the feedback gain parameters can keep constant in a special speed range and change to different new constant values when the rotation speed enters a close range. It is also possible to use a special method in the previous speed range and use another method in the close range. The switch between unbalance control algorithms needs a suitable method to ensure the stability and smoothness of a switch process. Different switch methods including a direct switch method, a linear switch method and an overlying switch method are introduced and verified in a flywheel system with AMBs. Their effects in switching between two General Notch Filter matrices were verified by simulation and experiments. The simple overlying switch method proved its performance and achieved a very stable and smooth algorithm switch.

Keywords : Active magnetic bearing, Unbalance control, Algorithm switch, Flywheel, Vibration

1. Introduction

For a high speed rotor supported by active magnetic bearings (AMBs), residual unbalance in the rotor greatly influences the stability of the system. The magnetic bearings of the rotor can work in a special way and let the rotor run about its mass center (Schweitze, et al., 1994). Then the unbalance force from the rotor to the bearing stators can be decreased markedly and the rotor can run at a force-free way. Such methods are attractive for vibration sensitive application such as flywheels (Filatov, et al., 2006) and turbo molecular pumps (Zhang, et al., 2011).

Many methods have been developed to achieve such a force-free operation. When a classical method is applied to the rotor, an additional feedback channel from the input of the AMB controller is first built. In the channel, the unbalance control algorithm observes the residual synchronous components in the input of the AMB controller (displacement error) and it produces a compensation signal according to the error and adds it to the reference signal of the AMB controller through the output of the channel. The compensation signal has the same amplitude and the opposite phase with the synchronous components in the displacement signals. When it is added with the displacement signal, the result signal is used as a new input for the controller. Then the synchronous components are removed from the control currents of bearings, and accordingly, the unbalance reaction forces in the bearing forces are removed.

In the feedback channel, a key component is a feedback matrix; it can be obtained according to the system model such as the General Notch Filter (GNF) (Herzog, et al., 1996), or calculated on-line by an adaptive method such as the Least Mean Square (LMS) method (Zhao, et al., 2000). For a rigid rotor, some methods can be used in the whole rotation speed range and some others can be only used when the rotor speed is above its rigid critical speed.

For the GNF method, the feedback matrix is calculated according to sensitive transfer functions of a system and the characteristics of the transfer functions change with frequencies. So its optimal feedback matrix is different when the rotor runs at different rotation frequencies. It is especially not convenient to use when the system model is changed obviously by some factors, such as gyroscopic effects.

There is another unbalance control method called AVC (Active Vibration Control) method (Betschon, et al., 2000). It is closely related to the GNF method, but its synthesis techniques are more straightforward. For such a method, Betschon developed a gain-scheduled AVC to achieve an effective unbalance control within a wide rotation speed for a rotor. To minimize memory and computational requirements imposed on hardware, a gain matrix used in the AVC algorithm was synthesized as functionally dependent upon the rotation speed with only the diagonal elements varying linearly with speed. The parameters were chosen carefully to ensure the stability of the gain-scheduled algorithm and the rotor tested was not very gyroscopic.

For the GNF and similar methods, a much simpler way is that only several constant feedback matrixes are chosen and used in different rotation speed ranges respectively. When the rotor speed reaches a designed rotation speed, the feedback matrix will switch from the one suitable for the rotor below the speed to the other one suitable for the rotor above the speed. In a direct switch, the system stability is influenced. A smooth switch is needed.

If the GNF method is used for a low speed range and the LMS method is used for a supercritical speed range, the stability of the system should also be kept for the algorithm switch between the GNF feedback channel and the LMS feedback channel.

In an AMB flywheel system, different switch methods between two GNF matrices were checked by simulation and experiments. It was shown that the performance of a direct switch method was acceptable but not smooth and the performance of a linear switch method was good but the switch stability couldn't be ensured previously. An overlying switch method could provide a very stable and smooth matrix switch process. In the overlying switch method, when the controller switched from a working algorithm (previous algorithm) to a new algorithm, the controller made use of the converged compensation results of the previous algorithm, worked at a much lower unbalance level and the impact of the algorithm switch could be reduced effectively.

Though detail results were not provided here, it had also been verified by experiments that a stable and smooth switch between the GNF output and the LMS output could be obtained by the overlying switch method in the flywheel system.

2. LMS method

LMS(least mean square) is an effective method for unbalance control of AMBs (Zhao, et al., 2000). When the LMS algorithm works, it modifies its gain parameters every sample time by a momentary gradient method and it has a synthesis structure as shown in Fig. 1, where $d(k)$ is a vibration signal; $y(k)$ is a compensation signal; $e(k)$ is a signal after compensation; $w_1(k)$ and $w_2(k)$ are Fourier coefficients for the compensation signal; f_s is a sampling frequency and f is a rotation speed in Hz; k is the sampling sequence number.

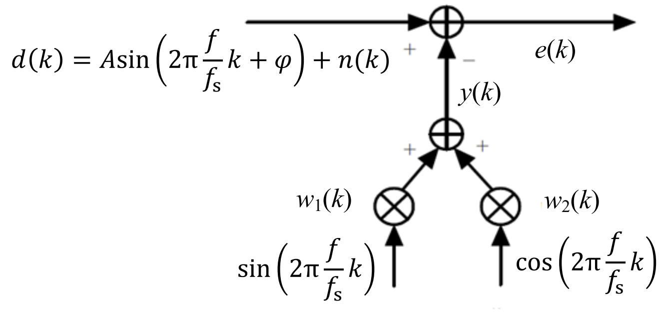

Fig. 1 Synthesis structure of the LMS algorithm.

An object function is defined as $J(\underline{w})=e^2(k)$, where $e(k)$ is defined as Eq. (1).

$$e(k)=d(k)-\underline{w}^{T}(k)\underline{x}(k) \tag{1}$$

$$\underline{w}(k)=[w_1(k) \quad w_2(k)]^{T} \tag{2}$$

$$\underline{x}(k)=[\sin(2\pi * f * k/f_s) \quad \cos(2\pi * f * k/f_s)]^{T} \tag{3}$$

The parameters are updated based on Eq. (4) by using the temporary gradient, where the c is a factor for adjusting.

$$\underline{w}(k+1) = \underline{w}(k) - c\,\Delta_{\underline{w}}\{J(\underline{w})\} = \underline{w}(k) + 2ce(k)\,\underline{x}(k) \tag{4}$$

The LMS method works based on Eq. (1) and (4). It can be used with little knowledge of model parameters of a system, but it can be used only at a supercritical speed range for a rigid rotor.

3. GNF (General Notch Filter) method

General Notch Filter (GNF) is another important developed method about unbalance control of AMBs (Herzog, et al., 1996). Compared with the LMS method, it can be used in almost all speed range for a rigid AMB rotor, but detail information about the close loop system is needed. The structure of the GNF is shown in Fig. 2.

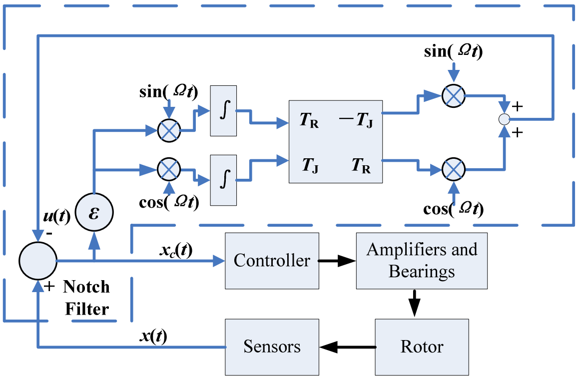

Fig. 2 Generalized Notch Filter structure.

The key of the GNF is obtaining a gain matrix A_N as below (n_s is number of sensors):

$$A_N = \begin{bmatrix} T_R & -T_J \\ T_J & T_R \end{bmatrix} \qquad (n_s \times n_s) \tag{5}$$

The equivalent transfer function of the GNF in Fig. 2 is as Eq. (6).

$$N(s) = \frac{s^2 + \Omega^2}{Is^2 + \varepsilon T_R s + \Omega^2 I - \varepsilon \Omega T_J} \tag{6}$$

$N(s)$ represents the whole MIMO system with the GNF included and it is equal to zero for $s = \mathrm{j}\Omega$ no matter how T_R and T_j are chosen. Parameter values of ε, T_R and T_J are very important. The stability of the system is decided by the parameter selection. The selection method is detailed presented by Herzog in (Herzog, et al., 1996).

For an AMB rotor, using the same gain matrix within its whole rotation speed range is usually not suitable and the AMB stability can't be ensured. But a gain-scheduled algorithm whose gain matrix parameters changed according to rotation speeds is too complex and expensive.

4. The flywheel with AMBs

The flywheel used to discuss the unbalance control algorithm switch problem here is a prototype reaction wheel for aerospace applications. Its structure is shown in Fig. 3.

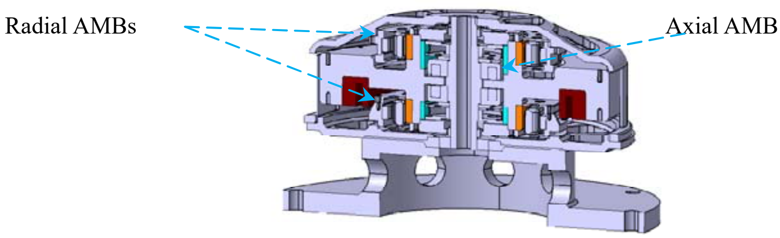

Fig. 3 Structure of the flywheel system.

It is developed to replace a system supported by conventional ball bearings for attitude control. The flywheel is sensitive to residual unbalance force transferred from its rotor to the stator structure. There is a critical acceleration vibration level limit for the system. The main vibration comes from synchronous vibration excited by residual unbalance of the rotor. It is difficult to effectively reduce the vibration simply by a high-accuracy dynamic balance. When the rotor runs at a high rotation speed, a more effective way for reducing the synchronous vibration is using unbalance control methods.

The main parameters of the flywheel system are as Table 1.

Table 1 Parameters of the flywheel.

Parameter	Value
Bearing Bias Current I_0(A)	0.5
Rotor Mass m(kg)	5.4
Maximum Rotation Speed Ω(rpm)	30000
Bearing Gap g_a (mm)	0.25
Backup Bearing Gap g_b (mm)	0.15
Radial Bearing Carrying Capacity f_{radial}(N)	120
Axial Bearing Carrying Capacity f_{axial}(N)	130
Polar Inertia J_p(kg.m2)	0.027
Transverse Inertia J_d(kg.m2)	0.014

To obtain accurate dynamic behaviors of the flywheel rotor, finite element analysis (FEA) is performed for it. In the FEA model, the rotor is supported by two radial ground springs at the centers of the two radial AMBs respectively. The spring stiffness is set to 1000 N/mm. Rotor dynamic analysis results show that the first bending frequency of the rotor is above 6000 Hz, the axial vibration mode of the rotor is near 5000 Hz and they are far above the highest rotation frequency of the rotor. So the rotor can be seen as rigid within its operation speed range. Its Campbell diagram is shown in Fig. 4. The rotor's polar-to-transverse inertia ratio is near 1.9 which is a very large value. The frequencies of the lateral vibration modes are markedly influenced by gyroscopic effects, especially the nutation and the precession of the rotor. In Fig. 4, it is seen that, due to the strong gyroscopic effects, the nutation frequency is about 1.9 times the rotation frequency when the rotor runs at a high rotation speed.

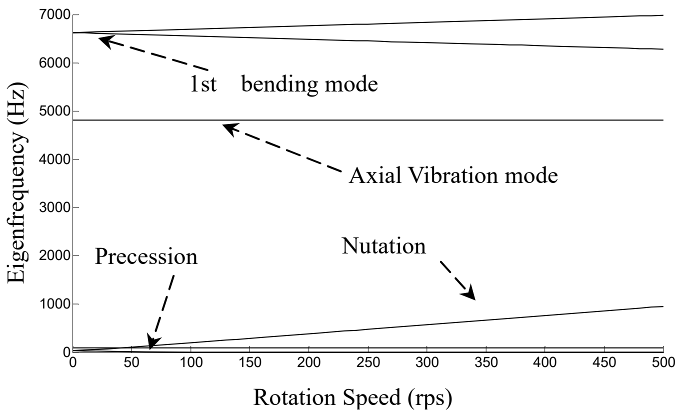

Fig. 4 Campbell diagram of the flywheel rotor.

In an AMB rotor system like the flywheel, the rotor has to pass its rigid critical speeds to reach a high operation speed. The LMS method can't be used during the whole operation process and it destroys stability of AMBs when rotors run below the rigid critical speeds. The GNF method and similar methods can work in a whole rotation speed range. But for the methods, their feedback matrices are calculated according to sensitive transfer functions of AMB systems and the frequency characteristics of the transfer functions change with frequencies. So their optimal feedback matrices are different when rotors run at different rotation frequencies. For the GNF method, the control algorithm will be simple if only one matrix is used in a whole rotation speed range. It is hard to find such a matrix especially when the rotor dealt with has obvious gyroscopic effects. A compromise way is to divide the whole speed range into several speed zones and choose suitable matrices for them respectively. For specially chosen discrete speeds Ω_k, if n number of

Ωs are chosen, k = 1, 2, 3 … n, the optimal gain matrix A_k can be calculated and saved previously. A gain matrix between these speeds can be calculated by interpolating the corresponding neighbor optimal gain matrices. The procedure is complex in calculation and requires much memory space for the flywheel system. It is not easy to find a method to reduce the number of gain matrices and increase the calculation effects.

5. Smooth switch of unbalance algorithms

When the GNF method is used in a wide rotation speed range composed of several smaller ones, if several constant feedback matrixes are chosen and directly used in the corresponding speed ranges without matrix interpolation, the calculation requirement will be decreased markedly. But when the rotor runs to a designed rotation speed, the feedback matrix will switch from the one suitable for the lower speed to the other one suitable for the higher speed. In such a matrix switch, the system stability is influenced. A smooth switch is needed. Besides using between two GNF matrices, switch methods are also needed when the algorithm switches between a GNF operation and a LMS operation.

Compared with the direct switch, there are different switch methods for such an algorithm switch including a linear switch method and an overlying switch method.

The direct switch method is the simplest one and it directly switches from the output of one GNF matrix to another one matrix when the rotation speed reaches a switching point. Its structure can be seen in Fig. 5.

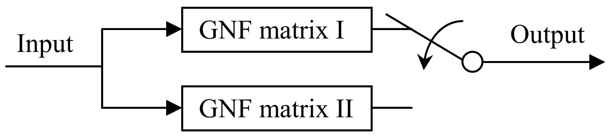

Fig. 5 Structure of the direct switch method.

The linear switch method switches linearly from the output of one GNF matrix to another one as Eq. (7). The linear calculation is simple. But the stability of the switch process can't be ensured previously.

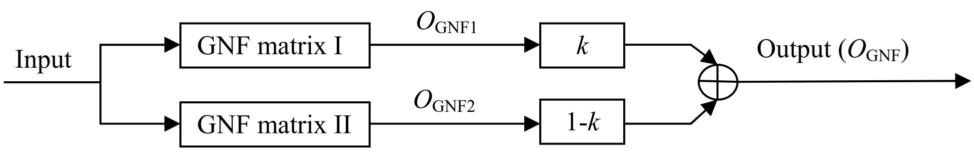

Fig. 6 Structure of the linear switch method.

$$\begin{cases} O_{GNF}=k*O_{GNF1}+(1-k)*O_{GNF2} \\ k=1, \quad \Omega<\Omega_1 \\ k=(\Omega-\Omega_1)/(\Omega_2-\Omega_1), \quad \Omega_1<\Omega<\Omega_2 \\ k=0, \quad \Omega>\Omega_2 \end{cases} \tag{7}$$

The structure of the overlying switch method is shown as Fig. 7.

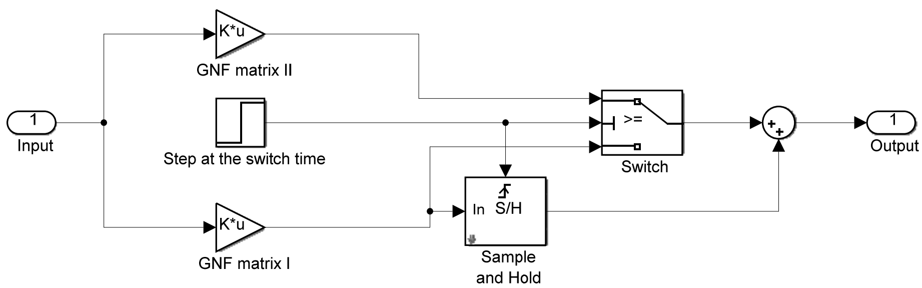

Fig. 7 Structure of the overlying switch method.

In the overlying switch method, when the controller switches from one GNF matrix (Matrix I) to another one matrix (Matrix II), the controller makes use of the converged compensation results of the Matrix I. The output of the Matrix I is kept unchanged (constant output I) and the integrator for the matrix is reset to zero. When a new displacement signal comes after that, it is first subtracted by the constant output I and then sent to the Matrix II. The Matrix II begins to work at a much lower unbalance level and the impact of the algorithm switch can be reduced effectively. It is simple but performs well.

Similarly, the switch methods can also be used to switch from one kind of working algorithm to another kind of algorithm, for example, from the GNF to the LMS or vice versa.

6. GNF gain matrices switching simulation

To compare the performance of the different switching methods, a simulation model for the flywheel rotor based on Simulink was built as shown in Fig. 8. For simplicity, the axial degree was not included in the model and only the four radial degrees were considered. In the model, “y” was the radial displacement signal with a sinusoidal disturbance, “c” was the output of the unbalance control module and “e” was the error between y and c.

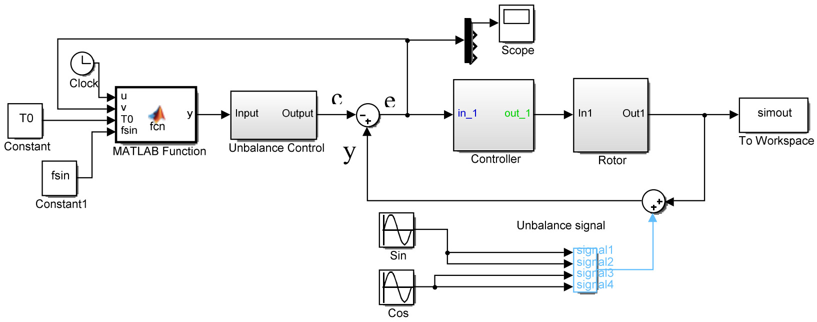

Fig. 8 Simulation model of the flywheel system.

Initially, four sinusoidal unbalance signals with different phases and a frequency of 70 Hz were used to simulate a rotor unbalance and added to the AMB displacements. The GNF algorithm in the system didn’t work at first. The rotor kept running at a rotation speed of 70 rps. After the simulation had run for 0.2 seconds, the GNF module began to work with a GNF matrix (Matrix I) and the compensated displacement signals converged to near zero soon. At 0.8 second, the unbalance control module directly switched from the Matrix I to another GNF matrix (Matrix II). One curve of the error signal e was shown in Fig. 9. It was seen in Fig. 9 that the error signal e jumped rapidly after the switch was triggered. Though the error converged soon after the switch, the increased vibration influenced the stability of the rotor.

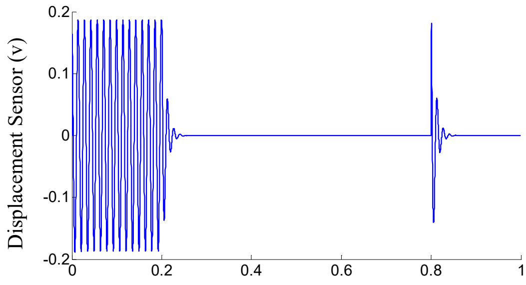

Fig. 9 One curve of the error signal e for the direct switch method.

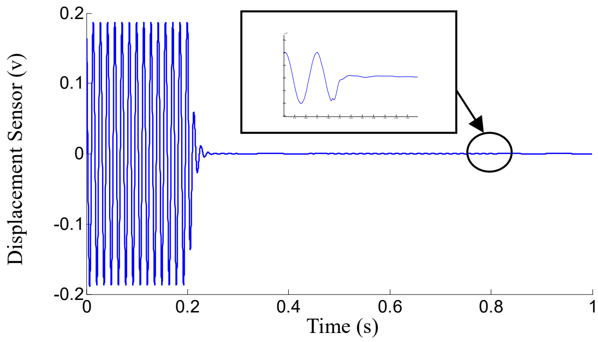

Fig. 10 One curve of the error signal e for the overlying switch method.

When the overlying switch method was used, the corresponding error signal curve was shown in Fig. 10. When the module with the GNF Matrix I began to work at 0.2 seconds, the error signal converged from about 1.9 to 0.19 soon. When the GNF matrix switch happened at 0.8 seconds, the error further converged to a much smaller value. During the process, no error jump happened and the switch was smooth.

7. Experimental results

The switch methods were tested on the flywheel system based on the GNF method. For simplicity, only two GNF matrices (the Matrix I and the Matrix II) were used to test the switch effects. When the rotor ran below 140 rps, the Matrix I was used to calculate the output of the GNF algorithm and the matrix could ensure the system stability in a speed range below 150 rps. When the rotor ran above 140 rps, the Matrix II was used and it could ensure the system stability in a speed range above 130 rps.

In the first experiment, when the fly rotor speeded up to 140 rps, the unbalance control algorithm used changed its GNF matrix from the Matrix I to the Matrix II directly. The switch process data corresponding to the displacement of one radial axial degree was shown in Fig. 11.

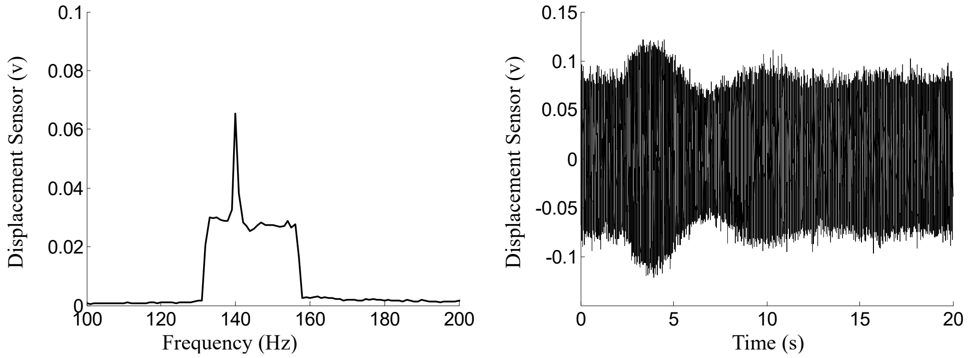

Fig. 11 Direct switch process data corresponding to the displacement of one radial axial degree.

In the left part of Fig. 11, the curve was the FFT peak-hold data of the displacement recorded when the rotor ran from the speed of 135 rps to 155 rps. It was seen that there were an obvious jump in the peak-hold curve when the speed reached 140 rps. When the switch happened, the displacement curve was shown as the right part of Fig. 11. The switch was successful but not smooth.

In the second experiment, the linear switch method was used and the switch process data was shown as Fig. 12. When the rotor speeded up from 140 rps to 145 rps, the unbalance algorithm switched linearly from the output of the GNF Matrix I to the GNF Matrix II as Eq. (7). The switch was stable and smooth. But the stability of the switch process couldn't be ensured previously when the switch rotation speed changed to another one.

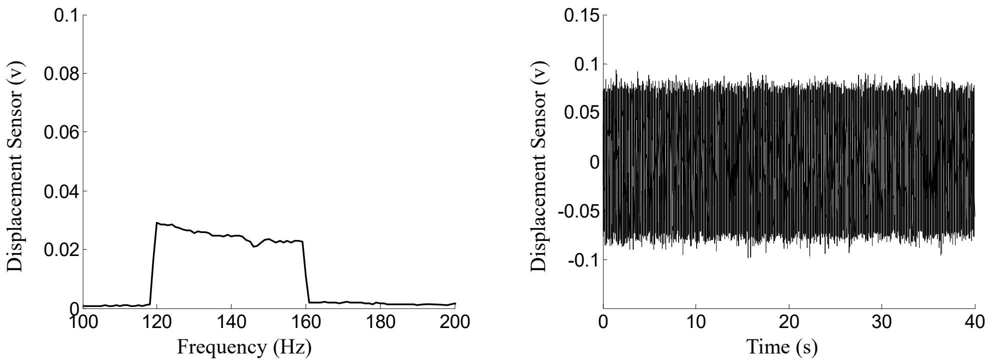

Fig. 12 Linear switch process data corresponding to the displacement of one radial axial degree.

In the third experiment, the overlying switch method was used and the switch process data was shown as Fig. 13. When the rotor speed reached140 rps, the unbalance control algorithm changed its GNF matrix from the Matrix I to the Matrix II by the overlying switch method. The switch was so stable and smooth that it was hard to detect in the curves.

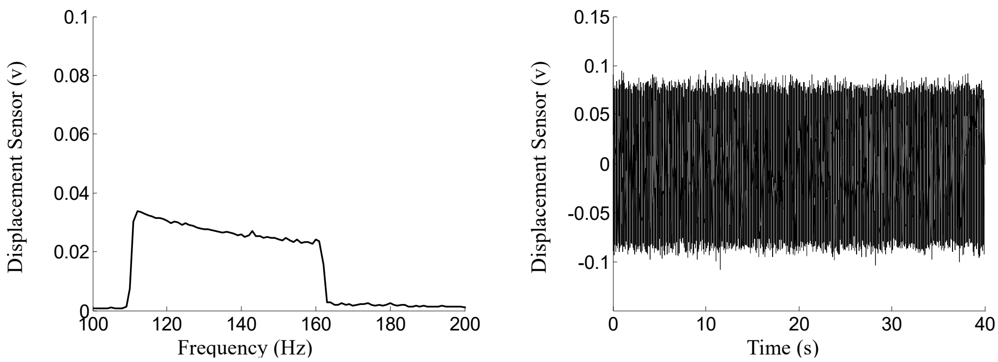

Fig. 13 Overlying switch process data corresponding to the displacement of one radial axial degree.

Though the experimental results were not provided here, it had also been verified by an experiment that a stable and smooth switch between the GNF output and the LMS output could be obtained by the overlying switch method in the flywheel system.

8. Conclusion

To simplify the application of the unbalance control methods such as the GNF method and LMS method in AMB systems, different switch methods were introduced and compared. The methods could be used to switch between two GNF matrices or between two different unbalance control algorithms according to the rotation speed. They included the direct switch method, the linear switch method and the overlying switch method. Their effects were verified in the AMB flywheel system by the simulation and the experiments. The simple overlying switch method was proved to have the best performance. It achieved a very stable and smooth unbalance control algorithm switch.

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