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RESEARCH ARTICLE

Review on Active Vibration Control Method of Magnetically Suspended System

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ABSTRACT Recently, magnetic bearings have been widely used in inertial actuators of spacecraft. Aiming at the problem of unbalanced vibration in magnetically suspended system, the research status of active vibration control method is described in detail. Firstly, the structure and working principle of magnetically suspended system are introduced, and the causes of unbalanced vibration are expounded. Then, the research status of active vibration control methods at home and abroad is introduced from two aspects of synchronous vibration and harmonic vibration, and the advantages and disadvantages of each control method are summarized. Finally, the future development trend of active vibration control technology for magnetically suspended system is prospected.

INDEX TERMS Active vibration control, unbalance vibration, magnetically suspended system, synchronous vibration.

I. INTRODUCTION

With the development of space missions, magnetic bearings with advantages of high speed, active control, no friction and long life have been widely used in inertial actuators of spacecraft. By magnetically suspended technology, the rotor is suspended without contact [1], [2], [3].

Although magnetically suspended inertial actuators has the above advantages, when the rotor rotates at high speed, the uneven mass distribution of the material and installation errors will lead to the existence of rotor mass imbalance. As a result, the center of mass and geometric center of the rotor do not coincide, and there is an offset and deflection between the geometric axis and the inertial axis, resulting in synchronous vibration when the rotor rotates at high speed. The mass unbalance of rotor is divided into static unbalance and dynamic unbalance [4], which will produce synchronous vibration force and torque [5]. They are transferred to the spacecraft platform, which will seriously affect the pointing accuracy and ultraagile maneuvering performance of the spacecraft. Therefore, it is necessary to suppress the unbalanced vibration in the magnetically suspended rotor.

II. INTRODUCTION OF MAGNETICALLY SUSPENDED ROTOR SYSTEM

Magnetically suspended control sensitive gyroscope (MSCSG) is a typical magnetically suspended rotor system. Full active magnetic bearing is used to control the axial and radial suspension of the rotor, and Lorentz force magnetic bearing (LFMB) is used to control the two-degree-of-freedom tilt of the rotor [6], [7], [8]. Taking MSCSG as an example, the structure and working principle of magnetically suspended rotor system are introduced.

As shown in Figure 1, MSCSG is mainly composed of gyro room, radial magnetic bearing, axial magnetic bearing, LFMB, rotor system, drive motor, displacement sensor and so on. The radial magnetic bearing controls the radial two-degree-of-freedom (2-DOF) suspension and axial magnetic bearing controls the axial suspension with one DOF. LFMB mainly controls the 2-DOF tilt of the rotor and the high-speed rotation is controlled by a drive motor. The closed-loop control system of MSCSG is shown in Figure 2. The eddy current

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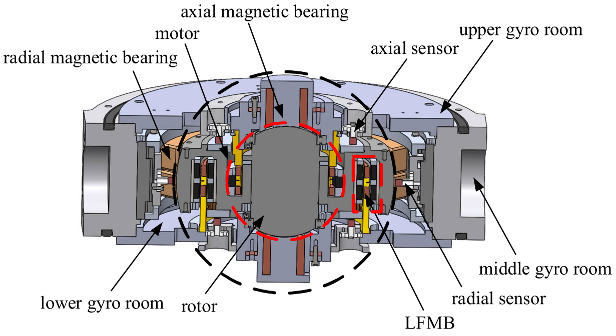


FIGURE 1. The structure of MSCSG.

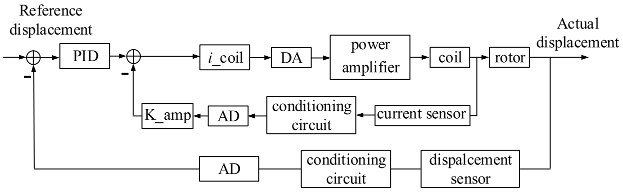


FIGURE 2. The closed-loop control system of MSCSG.

displacement sensor is used to detect the actual displacement of the rotor, and the detected voltage signal is adjusted by the conditioning circuit to protect the DSP chip, which is input signal of PID controller after A/D conversion and the control signal is obtained. The control signal enters the current ring, and the control current is obtained through the power amplifier. After entering the magnetic bearing coil, the magnetic field force is generated to control the rotor. And then, the real-time current is detected by the current sensor. The parameters of the current ring are adjusted according to the rotor's state information detected by the sensor, and the current of coil is adjusted, so that the rotor is suspended in the equilibrium position.

III. ACTIVE VIBRATION CONTROL METHOD OF MAGNETICALLY SUSPENDED SYSTEM

A. PRINCIPLE OF UNBALANCED VIBRATION GENERATION IN MAGNETICALLY SUSPENDED SYSTEM

Studies have shown that rotor unbalance is the main vibration source of magnetically suspended system [9]. The unbalance vibration mainly includes the synchronous and harmonic vibration introduced by mass unbalance and sensor runout. When the rotor rotates at high speed, the uneven distribution of material mass and machining errors will lead to the rotor mass imbalance. As a result, the center of mass and geometric center of the rotor do not coincide, and the inertia spindle does not coincide with the geometric axis, resulting in the same frequency vibration with the rotor speed. The mass unbalance of rotor can be divided into static unbalance and dynamic unbalance. As shown in Figure 3, static unbalance caused by the non-coincidence of the center of mass and geometric center will generate synchronous vibration force. The dynamic unbalance caused by the non-coincidence of the inertial axis and the geometric axis will produce synchronous vibration torque.

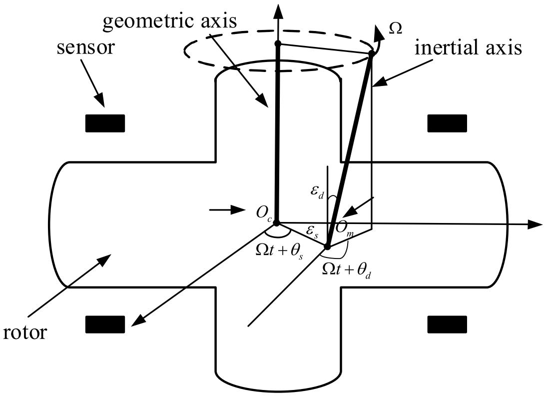


FIGURE 3. The rotor mass unbalance of magnetically suspended system.

As can be seen from Figure 3, the static unbalance and dynamic unbalance of the rotor can be expressed as:

$$\begin{cases} \Theta_x = \varepsilon_s \cos(\Omega t + \theta_s) \\ \Theta_d = \varepsilon_d \cos(\Omega t + \theta_d) \end{cases} \tag{1}$$

where, Θ_x and Θ_d are the rotor static unbalance and dynamic unbalance respectively, ε_s and θ_s are the eccentricity and initial phase between the center of mass and the geometric center respectively, ε_d and θ_d represent respectively the eccentricity and initial phase between the inertial axis and the geometric axis, Ω is the rotor speed. smooth circle, as shown in Figure 4. When the rotor starts to rotate, the irregular rotation curve also starts to rotate at the speed, resulting in periodic interference, that is, sensor runout. Therefore, the output signal of the displacement sensor will contain synchronous and harmonic components, which can be expressed in the form of Fourier series:

$$d_x = \sum_{k=1}^{n} a_k \cos(k\Omega t + b_k) \tag{2}$$

where, d_x is the harmonic component contained in the sensor output signal caused by sensor runout, a_k and b_k are the amplitude and initial phase of the harmonic component respectively. From Equation (2), it can be seen that the sensor runout will not only generate synchronous vibration ($k = 1$), but also generate harmonic vibration ($k = 2, 3, 4 \ldots$).

Firstly, the translational electromagnetic force model of a magnetically suspended rotor system affected by unbalanced vibration is established. In MSCSG, the radial suspension of rotor is realized by the radial magnetic bearing. The electromagnetic force model generated by the MSCSG radial bearing can be expressed by the following formula:

$$F_x = k_i \cdot i_x + k_s \cdot X_x \tag{3}$$

where k_i is the current stiffness coefficient, k_s is the displacement stiffness coefficient, i_x is the coil current of the radial X-channel, X_x is the ideal displacement of the rotor system.

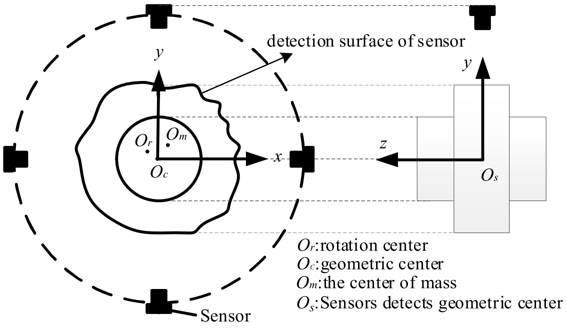


FIGURE 4. **Schematic diagram of sensor.**

The above formula is the ideal electromagnetic force generated by the radial magnetic bearing, but when the rotor rotates at high speed, due to the existence of mass imbalance and sensor runout, it will induce synchronous and multifrequency vibrations caused by the mass unbalance and sensor runout, which will affect the accuracy of the rotor radial suspension. Therefore, it is necessary to establish the dynamic modeling of MSCSG with mass unbalance and sensor runout as shown in Figure 5.

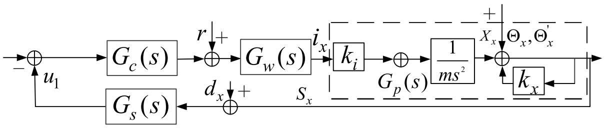


FIGURE 5. **Modeling of force with mass unbalance and sensor runout in magnetically suspended system.**

From Figure 5, the relationship between the actual output displacement of the rotor and the ideal displacement of the rotor system is:

$$S_x = X_x + \Theta_x + d_x \tag{4}$$

After introducing imbalance vibration, the control current can be expressed as:

$$i_x = (X_x + \Theta_x + \Theta_x' + d_x) \cdot G_s(s) \cdot G_c(s) \cdot G_w(s) \tag{5}$$

where S_x is the actual output displacement of the X-direction sensor, X_x is the ideal displacement of the X-direction sensor, $G_c(s)$ is the transfer function of the controller, $G_w(s)$ is the transfer function of the power amplifier, $G_p(s)$ is the transfer function of the rotor radial control system. Therefore, the dynamic model of magnetically suspended rotor with imbalance vibration can be expressed as:

$$\begin{aligned} F_x \approx k_i \cdot (X_x + \Theta_x + d_x) \cdot G_s(s) \cdot G_c(s) \\ \cdot G_w(s) + k_x \cdot (X_x + \Theta_x) \end{aligned} \tag{6}$$

It can be seen from Equation (6) that the control currents of the magnetically suspended rotor system contain not only the synchronous component caused by the mass unbalance, but also the synchronous and multifrequency components introduced by the sensor runout and nonlinear devices in these circuits.

Secondly, the electromagnetic torque model of magnetically suspended rotor system affected by unbalanced vibration is established. According to the tilt dynamic equation of MSCSG and the control principle of LFMB, it can be obtained:

$$\begin{cases} J_x\ddot{\alpha} + J_z\Omega\dot{\beta} = 4NBI_yL_r^2\varphi \\ J_y\ddot{\beta} - J_z\Omega\dot{\alpha} = 4NBI_xL_r^2\varphi \end{cases} \tag{7}$$

where, N represents the number of turns of the coil, I_x and I_y represent the control current of LFMB, B represents the magnetic field strength of LFMB, L_r represents the radius of stator skeleton, and φ represents the central angle corresponding to the coil. J_x, J_y and J_z are the moments of inertia of the rotor about each axis, α and β are the rotational angular velocity of the rotor about the X-axis and Y-axis respectively, Ω is the rotor speed.

Considering the rotor mass dynamic unbalance and sensor runout, rotor tilt angle detected by sensor can be expressed as:

$$\begin{cases} \alpha_r = \alpha + \alpha_d + \alpha_s \\ \beta_r = \beta + \beta_d + \beta_s \end{cases} \tag{8}$$

where, α and β are the rotor tilt angle under ideal conditions, respectively; α_r and β_r are the actual tilt angle with mass unbalance; α_d and β_d are the tilt disturbance angle caused by mass unbalance; α_s and β_s are the tilt disturbance angle caused by sensor runout.

Combined with (1) and (2), (8) can be further expressed as:

$$\begin{cases} \alpha_r = \alpha + \varepsilon_d \cos(\Omega t + \theta_d) + \sum\limits_{k=1}^{n} a_{dk} \cos(k\Omega t + \varphi_{dk}) \\ \beta_r = \beta + \varepsilon_d \sin(\Omega t + \theta_d) + \sum\limits_{k=1}^{n} a_{dk} \sin(k\Omega t + \varphi_{dk}) \end{cases} \tag{9}$$

According to Figure 6, after the tilt displacement signal detected by the sensor going through the controller and power amplifier, the synchronous and multifrequency disturbance current will be generated. Where, the harmonic current can be expressed as:

$$\begin{cases} I_{xs} = \chi_x \cos(\Omega t + \theta_d) + \sum\limits_{k=1}^{n} \eta_x \cos(k\Omega t + \varphi_k) \\ I_{ys} = \chi_y \sin(\Omega t + \theta_d) + \sum\limits_{k=1}^{n} \eta_y \sin(k\Omega t + \varphi_k) \end{cases} \tag{10}$$

where, $\chi_x^{\text{and}}\chi_y$ represent the coefficient of synchronous disturbance current, $\eta_x^{\text{and}}\eta_y$ represent the coefficient of multifrequency disturbance current, which is related to the rotor speed and increases with the increase of the rotor speed.

Substitute (7) into (10), it can be obtained that:

$$\begin{cases} M_x + (J_x - J_z)P = J_x\ddot{\alpha} + J_z\Omega\dot{\beta} \\ M_y + (J_y - J_z)Q = J_y\ddot{\beta} - J_z\Omega\dot{\alpha} \end{cases} \tag{11}$$

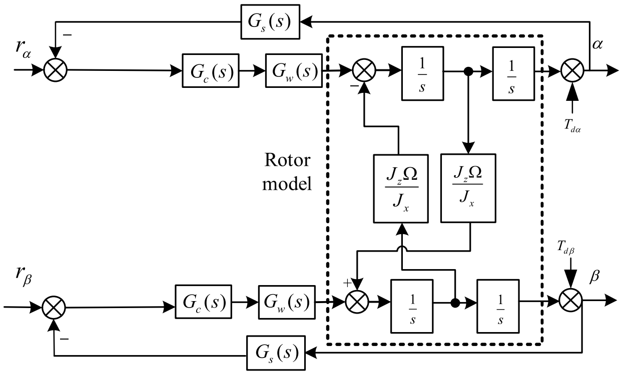


FIGURE 6. Modeling of torque with mass unbalance and sensor runout in magnetically suspended system.

$$\text{where}\begin{cases} P = \varepsilon_d\Omega^2\cos(\Omega t+\theta_d)+k^2\Omega^2\sum_{k=1}^{n}\eta_x \\ \qquad\cos(k\Omega t+\varphi_k) \\ Q = \varepsilon_d\Omega^2\sin(\Omega t+\theta_d)+k^2\Omega^2\sum_{k=1}^{n}\eta_x \\ \qquad\sin(k\Omega t+\varphi_k) \end{cases} \tag{12}$$

$$\text{Let}\begin{cases} M_{d\alpha} = (J_x-J_z)P \\ M_{d\beta} = (J_y-J_z)Q \end{cases} \tag{13}$$

As can be seen from (13), the unbalance vibration torque of MSCSG mainly consists of two parts, including synchronous vibration torque generated by rotor dynamic unbalance and multifrequency vibration torque generated by sensor runout.

B. CONTROL METHOD OF SYNCHRONOUS VIBRATION OF MAGNETICALLY SUSPENDED SYSTEM

In order to reduce the influence of synchronous vibration caused by the mass unbalance of the rotor on the magnetically suspended system, the above mentioned synchronous vibration can be actively suppressed by the advantage of active control of the magnetically suspended rotor.

As shown in Figure 7, active vibration control strategies are mainly divided into two categories, namely active balancing and unbalance compensation. Active balancing aims to reduce the harmonic component of the control current in the magnetic bearing system, so as to weaken the active control effect of the magnetic bearing and force the rotor to rotate around the inertial axis, in order to minimize the unbalance control force of the rotor. Therefore, the method is also called "zero-force" method, which is suitable for the occasions where the synchronous vibration force and torque need to be reduced. Unbalance compensation is to increase the control current by certain measures or compensation algorithm to enhance the active control effect of magnetic bearing, forcing the rotor to rotate around the geometric axis, so as to minimize the vibration displacement of the rotor. Therefore, this method is also called "zero displacement" method, which is suitable for rotating machinery and equipment requiring higher pointing accuracy [10].

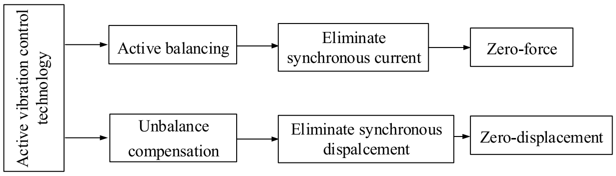


FIGURE 7. Classification of active vibration control methods.

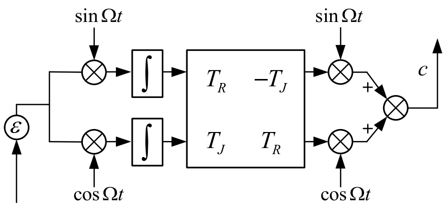


FIGURE 8. The generalized multivariable notch filter.

According to the difference of principle, synchronous vibration suppression method can be classified as synchronous vibration suppression algorithm, there are Repetitive Control (RC), Resonant Controllers (RSC), Least Mean Square (LMS), and Adaptive Frequency Estimation (AFE), Synchronous Rotating Frame (SRF), variable step size iterative algorithm, sliding mode control, etc.

Notch filter has the advantages of simple structure and easy implementation, so it is widely used in the engineering practice of vibration control, but the conventional notch filter will affect the stability of magnetically suspended rotor system. In 1996, a generalized multivariable notch filter was proposed in [11], as shown in Figure 8. A sensitivity adjustment matrix T was inserted into the universal notch filter to adjust the position of the system poles, so as to ensure the stability of the system. In 2015, Cui et al. proposed a full-frequency adaptive control method for unbalanced vibration of magnetic bearing based on phase notch filter, which directly takes the synchronous vibration force as the control objective, solving the problem that conventional notch filter affects the system stability, and eliminates the synchronous vibration force [12]. In 2016, Zheng et al. compared the suppression effect of phase notch filter in series and parallel mode, and proposed a phase notch filter in parallel mode to better suppress the synchronous vibration in the active magnetic bearing system compared with the series mode [13]. In 2017, Peng et al. proposed a second-order notch filter to eliminate synchronous vibration of magnetically suspended rotor system with strong gyroscopic effect, and derived the solution of switching to distinguish between low speed and high speed in order to ensure the stability of the system in the full speed range by adjusting the phase angle [14]. In 2018, Peng et al. proposed a novel cross-feedback notch filter for obvious gyroscopic effect and severe coupling dynamics in magnetically suspended flywheel, and analyze the stability of MIMO cross-coupling system by the equivalent complex coefficient stability criterion [15]. In 2021, Yin et al. proposed an adaptive notch filter that could adjust the depth and

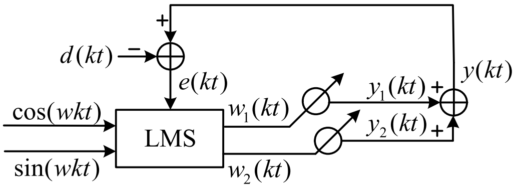


FIGURE 9. The principle of LMS algorithm.

frequency of notch filter to suppress synchronous vibration torque and synchronous harmonic current of MSCSG, and the measurement accuracy of attitude angle rate was significantly improved [16]. In 2022, Cui et al. proposed an improved dual-channel notch filter to suppress synchronous vibration torque in the magnetically suspended control torque gyroscope and improve the stability of the system by introducing phase compensation angle and notch factor [17]. However, the above improved notch filter still have some problems, such as affecting the stability of the magnetically suspended rotor system and causing greater vibration when the polarity switch or two-stage switch is switched.

Repetitive control can suppress periodic disturbance signals with known period, unknown amplitude and multi-frequency components. But when the frequency changes, there are problems such as slow response speed and poor robustness. Moreover, the phase delay and amplitude attenuation introduced by the low-pass filter in the high frequency band will limit the vibration suppression ability of the repetitive controller in the magnetically suspended rotor system. In addition, it is different from the electronic power system or the rotor system, the high speed of the rotor will lead to high frequency harmonic vibration, and the system is unstable in the case of open loop. Therefore, the stability of the system should be considered after adding the repetitive controller. In order to solve the above problems, in 2013, Xu et al. used the repetitive control method to suppress the synchronous and harmonic current in the magnetically control moment gyroscope [18]. The closest approach to repetitive control is the resonant controller, also known as finite-dimensional RC, which is a finite-dimensional internal model structure used to compensate periodic signals. It can not only suppress the low-order primary frequency component selectively, but also achieve zero steady-state error tracking because of the finite gain used at the specified frequency [19]. However, the conventional MRC method above has potential instability. In order to solve the above problems, phase compensation factor is introduced, which is independently adjusted to change the sensitivity function of the overall system at each resonant frequency when the MRSC plugged into the baseline control system so that the satisfactory stability performance can be insured and wider stability margin due to the time-varying harmonic frequency can be achieved.

LMS algorithm was applied in the field of active vibration control of magnetically suspended rotor system in the 1990s. As shown in Figure 9, it is a discrete adaptive notch filter in essence, with simple principle and strong robustness, but it requires a lot of computation and has a slow convergence rate. In 2004, J. Suhi et al. used LMS algorithm to suppress vibration displacement and vibration current in magnetically suspended rotor system [20]. In 2009, Ihn et al. used frequency-domain LMS algorithm to suppress unbalanced vibration of high-speed rotating disks [21]. In 2014, Xiang et al. proposed an adaptive feedforward compensation automatic balancing control scheme based on LMS algorithm. Compared with the conventional proportional feedforward, the synchronous vibration was reduced by 40% [22]. However, the calculation amount of the above method will increase with the increase of frequency components to be suppressed, and it is difficult to ensure the same convergence rate among different frequency components. In order to solve the above problems, scholars proposed the fast block least mean square (FBLMS) algorithm, which divides the multifrequency vibration signal into different data blocks, and updates the weights at different frequencies in the frequency domain after FFT (Fast Fourier Transformation). Compared with the classical LMS algorithm which updates weight in the time domain, the computation amount is reduced obviously, but the transient response is still slow. In order to suppress the harmonic force in the magnetically suspended rotor system, Cui et al. proposed a frequency domain adaptive LMS algorithm. The harmonic force is taken as the input signal of the filter, and the convergence factor of the step update strategy is introduced to improve the convergence speed. However, it is difficult to balance the contradiction between convergence rate and steady-state error due to the fixed-step size algorithm [23]. In order to ensure both fast convergence rate and small steady-state error, Cui et al. proposed a variable step size FBLMS algorithm. According to the error signal, reference input and the magnitude of multi-frequency harmonic current, the step size corresponding to each weight is adjusted adaptively, which greatly improves convergence speed of the algorithm and effectively suppresses multifrequency vibration [24]. Aiming at micro-jitter of magnetically suspended control moment gyroscope (MSCMG), Li et al. proposed a dual-channel adaptive LMS algorithm, which effectively suppresses synchronous vibration force caused by rotor mass imbalance in advantage of the orthogonality of radial two channels' displacement signals [25].

In addition to the above methods to suppress the synchronous and harmonic vibration in the magnetically suspended rotor system, the method of synchronous rotating frame (SRF) transformation has attracted the attention of many scholars in recent years because of its advantages such as simple structure, easy implementation, few adjustable parameters, and small computational complexity. SRF method is equivalent to a novel notch filter, and its principle is shown in Figure 10. The input signal is two orthogonal AC signals, which are converted into DC signals through the SRF conversion matrix, which contains both synchronous signals and high-frequency noise.

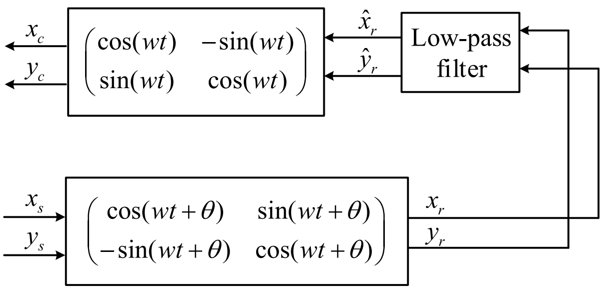


FIGURE 10. **TThe principle of SRF method.**

After the filtering effect of LPF, the high-frequency noise in the DC signal is eliminated, and only the synchronous vibration signal is left. Finally, through the inverse SRF conversion matrix, the DC signal is converted into AC signal. At this time, AC signal only contains synchronous vibration signals. By taking the reverse compensation into the original system, the synchronous vibration signals caused by the rotor mass unbalance can be eliminated. In 2003, Mou et al. proposed a notch filter based on coordinate transformation and explained the basic principle of SRF method in detail. The simulation results verified the suppression effect of SRF method on unbalanced vibration signals in active magnetic bearings [26]. In 2011, Chen et al. used the unbalance vibration suppression method based on coordinate transformation to suppress the synchronous vibration of magnetically suspended flywheel, and proposed a notch filter based on lead-lag correction to improve the phase lag problem of LPF in SRF [27].

In 2015, Zheng et al. applied the SRF method for motor drive control to the magnetic bearing system, and effectively suppressed the synchronous vibration in the active magnetic bearing system through the SRF method [28]. In 2019, Peng et al. proposed an improved SRF method to effectively suppress synchronous vibration torque and ensure the stability of the system through phase compensation considering the serious gyroscope effect in magnetically suspended flywheel system [29]. Peng et al. proposed an improved SRF method, which takes the synchronous vibration force as the input signal of controller instead of displacement signal. And it completely eliminates synchronous vibration force in the magnetically suspended flywheel system [30]. In 2021, Du et al. proposed a high-precision closed-loop synchronous signal detection method. Aiming at the problem of low detection accuracy in open-loop synchronous detection method due to phase lag in LPF. A closed-loop synchronous detection method based on an integrator is proposed to suppress the synchronous current caused by rotor mass imbalance in magnetically suspended control torque gyroscope more precisely [31].

The above methods for high-precision vibration suppression within the working speed range of the magnetically suspended rotor all require the actual rotor speed. However, when the Hall speed sensor has large measurement error or fails, it is necessary to estimate the actual speed signal of the rotor. Scholars at home and abroad have proposed a series of methods for frequency estimation and vibration suppression. Among them, the representative one is the adaptive frequency estimation (AFE) algorithm.

In 2004, Karimi et al. extracted sinusoidal components of input signals by constructing a state-space formula, which laid a theoretical basis for AFE method [32]. In 2015, Chen et al. proposed a novel AFE method based on radial two-channel signals. While realizing rotor speed estimation, the synchronous disturbance current in the system was suppressed [32]. However, according to the generation principle of magnetic force in magnetically suspended rotor system, when synchronous current is suppressed, the synchronous vibration force still cannot be completely eliminated. Therefore, it needs to introduce the notch filter to suppress the residual displacement stiffness disturbance force [33]. In 2019, Liu et al. proposed a dual-channel input AFE method, by introducing convergence factor and phase compensation, the synchronous current can be effectively suppressed within the full speed range of the rotor [34]. In 2020, Li et al. proposed an improved AFE algorithm based on radial single channel, which could adjust the compensation phase at different rotating speed to suppress the synchronous component in radial X-channel control current [35].

In addition to the above active control methods for synchronous vibration, In 2017, Mao et al. proposed a variable step size real-time iterative search algorithm to find the equivalent unbalance coefficient in an active magnetic bearing system in real time, thereby suppressing unbalanced vibration [36]. In 2020, Gong et al. proposed a variable angle compensation algorithm to suppress synchronous vibration during a finite iterative search process based on the real-time position of the rotor [37].

C. CONTROL METHOD OF HARMONIC VIBRATION OF MAGNETICALLY SUSPENDED SYSTEM

The above active vibration control method used to suppress synchronous vibration can also be used to suppress harmonic vibration caused by sensor runout by means of parallel or series controllers.

In 2002, Setiawan et al. proposed a multi-frequency compensation algorithm based on Lyapunov function to simultaneously suppress the disturbance caused by mass im-balance and sensor runout, but experimental verification was not carried out [38]. In 2016, Cui et al. proposed a multichannel phase-shift notch filter to suppress harmonic currents in magnetically suspended flywheel system [39]. In 2020, He et al. proposed a cascade phase notch filter to suppress harmonic vibration in high-speed magnetically centrifug-es [40], in which a resonant controller is used in parallel to each frequency to form a multi-resonant controller. Peng et al. proposed a novel multi-resonant controller to suppress harmonic current in the magnetically suspended flywheel system [41]. In 2018, Cui et al. proposed a quasi-resonant controller, which guaranteed the stability of the system in the full speed range through mixed phase compensation, and connected the quasi-resonant controllers of each frequency in parallel to the original system to effectively suppress har-monic current in magnetically suspended rotor system [19]. In 2022, Li et al. proposed an improved resonant controller, which is connected in parallel with the original controller of the system. Compared with the conventional resonant controller, it has better performance in terms of dynamic response and stability, and can better suppress harmonic vibration in magnetically suspended control torque gyro [42].

In addition to suppress synchronous vibration, the repetitive controller can also be used for the suppression of harmonic vibration. In 2016, Cui et al. proposed an improved repetitive controller, which changed the LPF in the conventional repetitive controller from the loop outward to reduce the tracking error of harmonic current and effectively suppress harmonic current [43]. In 2018, Cui et al. proposed a hybrid fractional repetitive controller that adopts a parallel structure, including a frequency adaptive dual-mode repetitive controller and a phase-shift notch filter. Compared with conventional repetitive controller, it has faster response and the control gain can be weighted, which improves the dynamic response of the system [44]. In 2019, Cai et al. proposed a zero-phase odd harmonic repeti-tive controller to improve the problems such as frequency shift and shallow notch depth, and replaced the LPF with a zero-phase LPF outside the inner loop to improve the suppression effect of odd harmonic vibration in the magnetically suspended rotor system [45]. As shown in Fig. 10, in 2020, Li et al. proposed a 3/2-order dual-mode fractional repetitive controller, which only suppresses the odd-order harmonic vibration without interference to other components [46]. Feng et al proposed a polyphase shift resonant controller to suppress the periodic torque disturbance in maglev control torque gyro whose frequency changes with the speed, and introduce different phase compensation at different disturbance frequencies to ensure the stability of the closed-loop system when the speed changes [47].

In addition to the above methods, the AFE and SRF methods mentioned in the previous section can also be used for harmonic vibration suppression. In 2022, Li et al. proposed a dual-channel AFE algorithm, which estimated the rotor speed accurately and suppressed harmonic current in use of the orthogonality of two-channel output signals in displacement sensor [48] In 2022, Cui et al. proposed a multi-frequency frame transformation method to suppress harmonic current and vibration force. Compared with conventional repetitive controller and resonant controller, it has better suppression effect.

Morever, neural network is used as a general approximator of nonlinear function instead of polynomial. Its advantage is that it does not need to establish the identification format of the actual system, and it can identify the essentially nonlinear system with only a small amount of prior knowledge of process structure. Chen proposed a direct control method based on BP neural network to meet the requirements of robustness, low power consumption and unbalance vibration suppression of maglev flywheel. A two-layer BP neural network controller is designed, and the online training of the neural network is realized based on the weight updating algorithm [49]. Liu took advantage of the fact that RBF neural network can track any complex nonlinear function, and proposes a self-tuning control method based on RBF neural network observer to identify rotor mass unbalance and thus suppress unbalance vibration in maglev flywheel [50]. In [51], a deep neural network with two hidden layers was used to establish the structure of a compensation controller, and a compensation controller was designed and added to PID feedback control by using deep learning theory. This method provides a new adaptive control method for active magnetic bearing control with minimum unbalance compensation, and can also be applied to other multi-dimensional vibration control.

IV. CONCLUSION

This paper firstly introduces the structure and working principle of magnetically suspended system with MSCSG as an example, and then analyzes the generation principle of rotor mass unbalance and sensor runout. The research status of active vibration control method of magnetically suspended system at home and abroad is introduced in detail from two aspects of synchronous vibration and harmonic vibration. Different control algorithms can be selected in suitable application situations.

Based on the analysis of existing active vibration control methods, some prospects are summarized:

(i) With the continuous development of automatic control technology and artificial intelligence technology, how to apply some new control algorithms, such as genetic algorithm, sliding mode control, fuzzy control, $H\infty$ control, etc., to the unbalanced vibration control of magnetically suspended rotor system to improve the performance of the system and vibration suppression effect is worthy of further study. In addition, the combination of classical control algorithms and intelligent algorithms and the use of intelligent algorithms such as machine learning and deep learning to improve the adaptive ability and robustness of unbalanced vibration control algorithms still need further research.

(ii) In practical application, due to the introduction of unbalanced vibration control in the magnetically suspended rotor system, the delay problem will be caused to the actual system. Therefore, it is necessary to analyze the time delay of the control system and the effect of time delay.

(iii) When the maglev rotor crosses the critical speed, the unbalance state of the rotor will change. How to design the unbalance vibration control algorithm applied to the rotor across the stage to reduce the vibration at this time needs to be further studied.

(iv) When the magnetic suspension rotor system is applied to the aerospace field, higher requirements are put forward for the complexity and computational amount of the control algorithm. How to reduce the computational amount and complexity of the algorithm while ensuring the effect of the unbalanced vibration control algorithm is worthy of further study.

REFERENCES

[1] S. Zheng, B. Han, and L. Guo, "Composite hierarchical antidisturbance control for magnetic bearing system subject to multiple external disturbances," *IEEE Trans. Ind. Electron.*, vol. 61, no. 12, pp. 7004–7012, Dec. 2014.

[2] T. Matsuzaki, M. Takemoto, S. Ogasawara, S. Ota, K. Oi, and D. Matsuhashi, "Novel structure of three-axis active-control-type magnetic bearing for reducing rotor iron loss," *IEEE Trans. Magn.*, vol. 52, no. 7, pp. 1–4, Jul. 2016.

[3] B. Han, Y. Chen, S. Zheng, M. Li, and J. Xie, "Whirl mode suppression for AMB-rotor systems in control moment gyros considering significant gyroscopic effects," *IEEE Trans. Ind. Electron.*, vol. 68, no. 5, pp. 4249–4258, May 2021.

[4] C. Peng, S. Zheng, Z. Huang, and X. Zhou, "Complete synchronous vibration suppression for a variable-speed magnetically suspended flywheel using phase lead compensation," *IEEE Trans. Ind. Electron.*, vol. 65, no. 7, pp. 5837–5846, Jul. 2018.

[5] Q. Chen, G. Liu, and B. Han, "Suppression of imbalance vibration in AMB-rotor systems using adaptive frequency estimator," *IEEE Trans. Ind. Electron.*, vol. 62, no. 12, pp. 7696–7705, Dec. 2015.

[6] Y. Ren, X. Chen, Y. Cai, H. Zhang, C. Xin, and Q. Liu, "Attitude-rate measurement and control integration using magnetically suspended control and sensitive gyroscopes," *IEEE Trans. Ind. Electron.*, vol. 65, no. 6, pp. 4921–4932, Jun. 2018.

[7] X. Chen, Y. Cai, Y. Ren, X.-D. Yang, and C. Peng, "Spacecraft angular rates and angular acceleration estimation using single-gimbal magnetically suspended control moment gyros," *IEEE Trans. Ind. Electron.*, vol. 66, no. 1, pp. 440–450, Jan. 2019.

[8] X. Chen, Y. Ren, Y. Cai, J. Chen, W. Wang, and X.-D. Yang, "Spacecraft vibration control based on extended modal decoupling of Vernier-gimballing magnetically suspension flywheels," *IEEE Trans. Ind. Electron.*, vol. 67, no. 5, pp. 4066–4076, May 2020.

[9] W.-Y. Zhou, G. S. Aglietti, and Z. Zhang, "Modelling and testing of a soft suspension design for a reaction/momentum wheel assembly," *J. Sound Vibrat.*, vol. 330, nos. 18–19, pp. 4596–4610, Aug. 2011.

[10] H. Wu and X. Tu, "Review on unbalanced vibration control for magnetic suspension rotor," *Bearing*, vol. 3, pp. 1–5.

[11] R. Herzog, P. Buhler, C. Gahler, and R. Larsonneur, "Unbalance compensation using generalized notch filters in the multivariable feedback of magnetic bearings," *IEEE Trans. Control Syst. Technol.*, vol. 4, no. 5, pp. 580–586, Sep. 1996.

[12] P. Cui, G. Zhao, and J. Fang, "Adaptive control of unbalance vibration for magnetic bearings based on phase-shift notch filter within the whole frequency range," *J. Vibrat. Shock*, vol. 34, no. 20, pp. 17–20, Oct. 2015.

[13] S. Zheng, Q. Chen, and H. Ren, "Active balancing control of AMB-rotor systems using a phase-shift notch filter connected in parallel mode," *IEEE Trans. Ind. Electron.*, vol. 63, no. 6, pp. 3777–3785, Jun. 2016.

[14] C. Peng, M. Zhu, K. Wang, Y. Ren, and Z. Deng, "A two-stage synchronous vibration control for magnetically suspended rotor system in the full speed range," *IEEE Trans. Ind. Electron.*, vol. 67, no. 1, pp. 480–489, Jan. 2020.

[15] C. Peng, J. Sun, C. Miao, and J. Fang, "A novel cross-feedback notch filter for synchronous vibration suppression of an MSFW with significant gyroscopic effects," *IEEE Trans. Ind. Electron.*, vol. 64, no. 9, pp. 7181–7190, Sep. 2017.

[16] Y. Cai, Z. Yin, Y. Ren, W. Wang, B. Fu, C. Yu, W. Han, and W. Han, "A novel attitude angular velocity measurement method based on mass unbalance vibration suppression of magnetic bearing," *IEEE Sensors J.*, vol. 22, no. 8, pp. 7717–7726, Apr. 2022.

[17] P. Cui, L. Du, X. Zhou, J. Li, Y. Li, and Y. Wu, "Synchronous vibration moment suppression for AMBs rotor system in control moment gyros considering rotor dynamic unbalance," *IEEE/ASME Trans. Mechatronics*, vol. 27, no. 5, pp. 3210–3218, Oct. 2022.

[18] X. Xu, J. Fang, G. Liu, and H. Zhang, "Model development and harmonic current reduction in active magnetic bearing systems with rotor imbalance and sensor runout," *J. Vibrat. Control*, vol. 21, no. 13, pp. 2520–2535, Oct. 2015.

[19] P. Cui, G. Zhang, Z. Liu, and H. Xu, "Quasi-resonant control for harmonic current suppression of a magnetically suspended rotor," *IEEE Trans. Power Electron.*, vol. 34, no. 5, pp. 4937–4950, May 2019.

[20] J. Shi, R. Zmood, and L. Qin, "Synchronous disturbance attenuation in magnetic bearing systems using adaptive compensating signals," *Control Eng. Pract.*, vol. 12, no. 3, pp. 283–290, Mar. 2004.

[21] Y. S. Ihn, J. K. Lee, D. H. Oh, H. S. Lee, and J. C. Koo, "Active correction of dynamic mass imbalance for a precise rotor," *IEEE Trans. Magn.*, vol. 45, no. 11, pp. 5088–5093, Nov. 2009.

[22] M. Xiang and T. Wei, "Autobalancing of high-speed rotors suspended by magnetic bearings using LMS adaptive feedforward compensation," *J. Vibrat. Control*, vol. 20, no. 9, pp. 1428–1436, Jul. 2014.

[23] P. Cui, Z. Liu, H. Xu, S. Zheng, B. Han, and D. Zhang, "Harmonic vibration force suppression of magnetically suspended rotor with frequency-domain adaptive LMS," *IEEE Sensors J.*, vol. 20, no. 3, pp. 1166–1175, Feb. 2020.

[24] P. Cui and J. Cui, "Harmonic current suppression of active-passive magnetically suspended control moment gyro based on variable-step-size FBLMS," *J. Vibrat. Control*, vol. 23, no. 8, pp. 1221–1230, May 2017.

[25] J. Li, G. Liu, S. Zheng, P. Cui, and Q. Chen, "Micro-jitter control of magnetically suspended control moment gyro using adaptive LMS algorithm," *IEEE/ASME Trans. Mechatronics*, vol. 27, no. 1, pp. 327–335, Feb. 2022.

[26] H. Mou, "Research on unbalance compensation of active magnetic bearing," Tech. Rep., 2003.

[27] X. Chen, "Study on vibration analysis and vibration suppression control of magnetic suspended flywheel system," Tech. Rep., 2011.

[28] S. Zheng, B. Han, R. Feng, and Y. Jiang, "Vibration suppression control for AMB-supported motor driveline system using synchronous rotating frame transformation," *IEEE Trans. Ind. Electron.*, vol. 62, no. 9, pp. 5700–5708, Sep. 2015.

[29] C. Peng, K. Cai, Z. Deng, and K. Li, "Vibration torque suppression for magnetically suspended flywheel using improved synchronous rotating frame transformation," *Shock Vib.*, vol. 2019, May 2019, Art. no. 3607164.

[30] C. Peng and Q. Zhou, "Direct vibration force suppression for magnetically suspended motor based on synchronous rotating frame transformation," *IEEE Access*, vol. 7, pp. 37639–37649, 2019.

[31] L. Du, P. Cui, X. Zhou, J. Li, Y. Li, and Y. Wu, "Unbalance vibration control for MSCMG based on high-precision synchronous signal detection method," *IEEE Sensors J.*, vol. 21, no. 16, pp. 17917–17925, Aug. 2021.

[32] M. Karimi-Ghartemani and A. K. Ziarani, "Performance characterization of a non-linear system as both an adaptive notch filter and a phase-locked loop," *Int. J. Adapt. Control Signal Process.*, vol. 18, no. 1, pp. 23–53, Feb. 2004.

[33] Q. Chen, G. Liu, and B. Han, "Unbalance vibration suppression for AMBs system using adaptive notch filter," *Mech. Syst. Signal Process.*, vol. 93, pp. 136–150, Sep. 2017.

[34] J. Li, G. Liu, P. Cui, S. Zheng, and Q. Chen, "Suppression of harmonic vibration in AMB-rotor systems using double-input adaptive frequency estimator," *IEEE Trans. Ind. Electron.*, vol. 69, no. 3, pp. 2986–2999, Mar. 2022.

[35] J. Li, G. Liu, P. Cui, S. Zheng, and Q. Chen, "Synchronous vibration suppression of magnetically suspended rotor system using improved adaptive frequency estimation," *IEEE Sensors J.*, vol. 20, no. 19, pp. 11212–11220, Oct. 2020.

[36] M. Chuan and Z. Changsheng, "Unbalance compensation for active magnetic bearing rotor system using a variable step size real-time iterative seeking algorithm," *IEEE Trans. Ind. Electron.*, vol. 65, no. 5, pp. 4177–4186, May 2018.

[37] L. Gong and C. Zhu, "Synchronous vibration control for magnetically suspended rotor system using a variable angle compensation algorithm," *IEEE Trans. Ind. Electron.*, vol. 68, no. 8, pp. 6547–6559, Aug. 2021.

[38] J. D. Setiawan, R. Mukherjee, E. H. Maslen, and G. Song, "Adaptive compensation of sensor runout and mass unbalance in magnetic bearing systems," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics*, Jun. 1999, pp. 800–805.

[39] P. Cui, S. Li, Q. Wang, Q. Gao, J. Cui, and H. Zhang, "Harmonic current suppression of an AMB rotor system at variable rotation speed based on multiple phase-shift notch filters," *IEEE Trans. Ind. Electron.*, vol. 63, no. 11, pp. 6962–6969, Nov. 2016.

[40] J. He, Z. Deng, C. Peng, and K. Li, "Reduction of the high-speed magnetically suspended centrifugal compressor harmonic vibration using cascaded phase-shifted notch filters," *IEEE Sensors J.*, vol. 21, no. 2, pp. 1315–1323, Jan. 2021.

[41] C. Peng, J. Sun, X. Song, and J. Fang, "Frequency-varying current harmonics for active magnetic bearing via multiple resonant controllers," *IEEE Trans. Ind. Electron.*, vol. 64, no. 1, pp. 517–526, Jan. 2017.

[42] J. Li, G. Liu, P. Cui, S. Zheng, X. Chen, and Q. Chen, "An improved resonant controller for AMB-rotor system subject to displacement harmonic disturbance," *IEEE Trans. Power Electron.*, vol. 37, no. 5, pp. 5235–5244, May 2022.

[43] P. Cui, S. Li, G. Zhao, and C. Peng, "Suppression of harmonic current in active–passive magnetically suspended CMG using improved repetitive controller," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 4, pp. 2132–2141, Aug. 2016.

[44] P. Cui, Q. Wang, G. Zhang, and Q. Gao, "Hybrid fractional repetitive control for magnetically suspended rotor systems," *IEEE Trans. Ind. Electron.*, vol. 65, no. 4, pp. 3491–3498, Apr. 2018.

[45] K. Cai, Z. Deng, C. Peng, and K. Li, "Suppression of harmonic vibration in magnetically suspended centrifugal compressor using zero-phase odd-harmonic repetitive controller," *IEEE Trans. Ind. Electron.*, vol. 67, no. 9, pp. 7789–7797, Sep. 2020.

[46] J. Li, G. Liu, P. Cui, S. Zheng, and X. Chen, "3/2-order dual-mode fractional repetitive control for harmonic vibration suppression in magnetically suspended rotor," *IEEE Sensors J.*, vol. 20, no. 24, pp. 14713–14721, Dec. 2020.

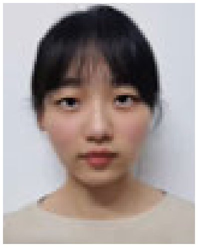
[47] J. Feng, Q. Wang, and K. Liu, "High-precision speed control based on multiple phase-shift resonant controllers for gimbal system in MSCMG," *Energies*, vol. 11, no. 1, p. 32, Jan. 2018.

[48] P. Cui, L. Du, X. Zhou, J. Li, Y. Li, and Y. Wu, "Harmonic vibration control of MSCMG based on multisynchronous rotating frame transformation," *IEEE Trans. Ind. Electron.*, vol. 69, no. 2, pp. 1717–1727, Feb. 2022.

[49] X. Chen, L. Li, and K. Liu, "Control of magnetic suspended flywheel using BP neural network," *Aerosp. Control*, vol. 28, no. 5, pp. 3–8, Oct. 2010.

[50] B. Liu, J. Fang, and G. Liu, "Self-tuning control based on RBF neural network observer in suppression of imbalance vibration of magnetically suspended flywheels," in *Proc. 2nd Int. Symp. Syst. Control Aerosp. Astronaut.*, Dec. 2008, pp. 1–5.

[51] X. Yao, Z. Chen, and Y. Jiao, "Unbalance vibration compensation control using deep network for rotor system with active magnetic bearings," in *Proc. 10th Int. Conf. Rotor Dyn. (IFToMM)*, 2018, pp. 72–81.



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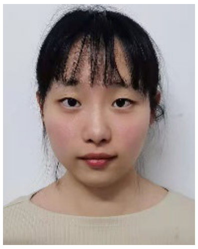

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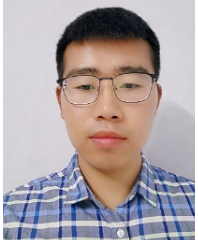

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