Research and Simulation Analysis on Control Algorithm of Eddy Current Damper

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Abstract. With the rapid development of the national economy, the mechanical vibration occurring in a high-speed rotary machine may affect or restrict the normal operation of the system and cause immeasurable losses in production and life. In this paper, a self-sensing eddy current damper is proposed and applied to a rotating disk vibration system to realize the active control of vibration. The mechanism and application of self-sensing eddy current damper are mainly studied from the theoretical research and simulation of control algorithm. Based on the theory of eddy current and electromagnetic force generation, the working principle of self-sensing eddy current damper is analyzed based on the theory of double-coil transmission eddy-current detection. The relationship between the vibration displacement and the input and output of the damper is explored. The correctness of the theoretical modeling is verified. The controller based on $H_\infty$ method is designed with robust control theory and the controller feedback gain $K(s)$ is analyzed. According to the control structure of the system, simulink simulation model is designed to simulate the rotating disk vibration system with different rotating speed. The vibration displacement responses before and after the control are compared and analyzed. The simulation results show that the designed controller can effectively reduce the lateral vibration of the rotating disk. The verification experiment of self-sensing eddy current damper and the active control experiment of the rotating disk vibration system are carried out. The experimental results are in good agreement with the simulation results.

1. Introduction

With the rapid development of modern economy, high-speed rotating machinery has been widely used in industry and manufacturing. However, the mechanical failure caused by the vibration in high-speed rotating machinery has brought a lot of adverse effects on human production and life. Therefore, how to solve the problem of mechanical vibration suppression of high-speed rotating machinery has become our focus. The vibration control theory shows that the main types of vibration control active control, semi-active control and passive control. The research on passive control and semi-active control has been basically mature both in theory and method, and active control is one of the hot research topics at present. In order to restrain the mechanical vibration of the disc rotor system and improve its service life, an external damping method is usually adopted. The common dampers used...
for vibration suppression include squeeze film damper (SFD), controllable squeeze film damper (CSFD), ERFD, MRFD, Shape Memory Alloy Regulator (SMMAA), Electromagnetic (Eddy Current) Damper (AMD or ECD) and the like. However, it has many drawbacks, such as the improper design or the deterioration of rotor system imbalance, which will increase the non-linearity of oil film force and bring about many harmful effects. If we can design a more suitable damper structure on the basis of the original electromagnetic damper, the mechanical vibration of the disc rotor can be better controlled actively.

In this paper, the mathematical model of self-sensing eddy current damper is established and the related characteristics are analyzed. On this basis, the dynamic model is transformed into the state space model. With the state space model of the system, the appropriate control algorithm is selected, and the controller is designed and the active vibration control of the rotating disk is studied. The controller is the core of the damper damping system. Whether the design of the controller is reasonable or not will directly affect the stability and control performance of the controlled system. The control algorithm is the key to realize the controller self-sensing control function. Therefore, the appropriate control algorithm is to design a good controller of the premise. At present, in order to meet the control requirements of various objects, a wide range of control algorithms are applied: optimal control method, intelligent control method, robust control method and PID control method. The robust control method tries to describe the uncertainty of the system model. At the same time, the control law is designed considering the stability and control performance of the system. The control system maintains a good control state within a certain range of model perturbation, System performance to achieve the best.

2. Research robust control theory and design of controller

2.1. Research on Robust Control Theory

Many control theories are based on the theoretical mathematic model of the controlled object, so if the external disturbance error exists in the mathematical model, the design performance of the controller is difficult to guarantee, and even the stability of the control system is difficult to guarantee. The robust control theory can consider the uncertainty of the mathematical model of the controlled object in the design of the controller. In the presence of uncertainties, a reasonable controller can be designed so that the system can still maintain good performance and state, the robustness often mentioned in robust control theory. Robust control theory has two branches: one branch is \( H_\infty \) control theory and the other branch is \( \mu \) control theory. Both of these robust control theories have been used by many researchers in structural vibration control. Among them, \( H_\infty \) control method is a common method of control system design, which has strong robustness and has the most applications in engineering, has caused great concern to people.

The basic idea of \( H \) method is to use the \( H_\infty \) norm as the control performance index, in the event of the worst disturbance, the system error is minimized under the condition that the infinite norm is meaningful, and then the interference problem is transformed into solving the closed loop System stability problems, and design the appropriate output feedback controller. The advantages of \( H_\infty \) control theory in practical application are as follows:

a). \( H_\infty \) control theory makes the design of robust controller based on a certain theoretical basis;

b). In the actual controller design process, some of the advantages of the state space method are still retained, and the calculation method is provided.

c). The control system can be closed-loop frequency characteristics and design linked;

d). Engineering and technical personnel easy to master \( H_\infty \) control theory and methods.

2.2. Controller Design Based on \( H_\infty \) Method

The established disk system dynamics model based on self-sensing eddy current damper:

\[
M \dot{x} + C \dot{x} + K x = q + f
\]
Considering only the vibration of the first $H\infty$ 4-order mode before the $0H\infty$ pitch circle of the rotating disk, and the effect of force is selected as $H\infty\phi = 0$, the state space model of the dynamic $H\infty$ mechanical model can be described as:

$$\begin{align*}
\dot{X} &= AX + B_1W + B_2U \\
Y &= C_1X
\end{align*}$$

Among, $X = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$, $Y = \sum_{m=0}^{M} \sum_{n=0}^{N} U_{mn} \alpha_{mn}$, $A = \begin{bmatrix} 0 & 1 \\ -M^{-1}K & -M^{-1}C \end{bmatrix}$, $B_1 = \begin{bmatrix} 0 \\ M^{-1} \end{bmatrix}$, $B_2 = \begin{bmatrix} 0 \\ M^{-1} \end{bmatrix}$, $C_1 = \begin{bmatrix} U_{mn} & 0 \end{bmatrix}$, $W = q$, $U = f$.

Where $A$, $B_1$, $B_2$ and $C_1$ are real constant matrices, $X$ is the state vector, $Y$ is the output vector, and $W$ and $U$ are the input vectors.

$H\infty$ control method the purpose of controller design is to find a suitable controller for the established generalized controlled object so that the closed-loop control system remains stable and minimizes the objective function. Let the system be linear when the system is unchanged, as shown in Figure 1.

![Figure 1. Linear system diagram unchanged](image1)

In the figure, $G(s)$ denotes the generalized controlled object (including the actual controlled object and the weighting function), $K(s)$ denotes the controller to be designed, $W$ denotes the external disturbance input signal, $Y$ denotes the control output signal, Measurement signal, $U$ indicates the control signal.

Because of the uncertainty of the actual system has a weighted function $W_d$, and with product-type structural uncertainty $G$, $G_0$ as a nominal system, so the actual system can be described as:

$$G(s) = G_0(I + \Delta GW_d)$$

The whole system is controlled by a robust controller $K(s)$, whose block diagram is shown in Fig.2.

![Figure 2. $H\infty$ control structure of rotating disk vibration system with uncertainty](image2)
In the modeling process, all the uncertainties of the system are grouped into the normalized transfer matrix $G$, which describes the difference between the nominal system $G_0$ and the actual system $G(s)$. The system performance index is the transfer function matrix for all allowed uncertainties, $G$, from $W$ to $Y$, which reaches a minimum in the sense of $H_\infty$ norm.

According to the state space model, uncertainty perturbation is mainly caused by external disturbances in the modeling process. Therefore, only considering the uncertainty caused by external disturbances to model $G$, the uncertainty of the system mainly consists of input $W$ decision, the actual rotating disk vibration system state feedback $H_\infty$ control block diagram shown in Figure 3.

![Figure 3. H_\infty control structure diagram of rotating disk vibration system](image)

When the external shock excitation force acting on the disc, the disc rotation, the initial input of the control system for $W = q$. In the actual system, the actual input control amount is $U^* = F^*_i(t)$, and is applied to the disc by the excitation coil of the eddy current damper. Energized coil current $I$ is the direct control of the control system, electromagnetic force $F^*_i(t)$ is indirectly controlled by the control system. The dashed line in Figure 3 is the excitation coil added to the damper by the computer control system. The detection coil converts the vibration displacement of the disk into a voltage signal, which is converted into a current signal and input to the excitation coil after being calculated and controlled by the controller. The excitation coil converts the conduction current into an electromagnetic force to compensate for the original damping, and then acts on the disk in order to restrain its transverse mechanical vibration.

3. Robust control simulation of rotating disk system

Based on the matrix and state space model above, a simulation model of the active disk vibration control system is established by using Simulink module in MATLAB environment. The matrix $P = \begin{bmatrix} 29587.9799 & -0.0011 \\ -0.0011 & 0 \end{bmatrix}$ and the feedback gain $K(s) = \begin{bmatrix} 12.3124 \\ 0 \end{bmatrix}$ are calculated from the previous theory when the disk rotation speed is $\Omega = 12 \text{ rad/s}$. The vibration displacement response when it is not controlled is shown in FIG. 5, and the vibration displacement response after the control is applied is shown in FIG. 6. The matrix $P = \begin{bmatrix} -1.2544e+009 & 1.1925 \\ 1.1923 & 0 \end{bmatrix}$ and the feedback gain $K(s) = \begin{bmatrix} 1.3364e+004 \\ 0 \end{bmatrix}$ are calculated from the theory of the previous section when the disk rotation speed is $\Omega = 30 \text{ rad/s}$. The vibration displacement response without control is shown in Figure 4-8. The vibration displacement response after the control is applied is shown in Figure 7. The matrix $P = \begin{bmatrix} 1.5791 & -1.2430 \\ -1.2430 & 0.6477 \end{bmatrix}$ and the feedback gain $K(s) = \begin{bmatrix} 1.3930e+004 \\ -0.7259e+004 \end{bmatrix}$ are calculated when the disk rotation speed is $\Omega = 62 \text{ rad/s}$. The vibration displacement response after the control is applied is shown in FIG. 9. For the three speeds, three sets of vibration displacement response curves before and after control were obtained by Simulink model simulation, and the amplitude changes of the response curves before and after the control were observed. From the amplitude comparison, it can be seen that the vibration displacement of the robust controller decreases obviously, and the amplitude of the vibration can be reduced by 85%-95% under the action of the controller. At the same time, we can see from the simulation process that the signal processed by Simulink model is a valid signal and
can be fed back to the damper to suppress the disk vibration. Therefore, it can be determined that the
damper can sense the vibration displacement signal of the disk and can be suppressed. Therefore, the
damper has the function of self-sensing and can suppress the vibration during the application. The
active control of the disk vibration can be realized by a reasonable control algorithm.

Figure 4. Simulink simulation model

Figure 5. The vibration displacement response of the rotating disk before (a) and after (b) the control
when $\Omega = 12$ rad/s

Figure 6. The vibration response of the rotating disk before (a) and after (b) control is obtained when
$\Omega = 30$ rad/s
Figure 7. The vibration displacement response of the rotating disk before (a) and after (b) the control when $\Omega = 62$ rad/s

4. Summary

H control theory, a robust controller is designed. This theory considers the uncertainty of the mathematical model of the controlled object in the design of the controller. Under the condition of uncertainties, a reasonable controller can be designed so that the system can still maintain Good performance and state, but the controller designed by this method needs to consider the external interference or the system's uncertainties, which makes the controller more computationally expensive and difficult to debug. Therefore, we should continue to study the controller under multivariable conditions design. In this paper, only one damper is used for vibration control, and for the point effect, a plurality of dampers should be considered for vibration suppression next, and the positions of the plurality of dampers are optimized, and the electromagnetic interference, Signal coupling and other issues.

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