Filter Design of Adjusting Common Phase for Vibration Suppression Control of Multi-degrees of Freedom System

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Abstract
In the flexible structure such as a stacker crane, the vibration generates by the high acceleration of the driving axis in the load transportation part. For the improvement of the productivity, the vibration suppression is necessary. We utilize the acceleration feedback control for the vibration suppression. The flexible structure has some natural vibration modes varying in phase, and the vibration suppression is difficult by the simple feedback control. The second mode is excited by the simple feedback control for the first mode when the phase between first mode and second mode are different like this flexible structure. This paper proposes the filter design of adjusting common phase for the feedback control. The filter using the operational amplifier reverses the phase of the second mode and makes it the same as the first mode. The effect of vibration suppression is verified by the simulation.

Key words: mechatronics, flexible structure, vibration suppression, filter design

1. Introduction
A stacker crane in an automatic warehouse has a flexible part. The flexible part is the mast, and the height is about 10m. It is the theme that the residual vibration of positioning should be improved.

In this study, we produce the flexible structure that assumed the stacker crane a control object. We aim at the suppression of the residual vibration by an acceleration feedback control**. The flexible structure has some vibration modes. Their phases are not same. We cannot suppress the vibration by a simple acceleration feedback.

In this paper, we propose the filter design adjusting common phase for the vibration suppression by the simple acceleration feedback.

2. Controlled object
The flexible structure as the controlled object** is shown in Fig.1. This is the flexible structure like a stacker crane. Two flexible plates are set up as cantilever beams. Its natural frequency is designed to 3Hz same as the crane. Its table is driven with the servomotor and makes linear motion with the ball screw.

We measured the frequency response of the flexible structure. The frequency response is shown in Fig.2. We input a random signal into torque of the servomotor and assumed the signal of the acceleration sensor installed in the tip of the beam the output.

The natural frequencies are 3Hz, 19Hz and 52Hz. The phase between the input signal and the output signal is opposite in the first natural frequency. The phase between the input and the output are same in the second and third natural frequency. We assume the same phase from -90deg. to 90deg. and assume opposite phase from 90deg. to 270deg. shown in Fig.3.

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The relationship of phase of the flexible structure is shown in Fig. 4.

3. Modeling

For the control system design, we estimate the transfer function of the flexible structure. The transfer function is similar to the sixth degree function using the least-squares method.

\[
G(s) = \frac{b_0 + b_1 s + \cdots + b_6 s^6}{a_0 + a_1 s + \cdots + a_6 s^6}
\]  

(1)

The estimated frequency response is shown in Fig. 5. The dashed line is the estimated frequency response \(G(s)\) by a curve fitting. The solid line is the measured frequency response shown in Fig. 2. Two curves coincide in the peaks. The estimate of the transfer function is carried out well. The phases of the estimated \(G(s)\) are shown in Fig. 6.

4. Control System

The acceleration feedback is used for the vibration suppression control. The acceleration sensor is installed in the tip of the flexible structure. The signal of the acceleration is integrated, and a proportion gain is multiplied, and it is feedback to the motor velocity. When the phase is different in every vibration mode, the controlled mode and the excited mode are separated by the feedback. We design the filter adjusting common phase for the feedback control and get a vibration suppression effect. The control system is shown in Fig. 7.

The servomotor is controlled by the position and the velocity feedback. The encoder of the servomotor is used by this feedback. \(K_p, K_v, T_i\) are the position loop gain, the velocity loop gain and the integral time.

The acceleration of the tip of the flexible structure is integrated and the signal is separated by the band pass filter (BPF). The phase of second mode is multiplied -1, it is adjusted the common phase with the phase of first mode.

5. Filter design

We design the filter to adjust the phase of each mode. The designed filter circuit is shown in Fig. 8. The three band pass filters separate the input signal \(V_i\) every mode. As for the signal of the second mode, phase is changed 180 degrees by an inverting circuit. An adder circuit composes three separated signals afterwards.

The experimental circuit is shown in Fig. 9. The measured frequency response of the circuit is shown in Fig. 10. The phase is 0 deg, in the first mode 3Hz neighborhood, and the phase is 180 deg, in the second mode 19Hz neighborhood.

In this paper, we verify that the effect of vibration suppression by simulation. By the simulation, it is modeled by the curve fitting of the transfer function of the actual machine. We perform the simulation that assumed the feedback of the actual machine by using the designed filter which can realize adjusting common phase by the true circuit show in Fig. 8.
The relationship of the phase of the structure $G_s(s)$ and the filter $G_f(s)$ are shown in the Fig.11. The phase of the second mode becomes opposite phase and was adjusted with the first mode by the filter.

6. Simulation

In this chapter, the effect of the vibration suppression is verified by the simulation of an impulse response. The impulse response of flexible structure is shown in Fig.13. The frequency components of the three modes are included in the response wave.

The feedback control with the acceleration loop is shown in Fig.14. $K$ is the proportional gain. The impulse response of the positive feedback control is shown in Fig.15. The first mode is suppressed but the second and the third mode is excited. The impulse response of the negative feedback control is shown in Fig.16. The second and third mode is suppressed within 1 second but the first mode is excited. The vibration is not suppressed by the simple acceleration feedback control since the phases of the three modes are different.

The filter designed in the foregoing chapter is utilized. The feedback control with the filter $G(s)$ is shown in Fig.17. The impulse response of the feedback control with the filter is shown in Fig.18. The settling time is short by the effect of the filter.

The effect of the vibration suppression is obtained in the simulation.
7. Conclusions

We propose the filter design adjusting common phase for the simple acceleration feedback. We got the following conclusions.
(1) We measured the frequency response function of the flexible structure and found a transfer function by the curve fitting.
(2) We designed the filter adjusting common phase for the first mode and the second mode.
(3) The designed filter is effective for the vibration suppression of the multi-degrees of system. We confirmed by the simulation.

References