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Experimental investigation of shaping disturbance observer design for motion control of precision mechatronic stages with resonances

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ABSTRACT

In this paper, shaping disturbance observer (SDOB) is investigated for precision mechatronic stages with middle-frequency zero/pole type resonance to achieve good motion control performance in practical manufacturing situations. Compared with traditional standard disturbance observer (DOB), in SDOB a pole-zero cancellation based shaping filter is cascaded to the mechatronic stage plant to meet the challenge of motion control performance deterioration caused by actual resonance. Noting that pole-zero cancellation is inevitably imperfect and the controller may even consequently become unstable in practice, frequency domain stability analysis is conducted to find out how each parameter of the shaping filter affects the control stability. Moreover, the robust design criterion of the shaping filter, and the design procedure of SDOB, are both proposed to guide the actual design and facilitate practical implementation. The SDOB with the proposed design criterion is applied to a linear motor driven stage and a voice motor driven stage, respectively. Experimental results consistently validate the effectiveness nature of the proposed SDOB scheme in practical mechatronics motion applications. The proposed SDOB design actually could be an effective unit in the controller design for motion stages of mechanical manufacture equipments.

1. Introduction

Precision mechatronic motion stages are widely used in modern mechanical manufacture equipments, such as machine tools and IC lithography tools [1–3]. Continuously rigid requirements on motion accuracy and speed make the motion control technology become more and more important [4,5]. To achieve the desired motion control performance, disturbance observer (DOB) is widely used as an inner loop controller unit to reject disturbance and improve the motion control performance [6–8]. One main advantage of the DOB is that it is an add-on inner disturbance rejection part with respect to the outer feedback controller and almost has no influence on the nominal performance of the system [9,10]. To some extent, the DOB and outer feedback controller could be designed separately, which leads that advanced DOB design method becomes an important issue to facilitate the controller design.

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In DOB, the inverse of the nominal model as well as a low-pass filter, i.e., Q, is used to estimate the disturbance of the plant system. The cut-off frequency of Q is limited by the un-modelled dynamics of the mechatronic motion plant in order to maintain robust stability for the DOB inner loop [11]. Xu [12] proposed a novel scheme of plant shaping DOB (SDOB) which utilized several notch filters to cancel the plant's major resonances. Herein, the notch filters were designed through optimization so that the shaped plant dynamics could approximate the nominal model.

Inspired by the characteristics of SDOB way, this paper studies the practical performance oriented design method of SDOB instead of mathematical optimization specially for mechatronic motion system with middle frequency zero/pole type resonance. This kind of resonance is common for mechatronic motion stages where the 1st-order modal frequency is usually not high (the reason is explained in Section 3.1). The resonance is cancelled by its inverse dynamics, i.e., pole-zero cancellation. And the stability is discussed when there exist uncertainties in resonance parameters. Moreover, the robust design criterion of SDOB shaping filter is proposed to facilitate actual implementation. The proposed SDOB design procedure is also presented to facilitate implementation. Finally, the SDOB with the proposed design criterion is applied to a linear motor driven stage and a voice motor driven stage, respectively. Comparative experimental results consistently verify the effectiveness nature of the proposed SDOB scheme in practical motion control applications. The proposed SDOB design actually provides an effective unit and could be well integrated with manual loop shaping design of the outer feedback controller for motion stages of manufacture equipments.

The remainder of this paper is organized as follows. Section 2 provides a brief review of standard DOB and SDOB. Section 3 discusses the robust performance of SDOB with respect to uncertainty of resonances through simulation analysis, and presents a robust design rule for SDOB. Section 4 describes the controller design for precision mechatronic motion stages with experimental investigation. The conclusions are drawn in Section 5.

2. DOB and SDOB

2.1. Standard disturbance observer

As computer control systems practically run digital controllers, the theory of discrete DOB is briefly described in the following [11,12]. Fig. 1 shows the block diagram of DOB based control loop, where $C_f(z^{-1})$ is the feedback controller, $G_p(z^{-1})$ is the plant, and the part inside the box with gray background is DOB. DOB includes the low pass filter $Q(z^{-1})$, the inverse model $[G_n^*(z^{-1})]^{-1}$, and the delay z^{-m}. $G_n^*(z^{-1})$ approximates the part in the actual plant apart from time delay (denoted by $G_p^*(z^{-1})$), and

$$G_p(z^{-1}) = z^{-m}G_p^*(z^{-1}) \tag{1}$$

The DOB loop in Fig. 1 inside the gray box could be transformed into its equivalent form as showed in Fig. 2. Then the transfer functions from the command, the disturbance and the noise to the plant output are

$$G_{yc}(z^{-1}) = \frac{z^{-m}G_p^*(z^{-1})G_n^*(z^{-1})}{G_n^*(z^{-1}) + Q(z^{-1})[z^{-m}G_p^*(z^{-1}) - z^{-m}G_n^*(z^{-1})]} \tag{2}$$

$$G_{yd}(z^{-1}) = \frac{z^{-m}G_p^*(z^{-1})G_n^*(z^{-1})[1 - z^{-m}Q(z^{-1})]}{G_n^*(z^{-1}) + Q(z^{-1})[z^{-m}G_p^*(z^{-1}) - z^{-m}G_n^*(z^{-1})]} \tag{3}$$

$$G_{yn}(z^{-1}) = -\frac{z^{-m}G_p^*(z^{-1})Q(z^{-1})}{G_n^*(z^{-1}) + Q(z^{-1})[z^{-m}G_p^*(z^{-1}) - z^{-m}G_n^*(z^{-1})]} \tag{4}$$

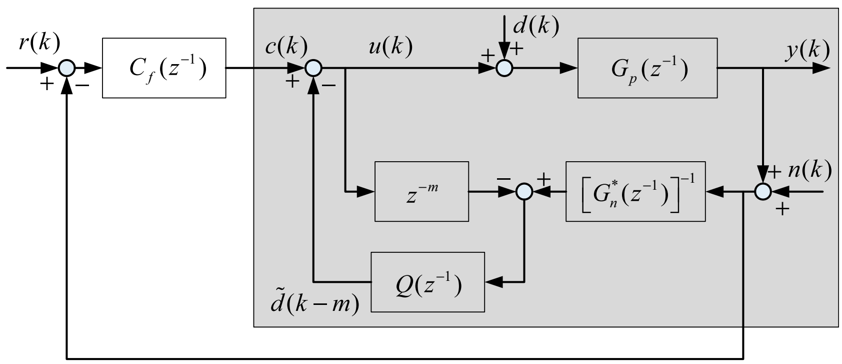

Fig. 1. Block diagram of DOB control loop.