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Experiments of optimal delay extraction algorithm using adaptive time-delay filter for improved vibration suppression †

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Abstract

In the previously introduced direct adaptive command shaping filter (ACSF), the time-delay value is fixed and only the magnitudes of the impulses are learned. The performance of the direct adaptive time-delay command shaping filter, however, depends on the select time-delay. In this paper, the authors introduce a new scheme to extract the optimal time-delay value for the improved vibration suppression in flexible motion system. To develop the optimal time-delay extraction scheme, the authors have analyzed the effect of the time-delay value on the performance of the direct ACSF. Based on the analysis result the authors have established a set of equations to extract the optimal time-delay toward the optimal vibration suppression performance of ACSF. Experimental results using a gantry robot with a single flexible link show the effectiveness of the proposed time-delay adaptation approach for the improved vibration suppression..

Keywords: Adaptive command shaping; Optimal time-delay; Vibration suppression; Flexible manipulator

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1. Introduction

The design of an effective command shaping filter for vibration suppression requires a priori knowledge of system parameters of the motion system [1]. One approach to retaining effectiveness of the filter in the face of uncertainty is to adapt the filter parameters (the number of impulses, and the size of the impulses) either directly or indirectly [2, 3].

A direct adaptation algorithm, where system parameters are never explicitly utilized, has been proposed in [4, 5]. The direct adaptation algorithm is to learn the optimal filter by adapting only the magnitude of the impulses with the number of impulses and the time-delay between the impulses fixed.

As the analysis in the previous research has shown, command shaping filters with different time-delay values designed for the same elastic mode would result in different frequency responses and different capability of vibration suppression [6]. With certain time-delay the converged command shaping filter would have amplification effect in higher frequency range, which would introduce undesirable effects, for example, decreased effectiveness of vibration suppression, excitation of higher elastic mode, etc.

In general, when we adapt the filter we want a time-delay that would result in the most cancelling effect at the lowest natural frequency of the system and the least amplification effect at the other frequency region, especially at the high frequency area. This goal can only be achieved by choosing (or adapting to) the optimal time-delay value. Park and Rhim have proposed a new scheme to adapt the time-delay in the direct adaptive command shaping filter without solving the complex non-linear problems otherwise [6]. The new scheme is based on the strong convergence property of the direct adaptation algorithm.

In this paper the extraction of the optimal time-

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delay value is carried out experimentally and the effectiveness of the use of the extracted optimal time-delay is experimentally verified.

2. Control scheme

The general form of the (*M+1*)-term time-delay filter can be expressed by its impulse response in the continuous-time domain as

$$c(t) = c_0 + c_1\delta(t - T_d) + \cdots + c_M\delta(t - MT_d) \qquad (1)$$

where c_k is the scaled amplitude of the delayed inputs, $\delta(t)$ is the unit impulse function centered at $t=0$, and T_d is the time delay. The filter $c(t)$ can be expressed in the discrete-time domain as

$$C(z) = c_0 + c_1 z^{-\Delta} + c_2 z^{-2\Delta} + \cdots + c_M z^{-M\Delta} \qquad (2)$$

where $\Delta = integer = T_d/T_s$ and T_s is the controller sampling time.

The filter coefficients c_i are to be calculated based on the parameters of the elastic mode to be cancelled by the filter. When the system parameters are not known, the direct adaptive algorithm can be used to learn the optimal filter coefficients. In the direct adaptive filter, however, the time-delay value needs to be pre-fixed before the adaptation of the filter coefficients. The effect of the time-delay value on the performance of the converged adaptive filter has been illustrated in [6].The Fig. 1 illustrates the control scheme of the extraction and the use of the optimal time-delay which is to be experimentally verified in the paper.

3. Experiments

The actual flexible system used in the experiments is shown in Fig. 2. The gantry robot system used in the experiments has one flexible link that moves in the horizontal plane. The tip acceleration is measured by an accelerometer attached at the tip of the flexible link. The flexible link has a dominant elastic mode at 16 Hz.

The adaptive command shaping control system has been implemented by using MATLAB/xPC Target in conjunction with a Simulink program. As the reference input given to the base feedback control system, a trapezoidal velocity trajectory is used and it moves the joint from a resting position to another position 200 mm away in 0.5 sec. A conventional PD controller with 1 kHz sampling rate is implemented for the joint feedback control.

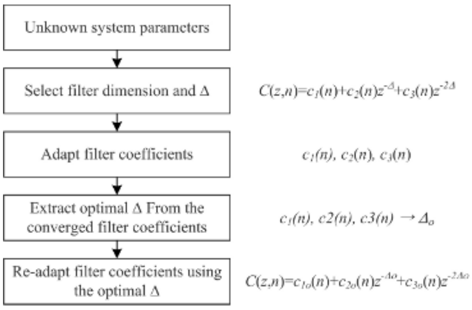


Fig. 1. Schematic diagram of control system configuration used in experiments.

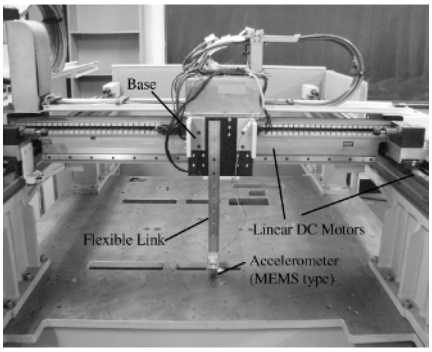


Fig. 2. Picture of actual gantry system used for experiments.

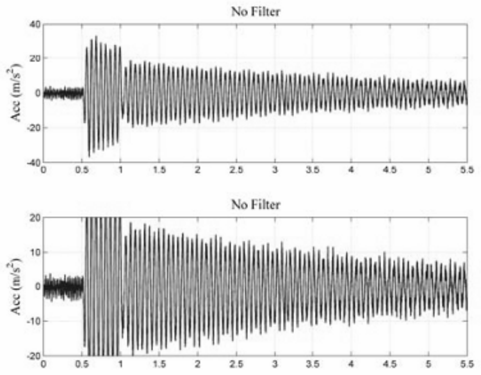
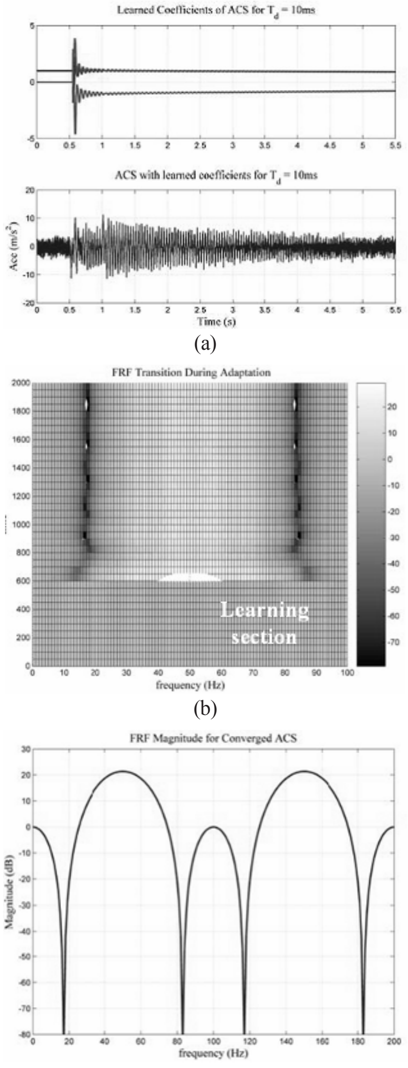


Fig. 3. Measured tip acceleration without using command shaping filter (the bottom plot is a magnification of the top plot).

Fig. 3 shows the measured tip acceleration when no command shaping filter is used. The bottom plot in Fig. 3 is a magnification of the top plot.

A direct adaptive command shaping filter was also implemented in the real-time control system. Initially, the time-delay value in the direct adaptive filter was

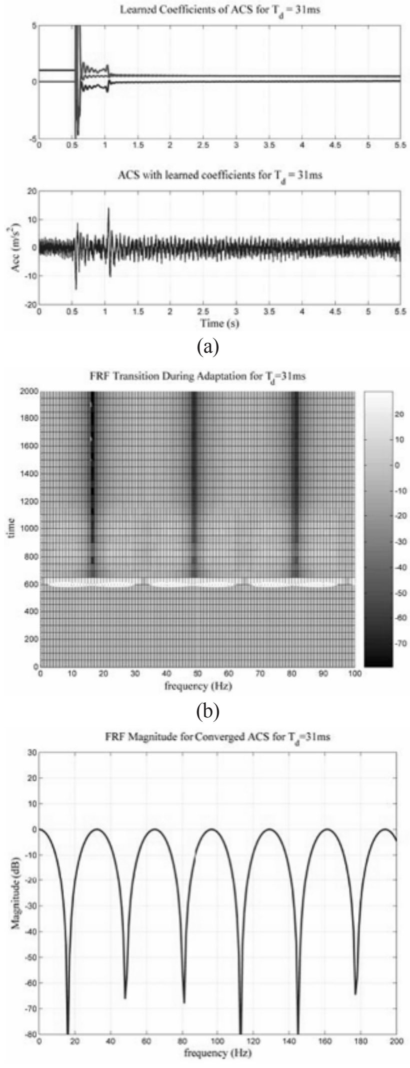


(a)

(b)

(c)

Fig. 4. Experimental results obtained when time-delay value 10 ms is used for the adaptation: (a) top) adaptation of filter coefficients, bottom) measured tip acceleration with converged shaping filter, (b) transition of frequency response of the adaptive filter (c) frequency response magnitude of the converged filter.



(a)

(b)

(c)

Fig. 5. Experimental results obtained when time-delay value 31 ms is used for the adaptation: (a) top) adaptation of filter coefficients, bottom) measured tip acceleration with converged shaping filter, (b) transition of frequency response of the adaptive filter (c) frequency response magnitude of the converged filter.

chosen to be 10 ms without knowing the exact system parameter of the flexible system. The top plot in Fig. 4(a) shows the transition of the filter coefficients during the adaptation process. After we obtained a converged command shaping filter from the adaptation process using an arbitrary 10 ms delay for the filter, we applied the filter to the control system. The bottom plot in Fig. 4(a) shows the measured tip acceleration when the converged adaptive command shaping filter is used. It is apparent that with the use of the converged filter the tip vibration has been decreased significantly compared to the no-filter case.

From the converged filter, we extracted the non-dimensional number $\omega_d T_d$ for the given flexible system, and from the extracted value we determined T_d that would make $\omega_d T_d$ to be π, which was calculated to be 31 ms [6]. The top plot in Fig. 5(a) shows the convergence of the filter coefficient during the adaptation process using a time-delay of 31 ms. The bottom plot in Fig. 5(a) shows the measured tip acceleration when a converged filter with 31ms time-delay is used With the use of converged filter with 31 ms time-delay the residual vibration has been decreased down to the significantly lower level than the 25 ms case.

Fig. 4(b) and Fig 5(b) show the transition of the calculated frequency response magnitude during the adaptation process. Fig. 4(c) and Fig 5(c) show the frequency response magnitude of the two converged filters for the given two time delay of 10 ms and 31 ms. The frequency response for the 10ms case shows a considerable amplification effect where the natural frequency of the second mode is. On the other hand, for the frequency response for the 31 ms case, the converged filter only has notches at the target frequency but no amplifications in other areas.

4. Conclusions

This paper experimentally verifies the effectiveness of the algorithm that extracts the optimal time-delay from the converged adaptive command shaping filter and the use of the optimal time-delay to further decrease the residual vibration in the flexible manipulator. The experimental results based on a gantry robot with a single link which has multi-elastic-modes show that the proposed scheme significantly reduces the residual vibration of the flexible link where there are system parameter uncertainties.

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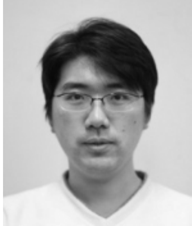

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