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Useful applications of closed-loop signal shaping controllers

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Abstract

Input shaping is a well-established open-loop technique used for reducing the vibratory response of dynamic systems. Some researchers have investigated the stability and utility of using this technique within a feedback control loop. The main contribution of the prior investigations was to identify stable configurations of in-the-loop input shaping systems. This paper identifies three promising applications of the stable controllers. Performance comparisons are made between the in-the-loop input shaping systems and more conventional feedback control strategies. Experimental results from a 10-ton industrial bridge crane, a portable bridge crane, and a portable tower crane are used to demonstrate the utility of the closed-loop input shaping control architecture.

Keywords: Input shaping; Closed-loop input shaping; Feedback control; Nonlinear; Human operation; Crane

1. Introduction

The control of flexible systems is an immense field of research. Many control strategies have been developed to mitigate undesired oscillation. These include feedback control, open-loop filtering methods, zero-phase error tracking control, and other combinations of feed-forward, open-loop, and closed-loop approaches.

One particularly effective form of vibration suppression is input shaping (Singer & Seering, 1990; Smith, 1957). Input shaping is a command modification technique that causes a system to cancel out its own motion-induced oscillation. It has been used to reduce transient and residual oscillation in cranes (Lewis, Parker, Driessen, & Robinett, 1999; Singer, Singhose, & Kriikku, 1997; Singhose, Porter, Kenison, & Kriikku, 2000), coordinate measuring machines, (Jones & Ulsoy, 1999; Singhose, Singer, & Seering, 1996), flexible spacecraft (Gorinevsky & Vukovich, 1998; Singh & Vadali, 1993a; Tuttle & Seering, 1997), and long-reach manipulators (Kwon, Hwang, Babcock, & Burks, 1994; Magee & Book, 1995).

An input shaper is a sequence of impulses. A general, n-impulse input shaper can be expressed in the time domain as

$$IS(t) = \sum_{i=1}^{n} A_i \delta(t - t_i), \quad 0 \leqslant t_i < t_{i+1}, \ \ A_i \neq 0, \tag{1}$$

where $\delta(t)$ is the Dirac delta function, A_i is the amplitude of the ith impulse, and t_i is the time of the ith impulse.

Input shaping is implemented by convolving an input shaper with a reference command. The convolution product, instead of the original command, is then issued to a plant. For reference commands that reach a steady-state value, and for correctly designed input shapers, a linear system can exhibit zero residual oscillation in response to the modified command. This scenario is illustrated in Fig. 1(a) for a reference step command and a two-impulse input shaper. A block diagram representing a general input-shaped system is shown in Fig. 1(b). IS is the input shaper, and H is the linear plant.

The two-impulse input shaper used in the preceding example is called a zero-vibration (ZV) shaper (Singer & Seering, 1990) because it results in zero residual system vibration when accurate estimates of system frequency and damping are available. The ZV shaper is defined as

$$IS(t) = A_1 \delta(t) + A_2 \delta(t - t_2). \tag{2}$$

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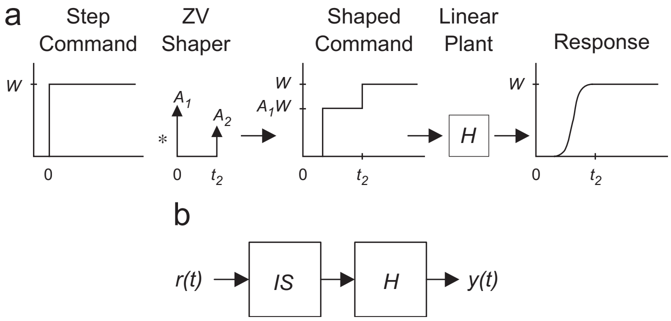

Fig. 1. Input shaping process. (a) Shaped command actuating a linear plant; (b) input shaping block diagram.

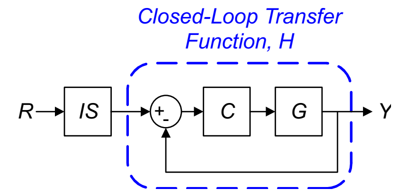

Fig. 2. Outside-the-loop input shaping control architecture (OLIS).

The input shaper parameters are functions of ζ and ω_n, the damping ratio and natural frequency of H, respectively:

$$A_1 = \frac{e^{\pi\zeta\omega_n/\omega_d}}{1 + e^{\pi\zeta\omega_n/\omega_d}}, \tag{3}$$

$$A_2 = 1 - A_1, \tag{4}$$

$$t_2 = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}} \equiv \frac{\pi}{\omega_d}. \tag{5}$$

If the frequency and damping ratio of a system cannot be estimated accurately, then higher-order input shapers that are robust to modeling errors can be used (Singhose, Porter, Tuttle, & Singer, 1997; Singh & Vadali, 1993b). The penalty associated with increased robustness is that shaper duration is lengthened. Subsequently, rise time also increases.

The vibration-reducing properties of an input shaper can be conceptually understood in the Laplace domain. The transfer function of the shaped system in Fig. 1(b) is

$$\frac{Y}{R} = IS \cdot H = \frac{IS \cdot H_n}{H_d} = \frac{IS \cdot H_n}{H_{dr} \cdot H_{di}}, \tag{6}$$

where H_n and H_d are the numerator and denominator of H, respectively. For an undamped second-order system, H_d defines the two imaginary poles of H. In the more general case, where H is an nth-order transfer function, H_d can be decomposed into two polynomials: H_{dr} and H_{di}. The real (non-oscillatory) poles of H are defined by H_{dr}. The imaginary (oscillatory) poles of H are defined by H_{di}.

For correctly designed input shapers, the input shaping parameters are selected so that the oscillatory poles of H (specified by the polynomial, H_{di}) are canceled by the zeros of IS (Bhat & Miu, 1990; Singh & Vadali, 1993b, 1994).

In many industrial implementations of input shaping control, the plant, H, is comprised of a feedback controller, C, and a linear block, G. This scenario is shown in the block diagram of Fig. 2. By utilizing input shaping in this serial configuration, outside of a feedback loop, motion-induced oscillation of the closed-loop system can be reduced by the input shaper. The input shaper parameters are selected so that the oscillatory poles of the closed-loop-transfer function are canceled by the zeros of the input shaper. Other sources of system oscillation, such as disturbances, non-zero initial conditions, and actuator saturation are addressed by the feedback control block. This type of control architecture is referred to as outside-the-loop input shaping (OLIS).

While the structure and implementation of input shaping resembles conventional filtering techniques, the design of input shaping filters is fundamentally different. The impulse sequence used in the shaping process is derived by solving a set of constraint equations that enforce a specified upper limit on residual vibration amplitude, even in the presence of modeling errors. Conventional filtering techniques do not usually directly impose constraints on vibration amplitude. They generally seek to minimize an energy cost function, or suppress frequencies in the commanded signal. Furthermore, virtually all conventional filters have pass bands where the filter attempts to pass frequencies without attenuation. This requirement imposes significant additional constraints that input shapers do not need to satisfy.

The subtle design differences between input shaping and conventional filters have a substantial influence on system performance. In Singhose, Singer, and Seering (1995), input shaping was compared with several common lowpass and notch filters. The comparison was made by measuring the residual vibration amplitude of a harmonic oscillator in response to filtered step commands. The commands were filtered either by an input shaper or a conventional lowpass/notch filter. The systems using input shaping exhibited lower levels of vibration and faster rise times then those using conventional filters, even when significant modeling errors were present.

Some key results from this study are summarized in Fig. 3. The bar graph in Fig. 3(a) represents the residual vibration amplitude for the various input shapers and filters that were tested. The bar graph in Fig. 3(b) represents the duration of the input shapers and filters. Filter/shaper duration is important because it provides a lower bound on rise time. These results were obtained for the case when a 15% modeling error in system frequency was present.

Ordinarily, input shaping is used in an open-loop manner previously illustrated in Fig. 2. Fig. 4 shows a different control architecture where an input shaper is located within a feedback loop. This “in-the-loop-shaping” architecture is referred to as closed-loop signal shaping (CLSS). Given the advantages of input shaping over traditional filtering techniques at reducing oscillation,