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Input Shaping for Configuration-Dependent Systems Using Fuzzy Interpolator

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Abstract

Configuration-dependent systems, such as multi-link robot manipulators, have varying dynamics, depending on the current configuration of the system. Input shaping is a technique to reduce residual vibration by destructive interference of impulse responses, that is, an impulse response can be cancelled by another impulse response, given appropriate impulse amplitudes and applied times. Therefore, in principle, the input shaping technique is only applicable to linear systems. When input shaping is being used in a configuration-dependent system, its performance degrades because the varying dynamics nature of the system. In this paper, for the first time, the Takagi-Sugeno fuzzy interpolator is used to interpolate among linear mappings of a configuration-dependent system. One linear mapping is found for one operating point of the configuration-dependent system. The Takagi-Sugeno fuzzy interpolator gives an output as a linear system that is an interpolation among the linear mappings of all operating points of the system. The input shaper is then designed on the linear system output from the fuzzy system. From simulations, significant performance improvement can be seen when the proposed technique is compared with an input shaping designed using a fixed nominal plant model.

***Keywords**:* Input shaping; Vibration reduction; Fuzzy interpolator; Takagi-Sugeno fuzzy system; Configuration-dependent system; Gain scheduling; Adaptive input shaping.

1. Introduction

Input shaping is an effective technique in reducing residual vibration in point-to-point movement of flexible systems. It is based on destructive interference of impulse responses, that is, an impulse response can be cancelled by another impulse response, given appropriate impulse amplitudes and applied times.

Input shaping uses knowledge of mode parameters, which are natural frequencies and damping ratios of the systems; therefore, its performance depends on the accuracy of these knowledge.

Several systems in practice are configuration-dependent. Their mode parameters change with their current configuration. The input shaping must be either robust or adaptive to parameter uncertainty to maintain its vibration suppression performance at a high level.

Robust input shapers, such as extra-insensitive shaper [1], least squares shaper [2], and specified-insensitivity shaper [3], usually require lengthening the shaper's duration, which slows down the settling time. Besides, the robust input shaper cannot cover wide range of parameter variation, so it is not suitable for configuration-dependent systems, whose parameters may vary considerably.

Adaptive input shapers are roughly divided into two categories. First is direct method where the input shaper is adapted directly from the adaptive algorithm. Second is indirect method where the plant's mode parameters are first identified before the shaper is designed. The proposed technique in this paper is closely related to the indirect adaptive input shaping.

Examples of the indirect adaptive input shaping are given here. Ref. [4] used a frequency-domain identification scheme called time-varying transfer function estimation (TTFE) to identify changing natural frequency of the system to redesign the input shaper. Ref. [5] applied algebraic identification technique to indirect adaptive input shaping of a second-order flexible system. Ref. [6] proposed a simplified formula of half the damped period of vibration for a 6-DOF configuration-dependent industrial robot. The period was found to be a linear function of reach-out length of the robot arm. The period is used to design an input shaper. Ref. [7] proposed an adaptive input shaping based on the idea from adaptive inverse control

This paper considers configuration-dependent systems whose mode parameters can vary largely with different configurations. For these systems, a linear model is usually obtained for one configuration. The interpolation among several linear models occupying several configurations may be complex. Human reasoning via fuzzy logic can be used to describe rules for appropriate interpolation. In this paper, the Takagi-Sugeno fuzzy system is used as fuzzy interpolator. The linear model output from the fuzzy interpolator is used in computing the ZV input shaper. This adaptive ZV input shaper is shown through simulations that it can reduce vibration of the configuration-dependent flexible system effectively.

This paper is organized in the following way. Section 2 discusses configuration-dependent systems. A two-mass rigid-flexible system is used as a representative of the configuration-dependent systems. Its equation of motion and state-space model are presented. Section 3 introduces the ZV input shaper and shows how its performance degrades in configuration-dependent systems. Section 4 presents input shaping using Takagi-Sugeno fuzzy interpolator. This section is followed by conclusions.

2. Configuration-Dependent Systems

Configuration-dependent systems have time-varying parameters, depending on their current configurations. An example is a two-link one-flexible-joint robot manipulator, whose sketch is shown in Fig. 1. The manipulator is operated in the horizontal plane. There are two motors; each motor is for driving each link. There is one torsional spring at the shoulder joint. This is a typical model for industrial robots. The spring is there to reduce damage during accidental collision. A spring at the elbow joint may not be necessary because the elbow link is lighter, allowing less damage. The natural frequencies and damping ratios of the system change, depending on the angular position θ_2 of the elbow link.

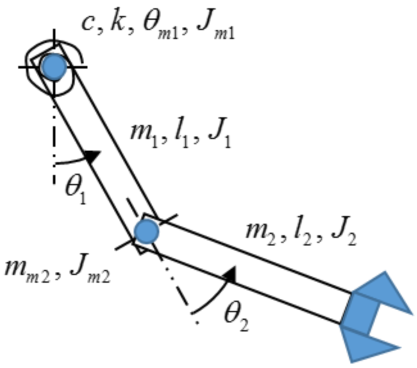

Fig. 1 Two-link one-flexible-joint robot manipulator.

In this work, a two-mass rigid-flexible system in Fig. 2 is considered. In general, the system represents two entities, connected via a flexible part, which encompasses a large majority of actual rigid-flexible systems. The driving one has an absolute position and mass of x_0 and m_0, and the driven one has x_1 and m_1. k, c_0, and c are spring stiffness and two damping constants. f is the control force. The objective is to move both masses from the origin to a displacement X with zero residual vibrations and in a shortest time possible T.

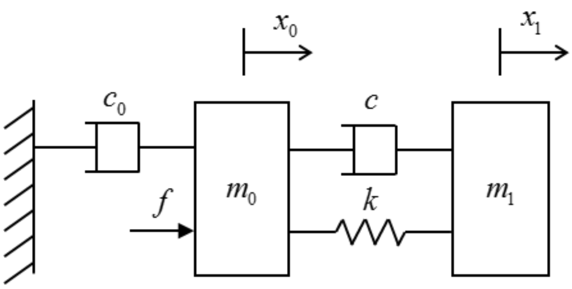

Fig. 2 Two-mass rigid-flexible system.

The equations of motion of the system in Fig. 2 can be found as

$$m_0\ddot{x}_0 + c\left(\dot{x}_0 - \dot{x}_1\right) + k\left(x_0 - x_1\right) + c_0\dot{x}_0 = f,$$
$$m_1\ddot{x}_1 - c\left(\dot{x}_0 - \dot{x}_1\right) - k\left(x_0 - x_1\right) = 0.$$

In most rigid-flexible systems, such as cranes, the command input is velocity v instead of acceleration or force f.

The corresponding state-space model is then given by

$$\begin{Bmatrix}\dot{x}_0\\ \ddot{x}_0\\ \dot{x}_1\\ \ddot{x}_1\end{Bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\dfrac{k}{m_0} & -\dfrac{(c+c_0)}{m_0} & \dfrac{k}{m_0} & \dfrac{c}{m_0} \\ 0 & 0 & 0 & 1 \\ \dfrac{k}{m_1} & \dfrac{c}{m_1} & -\dfrac{k}{m_1} & -\dfrac{c}{m_1}\end{bmatrix}\begin{Bmatrix}x_0\\ \dot{x}_0\\ x_1\\ \dot{x}_1\end{Bmatrix}$$
$$+\begin{Bmatrix}0\\ \dfrac{1}{m_0}\\ 0\\ 0\end{Bmatrix} f,\ \ y = \begin{bmatrix}0 & 0 & 1 & 0\end{bmatrix}x, \qquad (1)$$

where $f = \dot{v}$.

For simulation purpose, let $c = 0.1\,\text{kg.s}^{-1}$, $m_0 = 2\,\text{kg}$, $c_0 = 30\,\text{kg.s}^{-1}$, and $k = 1\,\text{kg.s}^{-2}$. To simulate configuration dependence, the mass m_1 is assumed to vary with the coordinate x_0, according to

$$m_1(t) = 10x_0(t) + 1\,\text{kg}. \qquad (2)$$

3. Performance Degradation in Configuration-Dependent Systems

This section shows that the performance of input shaping is degraded in configuration-dependent systems.

3.1 ZV input shaping

Input shaping is based on destructive interference of impulse responses. A good tutorial paper is [8].

The ratio between the n-impulse response amplitude at time $t \ge t_n$ and the single-impulse response amplitude at time $t \ge t_1$ is given by

$$V(\omega_n,\zeta) = e^{-\zeta\omega_n t_n}\sqrt{\left[C(\omega_n,\zeta)\right]^2 + \left[S(\omega_n,\zeta)\right]^2},$$

$$C(\omega_n,\zeta) = \sum_{i=1}^{n} A_i e^{\zeta\omega_n t_i}\cos\left(\omega_n\sqrt{1-\zeta^2}t_i\right),$$

$$S(\omega_n,\zeta) = \sum_{i=1}^{n} A_i e^{\zeta\omega_n t_i}\sin\left(\omega_n\sqrt{1-\zeta^2}t_i\right),$$

where V is the so-called *percentage vibration*, normally used in the literature to quantify the residual vibration, ω_n is the natural frequency of the applied linear system, ζ is its damping ratio, t_i is the time the i^{th} impulse is applied and A_i is the i^{th} impulse's amplitude.

The amplitudes A_i and time locations t_i of the impulse sequence are computed by solving the following equations:

$$V(\omega_n,\zeta) = 0, \quad (3)$$

$$\sum_{i=1}^{n} A_i = 1, \quad (4)$$

$$t_1 = 0, \quad (5)$$

which requires the knowledge of ω_n and ζ.

Eqns. (3) - (5) are used to solve four unknowns, which are the amplitudes and time locations of two impulses:

$$t_1 = 0,\ A_1 = \frac{1}{1+K}, \quad (6)$$

$$t_2 = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}},\ A_2 = \frac{K}{1+K}, \quad (7)$$

$$K = e^{-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}}. \quad (8)$$

This two-impulse input shaper is known in the literature as zero-vibration (ZV) shaper. It was originated back in 1957 by [9].

The input shaper is implemented in an open-loop system as shown in Fig. 3. v_b is the baseline velocity command given by an operator to the mass m_0 in the form of step functions. v_s is the shaped velocity command from the ZV input shaper. x_1 is the position of the mass m_1. The ZV input shaper is given by (6) - (8) whereas the flexible system is given by (1).

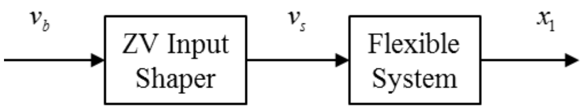

Fig. 3 Open-loop input shaping system.

3.2 Performance degradation in configuration-dependent systems

Because the input shaper is designed from the knowledge of the natural frequencies and damping ratios of the flexible system, when these parameters change due to changing configuration, performance of the input shaper in suppressing the residual vibration will degrade.

Recall that the mass $m_1(t)$ is changing with respect to $x_0(t)$ according to (2). When the mass $m_1(t)$ changes, the natural frequency and damping ratio of the flexible system also change according to (1).

Fig. 4 contains the result when the ZV input shaper is designed from one set of parameters, which are the natural frequency and damping ratio when the mass m_0 reaches the first step. As a result, when m_0 moves away from the first step to other steps, the mode parameters change and the performance of the input shaper degrades as can be seen from increasing oscillation in x_1 in Fig. 4(Top). Note that the vibration increases as the system moves further from the first step. Fig. 4(Bottom) shows the corresponding shaped velocity command v_s.

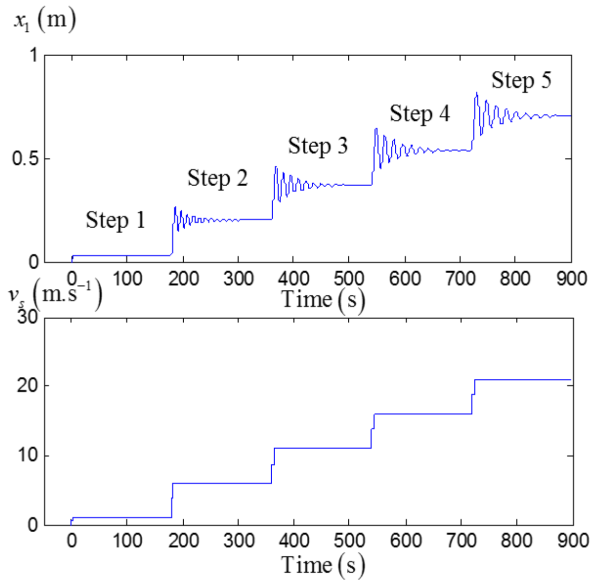

Fig. 4 Input shaping using one set of parameters. (Top) System output $x_1(\mathrm{m})$. (Bottom) Shaped velocity command $v_s(\mathrm{m.s^{-1}})$.

Fig. 5 contains the result when the ZV input shaper is designed from two sets of parameters, which are the mode parameters when m_0 reaches the first and fifth steps. As a result, the input shaper's performance is better when x_0 and x_1 are around the first and the fifth steps as can be seen from Fig. 5(Top). Fig. 5(Bottom) shows the corresponding shaped velocity command v_s.

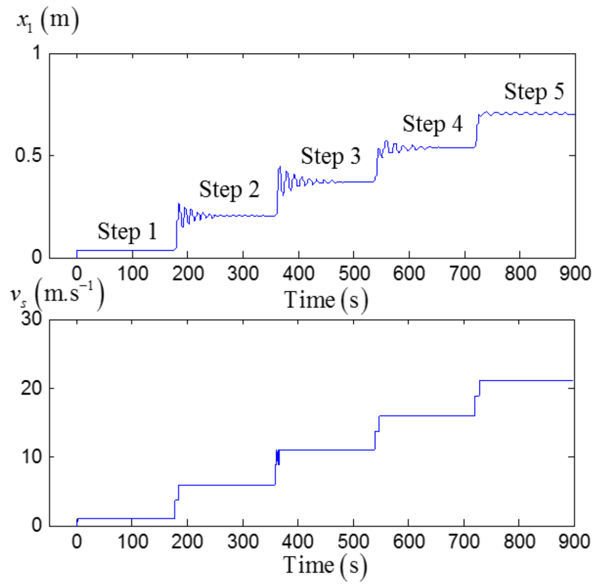

Fig. 5 Input shaping using two sets of parameters. (Top) System output $x_1(\mathrm{m})$. (Bottom) Shaped velocity command $v_s(\mathrm{m.s^{-1}})$.

In generating the result in Fig. 5, the mass m_1 of the flexible system varies according to (2) whereas the mass m_1 used to designed the input shaper is obtained from

$$\begin{aligned} m_1 &= 8, \quad \text{if } x_0 > 0.35, \\ m_1 &= 1.2, \quad \text{if } x_0 \le 0.35. \end{aligned} \tag{9}$$

In practice, system identification of a configuration-dependent system is often performed by obtaining one linear model per one configuration. Eqn. (9) corresponds to obtaining two linear models for two configurations. The two configurations are when the mass m_0 is at the first and fifth steps.

The result in Fig. 5 motivates an idea of using interpolation between configurations so that the vibration can be reduced in-between configurations.

4. Input Shaping Using Fuzzy Interpolator

In configuration-dependent systems, it is typical to obtain one linear mathematical model per one configuration. Sometimes a large number of linear models cannot be obtained due to various reasons such as limited time, avoiding operational disruption, or safety. The performance of the input shaper can be improved if it is designed from these linear models as well as from their interpolations.

4.1 Takagi-Sugeno fuzzy interpolator

Takagi-Sugeno fuzzy system [10] is called functional fuzzy system because its linguistic terms are functions. It can be used as an interpolator between linear systems. Its rules are then given in the form

$$\text{If } \tilde{z}_1 \text{ is } \tilde{A}_1^j \text{ and } \tilde{z}_2 \text{ is } \tilde{A}_2^k \text{ and} \ldots \tilde{z}_p \text{ is } \tilde{A}_p^l,$$
$$\text{then } \dot{x}^i(t) = A_i x(t) + B_i u(t),$$

where $x \in \mathbb{R}^n$ is the state vector, $u \in \mathbb{R}^m$ is the input vector, z_i are p crisp inputs, $\tilde{z}_i$ are p linguistic variables, A_i and B_i are constant matrices and vectors, and $\tilde{A}_i^j$ denotes the j^{th} linguistic value of the linguistic variable $\tilde{z}_i$. Many choices are possible for the crisp input z. For example, $z(t) = \left[x^T(t), u^T(t)\right]^T$, $z(t) = x(t)$.

4.2 Input shaping using fuzzy interpolator

In our case, $m = p = 1$, $n = 4$. There are two linguistic values: $\tilde{A}_1^1 = \text{step}\,1$ and $\tilde{A}_1^2 = \text{step}\,5$. The input membership functions μ_i are shown in Fig. 6, representing the linguistic values. $z_1 = x_0$, which is the current position of the first mass m_0. The two rules are given by

$$\text{If } \tilde{z}_1 \text{ is } step\,1, \text{ then } \dot{x}(t) = A_1 x(t) + B_1 \dot{v}(t),$$
$$\text{If } \tilde{z}_1 \text{ is } step\,5, \text{ then } \dot{x}(t) = A_2 x(t) + B_2 \dot{v}(t).$$

$\dot{x}(t) = A_1 x(t) + B_1 \dot{v}(t)$ is the plant model (1) when x_0 is at step 1 and m_1 is computed from (2). $\dot{x}(t) = A_2 x(t) + B_2 \dot{v}(t)$ is when x_0 is at step 5.

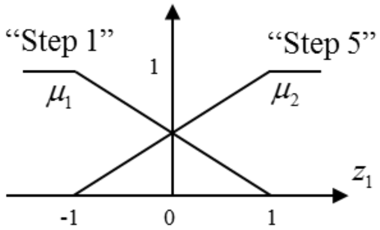

Fig. 6 Input membership functions.

The output of the fuzzy system is

$$\dot{x}(t) = \frac{\sum_{i=1}^{2} \left(A_i x(t) + B_i \dot{v}(t)\right) \mu_i\left(z_1(t)\right)}{\sum_{i=1}^{2} \mu_i\left(z_1(t)\right)}.$$

The fuzzy system interpolates between the two linear systems.

One linear system can be thought of as valid on a region of the state space that is quantified via μ_1 and another on the region quantified by μ_2 with a fuzzy boundary in between. As the state evolves, different rules turn on, indicating that other combinations of linear models should be used.

Note that if more than two linear models are available, additional input membership functions can be added.

Fig. 7 contains the result when the ZV input shaper is designed from the output of the fuzzy interpolator. It can be seen that the input shaper's performance in suppressing vibration significantly improves for all steps.

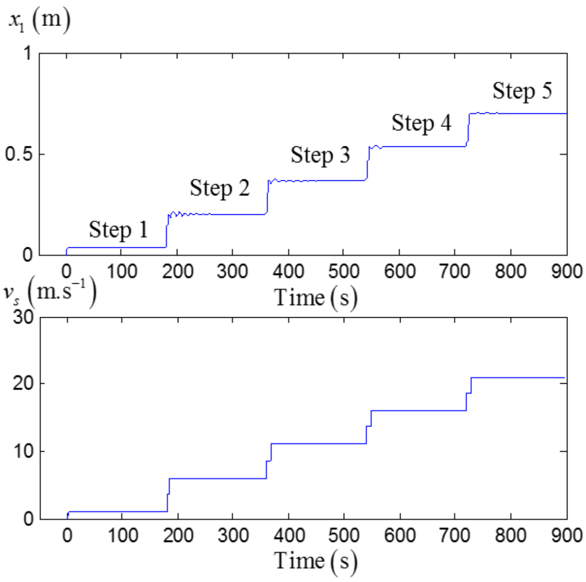

Fig. 7 Input shaping using fuzzy interpolator. (Top) System output $x_1(\mathrm{m})$. (Bottom) Shaped velocity command $v_s(\mathrm{m.s^{-1}})$.

Fig. 8(Top) shows the changing natural frequency of the flexible system, and Fig. 8(Bottom) contains the changing damping ratio. This is when the fuzzy interpolator is used.

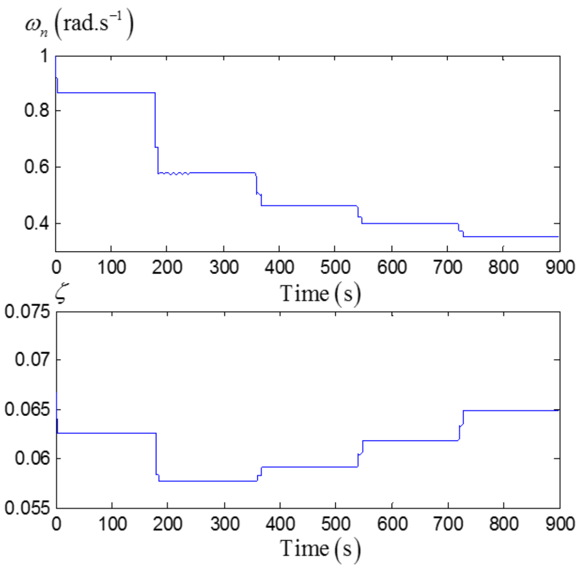

Fig. 8 System's mode parameters. (Top) Natural frequency. (Bottom) Damping ratio.

5. Conclusions

Configuration-dependent system has mode parameters that vary by configuration of the system. Input shaper is designed from mode parameters; therefore, when they change, its performance degrades. Linear models of the configuration-dependent system are usually available for some configurations. This paper proposes, for the first time, using the Takagi-Sugeno fuzzy system as interpolator among the linear models. The input shaper is adaptive as it uses different mode parameters from different linear model supplied by the fuzzy interpolator. As a result, the vibration reduction performance of the input shaper is maintained at a high level over a wide range of configurations.

Future work includes applying the proposed technique to more complex systems and implementing the technique with actual physical systems.

6. References

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