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Hybrid input shaping to suppress residual vibration of flexible systems

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Abstract
This paper presents a hybrid input shaping method to eliminate residual vibration of multi-mode flexible systems. This method, initially designed for one degree of systems, is modified to apply on linear and nonlinear multi-mode systems. In this method, firstly the flexible system is uncoupled using modal analysis method, and then the parameters of the decoupled system are used to shape the command template signal. A ramp plus ramped cycloid plus ramped versine is proposed as the command template signal to be preshaped. The template function is preshaped to yield zero residual vibration for point to point motion and then the resulting trajectory is convolved with a sequence of two impulses to obtain a twice shaped input. The proposed method is applied to eliminate residual vibration of a linear multimass and flexible joint manipulator types of systems. Simulation results show that the oscillations are considerably decreased with a high degree of robustness in the presence of system parameters uncertainty.

Keywords
Command shaping, lightly damped flexible system, multi-mode, residual vibration

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1. Introduction

When a flexible system is moved, it has a tendency to vibrate. Control of such a system is more difficult especially if it consists of light components and is used for a fast response required area. There is a great deal of literature relating to control vibration of flexible systems. Among these methods, command preshaping or input shaping based methods have attracted the attention of many researchers (Blackburn et al., 2010; Chan et al., 2003; Dharne et al., 2007; Masoud et al., 2003, 2007). One of the solutions suggested in the literature is a feedforward control method which alters the shape of command signal to reduce system oscillations. The earliest form of command preshaping was the use of posicast control by Smith (1958). This technique involves breaking a step input into two smaller steps, one of which is delayed in time. Superposition of the step responses results in cancellation of vibration. **It also allows reduction** in the settling time. However, this method is not generally favoured due to problems related to robustness in natural frequency and damping ratio uncertainties. Another approach to command shaping is the study of Aspinwall (1980). This method includes shaping rectangular or 'bang-bang' forcing function by a short, finite Fourier series to reduce residual response of a system. Meckl and Seering (1990) suggested construction of input signal from either ramped sinusoids or versine functions. If all harmonics of one of these template functions are added, a time optimal rectangular input function is obtained in a similar manner to the former method. However, in this method, the motion is completed in a shortened period of time owing to the shaped signal approach of the rectangular function. A more recent technique is based on shaping the input signal by inverse dynamic analysis as reported by Piazzi and Visioli (2000), who proposed a polynomial function as a desired output to produce the input signal and compared it with the bang-bang and other impulse shaping input

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methods. However, the suggested input function must be changed to another function at the end point to control the motion. This causes a sudden step change in acceleration at this point. In faster motion cases, this effect causes excitations and results in vibrations. On the other hand, Sahinkaya (2001, 2004) suggests third order exponential function for the output motion to shape input signal using inverse dynamics. But inverse dynamic analysis can be a tedious task. Besides, it requires relatively more computation time. One of the most popular methods is the input shaping technique that is implemented by convolving the reference command with a sequence of impulses (Changa and Park, 2005; Cutforth and Pao, 2004; Gurleyuk and Cinal, 2007; Gurleyuk, et al, 2007; Mimmi and Pennachi, 2001; Park and Chang, 2004;) where the residual vibration of flexible systems are studied. The shaped command is then used to drive the system. Although with more impulses the shaped signal becomes more robust to uncertainty in the system parameters, it also results in longer delays in system responses (Singer 1989; Singer and Seering, 1990). Magee and Book (1993) employed an adaptive approach to implement a two-mode shaper on a two-link robot. Alıcı et al. (2000) have proposed a ramp superimposed onto a cycloid for input shaping in order to compare the aforementioned input shaping method. Kapucu et al. (2001) on the other hand, suggested a hybrid input shaping method that includes convolution of a cycloid plus ramp function with two impulse sequences.

The technique presented in this study is an extension of the hybrid input shaping method to the residual vibration elimination of single input single output multi-mode linear and nonlinear systems by Kapucu et al. (2001). However, it should be emphasized that the problem considered here differs from the motion design problem reported in the previous work by Kapucu et al. (2001) in three aspects. Firstly, the present systems are damped system types. Secondly, the systems under consideration are multi-mode systems, and finally, the command template function used in the present study is different. The proposed hybrid input shaping technique is, in fact, based on the two input shaping methods reported by Kapucu et al. (2001). Another study reported by Kapucu et al. (2008) presents an approach where a multi-mode-system-based residual vibration elimination study is performed. Although physically it may not be possible, theoretical analysis of the approach appears to fail due to the matching natural frequencies of the modes. However, the presented method is also superior to the method reported in Kapucu et al. (2008) as its performance does not degrade with closer natural frequencies of modes of vibration.

Simulation results presented in this paper indicate the effectiveness of this technique in reducing residual vibration. The proposed method considers a trajectory based on a cycloidal and versine motion, which is commonly used as a high-speed cam profile, continuous throughout one cycle, plus a ramp. The amplitude of the ramp, the cycloidal function and versine function are determined such that the total travelling distance and the transportation time conditions are satisfied. Then the resulting trajectory is convolved with a sequence of two impulses to obtain a twice-shaped input. It is believed that this method contributes to the efforts in reducing the vibration of multi-mode systems in the presence of uncertainty in the dynamic parameters of the flexible system such as its modal natural frequencies and the damping ratios.

The proposed technique has been implemented on a linear multi-mode (mass) and flexible joint planar manipulator systems. The simulation results for these studies indicate that a residual vibration free stop is obtainable at the end of a point-to-point move with a high degree of robustness. It is worth pointing out that the use of the proposed hybrid technique allows very high levels of robustness in spite of the presence of uncertainties in the system properties such as modal frequencies and damping ratios.

2. Modelling of the systems

In this study, two mass linear flexible mechanical and flexible joints manipulator systems are selected as examples of single input multi-mode type of flexible systems, as shown in Figures 1 and 2, respectively. Consider the two mode flexible system, in Figure 1, with k_1, k_2 springs and c_1, c_2 dashpots in which masses m_1 and m_2 are moved in coordinates of $x_1(t)$ and $x_2(t)$, respectively.

The system is actuated by displacement input $y(t)$. Applying Newton's second law for the masses m_1 and m_2, respectively, the resulting differential equations are

$$\begin{aligned} m_1\ddot{x}_1 &= -c_1(\dot{x}_1-\dot{y})+c_2(\dot{x}_2-\dot{x}_1)-k_1(x_1-y)+k_2(x_2-x_1) \\ m_2\ddot{x}_2 &= -c_2(\dot{x}_2-\dot{x}_1)-k_2(x_2-x_1) \end{aligned} \tag{1}$$

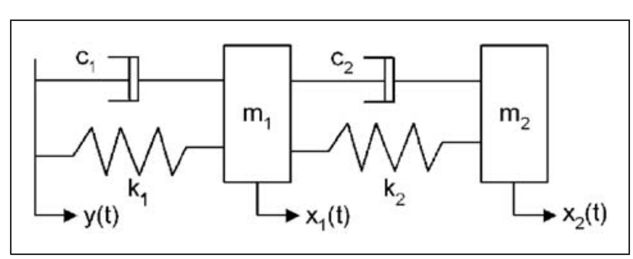

Figure 1. A lightly damped linear multi-mass-spring system with damping.

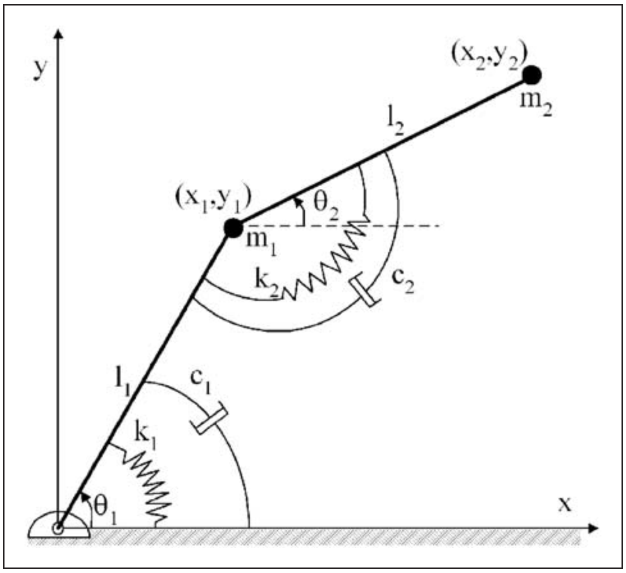

Figure 2. A flexible revolute joint manipulator with damping coefficients c_1, c_2 and spring stiffness k_1 and k_2.

The equation of motion of a two degree-of-freedom Revolute – Revolute (RR) flexible joint manipulator in a horizontal plane with angular displacement input on base joint ψ can be derived using Newton-Euler equations. Let (x_1, y_1) and (x_2, y_2) be the coordinates of mass centres and I_1 and I_2 be the moments inertia of m_1 and $m_2$with respect to the axis of rotation. It can be shown that the equation of motion of this flexible system is

$$\begin{aligned}
&(m_1\ddot{x}_1 + m_2\ddot{x}_2)l_1\sin\theta_1 - (m_1\ddot{y}_1 + m_2\ddot{y}_2)l_1\cos\theta_1 \\
&\quad - c_1\dot{\theta}_1 - k_1\theta_1 + c_2(\dot{\theta}_2 - \dot{\theta}_1) + k_2(\theta_2 - \theta_1)m_2\ddot{x}_2 l_2\sin\theta_2 \\
&\quad - m_2\ddot{y}_2 l_2\cos\theta_2 - c_2(\dot{\theta}_2 - \dot{\theta}_1) - k_2(\theta_2 - \theta_1) = 0 \\
&\quad + c_1\dot{\psi} + k_1\psi = 0
\end{aligned} \tag{2}$$

$$\text{Where}\quad \begin{aligned}
x_1 &= l_1\cos\theta_1 \\
x_2 &= l_1\cos\theta_1 + l_2\cos\theta_2 \\
y_1 &= l_1\sin\theta_1 \\
y_2 &= l_1\sin\theta_1 + l_2\sin\theta_2
\end{aligned}$$

$$\text{Hence}\quad \begin{aligned}
\ddot{x}_1 &= -l_1\cos\theta_1\dot{\theta}_1^2 - l_1\sin\theta_1\ddot{\theta}_1 \\
\ddot{x}_2 &= -l_1\cos\theta_1\dot{\theta}_1^2 - l_1\sin\theta_1\ddot{\theta}_1 \\
&\quad -l_2\cos\theta_2\dot{\theta}_2^2 - l_2\sin\theta_2\ddot{\theta}_2 \\
\ddot{y}_1 &= l_1\sin\theta_1\dot{\theta}_1^2 + -l_1\cos\theta_1\ddot{\theta}_1 \\
\ddot{y}_2 &= -l_1\sin\theta_1\dot{\theta}_1^2 + l_1\cos\theta_1\ddot{\theta}_1 \\
&\quad -l_2\sin\theta_2\dot{\theta}_2 2 + l_2\cos\theta_2\ddot{\theta}_2
\end{aligned}$$

Equation of motion of these systems described in equations (1) and (2) is coupled, in that both coordinates appear in each equation. In order to shape input of the flexible system, the system parameters such as the damping ratio and the natural frequency of the system should be known. These parameters can be found by using a modal analysis method such as that of Park (2003), where it is described as a process of deriving the system response by transforming the equation of motion into an independent set of equations. Parameters used in the simulations for both systems are listed in Table 1. There is no limitation for travelling distance, i.e. it may have any value. However, there is a limitation for travelling time due to the nature of the input shaping technique. The travelling time should be greater than the half of the period of oscillation of the systems (see equation (10)).

Table 1. Simulation parameters

Modal parameters	Multi-mode (mass) system	Two flexible joint manipulator
m_1, kg	1	1
m_2, kg	1	0.5
k_1, N/m	5000	800
k_2, N/m	3000	400
c_1, Ns/m	9	9
c_2, Ns/m	5.4	4.5
ω_1, rad./s	39.9359	14.6410
ω_2, rad/s	96.8000	54.6410
ζ_1	0.0359	0.0824
ζ_2	0.0873	0.3074
y, L	0.2 m	0.5 rad
τ_t, s	0.2	0.4

3. Reference command function

The reference input consists of three functions. The total distance to be covered from the beginning to end of a move within a specified time is the sum of the distances to be travelled by each of the three functions within the same travel time. By adjusting excursion distance of each function, vibration can be eliminated provided that the specified move time and the total distance are unchanged. Each component of the reference input creates oscillations such that these oscillations cancel each other and no vibration results. Most elastic mechanical systems are composed of masses moving under the action of position and velocity dependent forces and hence can be modelled by a second order differential equation. The simplest mechanical system can have an inertia element movable in a single coordinate $x(t)$ under the effect of position and velocity dependent forces and externally applied actuation displacement $y(t)$ or force. A great many elastic mechanical systems can effectively be assumed to have this format. Equation of motion of such a system with damping ratioζ and natural frequency ω_n can be written as

$$\ddot{x}(\mathrm{t}) + 2\zeta\omega_n\dot{x}(\mathrm{t}) + \omega_{\mathrm{n}}^2\mathrm{x}(\mathrm{t}) = 2\zeta\omega_n\dot{y}(\mathrm{t}) + \omega_n^2\mathrm{y}(\mathrm{t}) \quad (3)$$

where $\omega_n = \sqrt{\frac{\mathrm{k}}{\mathrm{m}}}$.

A motion profile of a cycloid-plus-ramped versine-plus-ramp function is expressed as

$$Y = \frac{L_1 Rt}{2\pi} + \frac{L_2}{2\pi}[Rt - \sin(Rt)] + \frac{L_3 Rt}{2\pi} + \frac{L_3}{2\pi}[1 - \cos(Rt)] \quad (4)$$

where L_1 is the maximum excursion distance to be travelled by ramp motion profile, L_2 is the maximum excursion distance to be travelled by cycloid motion profile, $L_3$is the maximum excursion distance to be travelled by ramped versine motion profile, t is time into motion, τ is the travelling time, and $R = 2\pi/\tau$. Furthermore, total distance can be written as$L = L_1 + L_2 + L_3$, then arranging the equation above becomes

$$Y = \frac{LRt}{2\pi} - \frac{L_2}{2\pi}\sin(Rt) + \frac{L_3}{2\pi}(1 - \cos(Rt)) \quad (5)$$

The corresponding velocity profile is

$$\dot{Y} = \frac{LR}{2\pi} - \frac{L_2 R}{2\pi}\cos(Rt) - \frac{L_3 R}{2\pi}\sin(Rt) \quad (6)$$

Solution of equation of motion under the positional input equation (5) and corresponding velocity equation (6) for zero initial condition to generate an input that yields zero residual vibration yields

$$L_1 = \frac{LR(R - 2\xi\omega_n)}{\omega_n^2} = \frac{L\tau_n(\tau_n - 2\xi\tau)}{\tau^2}$$

$$L_2 = L\left(1 - \frac{R^2}{\omega_n^2}\right) = L\left(1 - \frac{\tau_n^2}{\tau^2}\right)$$

$$L_3 = \frac{L2\xi R}{\omega_n} = \frac{L2\xi\tau_n}{\tau}$$

Note that

$$L = L_1 + L_2 + L_3 \quad (7)$$

The variation of L_1, L_2, and $L_3$with travelling time τ which results in oscillation-free displacement of a system.

Differential equations of motion given in equation (1) are solved on a digital computer to show the effectiveness of the proposed method. Firstly, excursion distances of functions for the linear multi-mode system are taken arbitrarily as:$L_1 = L/3$, $L_2 = L/3$, and $L_3/3$ without considering equation (7). Then, the preshaped displacement input y(t) is applied to the system. The initial study on the two mass systems is performed for arbitrarily selected travel distance, $\mathrm{y} = L = 0.2$ m and travel duration, $\tau = \tau_t = 0.17$ s. Besides, excursion distances of functions are also taken arbitrarily as: $L_1 = L/3$, $L_2 = L/3$, and $L_3 = L/3$ without considering equation (7). The response of the system together with the input is depicted in Figure 3. The figure shows that oscillation of the last mass $\mathrm{m}_2$is not eliminated. Later, the displacement input $\mathrm{y(t)} = Y$ is formed by calculating the excursion distances of functions given in equation (7).

Further study of the two mass systems is performed for arbitrarily selected travel distance, $\mathrm{y} = L = 0.2$ m and travel duration, $\tau = \tau_t = 0.17$s. The displacement input $\mathrm{y(t)} = Y$ is formed by calculating the excursion distances of functions as defined in equation (7). The response of the system together with the input is shown in Figure 4, which shows that the oscillation of the mass m_2 is considerably eliminated.

Differential equations of motion given in equation (2) are also solved on a digital computer to indicate the applicability of this method to flexible joint manipulator. The displacement input $\psi(\mathrm{t}) = Y$ is formed by calculating the excursion distances of functions given in equation (7). The study of the two mass systems is

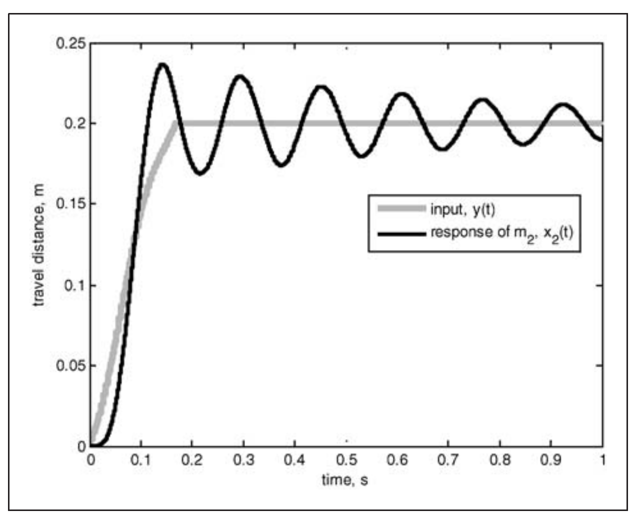

Figure 3. Initial study results for the two mass system. The total travel distance, L, the travel duration, τ and the excursion distances of equation (4) L_1,L_2,L_3 are taken arbitrarily as 0.2 m, 0.17 s, and L/3, L/3, L/3, respectively.

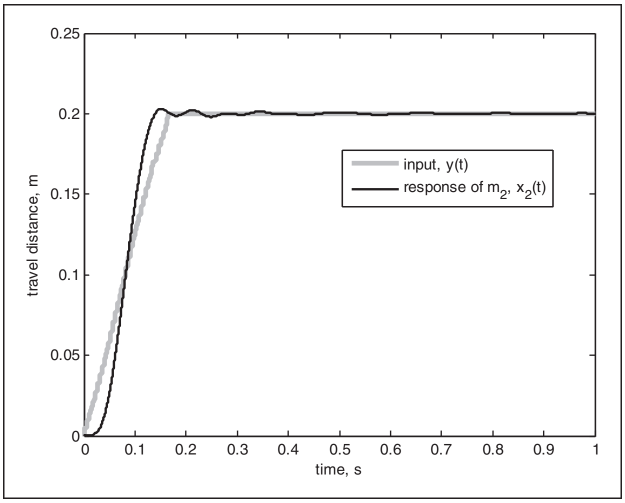

Figure 4. The study results for the two mass system. The total travel distance, L and the travel duration, τ are taken arbitrarily as 0.2 m, 0.17 s, respectively. The excursion distances are calculated using equation (7) to form the displacement command input.

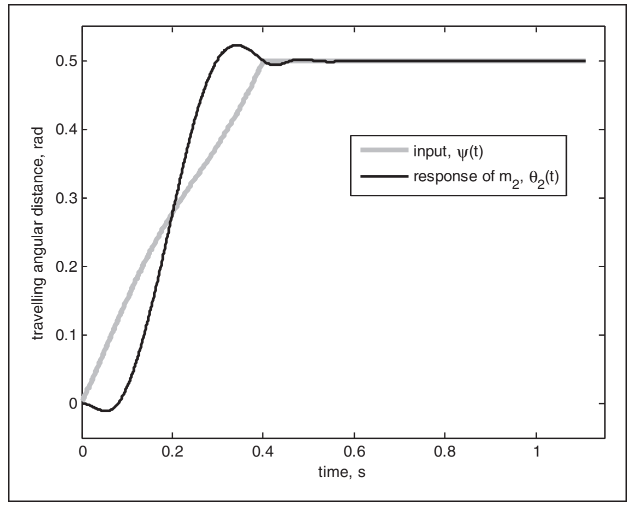

Figure 5. The study results for the RR flexible joint manipulator. The total travel distance, L and the travel duration, τ are taken arbitrarily as 0.5 rad, 0.4 s, respectively. The excursion distances are calculated using equation (7) to form the displacement command input.

performed for arbitrarily selected travel distance, $\psi = L = 0.5$ rad and travel duration, $\tau = \tau_t = 0.4$s. The displacement input $\psi(t) = Y$ is formed by calculating the excursion distances of functions given in equation (7). The response of the system together with the input is depicted in Figure 5, which shows that the oscillation of the end mass m_2 is considerably eliminated.

4. Input shaping

This method includes convolving desired command with a sequence of impulses in order to produce the shaped input that makes the same motion without any vibration. Further details of the method can be found in Singer (1989) and Singer and Seering (1990). The input shaping method is based on the transient response of a second order system with natural frequency of ω_n and the expected damping ratio of ζ to an impulse input. The transient response of y(t)is expressed as

$$\mathrm{y(t)} = \frac{A\omega_n}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_n(\mathrm{t}-\mathrm{t}_o)} \sin[\omega_n \sqrt{1-\zeta^2}(\mathrm{t}-\mathrm{t}_o)] \quad (8)$$

where A and t_o are the amplitude and time of the impulse signal, respectively. Since any arbitrary function can be formed from a sequence of impulses, the impulse sequence can be used to reduce the vibration of the flexible system. This is accomplished by convolving any desired trajectory with a sequence of impulses. However, this operation extends move time which is equal to the length of the impulse sequence. The amplitude and time of two impulses as defined by Singer and Seering (1990) as

$$\mathrm{t}_1 = 0\, \mathrm{t}_2 = \frac{\pi}{\omega_d},$$

$$\mathrm{A}_1 = \frac{1}{1+\mathrm{K}},\ \mathrm{A}_2 = \frac{\mathrm{K}}{1+\mathrm{K}}, \quad (9)$$

where $\mathrm{K} = e^{-\zeta\pi/\sqrt{1-\zeta^2}}$.

A template function cycloid-plus-ramped versine-plus-ramp is taken with arbitrarily selected excursion distances of functions as: $L_1 = L/3$, $L_2 = L/3$, and $L_3 = L/3$, then the resulting command is convolved with two impulse sequence given by equation (9) for which the input shaping is used for only the first mode's frequency and damping ratio. And then, pre-shaped input is applied to a linear multi-mode system and flexible joint manipulator. The input shaping study on the two mass system is performed by arbitrarily selecting the travel distance, $y = L = 0.2$ m and travel duration, $\tau = \tau_t = 0.17$s. For a template function, cycloid-plus-ramped versine-plus-ramp is taken with excursion distances of functions as: $L_1 = L/3$, $L_2 = L/3$, and $L_3 = L/3$, then the resulting command is convolved with two impulse sequences given by equation (9). The input shaping study on the RR flexible joint manipulator is, on the other hand, performed by arbitrarily selected travel distance, $\psi = L = 0.5$ rad and travel duration, $\tau = \tau_t = 0.4$ s. For a template function, cycloid-plus-ramped versine-plus-ramp is taken with excursion distances of functions as; $L_1 = L/3$, $L_2 = L/3$, and $L_3 = L/3$, then the resulting command

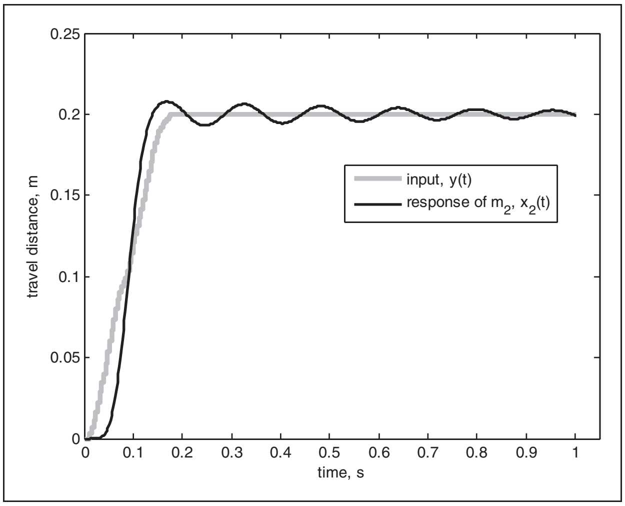

Figure 6. Input shaping response of two mass system. Only first mode frequency and damping ratio of the system is taken into consideration.

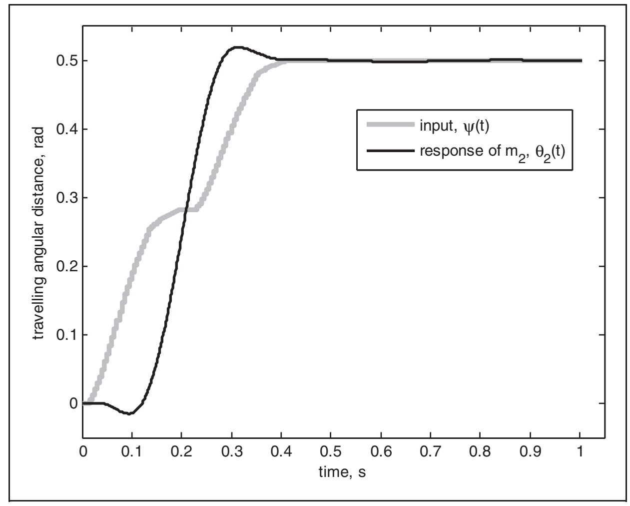

Figure 7. Input shaping response of RR flexible joint manipulator. Only first mode frequency and damping ratio of the system is taken into consideration.

is convolved with two impulse sequences given by equation (9). Figures 6 and 7 show that using only first mode frequency and damping ratio of the systems, input shaping reduces the oscillation, but does not eliminate it.

5. Hybrid input shaping

The proposed hybrid input shaping technique involves the convolution of the preshaped input with the input shaping method of two impulse sequences. Singer and Seering (1990) address the issue of a system with more than one frequency of vibration where shapers for each mode frequency are formed by equation (9). Since input shaping is a linear operation, shapers can be convolved together. However, this method increases the time delay which is equal to the sum of the damped periods of vibration. Therefore, a sequence for m modes generated by convolving two impulse shapers together will have a time delay (τ_{delay}) defined as

$$\tau_{delay} = \sum_{i}^{m} \frac{\pi}{\omega_{n_i}\sqrt{1-\xi_i^2}} \tag{10}$$

where ω_{ni} and ξ_i are the frequency and damping of the i'th mode and τ_{delay} is the time delay of the last impulse.

For a specified travelling time and displacement, implementation of the hybrid-shaping technique to the multi-mode system is as follows:

1. Travelling time for the template function is calculated from $\tau_1 = \tau_t - \tau_{delay}$ in order to satisfy the total travelling time τ_t. Note that τ_t should be greater than the τ_{delay}.
2. The distances L_1, L_2 and L_3 for the template are calculated from equation (7)
3. Shapers for each mode frequency and damping ratio are formed
4. The shapers are convolved together
5. The preshaped trajectory is convolved with the sequence of m modes generated by two impulse sequences.

The hybrid input shaping study on the two mass system is performed by arbitrarily selected travel distance, $y = L = 0.2$ m and travel duration, $\tau = \tau_t = 0.17$ s. For a template function cycloid-plus-ramped versine-plus-ramp excursion distances are calculated using equation (7), then the resulting command is convolved with two impulse sequences given in equation (9) assuming that all mode frequency vibrations exist in the system. The results of the study for the system are illustrated in Figure 8.

The hybrid input shaping study on the RR flexible joint manipulator is performed by arbitrarily selected travel distance, $\psi = L = 0.5$ rad and travel duration, $\tau = \tau_t = 0.4$ s. For a template function cycloid-plus-ramped versine-plus-ramp excursion distances are calculated using equation (7), then the resulting command is convolved with two impulse sequences given in equation (9) assuming all mode frequency vibration exist in the system. The result of the study for the system is illustrated in Figure 9.

It can be seen from Figures 8 and 9 that the vibration is considerably eliminated with convolving the preshaped input of cycloid-plus-ramped versine-ramp function with the sequence of all modes generated by two-impulse sequences.

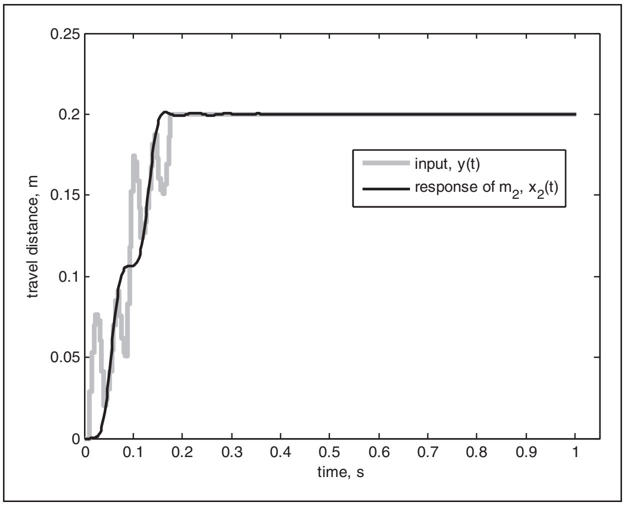

Figure 8. Hybrid input shaping response of two mass systems. Note that specified travelling time ($\tau = \tau_t$) is not increased. Time extension is tolerated by reference command shaping function.

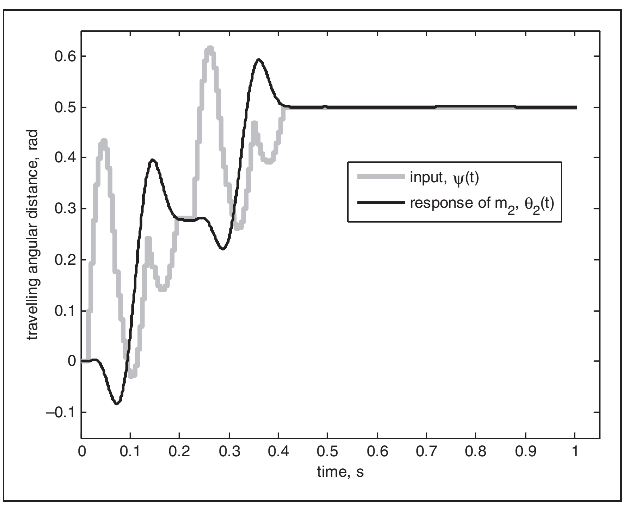

Figure 9. Hybrid input shaping response of RR flexible joint manipulator. Note that specified travelling time ($\tau = \tau_t$) is not increased. Time extension is tolerated by reference command shaping function.

6. Robustness

Robustness to uncertainty of system parameters such as damping ratio and natural frequency are two important properties that define whether a command shaping method is superior or not. Because mathematical models of any flexible system cannot be modelled perfectly, change of the system parameters influences the shaped signal and also the system response. Therefore, robustness of shaped signal to modelling uncertainty is an important comparison tool for command shaping methods. To analyze the robustness of a signal, the

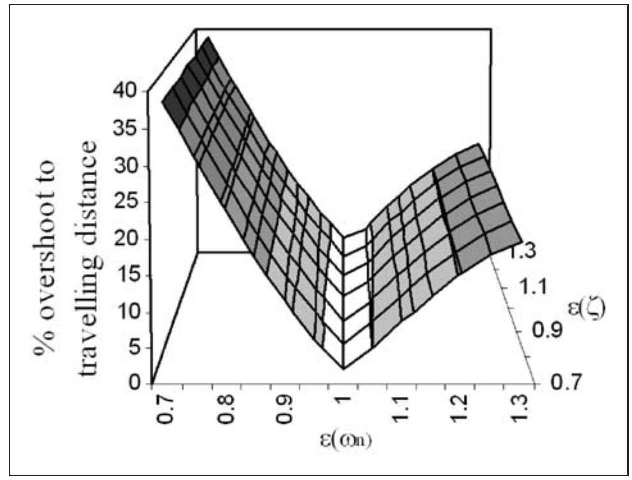

Figure 10. Robustness of the system to uncertainties in the mode frequencies and damping ratios for the cycloid-plus-ramped versine-plus-ramp function.

sensitivity curve and/or sensitivity surface definitions are used (Sahinkaya, 2001). Percentage of residual vibration (PRS, % overshoot to travelling distance), error functions, $\varepsilon(\omega_n)$ and $\varepsilon(\zeta)$ are defined as

$$PRS = \frac{Maximum\ amplitude\ of\ residual\ vibration\ of\ shaped\ response}{travelling\ dis\tan ce} * 100$$

$$\varepsilon(\omega_n) = \frac{\omega_n^*}{\omega_n} - 1,\ \varepsilon(\zeta) = \frac{\omega_n^*}{\zeta} - 1 \tag{11}$$

where ω_n^* and ζ^* are the uncertain values of natural frequency and damping ratio, respectively. The shaped input of the aforementioned methods are produced according to different values of $\varepsilon(\omega_n)$ and $\varepsilon(\zeta)$. The parameters varied within the range of -0.3 and $+0.3$ and are given to the system to investigate the maximum amplitude of the residual vibration as a percentage of the total travelling distance; results are plotted in Figures 10, 11 and 12. Robustness of the reference command shaping, input shaping and hybrid shaping can be compared quantitatively by defining the sensitivity curve width at a specific level of % overshoot to travelling distance. For example, 5% insensitivity width is indicated in Figures 10, 11 and 12. as a white color. Figures 9 and 10 show almost the same robustness for error to system parameter knowledge. However, Figure 12 shows that hybrid input shaping is far more robust then the input shaping or template function of cycloid-plus-ramped versine-plus-ramp.

It should be noted that robustness of the reference command function is limited and that of the input shaping depends on the number of impulses. As the number of impulses increases, the travelling time is lengthened by the total time of impulses. But the

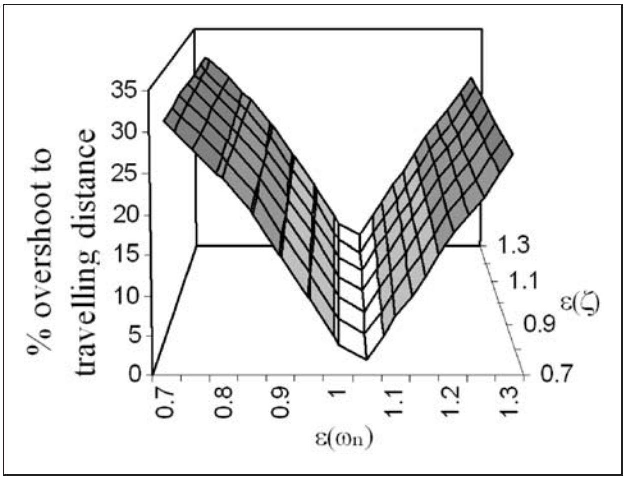

Figure 11. Robustness of the system to uncertainties in the mode frequencies and damping ratios for the input shaping.

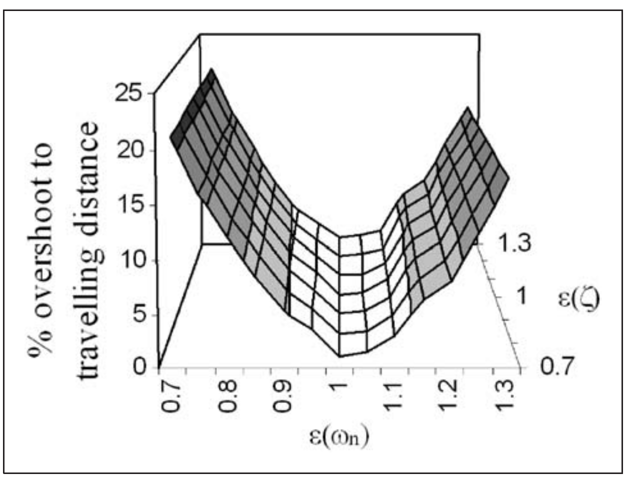

Figure 12. Robustness of the system to uncertainties in the mode frequencies and damping ratios for the hybrid input shaping.

hybrid shaping such as travelling time can be adjusted, can be used for single input-multi-mode system, and is more robust than the abovementioned techniques.

7. Conclusions

Simulation results show that preshaped input generated for one degree-of-freedom of the flexible system can also be used to eliminate residual vibration of multi-degree systems. A preshaped input method, known as a 'cycloid-plus-ramped versine-ramp function', actually uses one-degree-of-freedom of the flexible system, and is applied on linear and nonlinear single input multi-mode flexible systems. Parameters of shaping command are found using modal analysis methods. Then, this shaped command is given two degree-of-freedom spring-mass system with damping and the flexible joint RR manipulator. Simulation results show that if the template input signal is produced using the lowest natural frequency and damping ratio, the residual vibrations are considerably reduced for point to point motion while not suffering from either displacement limit exceeding, or from move time increase-related issues. However, the input shaping method consists of convolution of an arbitrary function that normally increases move time by a half damped period. In the case of driving a lightly damped flexible system, as far as the results of the studies are concerned, the proposed hybrid input shaping technique appears to be far more superior in robustness to system mode frequency and damping ratio uncertainties compared with the others, although it possesses the characteristics of the template function method and input shaping method. Besides, the presented method is superior to the method reported in Kapucu et al., (2008) as its performance does not degrade with closer natural frequencies of modes of vibration. It can be concluded that the vibrations of a multi-degree of flexible system is considerably eliminated with convolving the preshaped input of cycloid-plus-ramped versine-ramp function with the sequence of all modes generated by two-impulse sequences with the cost of a time delay. Besides, the uncertainties of the damping ratios and mode frequencies of the multi-mode systems are highly tolerated and have also shown that these uncertainties do not cause significant vibrations.

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References

Alıcı G, Kapucu S and Bayseç S (2000) On preshaped reference inputs to reduce swing of suspended objects transported with robot manipulators. *Mechatronics* 10: 609–626.

Aspinwall DM (1980) Acceleration profiles for minimizing residual response. *ASME Journal of Dynamic Systems, Measurement and Control* 102: 3–6.

Blackburn D, Singhose W, Kitchen J, Patrangenaru V, Lawrence J, Kamoi T and Taura A (2010) Command shaping for nonlinear crane dynamics. *Journal of Vibration and Control* 16(4): 477–501.

Chan T, Godbole K and Hou E (2003) Optimal input shaper design for high-speed robotic workcells. *Journal of Vibration and Control* 9(12): 1359–1376.

Changa PH and Park HS (2005) Time-varying input shaping technique applied to vibration reduction of an industrial robot. *Control Engineering Practice* 13: 121–130.

Cutforth CF and Pao LY (2004) Adaptive input shaping for maneuvering flexible structures. *Automatica* 40: 685–693.

Dharne AG and Jayasuriya S (2007) Robust adaptive control of residual vibration in point-to-point motion of flexible bodies. *Journal of Vibration and Control* 13(7): 951–968.

Gurleyuk SS and Cinal S (2007) Robust three-impulse sequence input shaper design. *Journal of Vibration and Control* 13: 1807–1818.

Gurleyuk SS, Hacioglu R and Cinal S (2007) Three-step input shaper for damping tubular step motor vibrations. *Journal of Mechanical Engineering Science* 221: 1–9.

Kapucu S, Alıcı G and Bayseç S (2001) Residual swing/vibration reduction using a hybrid input shaping method. *Mechanism and Machine Theory* 36: 311–326.

Kapucu S, Yildirim N, Yavuz H and Bayseç S (2008) Suppression of residual vibration of a translating–swinging load by a flexible manipulator. *Mechatronics* 18: 121–128.

Magee DP and Book WJ (1993) Implementing modified command filtering to eliminate multiple modes of vibration. *Proceedings of the American Control Conference*. San Francisco, CA: 2–4 June, pp. 2700–2704.

Masoud ZN, Nayfeh AH and Al-Mousa A (2003) Delayed position-feedback controller for the reduction of payload pendulations of rotary cranes. *Journal of Vibration and Control* 9(1): 257–277.

Masoud ZN, Nayfeh AH and Nayfeh NA (2005) Sway reduction on quay-side container cranes using delayed feedback controller: simulations and experiments. *Journal of Vibration and Control* 11(8): 1103–1122.

Meckl PH and Seering WP (1990) Experimental evaluation of shaped inputs to reduce vibration for a Cartesian robot. *ASME Journal of Dynamic Systems, Measurement and Control* 112: 159–165.

Mimmi G and Pennacchi P (2001) Pre-shaping motion input for a rotating flexible link. *International Journal of Solids and Structures* 38: 2009–2023.

Park JG (2003) Vibration simulation using MATLAB. Department of Precision Engineering, Kyoto University, Kyoto, Japan, May.

Park JY and Chang PH (2004) Vibration control of a telescopic handler using time delay control and commandless input shaping technique. *Control Engineering Practice* 12: 769–780.

Piazzi A and Visioli A (2000) Minimum-time system-inversion-based motion planning for residual vibration reduction. *IEEE/ASME Transactions on Mechatronics* 5 1.

Sahinkaya MN (2001) Input shaping for vibration-free positioning of flexible systems. *Proceedings of the Institution of Mechanical Engineers, Part I* 215: 467–481.

Sahinkaya MN (2004) Exponential input shaping for vibration free positioning of lightly damped multi-mode dystems. *7th International Conference on Motion and Vibration Control*, 8–11 August, St. Louise, USA.

Singer NC (1989) Residual vibration reduction in computer controlled machines. MIT Artificial Intelligence Laboratory, PhD thesis, January.

Singer NC and Seering WP (1990) Preshaping command inputs to reduce system vibration. *ASME Journal of Dynamic Systems, Measurement and Control* March 112: 76–82.

Smith OJM (1958) *Feedback Control Systems*. New York: McGraw-Hill.