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A smooth multimode waveform command shaping control with selectable command length

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ABSTRACT

Input and command shapers are great open-loop control strategies in reducing residual vibration in rest-to-rest maneuvers. The generation of such command usually contains multiple impulses and jerks. Multiple impulses usually degrade the performance due to actuation delay and mismatch timing while jerks reduce the life expectancy of actuator and increase maintenance. In this work, a smooth single multimode command shaping control is proposed and tested numerically and experimentally to eliminate residual vibration in rest-to-rest maneuvers. The advantages of the technique are summarized as, the proposed technique has an adjustable maneuvering time, can eliminate all vibration modes regardless of the number, the required parameters are found analytically which eliminate the need of complex or lengthy calculation needed for most multimode shaper, smooth command profile to eliminate jerks i.e. inrush current, and it is continuous with single actuation to eliminate inaccurate timing and delay. The technique performance is validated numerically and experimentally. Numerical simulations prove that the shaped commands are capable of completely eliminating residual vibrations of multimode systems. Furthermore, the proposed technique is utilized to reduce the sensitivity of the shaper to modeling errors. Unlike other shaper the proposed reduction in the sensitivity can be implemented for all modes with no added complexity.

1. Introduction

In modern industries, it is common that products are moved between locations along automated production lines in repeated cycles. Robotic manipulators and cranes are commonly used to perform this task using what is known as *rest-to-rest maneuvers*. Research, in the past three decades, focused on enhancing the accuracy of such maneuvers, while ensuring safety and cost effectiveness.

Although more accurate, feedback control strategies for multimode systems, such as robotic manipulators, have a major drawback which is that feedback control strategies require real-time measurements of the vibrating modes of the system. As the number of modes increases, such information becomes harder to acquire and process. This drawback makes open-loop control a more attractive choice for pre-defined rest to rest maneuvers. Command shaping, an open-loop technique, is a commonly used control technique for rest-to-rest maneuvers [1,2]. As indicated by its name, command shaping is the process of shaping the profile of a driving command to a system actuator in a way that this command mitigates its own

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excited vibrations. The basic concept of command shaping was introduced in the fifties [3–5]. The idea was revisited later by Starr [6] in 1985, but it wasn't until the nineties that command shaping was made popular by the introduction of robust shapers of Singer and Seering [7].

Several techniques are used to generate shaped command profiles including; input shaping, optimal control, genetic algorithms, neural networks, and many others [8]. Input shaping is one of the most commonly used command shaping techniques. Essential idea of input shaping was patented by [9] and [10]. Input shaping generates shaped commands through the convolution of multiple timed impulses with a general input command. As the order of a system increases, the number of impulses required increases leading to several disfavored jerks in the system. More impulses are also needed to improve the robustness of the technique [1]. Positive and negative impulses produce faster commands [11,12], which results in even more jerks.

Multimode input shaping control is classified into two main groups; convolved input shapers and simultaneous input shapers. Convolved input shapers are based on convolving multiple sequences impulses with a general input command. Each sequence targets vibrations in one of the system frequencies [13–16]. However, a problem arises when high frequencies are involved. The rate of impulses may be so high that the shaper becomes practically inapplicable [14]. Simultaneous input shapers have slight robustness disadvantage, but are usually faster [17–19]. Negative input shapers [11,12] are proven to have several advantages [20,21] in terms of speed and robustness, however, they incur large jerks and large number of impulses [22,23].

Jerks in a command signal to electric actuators introduce inrush current, which have detrimental effects on their performance and lifetime [24–27]. The situation worsens as the number of impulses increases with multimode shaping. When alternating current motors, transformers, and other AC devices are first turned ON, they draw current several times their normal full-load rated current for few cycles. Manufacturers tend to use capacitors, fuses and/or circuit breakers to protect against over-current. Unfortunately, surge protection leads to large time delays in the command signal. Shaped commands are highly sensitive to signal timing. Delays may lead to undesirable system performance.

To reduce the number of jerks in multimode input shapers, some research was geared towards combining single-mode input shapers with different types of filters such as; notch filters, low-pass filters, band-stop filters, and time-delay filters [28–34]. Single-mode input shapers can also be utilized in multimode control when all higher mode frequencies are odd-multiples of the fundamental frequency of the system [14]. However, such condition is generally not true for real world systems. Nevertheless, model-based feedback has been used to enforce this condition [35–39]. Optimization techniques and numerical methods [1,2,8] can reduce vibrations, however, implementation challenges increases as the number of modes increases, and generally requires extensive computational power.

Several studies were conducted to compare performance of various input shaping techniques in terms of the amplitude of transient oscillations, maneuver duration, ease of implementation, and robustness to modeling errors [40], and smoothness [41]. Studies concluded that impulse shaped commands are more efficient compared with smooth shaped commands. Smooth shaped commands incur large rise-time penalties [42–44]. For example, *S*-curve smooth functions are four times slower than conventional step commands [41].

Using modern digital control hardware, shaped commands are applied as discrete signals. This may result in performance degradation or position errors due to mismatch between hardware sampling rate and shaper impulse timing [13,17,18,46,54]. Optimization techniques can be used to resolve this mismatch [48,55]. This impact of this mismatch is lower in the case of smooth shaped commands.

In an attempt to reduce the number of jerks in fast single-mode shapers, cosine-based waveform commands are used [45,46]. Speed of resulting shapers was comparable to that of impulse shapers. The work was further extended to damped time-variant systems [47–49]. Jerks were completely eliminated using sine-based waveform commands [50,51]. The use of cosine-based waveform shapers [45,46] was extended to two-mode systems [51,52], and later to multimode systems [53]. Jerks in the shaper were reduced to shaper start and shaper end jerks. Shaper duration was adjustable with sensitivity comparable to other multimode impulse shapers.

In this work, an algorithm is proposed for generating a smooth shaped command for rest-to-rest maneuvers that eliminates vibrations in all modes of a multimode system. Based on an earlier work by the Authors [53], the goal of this work is to eliminate jerks in the shaped command, which is detailed in Section 3 of this paper. To avoid shaper/hardware mismatch issue, the time-length of the shaped command signal is made design selectable, and independent of the system's resonant frequencies. The algorithm does not require full knowledge of the system model. Only resonant frequencies of the system are required. Theoretical development and performance validation using numerical simulations and experiments are presented. The complexity of the shaper does not increase as the number of modes increases since the shaper parameters can be determined analytically. The robustness of the shaped command can be boosted by introducing additional virtual frequencies to the system to widen the insensitivity spectrum.

2. Mathematical model

Linear multimode systems can be presented as

$$\mathbf{M}\ddot{\Phi}(t) + \mathbf{K}\Phi(t) = \mathbf{B}u(t) \tag{1}$$

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