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Time-varying input shaping technique applied to vibration reduction of an industrial robot

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Abstract

It is widely and frequently observed that industrial robots conducting fast motion involve serious residual vibration, the period of which varies with time. To address this time-varying residual vibration problem, this paper presents a *practical solution* based on a time-varying input shaping technique (TVIST). First, to suppress the time-varying vibration, a guideline for designing a practical TVIST is presented. Following the guideline, a TVIST for a heavy 6 DOF industrial robot is designed. In doing so, a simple yet effective equation is derived from robot dynamic equations to schedule the time-varying period. Furthermore, a simple payload-adaptation scheme is also included. Then, experiments are performed by using the TVIST for the industrial robot under spatial motion and payload variation. The experimental results show that the residual vibration is reduced to less than 14% of the original level in magnitude and the time delay caused by pre-filtering is shortened, demonstrating the efficiency and effectiveness of the proposed TVIST.

Keywords: Residual vibration; Vibration control; Industrial robot; Time-varying vibration

1. Introduction

This paper presents a *practical solution* to the residual vibration problem frequently and widely found in industrial robots. Provided below are the background and context associated with the problem and our solution approach.

It is well known that industrial robots need to achieve higher speed and precision to increase productivity. To this end, one of the major obstacles to overcome is the residual vibration coming from joint flexibility primarily due to the transmissions on the motor axes. Take the example of a heavy industrial robot performing spot welding in an automobile factory. The welding process can only be started after positioning the end-effector to a proper position. However, the robot must wait for the residual vibration to be decayed out before beginning the welding. For this reason, residual vibration increases task execution time thereby decreasing productivity. However, the residual vibration problem is difficult to solve since the residual vibration the robots exhibit tends to be nonlinear and time-varying, owing to configuration[1]-dependent inertia variation and nonlinear stiffness of the gears. Moreover, the vibration becomes further complicated by the different payloads the industrial robot handles.

For suppressing vibrations, there have been two distinct approaches: open-loop feedforward (Asada, Ma, & Tokumaru, 1987; Aspinwall, 1980; Bayo, 1988) and closed-loop feedback (Pfeiffer, & Gebler, 1988; Kotnik, Yurkovich, & Ozguner, 1988). In terms of performance, the latter is more attractive than the former because it is inherently robust against disturbances and parameter variations. However, the closed-loop approach makes overall systems complex and expensive because the increased number of states due to vibration modes increases the order of the control law, thereby requiring more computation power and more

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[1] In this paper, the configuration is meant by the robot posture determined by joint variables.

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sensors. As a remedy, many researchers have considered feedforward controllers (Singer & Seering, 1990; Magee & Book, 1993). The feedforward controller requires no additional cost because it does not need any sensors. In addition, when it is combined with simple feedback controllers, the robustness against disturbances or parameter variations can be preserved without incurring much more expense. This scheme is very attractive for practical applications and, with this in mind, this paper focuses on a feedfoward controller design which can be combined with any type of feedback controller.

Among feedforward controllers, this paper considers an extended version of input shaping technique (IST) (Singer, 1988) because of its well-proven efficiency and effectiveness. The efficiency and effectiveness of the original IST have been already confirmed in many practical systems such as a surface mounting machine (Chang & Park, 1996), a single-link flexible spacecraft (Liu & Wie, 1992), and an open container of liquid (Feddema et al., 1997). Nevertheless, since the IST was proposed originally for linear time-invariant systems (Singer & Seering, 1990; Singer, 1988), it is not that effective for systems with nonlinearity and time-varying characteristics. Even robust IST (Singer & Seering, 1990; Singer, 1988), which handles inaccuracy of period estimation, is not of much help for these systems.

As such, many researchers have extended IST to nonlinear time-variant systems. Rappole (1992) applied time-varying input shaping technique (TVIST) to a two-link flexible manipulator using look-up table that contains the information of configuration-dependent frequency. Magee and Book (1993) modified the IST to eliminate the first two modes of vibration in a large and flexible manipulator having configuration-dependent inertia. Cho and Park (1995) proposed a method for determining the exact time-varying impulse sequence for linear time-variant systems, and applied it to a two-link flexible robot. An adaptive IST was proposed for a time-variant system that uses a real-time identification scheme (Tzes & Yurkovich, 1993).

The aforementioned TVIST's, however, appear to be more or less theoretical in the sense that (1) they tend to be limited to highly flexible robots, rarely found in practice except for some special-purpose robots; and (2) the practical issues associated with implementation do not seem to be their immediate concerns. For instance, the look-up table scheme (Rappole, 1992) needs to consider the size requirement and availability of memory, whereas the TVIST's having complicated structures (Cho & Park, 1995; Tzes & Yurkovich, 1993), must take into account the CPU power. To our knowledge, there have been few research works that address these issues and apply TVIST to practical time-varying systems such as 6 DOF industrial robots.

In response, this paper presents a practical design guideline for TVIST applicable to most industrial robots. This guideline is presented in Section 2. Using this guideline, a much more simplified version of TVIST is proposed in Section 3 for a real example of a heavy industrial robot. Finally, in Section 4, the TVIST is experimented on a heavy industrial robot to verify its effectiveness, thereby demonstrating that a *practical solution* to the residual vibration problem in industrial robots is provided.

2. Design guideline for TVIST

2.1. Brief review of IST

IST was firstly proposed by Singer and Seering in 1990 as a solution for suppressing residual vibration. The basic idea of IST is described in Fig. 1. When two appropriate impulses are applied to a vibratory system, the responses to the impulses are superposed and the resultant response is free of vibration as indicated by the thick solid line in Fig. 1. Based on this observation, IST has been proposed in detail as follows.

The conventional IST was originally developed for a linear second-order system (1) having natural frequency, ω_n, and damping ratio, ξ. For (1), the response to a sequence of N impulses is described by (2).

$$G(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n + \omega_n^2}, \quad (1)$$

$$y(t) = \sum_{i=1}^{N} \left[\frac{A_i \omega_n}{\sqrt{1-\xi^2}} e^{-\xi\omega_n(t-t_i)} \sin\left(\omega_n\sqrt{1-\xi^2}(t-t_i)\right) \right], \quad (2)$$

where A_i and t_i are the amplitude and the application time of the ith impulse, respectively; these are the parameters to be determined for the IST design.

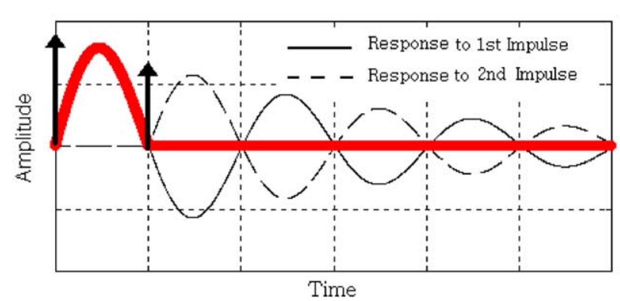

Fig. 1. Basic idea of IST; the responses (thin solid and dashed lines) caused by two impulses (vertical arrows) are superposed to result in nonvibratory response (thick line).