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

\[^{\text{1}}\text{In this paper, the configuration is meant by the robot posture determined by joint variables.}\]
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 feedforward 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 (Fedema 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 characteristics, 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 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, \(\omega_n\), and damping ratio, \(\xi\). For (1), the response to a sequence of \(N\) impulses is described by (2).

\[
G(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2};
\]

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

where \(A_i\) and \(t_i\) are the amplitude and the application time of the \(i\)th 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).](image)
where \( q = 0, 1, \ldots, N - 2 \). The above two constraints were derived from the requirements that the amplitude of \( y(t) \) and its derivatives (with respect to \( o_n \)) be made zero for \( t > t_N \), which imply zero amplitude of vibration after \( t_N \).

In addition, two further constraints need to be added:

\[ t_1 = 0, \quad t_j = 1, \quad (j = 2, 3, \ldots, N), \] (5)

\[ \sum_{i=1}^{N} A_i = 1. \] (6)

The first constraint, (5), simply reflects the choice of a time origin; the second constraint, (6), reflects the requirement that the total sum of \( A_i \) be equal to unity. Note that as \( N \) is increased from its minimum number, \( N = 2 \), IST becomes less sensitive to the estimation errors of \( o_n \) and \( \zeta \) due to system uncertainty (Singer, 1988). However, the larger \( N \) becomes, the larger the time delay becomes due to IST.

From the above equations, \( A_i \) and \( t_j \) are determined as the following (Singer & Seering, 1990; Singer, 1988):

\[ A_j = \frac{\left(N - 1\right)}{\left(j - 1\right)} K^{j-1}, \] (7)

\[ t_j = (j - 1) - \frac{\pi}{o_n \sqrt{1 - \zeta^2}}, \] (8)

where \( K = \exp -\left(\pi \zeta\right)/\left(\sqrt{1 - \zeta^2}\right)\).

For real application of IST, the impulse sequence is convoluted with a trajectory to obtain a smooth command yet it still reduces residual vibration. The block diagram shown in Fig. 2 describes how IST is implemented together with a closed-loop system. For a known natural frequency and damping ratio of a closed-loop system, IST operates as a pre-filter which has a very simple structure. It convolutes a desired trajectory, \( \theta_d \), with the appropriate sequence of impulses to get a filtered trajectory, \( \theta^*_d \), thereby obtaining a non-vibratory response \( \theta \). Of course, IST is applicable to an open-loop system provided that the frequency and damping ratio of vibration are known.

### 2.2. Design guideline for TVIST

Based on the basic idea of IST, TVIST can be proposed for reducing the vibration of a time-varying nonlinear system such as a spatial robot. The essential difference between TVIST and IST lies in the fact that TVIST requires real-time scheduling of the parameters: the period and the damping ratio of the residual vibration. Hence, a practical TVIST should be able to determine which of the two parameters to schedule and how to do so. Accordingly, our design procedure begins with these two decisions, as illustrated in the flowchart in Fig. 3.

More specifically, it needs to be discerned in the first step that which parameter should be treated as time-varying and which parameter as constant. For instance, the damping ratio for most mechanical systems is closely related to the viscosity, which does not change rapidly. Consequently, the damping ratio can be assumed as a constant with respect to time, whereas the period of

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**Fig. 2.** Application of IST filter to a closed-loop system.

**Fig. 3.** Flowchart for the TVIST design procedure.
vibration is treated as time-varying. However, if the variation of the damping ratio is not negligible, it should also be treated as a time-varying parameter, and the real-time scheduling rule should be designed accordingly.

In the design of a practical TVIST, it is crucial to have a reliable method to schedule the time-varying parameters. The scheduling methods may be classified into two groups:

- A look-up table is used to provide the values of the time-varying parameters for each joint configuration of a robot (Rappole, 1992).
- A robot dynamics model is computed on-line to obtain the values of the time-varying parameters (Magee & Book, 1993; Cho & Park, 1995; Tzes & Yurkovich, 1993).

Obviously, the former is appropriate for systems with sufficient memory size and sufficient experimental data; the latter for systems with sufficient computational power and well-known dynamics.

In the look-up table method, the memory size determines the number of data in the look-up table. Once the number of data is determined, the selected time-varying parameters are measured through experiments at every configuration. Finally, the data are memorized in the look-up table.

In the real-time computation of robot dynamics model, an analytic equation is constructed from the system model. The amount required for computing the equation must then be compared to the given computational power of the CPU. If the CPU power is not sufficient to perform real-time computation, the scheduling rule should be simplified to reduce the amount of computation, either by decreasing the scheduling rate or by simplifying the scheduling equation.

3. Practical design of TVIST for the industrial robot

The industrial robot of our concern has a parallelogram-linkage structure with 6 DOF, the schematic diagram of which is shown in Fig. 4. The descriptions and the approximated values for the parameters in Fig. 4 are listed in Table 1. As the size of the robot implies, it is intended for heavy-duty material handling or spot welding, the maximum payload of which is 120 kg. Since all the joints are of revolute type, the period of vibration varies with the configuration of the robot. From experimental observation, the period of the residual vibration varies from 125 to 300 ms within the workspace the robot, whereas the damping ratio does not vary significantly. Hence, the period is treated as a time-varying parameter and the damping ratio is set to be constant. Therefore, the period of vibration is the only variable to be scheduled in real-time.

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>la and lc</td>
<td>Length of link a and link c</td>
<td>1.25 (m)</td>
</tr>
<tr>
<td>lb</td>
<td>Length of link b</td>
<td>0.5 (m)</td>
</tr>
<tr>
<td>ld</td>
<td>Length of link d</td>
<td>1.8 (m)</td>
</tr>
<tr>
<td>ma</td>
<td>Mass of link a</td>
<td>160 (kg)</td>
</tr>
<tr>
<td>mb</td>
<td>Mass of link b</td>
<td>260 (kg)</td>
</tr>
<tr>
<td>mc</td>
<td>Mass of link c</td>
<td>30 (kg)</td>
</tr>
<tr>
<td>md</td>
<td>Mass of link d</td>
<td>260 (kg)</td>
</tr>
</tbody>
</table>

The controller of the robot has a CPU of TMS320C25 and memory of 192 kb. This controller, were it used for TVIST only, would be suitable for both the look-up table and on-line computation. Yet, it turns out that most of the computational resources are used for other purposes such as safety functions, many user interfaces, and so on. Since the left-over memory is not sufficient for any type of look-up table, the only option left is to adopt the on-line computation of the period by using a scheduling equation in a substantially simplified form. In order to construct a scheduling equation, dynamic equation of the robot is derived; its dynamic behavior is analyzed; and finally a simple yet physically meaningful equation is determined to schedule the period.

3.1. Dynamic equation of the industrial robot

As shown in Fig. 4, the first axis, specified as $\theta_1$, is the swing-axis, which rotates the overall linkage. The vertical axes angles, $\theta_2$ and $\theta_3$, determine the configuration of the parallelogram-linkage. The last three axes, the rotations about which are $\theta_4$, $\theta_5$, and $\theta_6$, respectively, determine the orientation of the end-effector. Note that the last three axes have little effect on the inertia-variation and thus on the period variation; therefore, the dynamic equation is derived only for the first three axes.

Since joint flexibility is considered the primary source of the robot vibration, it is considered in the model. The
3.2. Scheduling of time-varying period

Since the inertia term, \( M_i(\theta) \), in the dynamic Eqs. (9)–(14) directly influence the period of vibration, it should be examined carefully. Assuming uniform and symmetric cross-section of the links, the elements of \( M_i(\theta) \) are expressed as the following:

\[
M_{11} = J_{m1},
\]

\[
M_{22} = (m_d l_a^2 + J_a + J_2) C_2^2 + (m_d l_a^2 + J_b + J_3) C_3^2 + m_c (l_b C_3 - l_a) C_2^2 + M(l_c C_2 + (l_d - l_b) C_3)^2,
\]

\[
M_{33} = J_{m2},
\]

\[
M_{44} = m_d l_d^2 + J_a + m_d l_d^2 + J_c + m_d l_d^2 + M_d,
\]

\[
M_{46} = M_{46} = m_d l_d g C_23 - m_e l_b l_e C_23 + M(l_d - l_b) C_23,
\]

\[
M_{55} = J_{m3},
\]

\[
M_{66} = m_d l_{gb}^2 + J_b + m_d l_{gb}^2 + M(l_d - l_b)^2,
\]

where \( l_i \) and \( l_{gb} \) (\( k = a, b, c, d \)) denote the length of the corresponding link and the length from the corresponding joint to the center of gravity, respectively. In the same manner, \( m_k \) and \( J_k \) represent the mass and the moment of inertia of the link, respectively. \( J_{mi} \) (\( i = 1, 2, 3 \)) denotes the moment of inertia of \( i \)th motor, and \( M \) the payload, which is attached at the end-effector. Finally, \( C_2 \), \( C_3 \), and \( C_23 \) represent \( \cos \theta_2 \), \( \cos \theta_3 \), and \( \cos(\theta_2 - \theta_3) \), respectively.

3.2.1. Derivation of time-varying period

Since the residual vibration of each and every joint contributes to determining that of the end-effector, it is necessary to schedule the period at each joint. The essence of the residual vibration at each joint can be represented with a model consisting of a mass and a spring, as shown in Fig. 5. The period of vibration for the \( i \)th joint, then, can be expressed as follows:

\[
T_i = 2\pi \sqrt{\frac{M_{22}(\theta)}{K_i} (i = 1, 2, 3)}.
\]

Note in (16) that the inertia about the swing-axis (\( i = 1 \)), \( M_{22} \), varies with \( \theta_2 \) and \( \theta_3 \), whereas \( M_{44} \) and \( M_{66} \) have constant values. Furthermore, \( M_{44} \) and \( M_{66} \) take smaller values compared to the swing-axis and so does the magnitude of vibration. This observation implies that the time-varying residual vibration of the end-effector is predominantly determined by that of the swing-axis.
This finding is practically very important because it enables us to concentrate on the swing-axis and design a TVIST for it. For the rest of other axes, it is possible to design other pre-filters for time-invariant systems such as the conventional IST.

Consequently, (16) and (22) serve as the central relationship for the scheduling of the time-varying period. In (16), in order to schedule \( M_{22}(t), \theta_2(t) \) and \( \theta_3(t) \) should be measured in real time. Although \( K_{T1} \) generally has nonlinear time-varying characteristics, it is assumed to be a constant based on the observation that the stiffness-variation is not substantial compared to the inertia-variation.

3.2.2. A simplified period scheduling

Many industrial controllers—like ours—could require a more simplified equation than (16) and (22) because (16) contains sinusoidal functions, which demand more computation than simple addition or multiplication. Moreover, the equations require estimation of many parameters such as mass, inertia, and stiffness, which are difficult to estimate. For simplification, a simple yet effective index is selected: \( s-w \) length. As shown in Fig. 4, the \( s-w \) length, \( x(t) \), is defined as the length from the swing-axis to the wrist-axis along the horizontal line.

Since the period of vibration is proportional to the square root of the moment of inertia \( (I) \) which is equivalent to effective mass \( (m_e) \) multiplied by square of effective length\(^2 \) \( (x_e) \), the period is proportional to the effective length as follows:

\[
T = 2\pi \sqrt{\frac{I}{K}} \approx 2\pi \sqrt{\frac{m_e x_e^2}{K}},
\]

(23)

where \( m_e \) denotes effective mass located at \( x_e \). From this simple idea, a linear equation for scheduling the period can be obtained by regarding the inertia as

\[
M_{22} = m_{eq} x_e^2 + C,
\]

(24)

where \( M_{22}, m_{eq}, C \) and \( C \) denote the inertia about the swing-axis, equivalent mass located at \( x \), and summation of other terms independent of \( x \), respectively. For larger \( s-w \) length, \( C \) is relatively small compared to \( m_{eq} x_e^2 \), hence the linearity between the period and \( x \) approximately holds.

To verify the linearity between the period and \( s-w \) length, periods of vibrations are measured with respect to various \( s-w \) lengths as shown in Fig. 6. The result verifies the linearity for the larger \( s-w \) lengths. For the shorter \( s-w \) lengths, the magnitude of \( C \) is not small compared to \( m_{eq} x_e^2 \) so that the linearity does not hold. Fortunately, however, the magnitude of vibration is sufficiently small at short \( s-w \) lengths owing to the low inertia about the swing-axis. For this reason, the approximation error is not problematic at short \( s-w \) lengths; and hence the linear period scheduling shows no problem for all \( s-w \) lengths in the workspace. From the experimental data, the half period is scheduled by the following linear equation:

\[
T_{\text{half}}(t) = ax(t) + b \text{ (s)},
\]

(25)

where the coefficients are determined for our robot as \( a = 0.095 \text{(s/m)} \) and \( b = 0.0475 \text{(s)} \).

In (25), \( x(t) \) is still the trigonometric function of the vertical angles, \( \theta_2 \) and \( \theta_3 \), however, no additional calculation is required because, in most industrial applications, \( x(t) \) usually has already been computed for other purposes such as the identification of end effector location in Cartesian space for the user-interface. As a result, (16) and (22) are simplified into (25), a linear function of \( x(t) \), so that the computational burden is greatly reduced.

3.2.3. Load adaptation

Normally, a robot is required to perform various tasks demanding different payloads, \( M \). Eqs. (16) and (22) clearly show that the variation in \( M \) immediately causes a change of period. In the period scheduling, thus, it is important to take this variation into account, so that the controller may be able to adjust \( T_{\text{half}} \) for a different value of \( M \) supplied by the user.

The period of vibration, as (16) and (22) imply, is proportional to the square root of \( M \); however, it is observed from experiments that the period tends to be approximately proportional to \( M \) in the range of \( 20 \text{kg} \leq M \leq 120 \text{kg} \), as shown in Fig. 7. This tendency also holds for different \( s-w \) lengths as shown in Fig. 7. Thus, from the experimental results, Eq. (25) is modified...
to adapt to the payload, $M$, as follows:

$$T_{\text{half}}(M,t) = ax(t) + b - c(120 - M) \text{ (s)},$$

where $c = 0.76\text{ (s/kg)}$.

Eq. (26) is our final updating equation to schedule the half period of the residual vibration. Once a user inputs the payload, $M$, depending on a given task, (26) determines the period of time-varying residual vibration. Recollecting the derivation procedure thus far, one can find that (26) covers a broad range of industrial robots.

### 3.3. Final design of TVIST

As for the implementation of TVIST, the time interval of the impulse sequence is determined from (26), and the time-varying impulse sequence is convoluted with the desired trajectory. If three impulses are considered for the robustness, the TVIST is implemented for a given desired trajectory, $\theta_{l,d}(t)$, as follows:

$$\theta_{l,d}(t) = A_1\theta_{l,d}(t) + A_2\theta_{l,d}(t - T_{\text{half}})u(t - T_{\text{half}}) + A_3\theta_{l,d}(t - 2T_{\text{half}})u(t - 2T_{\text{half}}),$$

where $A_1$, $A_2$, and $A_3$ are the magnitudes of each impulse and $u(t - a)$ is a unit step function defined as follows:

$$u(t - a) = \begin{cases} 
0 & \text{for } t < a \\
1 & \text{for } t \geq a 
\end{cases}.$$

As shown in Section 2, $A_1$, $A_2$, and $A_3$ are calculated from $\xi$ by using (7). In our case, $A_1 = 0.27$, $A_2 = 0.50$, and $A_3 = 0.23$.

### 4. Experimental results

The proposed TVIST is embedded in the robot controller so that any additional user’s interactions may not be necessary to perform various tasks. In the experiments, the vibration is measured by an accelerometer to observe the performance of the proposed TVIST filter. It should be noted that no additional sensor is required for implementation of TVIST.

For fast and accurate operations, it is necessary to reduce the magnitude of vibration as well as the time delay due to pre-filters. These two factors, vibration reduction ratio and time delay, are taken into account to measure the performance of TVIST. The performance of TVIST is compared with the conventional IST and another well-known pre-filter, a low-pass filter (LPF). The gains of the LPF were obtained under long time period of development, therefore, it could be believed that the LPF has optimized parameters.

First, it is verified that the proposed TVIST works at different configurations by testing its performance at various configurations with a 120 kg load. At each fixed configuration of $\theta_2$ and $\theta_3$ shown in Fig. 8, the swing-axis rotates $10^\circ$ following a given trajectory. In these experiments, the s-w length, $x$, does not vary during the $10^\circ$ rotation so that Eq. (26) returns an invariant value during the rotation. Therefore, the TVIST has the same performance as the conventional IST provided that the conventional IST is tuned for each configuration. However, the TVIST automatically schedules its parameter at different configurations whereas the conventional IST requires parameter setting at each different configuration. The results shown in Figs. 9–12 correspond to the experimental results at configurations 1–4. The comparison of performance measures, the vibration reduction ratio and time delay, are given for the TVIST and the LPF as shown in Table 2.

In configuration 1, Fig. 9(a) shows that the robot has low residual vibration originally since the robot has low inertia at the configuration, therefore, it is hard to measure the vibration reduction ratio for both the TVIST and the LPF. But, for other configurations, the vibration is reduced largely for both the TVIST and the LPF. As summarized in Table 2, the TVIST shows slightly better performance on vibration reduction than the LPF. This implies that the TVIST as well as the LPF suppressed large amount of residual vibration. However, as to the time delay induced by filters, TVIST shows better performance than the LPF, which implies that the TVIST enables faster operation. This shortening of time delay is beneficial in real applications since it increases the productivity. For example, in a spot welding process, a robot usually performs many move-and-stop motions to weld an object such as the frame of a car. As shown in Fig. 13, a small-time savings in one pitch motion accumulates to the large amount of time.

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3Vibration reduction ratio is defined as $(A - B)/A$, where $A$ and $B$ denote the magnitude of original vibration and magnitude of reduced vibration, respectively.
saved for the entire process. As shown in Table 3, the TVIST can save 8% of task execution time compared to the LPF. In addition, TVIST has another advantage...
that it can be adapted to various configurations (even for time-varying configurations) with a simple scheduling rule, whereas LPF needs precise gain tuning at each configuration. Note that this advantage comes from the dynamic analysis incorporated with the basic idea of IST.

In the second experiment, the TVIST is applied to a task that brings time-varying vibration. The vertical axes move from configurations 2 to 3 while the swing-axis simultaneously rotates 50°. Therefore, the inertia about the swing-axis varies during the motion as does the period of vibration. The result in Fig. 14 shows that the proposed TVIST suppresses the residual vibration, whereas the conventional IST with a fixed parameter does not. Likewise, as in the initial set of experiments, the time delay of the TVIST is shorter than that of the LPF. From this experiment, it is confirmed that the TVIST can also suppress time-varying vibration by using the simple parameter scheduling of (26).

In the final experiment, the load-adaptability is confirmed. The same operation is repeated as in the first experiment at configuration 3; but, this time, with payload of 40 kg and 120 kg, respectively. Fig. 15 shows the comparison between two TVIST’s: (a) the one without load-adaptation scheme, and (b) the other with it. The latter clearly suppresses vibrations with both 120 kg and 40 kg, effectively adapting to the load variation, whereas the former with a design fixed to a 120 kg load does not suppress the vibration effectively when 40 kg load is attached.

5. Conclusions

For suppression of time-varying residual vibration in industrial robots, a practical design procedure of TVIST
is presented and the procedure is applied to an industrial robot. The parameter scheduling rule of the TVIST is practically designed for computational efficiency so that it can be implemented in a system without enough leftover memory and computational power.

In designing the TVIST, the period of vibration needs to be scheduled in real-time. By using $s-w$ length as a time-varying variable, the period of vibration at each configuration can be scheduled efficiently. In addition, the TVIST is modified to adapt to various payload. As a result, the proposed TVIST reduces 90% of the residual vibration in magnitude and also shortens the time delay due to filtering.

Through this research, it is shown that the TVIST can be designed for practical systems without sacrificing computational efficiency. As an example, it is shown that the TVIST works well on such a realistic system as a 6 DOF industrial robot even though it is simplified for computational efficiency. Recollecting that the derivation of the scheduling rule is readily applicable to a wide range of industrial robots, this work can provide a promising example for the application of TVIST to various industrial robots.

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