Vibration Suppression Motor Drive Control for Industrial Robot Using Notch Filter with Little Phase Error

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Abstract— This paper proposes a new generation method of position reference without the resonant frequency and phase error for industrial robots. It is important for the industrial robot to drive high speed and high accuracy. However, the vibration phenomenon is generated by the resonant frequency in such cases. Conventionally, the notch filter is used to suppress the vibration phenomenon. It is able to eliminate a particular frequency. However, it also has a disadvantage that the reference phase error is generated. Generating the phase error in the reference, the critical error is generated in the locus which the robot draws. Therefore, the accuracy of the robot is deteriorated by using the notch filter. The proposed method overcomes this problem by using the compensation gain. The compensation gain is used to calculate the reference phase error. The compensation of the reference phase error is performed by the feedforward. The simulation results and the experimental results show that the proposed method is superior to suppress the resonant frequency and improves the phase error.

Keywords— Resonant Frequency, Notch Filter, Residual Vibration, Phase Error, Two-inertia Resonant System.

I. INTRODUCTION

Recently, it is required that the industrial robot is operated with high speed and high accuracy for improving the productivity and quality. However, when the robot is driven with high speed, the large vibration often occurs. Such phenomenon is caused by the speed reduction mechanism, such as the harmonic drive [1], used in each joint axis of industrial robot as illustrated in Fig.1. The joint axis considering speed reduction mechanism is represented by two-inertia resonant system. The two-inertia resonant model comprises of mechanical inertias connected between load side and motor side by the elastic element. Thus, it certainly has a vibration by axis twist between the load and the motor. If the resonant frequency is varied by the variation of robot configuration, it is difficult to suppress the vibration phenomenon.

Therefore, the mechatro servo systems should have a robust control algorithm to suppress the vibration phenomena such as two-mass resonance system. In order to suppress the torsional vibration torque, the several control method been proposed[2][3][4][5][6][7]. These control method can reduce the speed ripple caused by vibration torque. However, these methods have residual vibration caused by parameter variation of robot manipulator.

In order to overcome this problem, this paper proposes a new motor drive control method using both the anti-vibration control system and the notch filter with little phase error for industrial robot. The proposed motor drive control system is based on the robust feedforward speed control and D-PD position control system[8][9]. The robust feedforward control system suppresses the resonant vibration caused by perturbation of load inertia. The D-PD position control system realizes the fast position control.

It is important for industrial robot to have high speed and high accuracy. Although, the vibration phenomenon are generated by the resonant frequency in such cases. In order to suppress the vibration phenomenon, notch filter is useful because it suppresses a particular of frequency. However, the position reference has the tracking phase error by using its notch filter. Therefore, the positional accuracy in robot arms declines. This paper proposes a new notch filter with little phase error for motor drive control of industrial robot. The simulation results and the experimental results show that the proposed method is valid for the suppression the resonant vibration and the tracking phase error.

II. MOTION CONTROL SCHEME OF EACH JOINT

As described in previous section, the plant is suffered from resonant of the two-inertia system. Industrial robots are normally controlled by cascade control scheme for single joint. The D-PD position controller has been proven to be applicable to elastic-joint manipulators [4]. D-PD control with
two-degree-of-freedom speed control scheme is used in this paper to cope with resonant vibration. PI controller with state feedback in speed control and feedforward controller compose the two-degree-of-freedom (2-DOF) speed control. With the robust pole assignment consideration, the stability is guaranteed against the parameter variation [9]. Robust control scheme for each joint of the robot is shown by the block diagram in Fig. 2. The feedforward controller is implemented for realizing two-degree-of-freedom speed control and eliminating the dominant poles of the feedback loop. Because the complex conjugate closed-loop poles of the speed control depend strongly on link parameters [10], the robust pole assignment for feedback-loop speed control is considered in this paper. The closed-loop property of speed control is indicated by the transfer function, two-inertia system. Two abscissas are coordinates representing location assigned as function of anti-resonant frequency of the system. Three-dimensional plot in Fig. 3 shows the dominant pole location assigned as function of anti-resonant frequency of the two-inertia system. Two abscissas are coordinates representing the relationship of the complex poles and the two-inertia parameters. The logarithmic values of real part and imaginary part ratio of the assigned pole (Re/Im) and ratio of imaginary part with system anti-resonant of the designated pole-pair (Im/ωr) are used for the abscissa coordinates. The ordinate represents ratio of the designated damping ratio, ζdesigated, and the fluctuated value, ζfluctuated, which is caused by inertia fluctuation. This ratio is expressed in decibel unit as

\[ \Delta \zeta = 20\log \left( \frac{\zeta_{fluctuated}}{\zeta_{desigated}} \right) \]  

where, the designated damping ratio is computed from the assigned pole as

\[ \zeta_{desigated} = \frac{Re}{\sqrt{Re^2 + Im^2}}. \]  

For the experimental setup, the robust conjugate poles are chosen at \(-0.1\omega_{ar} + j\omega_{ar}\) which is shown by the cross-hair in Fig. 3. Position control in external loop is designed with robust control design approach, CDM (Coefficient Diagram Method) [5]. The PD gains, \(K_{pd}\) and \(K_{pp}\) are designated by considering the stability condition and settling time of the system. Equation (6) shows the desired values of stability index \(\gamma_1\) and the equivalent time constant \(\tau_c\), used in position controller gain computation. D-PD control utilizes both position and speed performance of the system is also deteriorated. In this paper, the robust pole allocation against the inertia variation by using pole location diagram is considered. The robust pole allocation \(-\left(Re \pm jIm\right)\) for two dominant complex conjugate poles \(-\alpha_1\) and \(-\alpha_2\) of the feedback configuration in (1) is considered. Pole fluctuation caused by inertia variation to the maximum value \(J_{Lmax}\) is set to three times of the nominal value \(J_L\). The anti-resonant frequency is an intrinsic physical characteristic which cannot be changed by using the feedback control. Hence, the idea for robust pole assignment for two-inertia system should tie with the anti-resonant frequency of the system.

![Fig. 2. Motion control system of each joint.](image)

![Fig. 3. Robust pole location with pole fluctuation caused by inertia variation](image)
reference which gives the performance close to the acceleration control scheme. The transfer function of closed loop position control is shown by,

\[
\begin{pmatrix}
K_{pd} \\
K_{pp}
\end{pmatrix} = \begin{pmatrix}
\alpha_3\alpha_4\alpha_5J_L \\
\alpha_3\alpha_4\alpha_5J_L(1 - (D_L\gamma_1)/(K_S\tau_c)) \\
\alpha_3\alpha_4\alpha_5J_L(D_L - K_S\tau_c)/K_S \\
-\alpha_3\alpha_4\alpha_5J_{Ln} + J_L\gamma_1(\alpha_3\alpha_4 + \alpha_4\alpha_5 + \alpha_3\alpha_5)/\tau_c
\end{pmatrix}^{-1}
\]

\[
\frac{\theta_M}{\theta_M^{ref}} = \frac{K_pK_F(K_{pp} + sF_{pd})(b_3s^2 + b_1s + b_0)}{s^4 + \alpha_{n3}s^3 + \alpha_{n2}s^2 + \alpha_{n1}s + \alpha_{n0}}.
\]

In order to confirm the validity of the proposed control system, this paper shows the numerical simulation results. The simulation condition for variation of the residual vibration is shown in Table I.

**TABLE I**

<table>
<thead>
<tr>
<th>Simulation conditions for variation of the residual vibration.</th>
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<tbody>
<tr>
<td>Fluctuation of load inertia</td>
</tr>
<tr>
<td>Moving load angular</td>
</tr>
<tr>
<td>Moving time</td>
</tr>
</tbody>
</table>

The stopping vibration of load position is shown in Fig. 4. From these results, it has no resonant vibration in case of the nominal load inertia. However, when the load inertia has fluctuated, the feedback control system has a resonant vibration.

![Residual vibration of stop motion](image)

**Fig. 4.** Residual vibration of stop motion

**III. NEW NOTCH FILTER WITH LITTLE PHASE ERROR**

**A. Vibration Suppression with Notch Filter**

From simulation results, the proposed D-PD position control system is well not regulated the vibration of load side when the load inertia is changed. The frequency response of motion control system is shown in Fig. 5. When designing with nominal parameters, the frequency response of position control becomes like a thin solid line in Fig. 5. Although, if the load inertia moment is varied, it becomes like a dotted line in Fig. 5.

![Frequency response of motion control system for using the notch filter.](image)

**Fig. 5.** Frequency response of motion control system for using the notch filter.

Conventionally, the notch filter is used to suppress the vibration phenomenon [11], [12] as shown in Fig. 6. Also in this paper, the appearing resonant phenomenon will be suppressed by the notch filter as shown in (8).

\[
\begin{align*}
F_n(s) &= \frac{s^2 + 2\zeta_2\omega_f s + \omega_f^2}{s^2 + 2\zeta_1\omega_f s + \omega_f^2} \\
\zeta_1, \zeta_2 &= \text{coefficients of the filter, and are designed on depth and width of the notch filter. Natural frequency of the filter is denoted by } \omega_f.
\end{align*}
\]

As the results, resonant phenomenon is suppressed as shown in solid line of Fig. 5. In Fig. 6, the position reference without the resonant frequency is generated by passing the speed reference to the notch filter. Although the notch filter has an advantage which can suppress the resonant frequency, it has a disadvantage which the phase error is generated to the position reference. Therefore, using the notch filter becomes increasing the phase error between the reference and the load position.

**TABLE II**

<table>
<thead>
<tr>
<th>Notch filter for simulation model</th>
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<tbody>
<tr>
<td>Filtering frequency } \omega_f</td>
</tr>
<tr>
<td>Filter coefficient } \zeta_1</td>
</tr>
<tr>
<td>Filter coefficient } \zeta_2</td>
</tr>
</tbody>
</table>

Fig. 7 shows that stopping motion with the conventional notch filter. The parameter of notch filter is shown in Table II.
The simulation results confirm that the conventional notch filter suppresses the resonant vibration. Otherwise, the delay time between the position reference and the load position increases from 0.038s to 0.442s.

The position reference error \( e(t) \) of the proposed notch filter is obtained as shown in (13).

\[
\begin{align*}
e(t) &= \theta^{ref}(s) - \theta^{ref}\ast(s) = \frac{1}{s}(1 - F_n(s) - K_{cmp}\omega_f s)\omega_f s \theta^{ref}(s) \\
&= G_{e}(s)\omega_f(s) \\
G_{e}(s) &= -K_{cmp}\omega_f^2 - 2K_{cmp}\omega_f\omega_s + 2(\zeta_1 - \zeta_2)\omega_f - K_{cmp}\omega_f^2
\end{align*}
\]

In (13), the position reference error \( e(t) \) is decided only by the parameter of the notch filter. For eliminating the steady state error of position reference, the compensation gain \( K_{cmp} \) is obtained as shown in (15).

\[
\frac{2(\zeta_1 - \zeta_2)\omega_f - K_{cmp}\omega_f^2}{\omega_f^2} = 0
\]

\[
K_{cmp} = \frac{2(\zeta_1 - \zeta_2)}{\omega_f}
\]

As the results, the total structure of proposed vibration suppression control system is reconstructed as shown in Fig.9. In order to confirm the validity of the proposed notch filter without little phase error, this paper shows the numerical simulation results as shown in Fig.10. From Fig.10, the proposed notch filter suppresses the vibration phenomena caused by parameter variation. The residual vibration is decreased to 25.7% comparing with Fig.7(b) and Fig.10(b). Moreover, Fig.10(a) points out that the proposed notch filter decreases the delay time to 56% comparing with Fig.7(a) and Fig.10(a). From these results, the validity of the proposed notch filter is confirmed.

IV. EXPERIMENTAL RESULTS

This paper shows the experimental results by using the model of the 3-DOF (three-degree-of-freedom) industrial robot manipulator. Fig.11 shows the 3-DOF robot manipulator. The experiments are implemented in the residual vibration under the conditions shown in Table III. For the experiment of the residual vibration, each joint is moved in such pattern in Fig.11.
Fig. 9. Motor drive control system using proposed method for industrial robot

Fig. 11. Experimental motion of robot manipulator

Table III

<table>
<thead>
<tr>
<th></th>
<th>1st joint</th>
<th>2nd joint</th>
<th>3rd joint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial load position [rad] ([deg])</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>-0.393 (-22.5)</td>
</tr>
<tr>
<td>Motor position [rad] ([deg])</td>
<td>0 (0) → -125.664 (-45)</td>
<td>0 (0) → -125.664 (-45)</td>
<td>-62.832 (-22.5) → -188.496 (-67.5)</td>
</tr>
<tr>
<td>Moving time for the residual vibration [s]</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Moving time for the locus error [s]</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>( \zeta_1 )</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>( \zeta_2 )</td>
<td>0.35</td>
<td>0.30</td>
<td>0.80</td>
</tr>
<tr>
<td>( \omega_f ) [rad/s]</td>
<td>43.9</td>
<td>43.7</td>
<td>29.8</td>
</tr>
</tbody>
</table>

The reference and the load is improved to 0.72s and the residual vibration decreases to approximately 42%. For 2nd joint shown in Fig.13(b), it decreases to approximately 15% in the maximum amplitude by using the notch filter. The phase error between the reference and the load increases from 0.72s to 0.86s. For the proposed method, the experimental result of the 2nd joint shown in Fig.13(b), the phase error between the reference and the load is improved to 0.71s. The response is faster than the system without the notch filter. In addition, the residual vibration decreases to approximately 57%. For 3rd joint shown in Fig.13(c), it seems that the proposed method is not too effective. However, it is because the resonant frequency did not appear by varying the load inertia. In those results, it is confirmed that the proposed method is validity for the vibration suppression.

V. CONCLUSION

This paper proposed a new motor drive control method using both the anti-vibration control system and the notch filter with little phase error for industrial robot. The proposed method is anti-vibration control system by using robust speed control system and D-PD position control system. The robust speed control system suppresses the resonant vibration of two-inertia system. The D-PD position control system realizes the fast position control. Moreover, this paper proposes a new notch filter with little phase error. The proposed method decreases the time delay of the conventional notch filter by inserting the compensation gain. Both of simulation results and experimental results show that the proposed method has
Fig. 12. Experimental results using proposed method of each joint.

Fig. 13. Residual vibration of stop motion by using the proposed notch filter

high potential to suppress resonant vibration and improves the phase error.

REFERENCES


