Decoupling Control of 2-Link Manipulator by Using Model Following Control

Linfeng Lan*, Hideki Honda**, and Ryuichi Oguro***

Abstract: In this paper, a new simple decoupling control scheme with a model following control is proposed for 2-link industrial manipulators. Based on a coupling model, we design a compensation torque to eliminate the coupling force between two links of a manipulator in a feed-forward controller and employ observers to estimate unmodelled dynamics errors and external disturbances. Making use of the estimations, this proposes a compensation method for unmodelled errors and external disturbances to ensure the robustness of the designed control system. Effectiveness of the proposed decoupling control scheme has been confirmed through some simulation results.

Key Words: industrial manipulator, decoupling control, model following control, disturbance observer.

1. Introduction

In order to make an industrial manipulator track a specified trajectory at a high speed and with higher accuracy, various studies have been made. Decoupling control theories have been established in 1980s which are considered as one of the most effective ways to realize high-speed and high-accuracy control of industrial manipulators.

For some kinds of multi-axis manipulators that include a direct drive (DD) robot illustrated in Fig. 1. Froud [1], Iwakane and Inoue [2] proposed a decoupling control method that compensates for the coupling forces between the links of the 2-link manipulator according to the dynamic equations. Decoupling control methods considered in robust control areas with disturbance observer have also been reported [3]–[6]. Moreover, Ito and Shiraishi [7] used a feed-forward (abbreviated as FF) control loop combined with a disturbance observer to accomplish simple robust decoupling control for articulated robots. All the literature realized the decoupling control based on the rigid control system. However, for the industrial manipulators equipped with flexible joints, Nakashima et al. [8] considered that the coupling force does not directly act on actuators and first showed a decoupling control scheme based on the model of 2-inertia system.

For all the decoupling control approaches of robots shown above, most of them employ basic feedback control (abbreviated as FB). Due to the requirement of highly accurate control for industrial robots, advanced control manner such as Model Following Control (MFC) should be used for decoupling control. The purpose of MFC is to force the dynamic response of a plant to follow the response of a reference model by a correction mechanism within itself. The MFC technique has been widely described in the literature [9]–[11]. Literature [12] presented a decoupling control method for industrial manipulators by using MFC, but additional compensation must be designed for FF controller except the compensation for coupling force. To be different from conventional decoupling control approaches, this paper proposes a new decoupling control scheme that uses Model Following Control with the model of the 2-inertia system.

In addition, we have also considered that it is more efficient to accomplish decoupling control of the manipulators if we employ MFC because of the following reasons.

1. The torque used to compensate for the coupling force that is called compensation torque can be designed independently. The conventional decoupling control [8],[12] for industrial manipulators with flexible joints used the information of the positions of motors to construct a semi-closed control loop. The position of a motor of each link includes acceleration interference components of the other link, and hence, an additional compensation torque has to be designed for FF controller except the compensation for coupling force. To be different from conventional decoupling control approaches, this paper proposes a new decoupling control scheme that uses Model Following Control with the model of the 2-inertia system.

2. The decoupling control by using MFC is widely used
for most of industrial manipulators. For general manipulators which are equipped with general-purpose servo systems, the decoupling control with FB control can not be easily implemented because of the restriction on bidirectional communication issue. However, there is no need to take the bidirectional communication issue into consideration in the case of decoupling control by using MFC.

Potential subjects that arise from the decoupling control by using MFC, include how to deal with modeling errors. The designed compensation torque is based on a dynamic model. It is obviously not enough to decouple the two links of the manipulator due to the modeling errors. In other words, the 2-link manipulator is still a coupling system. For the new subjects about modeling errors, we design the FB controller and use observers to cope with them. In FB controllers, the authors propose a compensation scheme for modeling errors and disturbances such as resistance forces applied to the end of the 2-link manipulator. The proposed compensation scheme can not only reinforce the robustness but also can provide more possibilities to realize high gain control of the flexible joints industrial manipulators.

In addition, we choose the 2-link manipulator as a decoupling control target in this paper, because the coupling effects mostly occur between the two links of the manipulators which rotate in the same plane. Especially, the coupling effects are severe between the two links of the point to point positioning robots although they have six or seven links. The proposed decoupling control scheme is presented in detail from section 2 to section 5 and conclusions are given in section 6.

2. Coupling Model of the 2-Link Manipulator

This section presents the coupling model of the 2-link manipulator.

Usually, the mechanical structure of industrial manipulators consist of three parts, servomotor, reducer and rigid load. Regarding the reducer as a spring system, links of industrial manipulators are mostly modeled as 2-inertia systems. With this understanding, we also use the 2-inertia system as the model of each link of the 2-link industrial manipulator in our paper. The block diagram of the 2-inertia system is shown in Fig. 2.

\[
\begin{align*}
\theta_m &= -\frac{K_c}{J_m}T_{ref} + \frac{1}{N}T_{ref}, \\
\theta_e &= \frac{1}{N}\theta_m - \theta_e.
\end{align*}
\]

where

\[
\begin{align*}
J_m : \text{motor inertia} & \quad \theta_m : \text{rotation angle of motor} \\
J_r : \text{rigid load inertia} & \quad \theta_e : \text{rotation angle of joint} \\
K_c : \text{spring constant} & \quad \theta_t : \text{twist angle} \\
N : \text{reduction ratio} & \quad T_{ref} : \text{torque reference}
\end{align*}
\]

Fig. 2  Block diagram of 2-inertia system.

From the block diagram, we can easily get the motion equation of the motor in Eq. (1).

\[
\dot{\theta}_m = -\frac{K_c}{J_m N} \theta_t + \frac{1}{J_m}T_{ref}. 
\]  (1)

In order to figure out the interrelation between the two links of the manipulator, we show a simple model of the 2-link manipulator in Fig. 3 where suffix L and U means lower link and upper link of the 2-link manipulator, respectively.

Then, according to Euler-Lagrange equation, we get the dynamical equation of motion for the 2-link manipulator in Eq. (3).

\[
M(q)\ddot{q} + h(q, \dot{q}) + g(q) = \tau 
\]  (3)

where

\[
\begin{align*}
M(q) & = \begin{bmatrix} M_{LL} & M_{LU} \\ M_{UL} & M_{UU} \end{bmatrix}, \\
h(q) & = \begin{bmatrix} h_{LU} \\ h_{UL} \end{bmatrix}, \\
g(q) & = \begin{bmatrix} g_L \\ g_U \end{bmatrix}, \\
\dot{\theta}_t & = \begin{bmatrix} \dot{\theta}_t \\ \dot{\theta}_t \end{bmatrix}
\end{align*}
\]

\[
\begin{align*}
M_{LL} & = \frac{m_L l_L^2}{2} + \frac{m_U l_L^2}{2} + 2m_U l_L g_U \cos(\theta_{UL}) + I_L + I_U \\
M_{LU} & = \frac{m_U l_L^2}{2} + \frac{m_U l_L g_U}{2} \cos(\theta_{UL}) + I_L + I_U \\
M_{UL} & = \frac{m_U l_L^2}{2} + \frac{m_U l_L g_U}{2} \cos(\theta_{UL}) + I_L + I_U \\
M_{UU} & = m_U l_U^2 + I_U \\
h_{LU} & = -m_U l_L g_U (2\dot{\theta}_t + \dot{\theta}_t) \dot{\theta}_t \sin(\theta_{UL}) \\
h_{UL} & = m_U l_L g_U \dot{\theta}_t \dot{\theta}_t \sin(\theta_{UL}) \\
g_L & = (m_L g_L + m_U g_U) \cos(\theta_{UL}) + m_U l_L g_U \cos(\theta_{UL}) + \dot{\theta}_t \\
g_U & = m_U g_U \cos(\theta_{UL}) + \dot{\theta}_t
\end{align*}
\]

\[
\tau = \begin{bmatrix} \tau_{UL} \\ \tau_{LU} \end{bmatrix}
\]

\[
\begin{align*}
\dot{\theta}_L & = \begin{bmatrix} \dot{\theta}_L \\ \dot{\theta}_U \\ \dot{\theta}_{UL} \end{bmatrix} \\
\dot{\theta}_U & = \begin{bmatrix} \dot{\theta}_L \\ \dot{\theta}_U \\ \dot{\theta}_{UL} \end{bmatrix}
\end{align*}
\]

\[
A = \begin{bmatrix} a_{21} & a_{22} & 0 & 0 & 0 & 0 \\ a_{11} & a_{13} & a_{43} & 0 & a_{45} & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ a_{61} & 0 & a_{63} & 0 & a_{65} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ a_{81} & 0 & a_{83} & 0 & a_{85} & 0 \end{bmatrix}
\]

Fig. 3 Simple model of 2-link manipulator in coordinate system.
\[
B = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}^T
\]

\[
T_{\text{ref}} = \begin{bmatrix}
T_{\text{refL}} & T_{\text{refU}}
\end{bmatrix}^T
\]

\[
a_{21} = -\frac{K_{\text{kl}}}{J_{\text{m}L}N_L^2}, \quad a_{23} = \frac{K_{\text{kl}}}{J_{\text{m}L}N_L}
\]

\[
a_{41} = \frac{J_{\text{at}}N_L}{K_{\text{cl}M_{\text{LU}}}}, \quad a_{43} = \frac{J_{\text{at}}}{K_{\text{cl}M_{\text{LU}}}}
\]

\[
a_{45} = -\frac{N_L(M_{\text{LL}}M_{\text{LU}} - M_{\text{UU}}M_{\text{UL}})}{K_{\text{cl}M_{\text{UL}}}}
\]

\[
a_{47} = \frac{M_{\text{LL}}M_{\text{LU}} - M_{\text{UU}}M_{\text{UL}}}{K_{\text{cl}M_{\text{UL}}}}
\]

\[
a_{65} = -\frac{N_L(M_{\text{LL}}M_{\text{LU}} - M_{\text{UU}}M_{\text{UL}})}{J_{\text{m}LN_L^2}}
\]

\[
a_{67} = \frac{1}{J_{\text{m}LN_L^2}}
\]

\[
\theta_{ai} = \frac{\omega_{ai}}{s^2(1 + \omega_{ai})} \frac{1}{J_{\text{m}LN_i}} T_{\text{refi}}
\]

where suffix \( i \) means \( L \) or \( U \).

\[
\omega_{ai} = \frac{K_{ai}}{J_{ai}}
\]

\[
\omega_{ai} = \frac{1}{J_{\text{m}LN_i^2} + K_{ai}}
\]

According to Eq. (9), we designed \( T_{\text{refLFF}} \) and \( T_{\text{refUUFF}} \) in Eqs. (10) and (11).

\[
T_{\text{refLFF}} = J_{\text{LLn}}N_{\text{Un}} \left\{ K_{\text{LLFF}}(\theta_{\text{arefl}} - \theta_{\text{dLFF}}) - \dot{\theta}_{\text{dLFF}} \right\}
\]

\[
- \frac{a_{2L\text{FF}}}{a_{3L\text{FF}}} \dot{\theta}_{\text{dLFF}} - \frac{a_{3L\text{FF}}}{a_{2L\text{FF}}} \theta_{\text{dLFF}}
\]

\[
T_{\text{refUFF}} = J_{\text{LTn}}N_{\text{Un}} \left\{ K_{\text{UFF}}(\theta_{\text{arefu}} - \theta_{\text{dUUFF}}) - \dot{\theta}_{\text{dUUFF}} \right\}
\]

\[
- \frac{a_{2U\text{FF}}}{a_{3U\text{FF}}} \dot{\theta}_{\text{dUUFF}} - \frac{a_{3U\text{FF}}}{a_{2U\text{FF}}} \theta_{\text{dUUFF}}
\]

where \( \theta_{\text{arefl}} \) and \( \theta_{\text{arefu}} \) are goal positions, \( \theta_{\text{dLFF}} \) and \( \theta_{\text{dUUFF}} \) are rotation angles of joints used in feed-forward numerical model. \( J_{\text{LTn}} \) and \( J_{\text{LTn}} \) are the total inertia of links, \( K_{\text{LLFF}}, K_{\text{UFF}}, K_{\text{LUFF}}, K_{\text{UFF}}, K_{\text{UFF}}, K_{\text{UFF}}, K_{\text{UFF}} \) are feed-forward control gains. Suffixed \( n \) means nominal value. With regard to the details of feedback gains determination, we do not present it in this paper because many methods have been proposed for it.

In Eqs. (10) and (11), we can see that \( T_{\text{refLFF}} \) and \( T_{\text{refUUFF}} \) are designed by only using states related to rotation angle of joints. Since without using states related to rotation angle of motors, our compensation design for the coupling force will become very simple. There is no need to design an additional compensation torque for feedback input like in the conventional decoupling control methods.

After the designing of \( T_{\text{refLFF}} \) and \( T_{\text{refUUFF}} \), we designed the compensation torque \( T_{\text{refLCFF}} \) and \( T_{\text{refUCFF}} \). Before we show the details, assume that the dotted line frame part in Fig. 4 has been removed. Then, we know the two links of the manipulator become two independent 2-inertia systems. The fourth order differential equation of \( \theta_{\text{daf}} \) is supposed to be like Eq. (12) which includes only self-state variables. In other words, the fourth order differential equation of \( \theta_{\text{daf}} \) does not include the interference terms of the other.

\[
\frac{d^4}{dt^4} \theta_{\text{daf}} = -K_{\text{S}} \ddot{\theta}_{\text{daf}} - K_{\text{2}} \ddot{\theta}_{\text{daf}} - K_{\text{1}} \dot{\theta}_{\text{daf}} - K_{\text{0}} \theta_{\text{daf}}
\]

+ \( \dot{K}_0 \theta_{\text{refi}} \)

(12)

where \( K_{\text{S}}, K_{\text{2}}, K_{\text{1}}, \) and \( K_{\text{0}} \) are control gains.

Based on the coupling model shown in Fig. 4 and Euler-Lagrange Equation, we have

\[
\ddot{\theta}_{\text{dLFF}} = \omega_{\text{LLd}} \theta_{\text{dLFF}} - \omega_{\text{ULd}} \theta_{\text{dUUFF}} - a_{\text{dLFF}}
\]

\[
\ddot{\theta}_{\text{dUUFF}} = \omega_{\text{ULd}} \theta_{\text{dUUFF}} - \omega_{\text{ULd}} \theta_{\text{dLFF}} - a_{\text{dUUFF}}
\]
\[ \ddot{\theta}_{\text{LFF}} = -(K_{Jn} + \omega_{LU}^2)\dot{\theta}_{\text{LFF}} + \frac{1}{J_{\text{LUn}}N_{\text{LUn}}} T_{\text{ref LFF}} + \omega_{LU}^2 \theta_{\text{AFF}} + a_{\text{AFF}} \]  
(15)

\[ \ddot{\theta}_{\text{UFF}} = -(K_{Jn} + \omega_{UU}^2)\dot{\theta}_{\text{UFF}} + \frac{1}{J_{\text{UU}n}N_{\text{UU}n}} T_{\text{ref UFF}} + \omega_{UU}^2 \theta_{\text{AFF}} + a_{\text{AFF}} \]  
(16)

where \( \theta_{\text{LFF}} \) and \( \theta_{\text{UFF}} \) are twist angles used in feed-forward numerical model, \( a_{\text{AFF}} \) and \( a_{\text{UFF}} \) are gravity terms.

\[ \omega_{LU} = \frac{K_{Jn}}{J_{\text{LUn}}}, \quad \omega_{UU} = \frac{K_{Jn}}{J_{\text{UU}n}} \]

Using Eqs. (13)–(16), we also arrive at

\[ \frac{d^2}{dt^2} \theta_{\text{LFF}} = -(K_{Jn} + \omega_{LU}^2)\dot{\theta}_{\text{LFF}} + K_{Jn}\frac{N_{\text{LUn}}}{J_{\text{LUn}}} T_{\text{ref LFF}} \]

\[ -K_{Jn}\omega_{LU}^2\dot{\theta}_{\text{LFF}} - \omega_{LU}^2 \theta_{\text{LFF}} = K_{Jn}a_{\text{AFF}} - \ddot{\theta}_{\text{LFF}} \]  
(17)

\[ \frac{d^2}{dt^2} \theta_{\text{UFF}} = -(K_{Jn} + \omega_{UU}^2)\dot{\theta}_{\text{UFF}} + K_{Jn}\frac{N_{\text{UU}n}}{J_{\text{UU}n}} T_{\text{ref UFF}} \]

\[ -K_{Jn}\omega_{UU}^2\dot{\theta}_{\text{UFF}} - \omega_{UU}^2 \theta_{\text{UFF}} = K_{Jn}a_{\text{AFF}} - \ddot{\theta}_{\text{UFF}}. \]  
(18)

In Eqs. (17) and (18), we can see the third and fourth terms of the right side of the equations are interference terms from the other link, and the fifth and sixth are gravity terms. To eliminate the interference and gravity terms, we make

\[ T_{\text{ref LUFF}} = \omega_{LU} \dot{\theta}_{\text{LUFF}} + \omega_{UU} \dot{\theta}_{\text{UFF}} + a_{\text{AFF}} \]  
(19)

\[ T_{\text{ref UUFF}} = \omega_{LU} \dot{\theta}_{\text{LUFF}} + \omega_{UU} \dot{\theta}_{\text{UFF}} + a_{\text{AFF}} \]  
(20)

where

\[ \omega_{LU} = \frac{K_{Jn}}{J_{\text{LUn}}}, \quad \omega_{UU} = \frac{K_{Jn}}{J_{\text{UU}n}} \]

By using Eqs. (15) and (16), we get the recalculated \( T_{\text{ref LUFF}} \) and \( T_{\text{ref UUFF}} \) in Eqs. (19) and (20)

\[ T_{\text{ref LUFF}} = \omega_{LU} \dot{\theta}_{\text{LUFF}} + \omega_{LU} \dot{\theta}_{\text{LUFF}} - \omega_{LU} \dot{\theta}_{\text{LUFF}} \left( T_{LU} + T_{UL} + T_{Lg} \right) \]  
(21)

\[ T_{\text{ref UUFF}} = \omega_{LU} \dot{\theta}_{\text{LUFF}} + \omega_{LU} \dot{\theta}_{\text{LUFF}} - \omega_{LU} \dot{\theta}_{\text{LUFF}} \left( T_{UU} + T_{UL} + T_{Ug} \right) \]  
(22)

where

\[ T_{LL} = \left( \omega_{LU} \dot{\theta}_{\text{LUFF}} - \omega_{LU} \dot{\theta}_{\text{LUFF}} - \omega_{LU} \dot{\theta}_{\text{LUFF}} \right) \]

\[ + \omega_{LU} \dot{\theta}_{\text{LUFF}} + \omega_{LU} \dot{\theta}_{\text{LUFF}} T_{\text{ref LUFF}} \]

\[ T_{LU} = \left( \omega_{LU} \dot{\theta}_{\text{LUFF}} - \omega_{LU} \dot{\theta}_{\text{LUFF}} \right) \]

\[ + \omega_{LU} \dot{\theta}_{\text{LUFF}} + \omega_{LU} \dot{\theta}_{\text{LUFF}} T_{\text{ref LUFF}} \]

\[ T_{UL} = \left( \omega_{LU} \dot{\theta}_{\text{LUFF}} - \omega_{LU} \dot{\theta}_{\text{LUFF}} \right) \]

\[ + \omega_{LU} \dot{\theta}_{\text{LUFF}} + \omega_{LU} \dot{\theta}_{\text{LUFF}} T_{\text{ref LUFF}}. \]

4. Design of Feedback Controller

In this section, we designed the feedback input to cope with the modeling error problems. The designed compensation torque in feed-forward loop is not able to make a thorough compensation for the coupling force and gravity in the actual controlled manipulator due to the modeling errors. Besides, disturbances such as resistance force applied to the ends of the 2-link manipulator also cause the accuracy deterioration of the operation. Hence, we design the feedback input \( T_{\text{ref LFB}} \) and \( T_{\text{ref UFB}} \) to reinforce the robustness of the whole control system.

Referring to Fig. 4, we can see that no matter the disturbances generated by modeling errors or the disturbances applied to the end of the 2-link manipulator, both of them are directly loaded to the joints. Due to this, the disturbances of each link of the 2-link manipulator also couple with each other. For usual industrial manipulators which have been equipped with the general-purpose servo control systems, each link of the 2-link manipulator are taken as an independent controlled system. Then, we consider that it is possible to design two independent FB controllers to solve the coupling disturbances problems. The model of the link with the modeling errors is shown in Fig. 5. \( T_{\text{ad}} \) is a torque disturbance.

The feedback input \( T_{\text{ref LFB}} \) and \( T_{\text{ref UFB}} \) are designed in Eqs. (23) and (24) to accomplish a thorough decoupling control.

\[ T_{\text{ref LFB}} = T_{\text{ref LUFF}} + T_{\text{ref LDC}} \]  
(23)

\[ T_{\text{ref UFB}} = T_{\text{ref UUFF}} + T_{\text{ref UDC}} \]  
(24)

where \( T_{\text{ref LFB}} \) and \( T_{\text{ref UFB}} \) are torque designed in Eqs. (25) and (26), \( K_{\text{PLFB}} \), \( K_{\text{VLFB}} \), \( K_{\text{PUBF}} \) and \( K_{\text{VUBF}} \) are feedback control gains. \( T_{\text{ref LDC}} \) and \( T_{\text{ref UDC}} \) are torque used to compensate the disturbances called disturbance compensation torque.

\[ T_{\text{ref LUFF}} = J_{\text{LUn}} \left[ K_{\text{PLFB}} \left( \theta_{\text{LUn}} - \theta_{\text{mL}} \right) \right] \]

\[ + K_{\text{VLFB}} \left( \theta_{\text{LUn}} - \theta_{\text{mL}} \right) \]  
(25)
\[ T_{refUFB} = J_{UTa} \left[ K_{PF} \theta_{aUFF} - K_{VF} \dot{\theta}_{aUFF} \right] + K_{VF} \left( \dot{\theta}_{aUFF} - \dot{\theta}_{aUFF} \right) \]  
\[ \theta_{adv} \text{ and } \theta_{aUFF} \text{ are the actual observed position of motors.} \]

For disturbance \( T_{adv} \), we can use an observer to get an estimation of \( T_{adv} \) shown as \( \hat{T}_{adv} \). With \( \hat{T}_{adv} \), we use two steps to compensate for the disturbance \( T_{adv} \).

Firstly, we compensate for the disturbance components included in joint angles. Based on Fig. 5, we give the fourth order differential equation of actual joint angle \( \theta \):  
\[ \frac{d^4}{dt^4} \theta_{adv} = -\frac{\omega_{\theta}^2}{J_{mi}} \theta_{adv} + \frac{\omega_{\theta}^2 T_{refUFB}}{J_{mi}} - \frac{\omega_{\theta}^2}{J_{mi} N_t} T_{adv} - \frac{N_t \omega_{\theta}^2}{K_{Ci}} \hat{T}_{adv} \]  

In Eq. (27), the third and fourth terms of the right side of the equation are disturbance components. We employ \( T_{refLDC1} \) and \( T_{refUFB} \) to eliminate them. By using Eqs. (23) and (24), we get

\[ T_{refLDC1} = \frac{1}{N_{La}} \dot{\theta}_{adv} + \frac{J_{mLa} N_{La}}{K_{Ci} J_{mLa}} \hat{\theta}_{adv} \]  
\[ T_{refUDC1} = \frac{1}{N_{Un}} \dot{\theta}_{advU} + \frac{J_{mLa} N_{Un}}{K_{Ci} J_{mLa}} \hat{\theta}_{advU} \]  

For the terms related to \( \ddot{\theta}_{adv} \) and \( \dot{\theta}_{advU} \), they can be regarded as zero terms if \( \hat{T}_{adv} \) does not change suddenly. Secondly, we compensate for the disturbance components included in the FB controller. Based on the model shown in Fig. 5, we also have

\[ \dot{\theta}_{adv} = \frac{1}{\omega_{\theta}^2} \ddot{\theta}_{adv} + N_t \dot{\theta}_{adv} + \frac{N_i}{K_{Ci}} T_{adv} \]  
\[ \ddot{\theta}_{adv} = \frac{1}{\omega_{\theta}^2} \dddot{\theta}_{adv} + N_t \dot{\theta}_{adv} + \frac{N_i}{K_{Ci}} \hat{T}_{adv} \]  

Substituting Eqs. (30) and (31) into Eqs. (25) and (26), we get \( T_{refLFB} \) and \( T_{refUFB} \) as follows.

\[ T_{refLFB} = J_{LTa} \left[ K_{PF} N_l \theta_{aUFF} - K_{VF} N_l \dot{\theta}_{aUFF} \right] \]  
\[ = K_{PF} N_l \dot{\theta}_{adv} - K_{VF} N_l \dot{\theta}_{adv} \]  
\[ = K_{PF} N_l \dot{\theta}_{adv} - K_{VF} N_l \dot{\theta}_{adv} \]  
\[ = K_{PF} N_l \dot{\theta}_{adv} - K_{VF} N_l \dot{\theta}_{adv} \]  

In Eq. (32), we can see that the FB controller includes disturbance components due to the feedback states \( \theta_{aUFF} \) and \( \dot{\theta}_{aUFF} \). \( T_{refLDC2} \) and \( T_{refUDC2} \) are employed to eliminate these disturbance components. Also by using Eqs. (23) and (24), we can get

\[ T_{refLDC2} = J_{LTa} \left[ K_{PF} N_l \dot{\theta}_{advU} + K_{VF} N_l \dot{\theta}_{advU} \right] \]  
\[ T_{refUDC2} = J_{UTa} \left[ K_{PF} N_{Un} \ddot{\theta}_{advU} + K_{VF} N_{Un} \ddot{\theta}_{advU} \right] \]  

Finally, we can get

\[ T_{refLDC} = T_{refLDC1} + T_{refLDC2} \]  
\[ T_{refUDC} = T_{refUDC1} + T_{refUDC2} \]

5. Simulations

One of typical examples of the accuracy deterioration due to the coupling phenomenon is in spot welding robots. High-speed positioning of the end of spot welding robots must be realized in very small operating range (30mm∼50mm). Compared with other motions, the operating accuracy is adversely affected in the case of spot welding motion. Hence, we took the spot welding robots as the assumed control objects in our simulations.

Several simulation results are employed to verify the effectiveness of proposed decoupling control scheme with parameters shown in Table 1. The resonant frequency of L and U used for simulations are 10 Hz and 19 Hz. The inertia of the rigid load \( J_e \) of each link and the spring constant \( K_C \) are calculated from Eqs. (4) and (9). Usually, those parameters of each link of the manipulators are determined by experimental results. Modeling error of \( K_C \) mostly happens due to the resonant frequency measurement errors. So, the simulations used to verify the modeling errors are considered with disturbances and \( K_C \) errors.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_L )</td>
<td>2.34 kg</td>
</tr>
<tr>
<td>( m_U )</td>
<td>3.00 kg</td>
</tr>
<tr>
<td>( I_L )</td>
<td>0.25 m</td>
</tr>
<tr>
<td>( I_U )</td>
<td>0.53 m</td>
</tr>
<tr>
<td>( l_L )</td>
<td>0.19 m</td>
</tr>
<tr>
<td>( l_U )</td>
<td>0.30 m</td>
</tr>
<tr>
<td>( J_{mL} )</td>
<td>7.81 × 10^{-3} kgm^2</td>
</tr>
<tr>
<td>( J_{mU} )</td>
<td>3.05 × 10^{-3} kgm^2</td>
</tr>
<tr>
<td>( N_L )</td>
<td>120</td>
</tr>
<tr>
<td>( N_U )</td>
<td>80</td>
</tr>
</tbody>
</table>

The simulation results shown in Fig. 6 are used to verify the effectiveness of the proposed decoupling control scheme in the case of no parameter errors. From the results, we can see in the case of no compensation for coupling force (without decoupling control), both lower and upper arms of the 2-link manipulator vibrated around the goal position. However, the lower and upper arm rotate independently and without vibration after we compensated for the coupling force. Besides, we can also say that the proposed compensation scheme for nonlinear gravity is effective because of the convergence of the responses.

A simulation results shown in Fig. 7 are used to verify the effectiveness of the proposed disturbances compensation method. The resistance forces will be applied to joints when the ends of the spot welding robots contact the surface of welding target. Due to the small operating range of the ends of the spot welding robots, rotation angle of arms will not change in a wide range. Hence the disturbances applied to the joints of the spot welding robots will not change continuously like a sinusoidal signal. Therefore, we used a step disturbance in this simulations. From the simulation results, we can see that the position responses of both the lower and upper arm converge at the goal position after disturbances compensation. Then, we can say that the proposed disturbances compensation scheme is effective.

6. Conclusions

This paper proposed a new decoupling control strategy for
the 2-link industrial manipulator using the model following control. The proposed scheme has the following advantages compared with conventional schemes.

(1) The design of compensation torque used for eliminating the coupling force and gravity is independent and becomes very simple.

(2) An usual observer is enough to cope with the modeling error problems in coupling robots. With the feedback of the estimation of the observer in coupling systems, the imperfect compensation torque designed in FF will be supplemented.

(3) The proposed scheme is also a countermeasure of the bidirectional communication problem which exists in most servo systems.

In this paper, the proposed decoupling control scheme is mainly considered for the typical coupling spot welding robots. Due to this, the designed FB control loops can still ensure the robustness for the nonlinear elements such as Coriolis and Centrifugal Force. However, for other robots which are used in an extensive work area, countermeasures for nonlinearity must be considered further. With experimental verification, both of them will be studied in our future work.

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