Decoupling Identification Method of Serial Two-link Two-inertia System for Robot Motion Control

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Abstract: The goal of our study is to obtain a precise dynamic model by applying the technique of system identification for the model-based control of a nonlinear robot arm, taking joint-elasticity into consideration. We previously proposed “decoupling identification method” for a planar serial two-link robot arm with elastic-joints caused by the Harmonic-drive reduction gears. First, this paper reviews the decoupling effectiveness of the proposed identification method. This method serves as an extension of the conventional rigid-joint-model-based identification, and treats the robot arm as a serial two-link two-inertia system with nonlinearity. The main idea of the decoupling method is nonlinear interaction torques between two links are utilized as identification inputs besides motor inputs. The torques can be computed using the rigid-joint-model parameters and link-accelerometer signals, and enable the serial two-link two-inertia system to be divided into two linear one-link systems. Typical multi-input multi-output linear model estimation algorithms can be applied for the identification method. Physical parameters such as motor inertias, link inertias, joint-friction coefficients and joint-spring coefficients of the dynamic model are estimated by applying the coefficient comparison method to the transfer functions of the one-link two-inertia systems. This is a gray-box modeling approach. Second, this paper extends the proposed method to closed-loop identification from open-loop identification. Thus the method is applicable for not only a SCARA (Selective Compliant Assembly Robot Arm) but also a PUMA (Programmable Universal Manipulation Arm) under gravity. Third, this paper unveils the robustness of the decoupling method against estimation errors of coupling-inertia parameters for computing nonlinear interaction torques; these parameters are obtained by the conventional rigid-joint-model-based identification. Several experiments using the planar serial two-link robot arm with elastic-joints are conducted to demonstrate the effectiveness and robustness of the decoupling identification method.

Keywords: Robot arms, Nonlinear systems, Mechanical resonance, Frequency response, Multivariable systems, Closed-loop identification, Nonlinear optimization, Gray-box modeling.

1. INTRODUCTION

Nowadays, the robot arms with serial links, called SCARA (Selective Compliant Assembly Robot Arm) or PUMA (Programmable Universal Manipulation Arm), are widely used in industry. The robot arms are increasingly required to be controlled with high acceleration and suppressed arm-tip vibration. This vibration is mainly caused by the elasticity of the Harmonic-drive reduction gears built in each joint of the robot arm. Furthermore, the structure of the serial links amplifies the vibration. Especially, it is important to suppress the vibration caused by a serial two-link arm near the robot’s base. This serial two-link arm is composed of the 1st and 2nd links of the SCARA or the 2nd and 3rd links of the PUMA. The serial two-link arm with elastic-joints is called “serial two-link two-inertia system” (Oaki et al. (2009)). The dynamic model-based control considering the joint-elasticity of the robot arm (e.g. Ott (2008)) is necessary to satisfy these requirement.

Although rigid-joint-model-based identification has been researched from quarter century ago (Khalil et al. (2002)), the field of elastic-joint-model-based identification is still in its infancy. Albu-Schäffer et al. (2001) showed a simple identification method for a 7dof elastic-joint robot using joint torque sensors, motor encoders, link encoders and motor brakes. However, coupled vibration effects among serial links, caused by the elastic-joints, are not considered. Besides such rich sensors are not usually equipped with.

We previously proposed “decoupling identification method” for a planar serial two-link robot arm with elastic-joints caused by the Harmonic-drive reduction gears (Oaki et al. (2009)). First, this paper reviews the decoupling effectiveness of the proposed identification method. This method serves as an extension of the conventional rigid-joint-model-based identification, and treats the robot arm as a serial two-link two-inertia system with nonlinearity. The main idea of the decoupling method is nonlinear interaction torques between two links are utilized as iden-
tification inputs besides motor inputs. The torques can be computed using the rigid-joint-model parameters and link-accelerometer signals, and enable the serial two-link two-inertia system to be divided into two linear one-link systems. Typical multi-input multi-output linear model estimation algorithms can be applied for the identification method. Physical parameters such as motor inertias, link inertias, joint-friction coefficients and joint-spring coefficients of the dynamic model are estimated by applying the coefficient comparison method to the transfer functions of the one-link two-inertia systems. This is a gray-box modeling approach. Second, this paper extends the proposed method to closed-loop identification from open-loop identification. Thus the method is applicable for not only a SCARA but also a PUMA under gravity. Third, this paper unveils the robustness of the decoupling method against estimation errors of coupling-inertia parameters for computing nonlinear interaction torques; these parameters are obtained by the conventional rigid-joint-model-based identification.

In the next sections, the decoupling identification method is described in detail. Several experiments using the planar serial two-link robot arm with elastic-joints are conducted to demonstrate the effectiveness and robustness of the decoupling identification method.

2. TARGET SYSTEM

In this paper, a controlled object is the planar serial two-link robot arm with elastic-joints shown in Fig. 1. A DC motor drives each joint with the Harmonic drive gear that behaves as an elastic spring element. The arm mechanism is similar in structure to the SCARA robot’s 1st and 2nd links. This means that two one-link two-inertia systems are located in series. The mechanism is called “serial two-link two-inertia system” (Oaki et al. (2009)). The drive systems for the 1st and 2nd joints have identical structures except their capacities. However, the 2nd joint performs not only rotational motion but also translational motion. Thus the coupled vibration characteristics of the 2nd joint are more complicated than those of the 1st joint.

An accelerometer for measuring the link translational acceleration is mounted on each link. Angular acceleration of each link is computed by the coordinate transformation. Angular velocity of each link is computed by the sensor-fusion operation using the difference of the encoder signal with a high-pass filter. Acceleration signal with a low-pass filter and the integration of the angular velocity signal with a high-pass filter.

3. DYNAMIC MODEL OF SERIAL TWO-LINK TWO-INERTIA SYSTEM

Fig. 2 shows an elastic-joint model as a two-inertia system for each link of the robot arm. In this model, six physical parameters are to be estimated, a motor-side inertia, a link-side inertia, a harmonic drive gear spring, a motor-side viscous friction, a link-side viscous friction, and a harmonic drive gear damping. Since motor-side Coulomb friction is nonlinear, it is independently estimated because of accuracy. The link accelerometer is attached for the decoupling identification method.

![Fig. 1. Planar serial two-link robot arm with elastic-joints.](image1)

![Fig. 2. Six physical parameters of each two-inertia system.](image2)
\[ M_L(\theta_L) = \begin{bmatrix} \alpha + \beta + 2\gamma \cos(\theta_{L2}) & \beta + \gamma \cos(\theta_{L2}) \\ \beta + \gamma \cos(\theta_{L2}) & \beta \end{bmatrix}, \] (3)

where \( \alpha, \beta, \) and \( \gamma \) are the base dynamic parameters (Khalil et al. (2002)) of the two-link robot arm. For convenience, \( m_{L1} \equiv \alpha + \beta + 2\gamma \) is defined for the maximum value of the element (1, 1) in the link inertia matrix. Also, \( m_{L2} \equiv \beta \) is defined for the constant value of the element (2, 2).

The Coriolis and centrifugal torque vector is given by
\[
eq \begin{bmatrix} -\gamma(2\dot{\theta}_{L1}\dot{\theta}_{L2} + \dot{\theta}_{L2}^2) \sin(\theta(\theta_{L2}) \right) \\ \gamma\dot{\theta}_{L1}^2 \sin(\theta_{L2}) \right) \end{bmatrix}. \] (4)

Since the torsional angles of the elastic-joints are very small, the trigonometric functions \( \cos(\theta_{L2}) \) and \( \sin(\theta_{L2}) \) can be computed using the approximation \( \theta_{L2} = \theta_{L2} - \frac{1}{2}\theta_{L2}^2 \).

The decoupling identification method estimates the physical parameters in (1) and (2). This method requires that two coupling-inertia parameters \( (\beta \) and \( \gamma \)) are to be estimated in advance. Thus we define the rigid-joint model in the low frequency range using the approximation \( \theta_M = N_G^{-1}\dot{\theta}_L \) in (1) and (2) as
\[
M(\theta_L)\ddot{\theta}_L + c_L(\dot{\theta}_L, \theta_L) + D \dot{\theta}_L 
+ N_G^{-1}f_M \text{sgn}(\theta_M) = N_G^{-1}Eu \] (5)

\[
M(\theta_L) = 
\begin{bmatrix} \alpha + \beta + 2\gamma \cos(\theta_{L2}) + m_{M1}/n_{G1} & \beta + \gamma \cos(\theta_{L2}) \\ \beta + \gamma \cos(\theta_{L2}) & \beta + m_{M2}/n_{G2} \end{bmatrix} \] (6)

\[
D = \text{diag}(d_{L1} + d_{M1}/n_{G1}, d_{L2} + d_{M2}/n_{G2}), \] (7)

where \( M(\theta_L) \) and \( D \) are the inertia matrix and viscous-friction coefficient matrix respectively. The parameters in (5) can be estimated by the conventional rigid-joint-model-based identification method (Khalil et al. (2002)).

Thus fourteen physical parameters are to be estimated. They are the six physical parameters for each link and the two coupling-inertia parameters \( (\beta \) and \( \gamma \)) between the two links. Since the \( \beta \) is equivalent to the 2nd link’s inertia \( m_{L2} \), thirteen physical parameters are to be actually estimated. The motor-side Coulomb friction torque \( f_M \) is the coefficient of the nonlinear function \( \text{sgn}(\dot{\theta}_M) \), thus the \( f_M \) is independently estimated because of accuracy.

4. DECOUPLING IDENTIFICATION PROCEDURE FOR SERIAL TWO-LINK TWO-INERTIA SYSTEM

First, this section reviews the decoupling identification method (Oaki et al. (2009)). The main idea of the decoupling method is nonlinear interaction torques between two links are utilized as identification inputs besides motor inputs. The torques can be computed using the rigid-joint-model parameters and link-accelerometer signals, and enable the serial two-link two-inertia system (1) and (2) to be divided into two linear one-link two-inertia systems. The method consists of three steps shown in Fig. 3. The 1st step is the physical parameter estimation for the rigid-joint model which approximates the elastic-joint model in the low frequency range. The 2nd step is the state-space model estimation for each of the links based on the elastic-joint model. The 3rd step is the physical parameter estimation for the elastic-joint model via two single-input single-output transfer functions converted from the state-space models, using the coefficient comparison method.

Second, this section describes an extension of the decoupling identification method for closed-loop identification. Because this method is originally designed for open-loop identification.

Third, this section discusses the robustness of the decoupling identification method against estimation errors of the two coupling-inertia parameters \( (\beta \) and \( \gamma \)) for computing nonlinear interaction torques.

4.1 Physical parameter estimation for rigid-joint model

The decoupling identification method requires that the two coupling-inertia parameters \( (\beta \) and \( \gamma \)) are to be estimated in advance. The conventional rigid-joint-model-based identification using the least-squares method (Khalil et al. (2002)) can be applied to estimate the physical parameters in (5) using arbitrary motion data of the two-link robot arm. The nonlinear interaction torques between the two links are computable using the estimated parameters \( (\beta \) and \( \gamma \)), the link angular accelerations and velocities. This fact plays an important role in the decoupling identification method. The independently estimated Coulomb friction torque is removed from each motor input data for the state-space model estimation in the next subsection.
4.2 State-space model estimation for elastic-joint model

In the procedure of the decoupling identification method, a pseudo random binary signal (PRBS) is applied to the 1st (or 2nd) joint by open-loop control as input data for identification while the 2nd (or 1st) joint is free because of no control. That is, the method is designed as open-loop identification. The decoupling identification method enables the serial two-link two-inertia system (1) and (2) to be divided into two linear one-link two-inertia systems. We define $\tau_1$ for the 1st joint, using the first lows of (1) and (2) as

$$
\tau_1 = - (\dot{\theta} + \dot{\gamma} \cos(\theta L)) \ddot{\theta} L_2 + \gamma (2 \dot{\theta} L_1 \dot{\theta} L_2 + \dot{\theta}^2 L_2) \sin(\theta L_2),
$$

(8)

where $\tau_1$ is the nonlinear interaction torque from the 2nd link, computed using the link angular accelerations and velocities. Next, we summarize the linear terms of (1) and (2), and move them to the left side as follows:

$$
\begin{bmatrix}
m_{M1} & 0 \\
0 & m_{L1}
\end{bmatrix}
\begin{bmatrix}
\ddot{\theta}_M \\
\ddot{\theta}_L
\end{bmatrix}
+ \begin{bmatrix}
m_{M1} + n^2_{G1} d_{G1} & n_{G1} d_{G1} \\
-n_{G1} G_{11} & d_{L1} + G_{11}
\end{bmatrix}
\begin{bmatrix}
\ddot{\theta}_M \\
\ddot{\theta}_L
\end{bmatrix}
+ \begin{bmatrix}
2 n_{G1} G_{11} & -n_{G1} G_{11} \\
-n_{G1} G_{11} & k_{G1}
\end{bmatrix}
\begin{bmatrix}
\theta_1 \\
\theta_2
\end{bmatrix}
+ \begin{bmatrix}
e_1 u_1 - f_{M1} \text{sgn}(\dot{\theta}_M) \\
e_2 u_2
\end{bmatrix}
= \begin{bmatrix}
\tau_1 \\
\tau_2
\end{bmatrix}.
$$

(9)

Then, we multiply both sides of (9) by

$$
\begin{bmatrix}
m_{M1} & 0 \\
0 & m_{L1}
\end{bmatrix}^{-1}
$$

and define a state variable vector $x_1 \equiv [\theta_M, \theta_L, \dot{\theta}_M, \dot{\theta}_L]^T$ and an output vector $y_1 \equiv [\dot{\theta}_M, \dot{\theta}_L]^T$. Finally, we obtain the state-space model expression for the 1st joint as

$$
\begin{align}
\dot{x}_1 &= A_1 x_1 + B_1 \begin{bmatrix}
e_1 u_1 - f_{M1} \text{sgn}(\dot{\theta}_M) \\
e_2 u_2
\end{bmatrix} \\
A_1 &\in \mathbb{R}^{4 \times 4}, \\
B_1 &\in \mathbb{R}^{4 \times 2}
\end{align}
$$

(10)

$$
y_1 &= C_1 x_1, \\
C_1 &\in \mathbb{R}^{2 \times 4},
$$

(11)

where

$$
A_1 \equiv \begin{bmatrix}
0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 \\
a_{31} a_{43} a_{33} a_{34} \\
a_{41} a_{42} a_{43} a_{44}
\end{bmatrix}, \\
B_1 \equiv \begin{bmatrix}
0 & 0 & 0 & 0 \\
1/m_{M1} & 0 & 0 & 0 \\
0 & 0 & 1/m_{L1}
\end{bmatrix}, \\
C_1 \equiv \begin{bmatrix}
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

The linear identification method “pem” (Ljung (2007)) is applicable to estimate the state-space model (10) and (11). The “pem” consists of an initial estimation of state-space model using the subspace identification method “n4sid” and an iterative prediction-error minimization based on the initial model. The estimated model has two inputs, two outputs and four state variables. In this case, the motor input $u_1$ and the computed torque $\tau_1$ are employed as inputs for linearizing and decoupling in the multi-input identification. Furthermore, the link and motor angular velocities are employed as outputs for improving accuracy in the multi-output identification.

The “pem” requires the element (1, 1) in (3) be constant during an identification motion. It is also necessary for $\tau_1$ to have “frequency richness condition” for accurate identification. Thus it is necessary to investigate the element (1,1) in (3), and the power spectral density of $\tau_1$ using experimental data. It is the same derivation procedure for the 2nd joint using (1) and (2). The nonlinear interaction torque from the 1st link can be computed using the link angular accelerations and velocities as

$$
\tau_2 = - (\dot{\theta} + \dot{\gamma} \cos(\theta L)) \ddot{\theta}_L - \dot{\gamma} \ddot{\theta}^2_L \sin(\theta L_2).
$$

(12)

4.3 Physical parameter estimation for elastic-joint model

Four single-input single-output transfer functions are obtained by converting from the state-space model (10) and (11) for the 1st joint as follows:

$$
\begin{align}
\hat{\theta}_M(s) &= G_{11}^1(s) u_1(s) + G_{12}^1(s) \tau_1(s) \\
\hat{\theta}_L(s) &= G_{21}^1(s) u_1(s) + G_{22}^1(s) \tau_1(s),
\end{align}
$$

(13)

(14)

where the superscript 1 means the 1st joint. The transfer function $G_{11}^1(s)$ from motor input $u_1$ to motor angular velocity $\dot{\theta}_M$, and $G_{21}^1(s)$ from motor input $u_1$ to link angular velocity $\dot{\theta}_L$ are expressed using the six physical parameters as

$$
G_{11}^1(s) = \frac{b_0 + b_1 s + b_2 s^2}{a_0 + a_1 s + a_2 s^2 + a_3 s^3},
$$

(15)

$$
G_{21}^1(s) = \frac{n_{G1}(b_0 + b_1 s)}{a_0 + a_1 s + a_2 s^2 + a_3 s^3},
$$

(16)

where

$$
\begin{align}
a_0 &= d_{M1} + n_{G1}^2 d_{G1} \\
a_1 &= m_{M1} + n_{G1}^2 m_{L1} + n_{G1} d_{G1} + d_{M1} d_{L1} + d_{M1} d_{G1} / k_{G1} \\
a_2 &= (m_{M1} d_{L1} + m_{G1} d_{G1}) / k_{G1} + m_{L1} d_{M1} + n_{G1} m_{L1} d_{G1} / k_{G1} \\
a_3 &= m_{M1} m_{L1} / k_{G1} \\
b_0 &= 1, \\
b_1 &= (d_{L1} + d_{G1}) / k_{G1}, \\
b_2 &= m_{L1} / k_{G1} \\
b_3 &= d_{G1} / k_{G1}.
\end{align}
$$

The numerator and denominator of the transfer function $G_{11}^1(s)$ have the second order and the third one respectively, and these of the $G_{21}^1(s)$ have the first order and the third one respectively. In contrast, the $G_{12}^1(s)$ and $G_{22}^1(s)$ have the same form as $G_{21}^1(s)$ and $G_{11}^1(s)$ respectively.

A set of six simultaneous equations is obtained by the coefficient comparison using (15) and the transfer function conversion from the estimated state-space model by the “pem”. The six physical parameters are obtained by solving the simultaneous equations.

However, when the sampling rate for identification is selected to be fast for estimating the vibrational characteristics caused by the elastic-joints, the results in the low frequency range may be inaccurate. In order to modify the low frequency range of the estimated transfer function...
(15), the first-order lag element of the denominator is replaced using the estimated physical parameters for the rigid joint model above as

\[ G_{11}(s) = \frac{b_0 + b_1 s + b_2 s^2}{(c_0 + c_1 s)(a_0 + d_1 s + d_2 s^2)}, \]  

(17)

where \( c_0 = d_M + n_{G1} d_{L1}, \ c_1 = m_{M1} + n_{G1} m_{L1}, \ d_0 = 1. \) This approximation is valid when the cut-off frequency of the first-order lag element is low enough compared with the frequency of the vibrational characteristics. The six physical parameters for the 1st joint are now obtained by solving (15) and (17). It is the same derivation procedure for the 2nd joint.

Furthermore, fine-tuning of the estimated physical parameters is performed using closed-loop simulations with the nonlinear least-squares optimization (Mathworks (2007)). The parameter search ranges are set to be small to ensure the convergence. All physical parameters are simultaneously optimized except the Coulomb friction torque because of its nonlinearity.

4.4 Extension for closed-loop identification

This subsection describes an extension of the decoupling identification method for closed-loop identification. In this case, a PRBS is applied to the 1st (or 2nd) joint by open-loop control as input data for identification while the 2nd (or 1st) joint is locked by closed-loop control using a PI velocity servo as

\[ u_i = k_{IVi} \int (\dot{\theta}_{M Ri} - \dot{\theta}_{M i}) \, dt - k_{PVi} \dot{\theta}_{M i}, \]

where \( \dot{\theta}_{M Ri}, \dot{\theta}_{M i} \) : motor angular velocity reference \((= 0)\)
\( \theta_{M Ri}, \theta_{M i} \) : motor angular velocity
\( k_{IVi}, k_{PVi} \) : integral feedback control parameter
\( u_i \) : input voltage (motor-current control reference).

The integral control enables to generate a torque for maintaining the link-posture under gravity. This method is also applicable to a PUMA-type vertical two-link robot arm. It can be considered that (18) is as a partial state-feedback. When the decoupling identification method using link-accelerometer signals ideally works for the 1st (or 2nd) joint, it should be noted that the 2nd (or 1st) joint is closed-loop controlled or not. In the next section, identification experiments using the two-link arm are conducted to verify the closed-loop effects.

4.5 Robustness against estimation errors of \( \beta \) and \( \gamma \)

There might be some estimation errors in the physical parameter estimation for the rigid-joint model which approximates the elastic-joint model in the low frequency range. It is necessary to discuss the robustness of the decoupling identification method against the estimation errors of the two coupling-inertia parameters \((\beta \gamma)\) for the computing nonlinear interaction torques. It is noted that \( \beta \) and \( \gamma \) are required by only \( \tau_1 \) as the identification input in (13) and (14). Thus it is expected that the estimation errors of the \( \beta \) and \( \gamma \) do not affect estimation results of the \( G_{11}(s) \) and \( G_{22}(s) \) in the two-input two-output identification. In contrast, estimation results of the \( G_{11}(s) \) and \( G_{22}(s) \) must involve errors to absorb the estimation errors of the \( \beta \) and \( \gamma \). Similar discussions can be applied for the \( \tau_2 \). In the next section, the robustness of the decoupling identification method against the estimation errors of the \( \beta \) and \( \gamma \) is verified through experimental data.

5. EXPERIMENTAL RESULTS AND DISCUSSIONS

The decoupling identification method was verified through experiments performed using the planar serial two-link robot arm (Fig. 1). The physical parameter estimation for the rigid-joint model was performed in advance.

5.1 Open-loop identification

A PRBS was applied to the 1st joint by open-loop control as input signal for identification while the 2nd joint was free because of no control. The sampling time for input and output signals was set to 0.025 ms. Since the PRBS (period: 1023) was produced at 1 ms intervals, data collection continued for 1.023 s. The sampling time 1 ms was changed to 2 ms using decimation. The PRBS amplitude was set to 10.0 V (maximum). These identification conditions were determined by some trial and error. Fig. 4 shows the PRBS input data (first 0.3 s of 1.023 s). Fig. 5 shows nonlinear interaction torque data and its power spectral density. Although the spectral density is somewhat bumpy, it is satisfactory in practice as another input data for multi-input identification. Furthermore, it was checked the cosine of the 2nd link angle was changing with value of 0.999 or more, during the 1st link motion for identification. Thus the element \((1,1)\) in (3) is regarded as constant.

In Fig. 6, the solid lines (MIMO: multi-input multi-output) estimated by the decoupling identification method, using the computed torques and motor inputs, show the typical vibrational characteristics of the one-link two-inertia system such as (15). The dashed lines estimated by the conventional methods which utilize only motor inputs (SIMO: single-input multi-output and SISO: single-input single-output) show coupled vibration characteristics between the two links. The characteristics are remarkable at the 2nd link, such as the right-hand figures in Fig. 6. These results demonstrate that the coupled vibration characteristics are completely decoupled by the MIMO identification method. In Figs. 7(a) and (b), dashed lines stand for the low frequency modification using (17).

Fig. 8(a) shows step responses of the 1st link angular velocity before and after optimization-based fine tuning of estimated physical parameters using repetitive step
5.2 Closed-loop identification

In this case, a PRBS was applied to the 1st (2nd) joint by open-loop control as input data for identification while the 2nd (1st) joint was locked by closed-loop control using the PI velocity servo. Fig. 9 shows good power spectral density of nonlinear interaction torque data for the 1st link identification, where the 2nd link is closed-loop controlled.

Fig. 10 shows closed-loop effects against estimated frequency responses from motor input to motor angular velocity. The left-hand figures show the results for the 1st link, where the 2nd link is free or closed-loop controlled. The right-hand figures show the results for the 2nd link, where the 1st link is free or closed-loop controlled. The dashed-dotted lines in each figure are shown as frequency response references using the optimized physical parameters. Small errors exist between the open-loop and closed-loop results in Fig. 10. Thus Figs. 8(a) and (b) show the errors between the open-loop and closed-loop results can be completely recovered by the optimization-based fine tuning. In this case, the two identification inputs for the decoupling method are correlated. However, the iterative prediction-error minimization in the “pem” can overcome the correlation. Table 1 summarizes the estimated physical parameter values before and after the nonlinear optimization, where 2nd (1st) link is free or closed-loop controlled, compared with nominal values referred to the inertia parameter values by precise hand-calculation and the catalog of the Harmonic-drive reduction gear. It is clear that accurate physical parameters have been obtained by both open-loop and closed-loop identifications.

5.3 Robustness verification

Figs. 11(a)–(d) show three variation effects of the $\beta$ and $\gamma$ to estimated frequency responses for the 1st link identification. Clearly, these figures demonstrate that the estimation errors of the $\beta$ and $\gamma$ do not affect estimation results of the $G_{11}(s)$ and $G_{21}(s)$ in the two-input two-output identification. In contrast, the gain estimation results of the $G_{12}(s)$ and $G_{22}(s)$ involve errors to absorb the estimation errors of the $\beta$ and $\gamma$. Similarly, Figs. 12(a)–(d) demonstrate the
6. CONCLUSION

Several new results have demonstrated the effectiveness and robustness of our previously proposed decoupling identification method. We expect that the method can provide a nonlinear gray-box modeling for sophisticated motion control of the SCARA, PUMA and any robot arms which have a planar serial two-link. Further studies involves an extension for a robot arm that has a planar serial three-link and more.

REFERENCES


Fig. 11. Variation effects of $\beta$ and $\gamma$ to estimated frequency responses for 1st link to show robustness.

Fig. 12. Variation effects of $\beta$ and $\gamma$ to estimated frequency responses for 2nd link to show robustness.