Inertia Adaptive Control Based on Resonance for Energy Saving of Mechanical Systems

Guangqiang Lu *, Sadao Kawamura *, and Mitsunori Uemura *

Abstract: This paper proposes a new energy saving method of mechanical systems. In the proposed method, the potential energy stored in mechanical springs is effectively utilized to make periodic motions. In other words, the proposed system is based on resonance. Particularly, we propose an inertia adaptive control method in which a mass is moved in order to change the moment of inertia and change the desired motion cycle. Convergence to desired periodic motions is mathematically proven and performance of the proposed method is demonstrated by several simulation results.

Key Words: energy saving, adaptive control, moving mass, resonance, direct-driven actuator.

1. Introduction

Energy saving is one of the most urgent issues all over the world. Engineering should play an important role to improve this situation. In robotics, several papers concerning energy saving have been published [1]–[3]. Some of them pointed out the importance of the use of the potential energy to generate robot motions. It is well known that potential energy is converted into kinetic energy in pendulum motions. A typical example is seen in human walking motions. In human walking, a swing leg effectively uses potential energy to make the walking motion. Inspired by this phenomenon, passive walking robots and brachiation robots have been intensively researched [4]–[8].

In many cases of robot manipulators including industrial robots widely used all over the world, high reduction gears are commonly utilized. High reduction gears waste energy as heat when the robot moves. Furthermore, due to the friction of reduction gears, it is difficult to effectively use potential energy. In many tasks of industrial robots, there are many kinds of periodic motions. Pick and place task is considered as a typical periodic motion. It seems that potential energy may be naturally used in order to make such periodic motions and the total energy can be saved. However, there is no industrial robot which can effectively change potential energy into kinetic energy to generate motions because of the friction of high reduction gears.

To save the energy of periodic motions, we should make good use of resonance. Potential energy charged in elastic elements of a robot should be effectively utilized to generate a periodic motion. If mechanical systems with one DOF do not have viscosity and dynamic parameters (mass and elastic parameters) of the system are known, a periodic motion which is determined in advance can continue. In practice, however, there are mainly three problems as follows:

(1) Amplitude of oscillation must become small as time tends to infinity because of viscosity. Suitable methods to supply the lost energy are necessary.

(2) In practice, it is strongly required that the desired cycle time can be changed depending on tasks of robots. Therefore, mechanical systems with fixed parameters (mass and elastic parameters) are not useful.

(3) In the case of more than 2DOF systems, chaotic motion presumably occurs if there is no additional control input. To avoid chaotic motion, use of actuator power is a solution. In such cases the controller must make the actuator energy as small as possible.

To overcome these three problems, the authors developed hardware systems and proposed several types of adaptive controllers [9]–[12]. The hardware system utilizes electric motors as well as elastic elements. Each robot joint is moved by an electric motor and an elastic element in parallel. The electric motor should have direct drive mechanisms or very low reduction gears not to lose energy. If electric motors can supply the lost energy, the first problem will be solved. In the authors’ previous works, an adaptive controller to supply the lost energy was introduced [10]. To solve the second problem, natural frequency should be changed. Therefore, the authors developed variable elasticity devices which can change elastic values mechanically [12]. Moreover, some adaptive controllers to tune elasticity were proposed [11]. In some of the proposed controllers, it is mathematically proven that the robot motion converges to a desired periodic motion and elastic values converge to desired values [9]. It means that the total energy given by the electric motors becomes as small as possible. Therefore, the third problem was also solved.

This paper proposes a new method based on inertia adaptive control to realize energy saving robots. The robot hardware whose individual joint has both an electric motor and an constant elastic element is utilized. In the proposed method, inertia values instead of elastic values are adaptively changed to make a desired periodic motion. In the system, a spring with a fixed value is used and a moving mass mechanism is introduced in order to change the moment of inertia of a link. We treat one joint motion as an simple example. Even though the mechanical system has one DOF, the total system dynamics has two DOF because the moving mass dynamics is considered. We propose

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a new adaptive method to control the moving mass. Convergence of the moving mass motion is mathematically proven. Moreover, usefulness of the proposed system is demonstrated by some simulation results and some characteristics of the proposed control method are investigated.

2. Dynamics

2.1 Model

A model of a mechanical system with one DOF is shown in Fig. 1. Here, the link can rotate around joint axis \(o\). The character \(r\) denotes the stiffness of the linear spring. The joint angle is given by \(q\). A motor (motor 1) is set to move the joint angle \(q\). On the link, there is a mass which can be moved by another motor (motor 2). By using the moving mass, the inertia of moment is adjusted. In the moving mass system, \(m\) denotes the mass of the moving mass, and \(l\) denotes the distance between joint axis and center of the moving mass.

2.2 Dynamics

Dynamics of the robotic system can be written as

\[
\begin{bmatrix}
    r + ml^2 & 0 & 0 \\
    0 & m & 0 \\
    k & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
    \ddot{q} \\
    \dot{l} \\
\end{bmatrix}
+ \begin{bmatrix}
    2mlq\ddot{q} \\
    -mql^2q' \\
    \tau \\
\end{bmatrix}
+ \begin{bmatrix}
    d_1 & 0 & d_2 \\
    0 & d_1 & 0 \\
\end{bmatrix}
\begin{bmatrix}
    \dot{q} \\
    \dot{l} \\
\end{bmatrix} = \tau. \tag{1}
\]

where \(d_1\) and \(d_2\) are viscosity coefficients of the joint and the moving mass, respectively. A vector of actuator torque and force is represented by \(\tau = (\tau_q, f_i)^T\).

2.3 Desired Motion

A desired motion \(q_d(t)\) is set as

\[q_d(t) = a \sin \omega_d t, \tag{2}\]

where \(a\) is an amplitude which is determined by tasks in advance but can be changed in real time if the task is changed. The desired angular velocity \(\omega_d\) is represented by

\[\omega_d = \sqrt{\frac{k}{r + ml^2}}, \tag{3}\]

where \(l_d\) means the desired position of the moving mass. The desired angular velocity \(\omega_d\) is also determined by the required task. We may set a larger desired angular velocity \(\omega_d\) in order to shorten the cycle time of the motion. Here, if the moving mass \(m\), the constant stiffness \(k\) and the moment of inertia \(r\) are precisely known and the desired angular velocity is determined, we can directly calculate the desired moving mass position \(l_d\) without requiring any adaptive controllers. However, the moment of inertia \(r\) significantly changes when the robot grasps an object. In particular, if the mass of the object is not known, it is impossible to calculate the desired moving mass position \(l_d\). Therefore, we introduce an adaptive controller in this paper to solve the problem. By using the adaptive controller proposed, the parameters of the desired motion (amplitude and angular velocity) can be changed in real time.

2.4 Error Dynamics

Joint angle error is given by

\[\Delta q(t) = q(t) - q_d(t). \tag{4}\]

We assume that distance \(l\) of the moving mass is bounded as

\[0 < c_1 \leq l \leq c_2, \tag{5}\]

where \(c_1\) and \(c_2\) are positive constants. We also assume that velocity \(\dot{l}\) is bounded as

\[|\dot{l}| \leq c_3, \tag{6}\]

where \(c_3\) is a positive constant. The error distance of the moving mass is defined by

\[\Delta l(t) = \dot{l}(t) - \dot{l}_d. \tag{7}\]

From Eq.(7) we get

\[\Delta \dot{l} = 2\ddot{l}, \tag{8}\]

\[\Delta \ddot{l} = 2\ddot{l} + 2\dot{l}^2. \tag{9}\]

From Eq.(5) and Eq.(6), the velocity error of the moving mass is bounded as follows:

\[|\Delta l| \leq 2|l| |\dot{l}| \leq 2c_2c_3. \tag{10}\]

By using Eq.(4),(7),(8) and (9), error dynamics is given by

\[
\begin{bmatrix}
    r + ml^2 & 0 & 0 \\
    0 & m/2l & 0 \\
    k & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
    \Delta \ddot{q} \\
    \Delta \dot{l} \\
\end{bmatrix}
+ \begin{bmatrix}
    2ml\dot{q} \Delta \dot{q} + m\dot{l} \Delta \dot{l} + m\dot{l}^2/4l^3 \\
    -m\dot{q} \dot{l} \Delta \dot{q} - m\dot{l} \Delta \dot{l} + m\dot{l}^2/4l^3 \\
    d_1 \dot{l}_d - d_1 \dot{q} \Delta \dot{q} + k \dot{l} \Delta \dot{l} \\
\end{bmatrix}
= \begin{bmatrix}
    \dot{q}_d \\
    \dot{l}_d \\
\end{bmatrix} + \tau. \tag{11}\]

In the following chapter we will introduce a new adaptive controller.

3. Inertia Adaptive Controller

In general, adaptive control does not need the exact values of dynamics parameters but estimate those for precise motion control. However, since it is not so difficult to measure the weight of the moving mass, here we assume that the weight of the moving mass is known. Moreover, we consider that joint angle position \(q(t)\), joint angle velocity \(\dot{q}(t)\), moving mass distance \(l(t)\) and moving mass velocity \(\dot{l}(t)\) can be measured.

Here, we proposed an inertia adaptive controller as follows:

\[\tau = \begin{bmatrix}
    \tau_q \\
    f_i \\
\end{bmatrix} = \begin{bmatrix}
    -k_{pq}\Delta q - k_{qv}\Delta \dot{q} + d_1 \dot{q}_d + ml^2\dot{q}_d - ml^2\dot{q}_d \\
    -k_v(l^2 - \dot{P}_2) - k_d \Delta l - ml^2\dot{q}_d \\
\end{bmatrix}, \tag{12}\]

where \(k_{pq}, k_{qv}, k_d\) and \(k_{ld}\) are feedback gains. The term \(d_1 \dot{q}_d\) means viscosity compensation. The coefficient \(d_1\) is given by

\[d_1 = \frac{1}{a} \dot{q}_d \Delta \dot{q}, \tag{13}\]

![Model of the robot with moving mass.](image-url)
where $\alpha$ denotes a positive constant. The coefficient $\hat{d}_1$ is updated by desired joint velocity and joint velocity error. The parameter $\hat{l}_d$ in Eq.(12) means an instantaneous desired position of the moving mass. The instantaneous desired position $\hat{l}_d(t)$ is updated by

$$\hat{l}_d = \frac{1}{2\hat{\beta}_d} (m\hat{q}_d\dot{\hat{q}} - 2k_pl\hat{l}),$$

(14)

where $\beta$ denotes a positive constant. The reason why those update laws are required will be explained in the following chapter.

In Eq.(12), the terms $ml^2\dot{\hat{q}}_d$, $m\dot{\hat{q}}_d\dot{\hat{q}}$ and $ml\dot{\hat{q}}_d^2$ are feedforward input and are calculated in real time because the length $l$ is measured, the instantaneous desired length $\hat{l}_d$ is calculated by Eq.(14), the mass is known, and the desired motion $q_d(t)$ is given by Eq.(2). Instead of Eq.(12), another feedforward input can be considered because the signals $q, \dot{q}, l$ and $\dot{l}$ are measured. For example, the nonlinear terms $2ml\dot{q}$ and $-ml\dot{q}^2$ in Eq.(1) can be canceled in real time if those terms are added in the input. However, velocity signals likely contain noise. Therefore, the feedforward input in Eq.(12) which does not use velocity signals was proposed in this paper. Here, it is important to know whether the torque $\tau_q$ and the force $f_t$ became small when the joint angle $q(t)$ converges to the desired one $q_d(t)$, and the instantaneous desired position and the actual position of the moving mass converge to the desired position $\hat{l}_d$. As seen in Eq.(12), the joint torque $\tau_q$ becomes $d_1\dot{q}_d$. Since the original parameter $d_1$ is not large, the $\tau_q$ can be kept small. On the other hand, the force $f_t$ becomes $-ml\dot{\hat{q}}_d^2$ which is not zero. From a view point of energy saving, this result is a drawback of the proposed control method because the moving mass system loses energy even though the joint system saves energy. In practice, however, the feedforward force $-ml\dot{\hat{q}}_d^2$ is not needed because high reduction gears are utilized in general and the friction force of the reduction gears can cancel the centrifugal force $ml\dot{\hat{q}}_d^2$, if the friction force is large enough.

At last, the error dynamics is represented by

$$2V = \begin{bmatrix} 0 & \dot{\hat{q}}_d \\ \Delta \dot{l} & 0 \end{bmatrix} \begin{bmatrix} r + ml^2 & 0 \\ 0 & m/2l \end{bmatrix} \begin{bmatrix} \Delta \hat{q} \\ \Delta l \end{bmatrix} + \begin{bmatrix} \Delta \hat{q} \\ \Delta l \end{bmatrix} \begin{bmatrix} d_1 + k_{q_d} & 0 \\ 0 & k_{\dot{q}_d} + d_3/2l \end{bmatrix} \begin{bmatrix} \Delta \hat{q} \\ \Delta l \end{bmatrix} + \begin{bmatrix} \Delta \hat{q} \\ \Delta l \end{bmatrix} \begin{bmatrix} 0 & k_{\dot{q}_d} \\ k_{\ddot{q}_d} & 0 \end{bmatrix} \begin{bmatrix} \Delta \hat{q} \\ \Delta l \end{bmatrix} + \begin{bmatrix} (\hat{d}_1 - d_1)\dot{\hat{q}}_d - m(\dot{l}_d^2 - \dot{l}^2)\dot{\hat{q}}_d \\ k_{\dddot{q}_d}(\dot{l}_d^2 - \dot{l}^2) \end{bmatrix}. \tag{15}$$

To drive Eq.(15) we used the following relation:

$$(r + ml^2)\dot{\hat{q}}_d + k_{\dot{q}_d} = 0. \tag{16}$$

### 4. Stability

For stability proof, a Lyapunov function $V$

$$2V = \begin{bmatrix} \Delta \hat{q} \\ \Delta l \end{bmatrix} \begin{bmatrix} r + ml^2 & 0 \\ 0 & m/2l \end{bmatrix} \begin{bmatrix} \Delta \hat{q} \\ \Delta l \end{bmatrix} + \begin{bmatrix} \Delta \hat{q} \\ \Delta l \end{bmatrix} \begin{bmatrix} d_1 + k_{q_d} & 0 \\ 0 & k_{\dot{q}_d} + d_3/2l \end{bmatrix} \begin{bmatrix} \Delta \hat{q} \\ \Delta l \end{bmatrix} + \begin{bmatrix} \Delta \hat{q} \\ \Delta l \end{bmatrix} \begin{bmatrix} 0 & k_{\dot{q}_d} \\ k_{\ddot{q}_d} & 0 \end{bmatrix} \begin{bmatrix} \Delta \hat{q} \\ \Delta l \end{bmatrix} + \alpha \Delta \dot{l}_d^2 + \beta (\dot{l}_d^2 - \dot{l}^2)^2 \tag{17}$$

is used where $\Delta \hat{d}_1 = \hat{d}_1 - d_1$. Time derivative of the Lyapunov function Eq.(17) is given by

$$\dot{V} = \begin{bmatrix} \Delta \hat{q} \\ \Delta l \end{bmatrix} \begin{bmatrix} d_1 + k_{q_d} & 0 \\ 0 & k_{\dot{q}_d} + d_3/2l \end{bmatrix} \begin{bmatrix} \Delta \hat{q} \\ \Delta l \end{bmatrix} + \begin{bmatrix} \Delta \hat{q} \\ \Delta l \end{bmatrix} \begin{bmatrix} -2mll\Delta \hat{q} - m\dot{l}\Delta l \\ -ml\Delta l^2 - 2ml\Delta \dot{q} - \Delta l^2/4l^3 \end{bmatrix} + \begin{bmatrix} \Delta \hat{q} \\ \Delta l \end{bmatrix} \begin{bmatrix} 2ml\Delta \dot{q} - 2ml\dot{q}\Delta l + m\Delta l^2/4l^3 \\ 2ml\dot{q} + k_{\ddot{q}_d} \end{bmatrix} + \begin{bmatrix} \Delta \dot{q} \\ \Delta l \end{bmatrix} \begin{bmatrix} 2ml(\dot{l}_d^2 - \dot{l}^2) & 0 \\ -ml/2l^2 & \Delta \dot{q} \\ \Delta l \end{bmatrix} + k_{\dddot{q}_d}(\dot{l}_d^2 - \dot{l}^2) + \alpha \Delta \dot{l}_d \Delta l + 2\beta \Delta l_d (\dot{l}_d^2 - \dot{l}^2).$$

From Eq.(5) and Eq.(6), the second and the third terms of the right hand side of Eq.(Dyn23) are bounded by

$$c_4 \|\Delta \hat{q}\|^2 + c_5 \|\Delta l\|^2,$$

where $c_4$ and $c_5$ are positive constants.

The fourth and fifth terms are rewritten into

$$\Delta d_1(\alpha \dot{\hat{d}}_1 + \Delta \dot{q} \hat{q}_d) + (\dot{l}_d^2 - \dot{l}^2)(2\beta \Delta \dot{l}_d - m\Delta \dot{q} \hat{q}_d + k_{\ddot{q}_d} \Delta l).$$

Therefore, if

$$\dot{d}_1 = -\alpha \hat{q}_d \Delta \hat{q},$$

(21)

and

$$\hat{l}_d = \frac{1}{2\hat{\beta}_d} (m\hat{q}_d \Delta \hat{q} - 2k_{\ddot{q}_d} \hat{l}),$$

(22)

then the time derivative of Lyapunov function Eq.(18) is represented by

$$\dot{V} \leq \begin{bmatrix} \Delta \hat{q} \\ \Delta l \end{bmatrix} \begin{bmatrix} d_1 + k_{q_d} - c_4 & 0 \\ 0 & d_3/2l + k_{\dot{q}_d} - c_5 \end{bmatrix} \begin{bmatrix} \Delta \hat{q} \\ \Delta l \end{bmatrix}. \tag{23}$$

If

$$d_1 + k_{q_d} - c_4 > 0,$$

(24)

and

$$d_3/2l + k_{\dot{q}_d} - c_5 > 0,$$

(25)

then

$$\dot{V} \leq 0.$$

(26)

In this case the maximum invariant set means $\Delta \hat{q} = 0, \Delta l = 2l_t = 0$. From Eq.(8), we know $\Delta l = 0$ means $l = 0$. Therefore we get

$$\begin{bmatrix} k + k_{p_d} & 0 \\ 0 & k_{\ddot{q}_d} \end{bmatrix} \begin{bmatrix} \Delta \hat{q} \\ \Delta l \end{bmatrix} = \begin{bmatrix} \Delta \dot{q} \hat{q}_d - m(\dot{l}_d^2 - \dot{l}^2) \hat{q}_d \\ k_{\dddot{q}_d}(\dot{l}_d^2 - \dot{l}^2) \end{bmatrix}. \tag{27}$$

Concerning the term $\Delta \dot{q}$, we have

$$(k + k_{p_d})\Delta \dot{q} - \Delta \dot{q} \hat{q}_d + m(\dot{l}_d^2 - \dot{l}^2) \hat{q}_d = 0. \tag{28}$$

Since $\Delta \dot{q} = 0$, the joint angle error $\Delta \dot{q}$ becomes a constant. Moreover, the desired motion $q_d(t)$ is a harmonic oscillation function. Therefore, if the Eq.(28) is satisfied, then $\Delta \dot{q} = 0, \Delta d_1 = 0$ and $m(\dot{l}_d^2 - \dot{l}^2) = 0$. From this, we obtain $\hat{l}_d = \hat{l}_d$.

From the term $\Delta \ddot{l}$ in Eq.(27), we have

$$\Delta \ddot{l} = \ddot{l}_d - \ddot{l}_d = 0.$$ \tag{29}

Namely, we get

$$l(t) \rightarrow \hat{l}_d.$$ \tag{30}
5. Simulation

5.1 Simulation Model and Condition

To confirm effectiveness of the proposed control method, we conducted numerical simulations. A model shown in Fig. 1 is used for the simulation.

The physical parameters used in simulation are shown in Table 1. The simulation conditions are shown in Table 2.

5.2 Result

The simulation results are shown in Fig. 2 (a-f). The joint angle \( q(t) \) is shown in Fig. 2 (a), the dotted line means desired motion \( q_d(t) \), and solid one denotes the actual motion \( q(t) \). The joint angle error \( \Delta q(t) \) is shown in Fig. 2 (b). As seen in Fig. 2 (a-b), the actual motion \( q(t) \) converges to the desired one \( q_d(t) \). The instantaneous desired length of the moving mass \( \hat{l}_d \) updated by the Eq.(14) is shown as the dotted line in Fig. 2 (c). The solid line in Fig. 2 (c) means the actual position of the moving mass. The instantaneous desired position of the moving mass (dotted line) started from the initial value 0.1[m], and finally converges to the desired position 0.2[m]. The actual position of the moving mass (solid line) also starts from 0.1[m] and after about 7 seconds finally converges to the desired position. This simulation result demonstrates that the proposed control method can effectively control the moving mass move and finally makes the system go into the resonance state.

The joint torque \( \tau_q \) is shown if Fig. 2 (d). After about 10 seconds the moving mass almost stopped at the desired position 0.2[m] and the joint torque \( \tau_q \) became small. The remaining joint torque as seen in Fig. 2 (d) means the viscosity compensation. The viscosity parameter updated by the adaptive control law Eq.(12) is shown in Fig. 2 (e). The estimated parameter started from 0 and finally converged to the correct value. The force to move the mass is given by Fig. 2 (f).

5.3 Different Initial Position of Moving Mass

We set different initial positions \( l(0) \) and the initial instantaneous desired position \( \hat{l}_d(0) \) of the moving mass, and carried out simulations. The simulation results are shown in Fig. 3. In these simulation results, all parameters excepting the initial values \( \hat{l}_d(0) \) and \( l(0) \) were same as the simulation results in Fig. 2.

In each case, the initial position of the actual moving mass also was set at the same value of the instantaneous desired position \( \hat{l}_d(0) \). It was confirmed that in all cases both of the instantaneous desired position and the actual position of the moving mass converged to the desired position \( l_d \).

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**Table 1 Physical parameters of the robotic system.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>The moment of inertia of arm</td>
<td>( r = 0.01 ) kg m(^2)</td>
<td></td>
</tr>
<tr>
<td>stiffness of spring</td>
<td>( k = 1.9739 ) Nm/rad</td>
<td></td>
</tr>
<tr>
<td>Viscosity Coefficient of Joint</td>
<td>( d_1 = 0.01 ) Nmsec/rad</td>
<td></td>
</tr>
<tr>
<td>Viscosity Coefficient of Moving Mass</td>
<td>( d_2 = 0.1 ) Nmsec/m</td>
<td></td>
</tr>
<tr>
<td>Moving Mass</td>
<td>( m = 1 ) kg</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2 Simulation conditions.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>desired motion ( q_d(t) = 0.25 \pi \sin (2\pi t) )</td>
<td></td>
</tr>
<tr>
<td>cycle time ( T ) during 0-20sec</td>
<td>1[s]</td>
</tr>
<tr>
<td>cycle time ( T ) during 20-40sec</td>
<td>0.8[s]</td>
</tr>
<tr>
<td>initial joint angle and velocity</td>
<td>( q(0) = 0, \dot{q}(0) = 0 )</td>
</tr>
<tr>
<td>initial position of moving mass</td>
<td>( l(0) = \hat{l}_d(0) = 0.1 ) m</td>
</tr>
<tr>
<td>desired position of moving mass</td>
<td>( l_d = 0.2 ) m</td>
</tr>
<tr>
<td>desired position of moving mass</td>
<td>( l_d = 0.167 ) m</td>
</tr>
<tr>
<td>initial value of viscosity compensation</td>
<td>( d_1(0) = 0 )</td>
</tr>
<tr>
<td>Gains</td>
<td>( \alpha = 0.3, \beta = 10, \gamma_p = 10, \gamma_v = 0.1, \dot{\gamma}_p = 15, \dot{\gamma}_v = 1 )</td>
</tr>
</tbody>
</table>
5.4 Convergent Speed

The convergent speed of the moving mass to the desired position $l_d$ should be faster in order to improve the performance of energy saving. To get the faster convergence of the moving mass, the instantaneous desired position $\hat{l}_d(t)$ should converge to the desired position as quick as possible at first. For this, it seems that the gain tuning of $\beta$ in Eq.(14) is effective because $\beta$ is a coefficient of the adaptive controller. The simulation results to investigate it are presented in Fig. 4. As seen in Fig. 4, if $\beta$ decreases, then the instantaneous desired position $l_d(t)$ quickly converges and has oscillation. Since the instantaneous desired position oscillates, the actual position of the moving mass also oscillates.

In the case that the oscillation of the actual moving mass is a serious problem, the oscillation must be reduced. For this, we considered two methods: (1) Increase of the viscosity coefficient $d_2$ of the moving mass system, (2) Increase of the gain $k_{vl}$ of $\Delta\dot{q}$. Figure 5 shows the results when the viscosity coefficient $d_2$ increases. It is observed in Fig. 5 that the oscillation of the actual position of the moving mass can be effectively reduced. On the other hand, Fig. 6 shows the results of the gain $k_{vl}$. In this case, even though the gain $k_{vl}$ is increased, the oscillation cannot be eliminated.

5.5 Simplifier Adaptive Controller

As seen in Eq.(13), the update law of the instantaneous desired position $\hat{l}_d$ has two terms. It seems that the first term works to make resonance and the second term works as a kind of damping. If this consideration is correct, the first term is enough as the update law. To investigate it, we conducted another simulation by using the following update law of the instantaneous desired position $\hat{l}_d$.

$$\dot{\hat{l}}_d = \beta_3 \dot{q}_d \Delta \dot{q},$$

(31)

where $\beta_3$ is a positive constant. The simulation results are shown in Fig. 7. In this simulation, excepting the update law of the instantaneous desired position $\hat{l}_d$, all conditions are same as the case in Fig. 2. As seen in Fig. 7, the results are almost same as those in Fig. 2. From these results, it is presumed that the first term of Eq.(13) mainly works as the update law.
6. Discussions

6.1 Robustness

In this paper, we assume that the value of the moving mass is known. It is a drawback of the proposed method. To guarantee the robustness for estimation error of the moving mass is crucial for the proposed control method. The simplifier adaptive controller in the simulation result shows the robustness of the estimated moving mass concerning instantaneous desired position $\dot{t}(t)$ because Eq.(31) does not include the estimated mass. However, the proof of the robustness is incomplete because Eq.(12) uses the exact value of the moving mass. To experimentally demonstrate the robustness is one of the important future works. Furthermore, we did not consider signal noise in this paper. The signal noise certainly worsens the adaptive control performance. In particular, since we used the velocity signals in Eq.(13) and Eq.(14) for adaptation, the velocity signal noise may become serious problems in real applications. It is also a very important future work in the proposed method.

6.2 Theoretical Assumption

We assumed that the moving mass motion is bounded as shown in Eq.(5) and Eq.(6). Namely the stability of the motion was proven in the sense of local stability. To apply the proposed controller to real mechanical systems such as robots, elimination of the assumption is very important.

7. Conclusion

A new energy saving control method for a mechanical system with one rotating joint has been proposed in this paper. In the proposed method, the link inertia of the mechanical system is adaptively controlled by a moving mass and finally the motion of the mechanical system converges to resonance. When the motion converges to resonance, the actuator torque is used only to compensate viscosity. In this paper, convergence to resonance has been mathematically proven taking account of nonlinear dynamics of the mechanical system. Moreover, the control performance of the proposed method has been demonstrated by several simulation results.

References


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