How to Design Force Sensorless Power Assist Robot Considering Environmental Characteristics - Position Control Based or Force Control Based -

Hirokazu Seki, Masahito Iso* and Yoichi Hori

Department of Electrical Engineering,
Faculty of Engineering, the University of Tokyo,
7-3-1 Hongo, Bunkyo, Tokyo, 113-8656, Japan
E-mail:seki@hori.t.u-tokyo.ac.jp, hori@hori.t.u-tokyo.ac.jp

*Matsushita Communication Industrial Co., Ltd.
4-3-1 Tsunashima-higashi, Kouhoku, Yokohama,
Kanagawa, 223-8639, Japan
Tel: +81-45-531-1231, Fax: +81-45-542-5105

Abstract— **In this paper, as one of important support for aged people, we present how to design force sensorless power assist robot assisting aged people's work and caregiver's motion. The proposed control methods in this paper are based on robust control and consider environmental characteristics because many kinds of environments exist in power assist motions.**

Two basic power assist methods, position control based and force control based, are compared through some experiments using a DD robot. The proposed position control based method makes use of impedance control. In force control based method, environmental observer is introduced to make robust against environmental parameter change. Both of them can realize stable power assist motion even if environmental characteristic is unknown. Some experimental results show the effectiveness of these methods.

I. Introduction

Japan is now a serious aging society and this problem will be more serious in the near future. Many other countries also have the same problem. Therefore, engineering support for aged people is required. We are establishing a new field of "Welfare Control Engineering" and aiming to support for aged people and disabled people using control and instrument technology. As an important example of such support, we have proposed a monitoring system for aged people[1]. In this paper, control methods of force sensorless power assist robot assisting aged people's work and caregiver's motion are proposed.

Some researches have been presented on the control scheme for power assist devices. Kazerooni[2] presented mechanism and control method for power assist robotic system called "Extender". Kosuge et al.[3] presented a control scheme for human-robot cooperation using virtual tool dynamics. Nagai et al.[4] discussed the design of a robotic orthosis for upper limbs.

In this paper, we present new control methods for power assist robot from a viewpoint of robust control. First, many kinds of power assist robots are classified considering both practical uses and control methods. Second, realization method of force sensorless power assist system using disturbance observer is presented. Third, it is focused on the difference between position control based method and force control based method, and power assist control methods considering the environmental characteristics are respectively presented.

II. Basic definitions and classification of power assist robot

A. Power assist technique for supporting aged people

Power assist technique is one of the important elements for supporting aged people and has great possibilities to contribute in various cases. For example, it is useful in caring motion such as lifting up a patient from bed and aged people's work such as carrying something heavy in the factory. "Power Assist" can be defined as assistance of motion for the purpose of increasing human ability or giving him/her some relief by multiplying his/her force. Then, some basic conditions such as increase of force, operability, natural and human-friendly motion, safety and no-anxiety are required.

Environment which receives power during the motion includes various objects such as a patient and a heavy baggage. Some environments having simple characteristics can be easily represented using numerical expression, however, most of environments cannot be easily represented because they have complicated nonlinear characteristics and it is not easy to identify them. It is not realistic to identify the accurate model before starting power assist motion. For example, when the robot gives power to a patient, environmental characteristic should change depending on his/her posture and clothes. Therefore, it is required to realize power assist motions to any kinds of environments even if we don't know the accurate characteristics of them.

B. Classification of power assist robots

Power assist technique can contribute in various cases as mentioned above, and many kinds of power assist forms can exist. Therefore, they must be classified to some extent considering practical uses and control methods. We classify them as the following:

(1) System with Human-Robot-Environment interface (HRE system)

In this system, two forces interact in Human-Robot and Robot-Environment. Robot gives force F_e (or torque τ_e) to Environment based on the interaction force F_m (or torque τ_m) in Human-Robot.

(2) System with Human-Robot interface(HR system)

In this system, Robot and Environment are nearly united into one and a force (or torque) interacts in Human-Robot. This includes the following two types:

(2a) HR system with high gravity

For example, when lifting up or raising a patient in our arms from bed, the motion has little accelaration and gravity term occupies a large part in the required force. Then, dynamic equation can be represented as

$$B\omega + G(\theta) = \tau \tag{1}$$

Such simple equation leads to many advantages in designing the controller.

(2b) HR system with high inertia

This system includes the case of carrying heavy objects using plane robots. Then, it has no gravity term, however, inertia moment is changed because Robot and Environment are nearly united into one. Dynamic equation can be represented as

$$(J + \Delta J)\dot{\omega} + B\omega = \tau \tag{2}$$

θ is angle, ω is angular velocity, J is inertia moment, ΔJ is change of inertia moment, B is viscous friction, $G(\theta)$ is gravity, and τ is torque.

Fig.1 shows these three basic power assist forms, however, there may be more complicated cases, for example, HR system may include both high gravity and high inertia, and HRE system may include high gravity or high inertia.

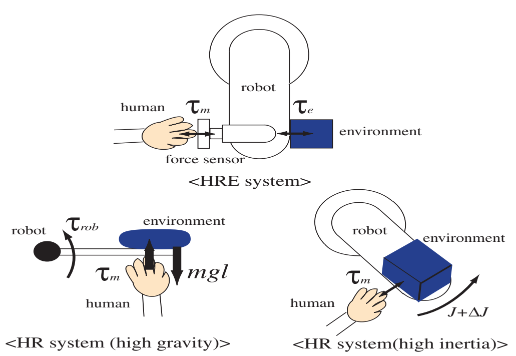


Fig. 1. Classification of power assist robot.

In this paper, we focus on (1)HRE system and show how to realize power assist motion based on position control based method and force control based method respectively. Some experiments are conducted using first axis of a DD robot as shown in the upper picture of Fig.1.

C. Evaluation of power assist motion

One of the primary purposes of power assist robot is to reduce required power for human and give him/her some relief. It is possible to ask some subjects about the feeling and impression after the power assist motion, however, we evaluate the required power numerically using evaluation value V defined in Equation (3).

$$V = \frac{\int_0^T F_m dt}{x_f - x_0} \tag{3}$$

T is time needed for the motion, x_f is the final position and x_0 is the initial position. This value represents impulse needed for moving at unit distance. The smaller this value is, the more easily he/she can move the object. This evaluation value will be applied to some experiments later.

III. Power assist method based on position control and force control

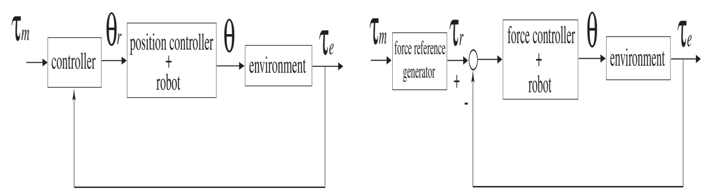
There are two basic methods in power assist control. One is to generate position reference from human force and environmental force. The other is to generate force reference from the two forces. We mention their basic configurations in this section.

A. Position control based power assist method

In this method, position reference θ_r given to the robot is generated from human input force (or torque τ_m) and environmental force (or torque τ_e). We name it "Position control based power assist method". Fig.2(a) shows the configuration of position control based power assist method. This can be realized using impedance control. In this method, environmental force (or torque τ_e) is not directly controlled, however, it is expected to specify the position trajectory and operability freely.

B. Force control based power assist method

In this method, force reference (or torque reference τ_r) interacting between robot and environment is generated from human input force (or torque τ_m). We name it "Force control based power assist method". Fig.2(b) shows the configuration of force control based power assist method. Environmental force (or torque τ_e) is directly controlled, therefore, it is expected to realize the desired assist ratio and give the desired power to the environment accurately.



(a) Position control based method

(b) Force control based method

Fig. 2. Configurations of two power assist methods.

IV. Estimation of environmental force using disturbance observer

In power assist control based on two forces, human input force and environmental force, they usually prepare two force sensors to measure them respectively. In this paper, the number of force sensor is reduced by estimating the environmental force using disturbance observer[5]. Realization of such power assist robot bring a lot of advantages, for example, the cost will be lower, the mechanism of robot will be simpler and the environment will be allowed to contact with every place of robot arm.

A. Principle of disturbance observer

Disturbance observer is often used in robust control and estimates disturbance torque included in each axis of robot. Fig.3 shows configuration of disturbance observer.

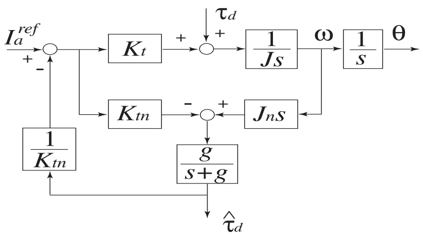


Fig. 3. Configuration of disturbance observer.

τ_d is disturbance torque, g is angular frequency of low pass filter, K_t is torque constant, K_{tn} and J_n are nominal values of torque constant and inertia moment, and I_a^{ref} is current reference. Estimated disturbance torque $\hat{\tau}_d$ is shown in Equation (4).

$$\hat{\tau}_d = \tau_{int} + \tau_g + F + D\dot{\theta} + \Delta J(\theta)\ddot{\theta} + \tau_{ext} \tag{4}$$

$\hat{\tau}_d$ includes some nonlinear term such as interference torque τ_{int}, gravity τ_g, friction torque $F + D\dot{\theta}$, inertia change $\Delta J(\theta)\ddot{\theta}$ and external torque τ_{ext}.

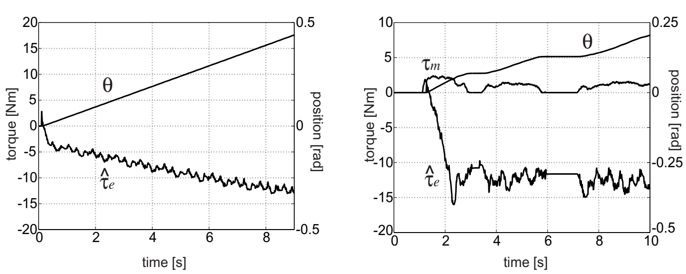
B. Estimation of the environmental force

Human input torque τ_m and enironmental torque τ_e can be regarded as external torque to the robot. Therefore, τ_e is estimated by subtracting τ_m measured by force sensor and other nonlinear terms from disturbance $\hat{\tau}_d$.

$$\hat{\tau}_e = \hat{\tau}_d - (\tau_m + \tau_{int} + F + D\dot{\theta} + \Delta J(\theta)\ddot{\theta}) \tag{5}$$

Fig.4(a)(b) show the experimental results of estimation of the environmental torque. First, a gum is used as a simple environment whose characteristic can be nearly represented as stiffness parameter. Fig.4(a) shows the environmental torque interacting between the gum and robot when the robot moves in constant velocity. Its characteristic can be identified as $K_e = 30[N/rad]$ from the result. Next, a cardboard box with some weights is used whose characteristic cannot be easily represented because of dent at the surface and friction against the ground. Fig.4(b) shows the the environmental torque when the robot is moved using impedance control of human input torque τ_m.

These environments will be used in power assist experiments later.



(a) gum (b) cardboard box

Fig. 4. Estimation of the environmental torque.

V. Position control based power assist method

As mentioned above, in position control based power assist method, position reference is generated from two torques τ_m and τ_e. The proposed position control based method is based on impedance control often used to power assist control.

A. Power assist method using Dual Impedance Control

Many kinds of environments such as a patient and complicated objects exist in power assist motions and it is required to operate the robot freely and contact with the environment safely. From this idea, we apply impedance control to both of two interaction points, Human-Robot and Robot-Environment. We name it "Dual Impedance Control". Fig.5 shows the configuration of position control based method using Dual Impedance Control.

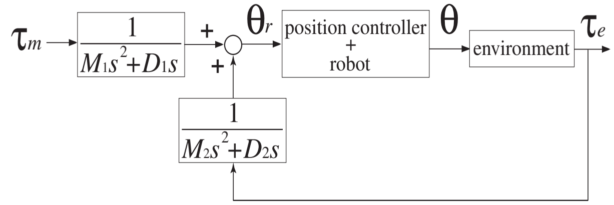


Fig. 5. Configuration of Dual Impedance Control.

Then, Two Degrees Of Freedom control system[6] which enables to determine the desired command response and suppression performance of disturbance independently is applied to position controller in this configuration.

Two impedance controllers and position reference are represented as Equation (6)(7).

$$C_1 = \frac{1}{M_1 s^2 + D_1 s}, \quad C_2 = \frac{1}{M_2 s^2 + D_2 s} \tag{6}$$

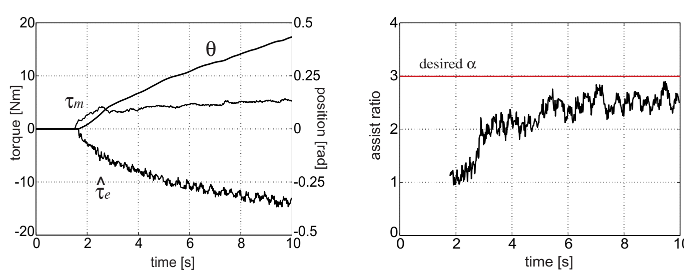
$$\theta_r = \frac{\tau_m}{M_1 s^2 + D_1 s} + \frac{\tau_e}{M_2 s^2 + D_2 s} \tag{7}$$

If $\ddot{\theta}_r \simeq 0$, $\dot{\theta}_r \simeq 0$, that is, the robot is moved slowly,

$$\frac{M_2 s + D_2}{M_1 s + D_1}\tau_m + \tau_e \simeq 0. \tag{8}$$

$\alpha \equiv \frac{M_2 s + D_2}{M_1 s + D_1}$ represents assist ratio from τ_m to τ_e. If $\frac{M_1}{D_1} = \frac{M_2}{D_2}$, this method is similar to virtual tool dynamics proposed by Kosuge et al.[3].

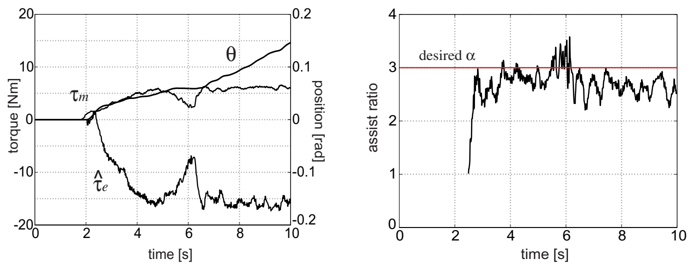
Fig.6(a)(b) show the experimental results of Dual Impedance Control using a gum. Impedance parameters are $M_1 = 0.5, D_1 = 20, M_2 = 1.5, D_2 = 60$, that is, $\alpha = 3$.



(a) Response of position and torque (b) $\frac{\tau_e}{\tau_m}$ in (a)

Fig. 6. Power assist experiment using Dual Impedance Control (gum).

Fig.7(a)(b) show the experimental results of Dual Impedance Control using a cardboard box. Impedance parameters are $M_1 = 0.5, D_1 = 30, M_2 = 1.5, D_2 = 90$, that is $\alpha = 3$.



(a) Response of position and torque

(b) $\frac{\tau_e}{\tau_m}$ in (a)

Fig. 7. Power assist experiment using Dual Impedance Control (cardboard box).

It is found that stable power assist motions can be realized against two types of environments using this method, however, accurate tracking of assist ratio cannot be realized because it isn't controlled directly.

Applying Dual Impedance Control to power assist robot caring a patient, it is expected not only to design the operability of a caregiver but also to contact with a patient safely even if he/she struggles violently.

B. Introduction of stiffness parameter

When using impedance controllers shown in Equation (6), the operator needs to keep creating force during assist motion. Therefore, stiffness parameter K_2 is introduced to impedance controller C_2.

$$C_2 = \frac{1}{M_2 s^2 + D_2 s + K_2} \tag{9}$$

Then, the operator will feel the environmental behavior only at the beginning of the motion and will not need to keep creating large force. Fig.8 shows the experimental result with $M_1 = 0.5, D_1 = 20, M_2 = 1.0, D_2 = 40, K_2 = 20$. It is found that the required human force can be reduced comparing with Fig.6(a).

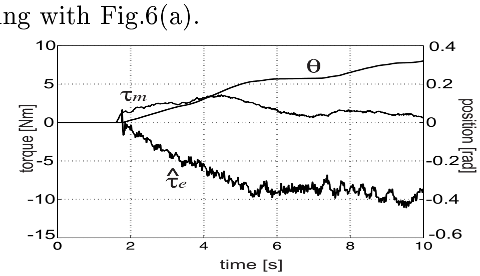


Fig. 8. Dual Impedance Control with stiffness impedance (cardboard box).

VI. Force control based power assist method

Force control based power assist method shown in Fig.2(b) is mentioned in this section.

A. Power assist method with conventional feedback control

As mentioned above, the environmental force is directly controlled in force control based power assist method. As the basis of this method, force control system using conventional feedback controller is shown in Fig.9. As a position controller in this configuration, Two Degrees Of Freedom position control system[6] is applied just as position control based method.

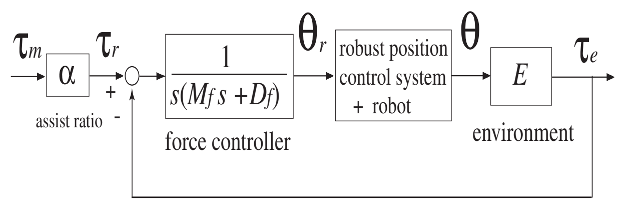


Fig. 9. Power assist control with conventional feedback controller.

If the environmental model is $D_e s + K_e$, it is possible to design the characteristic from τ_r to τ_e as two order system by using force controller $\frac{1}{s(M_f s + D_f)}$.

$$\frac{\tau_e}{\tau_r} = \frac{D_e s + K_e}{M_f s^2 + (D_f + D_e)s + K_e} \tag{10}$$

Then, parameters M_f, D_f of force controller are easily calculated using the environmental nominal model D_{en}, K_{en}, and time constant τ_f of the desired command response.

$$\frac{\tau_e}{\tau_r} = \frac{1}{\tau_f^2 s^2 + 2\tau_f s + 1} \tag{11}$$

$$M_f = K_{en}\tau_f^2 \tag{12}$$

$$D_f = 2K_{en}\tau_f - D_{en} \tag{13}$$

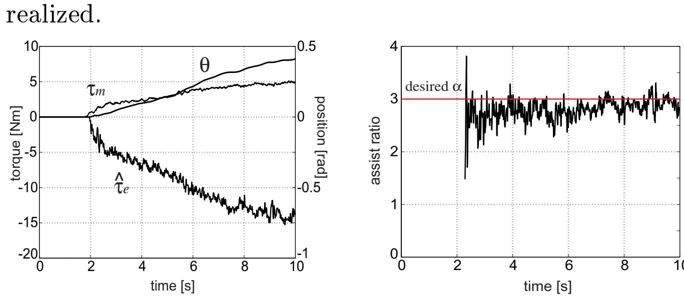
From Equation (13), if we have a nominal model so that

$$2K_{en}\tau_f - D_{en} < 0, \tag{14}$$

the system has an internal unstable pole in the force controller.

Power assist control can be realized by inputting torque reference τ_r which is calculated using human input torque τ_m and assist ratio α as shown in Fig.9.

Fig.10(a)(b) show the experimental result of power assist control with conventional feedback controller. The environment is a gum ($K_e = 30[N/rad]$) and the environmental nominal model is the same as it ($K_{en} = 30[N/rad]$). Stable power assist motion and the desired assist ratio can be realized.



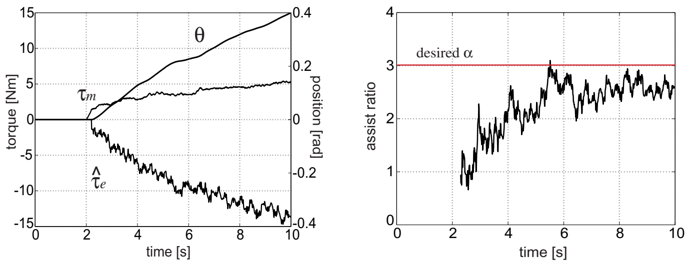
(a) Response of position and torque

(b) $\frac{\tau_e}{\tau_m}$ in (a)

Fig. 10. Power assist control with conventional feedback controller (gum).

Next, the environmental nominal model $K_{en} = 120[N/rad]$ is used in tha same experiment, and

Fig.11(a)(b) show its result. It is shown that the environmental parameter change leads to force response and desired power assist motion cannot be realized when using conventional feedback controller.



(a) Response of position and torque (b) $\frac{\tau_e}{\tau_m}$ in (a)

Fig. 11. Power assist control with conventional feedback controller (gum).

B. Power assist method robust to environmental change

It is required to realize the desired force response and assist ratio even if the environmental characteristics change. Therefore, environmental observer[6] which enables to make robust to environmental parameter changes is applied to force control based power assist method. Fig.12 shows the configuration of force control based power assist method introduced environmental observer.

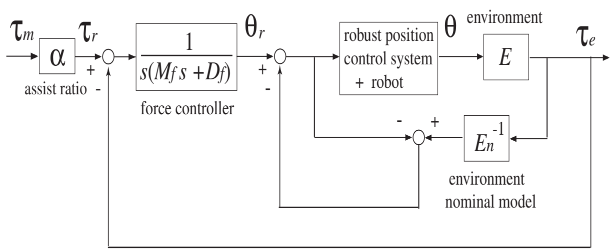
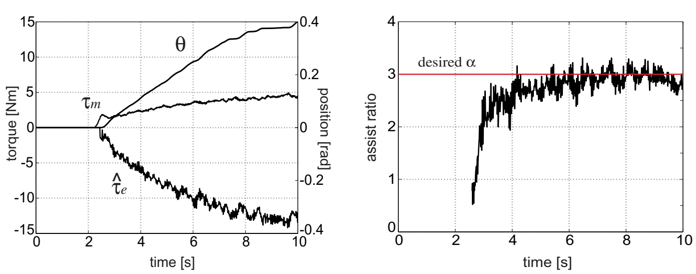


Fig. 12. Power assist control using environmental observer.

Fig.13(a)(b) show the experimental result of force control based method with environmental observer. Environment is a gum whose charcteristic is $K_e = 30[N/rad]$, environmental nominal model is $K_{en} = 120[N/rad]$ and the desired assist ratio is $\alpha = 3$.



(a) Response of position and torque (b) $\frac{\tau_e}{\tau_m}$ in (a)

Fig. 13. Power assist control with environmental observer (gum).

It is found that the accurate assist ratio can be realized using environmental observer even if the nominal model is different from the actual characteristic.

Fig.14 shows the evaluation of power assist motion using V defined in Equation (3). Conventional feedback controller without environmental observer cannot realize the desired assist ratio and requires human to create larger force as the environmental characteristic changes. The proposed method with environmental observer doesn't require large force even if the environmental characteristic changes. The effectiveness of introduction of environmental observer is shown.

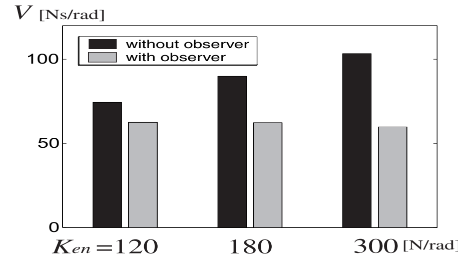


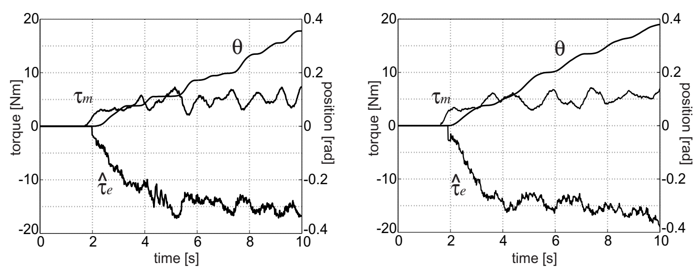
Fig. 14. Evaluation of the effectiveness of environmental observer.

Next, the proposed method with environmental observer is applied to power assist motion to carry a heavy cardboard box. When the environmental nominal model includes viscosity coefficient D_{en}, that is, $\frac{1}{D_{en}s+K_{en}}$, it becomes low pass filter, and $\frac{D_{en}}{K_{en}}$ represents time constant τ_{en} of low pass filter.

$$E_n^{-1} = \frac{1}{D_{en}s + K_{en}} = \frac{1}{K_{en}}\frac{1}{\frac{D_{en}}{K_{en}}s + 1} \tag{15}$$

$$\tau_{en} = \frac{D_{en}}{K_{en}} \tag{16}$$

Fig.15(a)(b) show the experimental results with $D_{en} = 10, K_{en} = 400$ and $D_{en} = 10, K_{en} = 800$ whose time constants are small. It is shown that both position response and human input torque have oscillation.

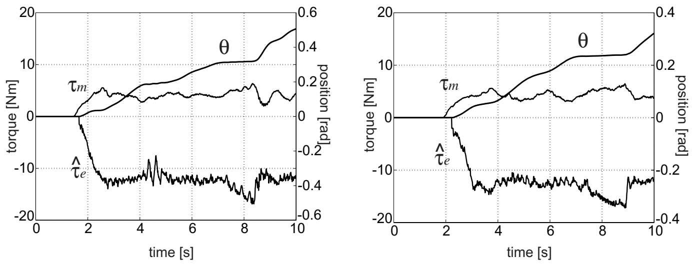


(a) $D_{en} = 10, K_{en} = 400$ (b) $D_{en} = 10, K_{en} = 800$

Fig. 15. Power assist control with environmental observer (cardboard box).

The output of environmental observer is directly inserted to position reference, therefore, position response has oscillation if complicated environments such as a cardboard box give interaction torque with oscillation and time constant τ_{en} is small. Position response with oscillation influences to human input torque and doesn't allow him/her to input stable torque.

Fig.16(a)(b) show the experimental results with $D_{en} = 20, K_{en} = 200$ and $D_{en} = 80, K_{en} = 800$ whose time constant is larger than Fig.15(a)(b). It is found that power assist motion with more stable position response can be realized by regulating the environmental nominal model.



(a) $D_{en} = 20, K_{en} = 200$ (b) $D_{en} = 80, K_{en} = 800$

Fig. 16. Power assist control with environmental observer (cardboard box).

C. *Force control based method using impedance control*

The operator needs to keep creating force during assist motion when using force controller shown in Fig.12. Therefore, force control based method using impedance control shown in Fig.17 is applied. This idea is similar to the proposed method by Nagai et al.[4] which torque reference τ_r produced by impedance equation (17) is applied to computed torque method.

$$\tau_r = M\ddot{\theta} + D\dot{\theta}_e + K\theta_e \tag{17}$$

$$\theta_e = \theta - \theta_m \tag{18}$$

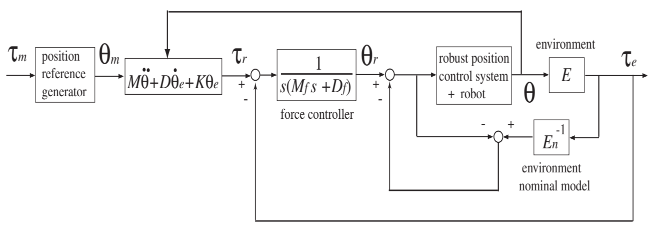
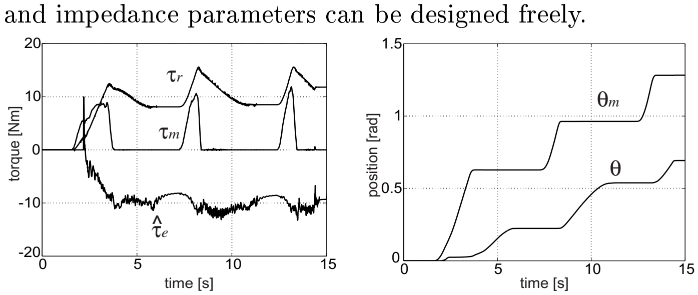


Fig. 17. Configuration of force control based method using impedance control.

Position reference generator in Fig.17 can be designed freely. Fig.18(a)(b) show the experimental result of force control based method using impedance control. Environment is a cardboard box. This method has the advantage that the operability including position reference generator and impedance parameters can be designed freely.



(a) Force response (b) Position response

Fig. 18. Force control based method using impedance control (cardboard box).

VII. Discussion

Two power assist control methods were campared and respective features and advantages were shown through some experiments. Position control based methods using Dual Impedance Control is superior in stablility because it surely generates a stable position reference whether the robot contacts with the environment or not. In addition, it enables us to specify the operability by changing impedance parameters and assist ratio to some extent. Force control based methods introduced environmental observer also has some advantages that it can realize the desired assist ratio even if the environmental characteristic changes. Furthermore, position response also can be stabilized by regulating the environmental nominal model.

Both of them can realize stable power assist motion even if environmental characteristic is unknown, and have possibilities to be applied to practical power assist devices. The former is useful specially to caring motion for a patient which safety should be given priority. Dual Impedance Control enables not only to design operability of a caregiver but also to contact safely even if a patient struggles violently. Furthermore, a caregiver can feel patient's behavior because it is reflected in position response. On the other hand, the latter is suitable for assistance of aged people's work which attaches importance to increase of human power, that is, assist ratio. It is possible to make proper use of these two methods by considering the features of power assist motions, their environments, and what will be given priority.

VIII. Conclusion

In this paper, we have proposed control methods of force sensorless power assist robot using robust control as one of support for aged people and disabled people. Two power assist methods, position control based and force control based, were compared considering environmental characteristics and practical uses.

Dual Impedance Control method proposed as one of position control based methods has many advantages for practical uses such as caring a patient. In force control based method, environmental observer was introduced into the conventional feedback control system and brought the better force response. It is possible to achieve the desired assist ratio accurately and reduce the required power for human. Some experiments have shown the effectiveness of these proposed methods and the possibilities to apply these methods to various practical power assist devices by making proper use of respective features and advantages.

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