Sensor Free Power Assisting Control Based on Velocity Control and Disturbance Observer

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***Abstract*— In this paper, we design a controller that makes a plant sensitive to disturbance, which can be adopted for power assisting systems. Conventional power assisting controllers need force sensing, and only focus on the amplification of the force. But our proposed controller does not need force sensing. We just focus on the physical dynamics of the assisted plant considering sensitivity function of feedbacked system.**

Recently, various electric motor systems are used near people including power assisting system. Controllers for those motor systems need other control specifications than precise tracking or strict disturbance rejections. Proposed method can be a good solution for these specifications and can be called frequency weighted assistance control.

Keywords: power assistance control, disturbance amplification control, human sensory control, compliance control, frequency weighted assistance, extended inertia control , wheelchair control

I. Introduction

Recently welfare systems including power assisting system are emerging as new application of the control theory. In the industrial application of control, precise position, velocity, force tracking and strict disturbance rejections became the main object of control. But in the case of welfare application, other factors such as smooth control are more important than precise tracking or strict disturbance rejections. And those applications are located so near human that control design should be more considerate. The plant is likely to endanger the operator when the controller fails to assist properly. This point makes control design for power assisting control difficult.

There is another example where advanced feedback power assisting control design is necessary. Motor systems used near people should react more sensitively to disturbance. There was an accident that explains a motor system controlled without this consideration did harm. An automatic revolving door in Tokyo crushed a child to death on March 2004. If that door would have acted more sensitively to the external force by the boy, he could have been saved.

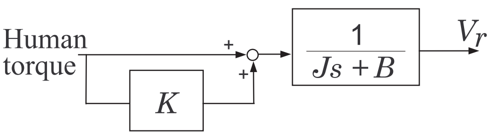


Fig. 1. Conventional Power Assisting System

To control motors in this sensitive way, many controllers employ force sensors, but it will cost much. Figure 1 shows the block diagram of the conventional power assisting controller. This gets person's force using sensor and amplify that force using motor.

In this paper we propose a power assisting controller that does not need force sensing. This can be achieved using the disturbance observer and disturbance reaction design.

We apply proposed method to two objects in this paper; one is a robot arm and the other is a wheelchair. Lastly some analysis on the controller parameter decision and the effect of the modeling error is given.

II. Power Assistance Control by Disturbance Response Design

A. Power Assisting Control Design without Force Sensor

Figure 2 shows the most general block diagram of power assisting control.

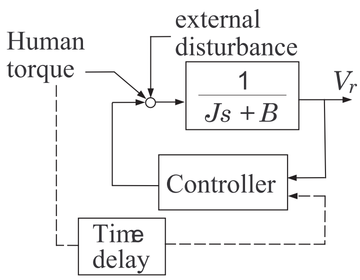


Fig. 2. Characteristics of Human torque as reference input

For power assisting control, human force should be obtained to make a motor sensitively to the force. Force sensor is a straightforward solution to get the information. But in the upper figure, we can figure out that human force acts as disturbance to the controller because any input to the plant that is not from the motor is recognized as disturbance in feedback control. From this viewpoint, human force can be estimated using the disturbance observer.

There are some researches that use the disturbance observer to get human force [1], [2]. These researches focus on retrieving the human force from observed disturbance, because they use the estimated human force as a force or acceleration reference. But they need very complicated calculation and can make the system too sensitive to the disturbance.

In this paper, we take a novel control strategy that will mask the intrinsic parameter of wheelchair preferable for power assisting control. It can be called a parameter control or a kind of compliance control[3].

B. Compliance Control for Disturbance Rejection

The structure shown in figure 3 is the simplest structure of proposed compliance control. We have suggested that the stiffness term in compliance is not necessarily required in some case such as wheelchairs[4], and this controller has no stiffness to disturbance according to our proposal. It can adjust the value of inertia and damping by changing the feedback gains J_A and B_A.

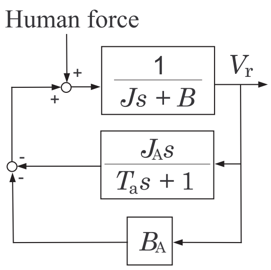


Fig. 3. Compliance Control for Flexible Disturbance Attenuation

The dynamics from human force to the velocity of a plant will be like this:

$$T_{c1}(s) = \frac{1}{(J + J_A)s + (B + B_A)} \quad (1)$$

In this dynamics, the time constant $\frac{J+J_A}{B+B_A}$, and the DC gain $\frac{1}{B+B_A}$ are two important physical parameters. By changing J_A and B_A, we can change these two parameters. [4] adopts this controller in the form of the 2 degree of freedom control and attenuates the gravity.

This structure may be good for disturbance attenuation but in order to make a plant sensitive to disturbance, this is not appropriate structure. Sensitizing to disturbance means makes inertia and damping small to disturbance. To this end J_A and B_A should be negative and it will make positive feedback. This is likely to make the system instable.

Here, we introduce another compliance control structure.

C. Sensitization of System to Disturbance Using Inertia Control

Hori[5] suggested an inertia control which can simulate the inertia value of motor using disturbance observer. Decreasing inertia is related to increasing sensitivity and it results in as power-assistance. In this section, we design power assisting controller using this inertia-decreasing technique. Hori's[5] inertia control only adjust inertia value in low frequency band. Adding damping factor into this control, we will have enough parameters that can adjust sensitivity function.

In figure 4, a controller design which includes the damping factor(B_M) is shown.

With this control system, the transfer function from human force to velocity is:

$$T_{c2}(s) = \frac{1}{Js + B + A}\left(\frac{J_M s + B_M + A}{J_M s + B_M}\right) \quad (2)$$

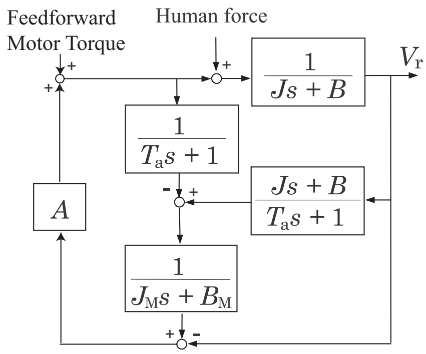


Fig. 4. Block Diagram of Proposed Control Design

J_M, B_M are parameters of model dynamics and can be chosen arbitrarily. A is a feedback gain for velocity tracking. Appropriately chosen J_M, B_M will make a system sensitive to a proper extent and provide good assistance.

In section IV, we will relate these parameters with some assistance performance index.

III. Analysis of the Proposed Assistance Control Using Simulations and Experiments

A. Application to a One-link Robot System

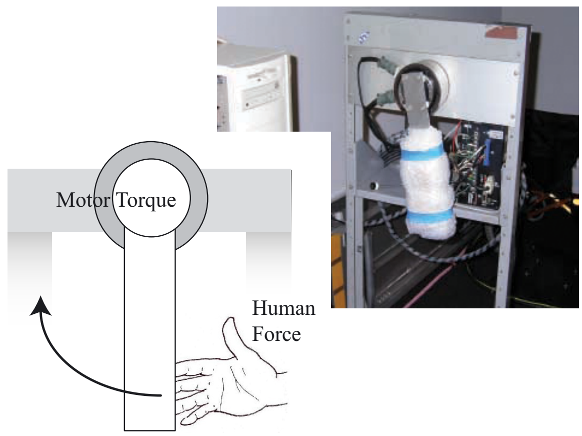
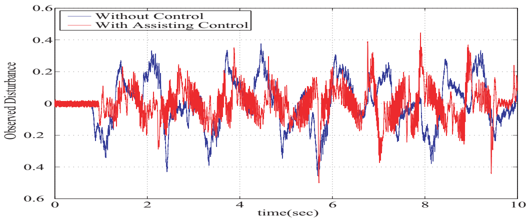


Fig. 5. Experimental Setup

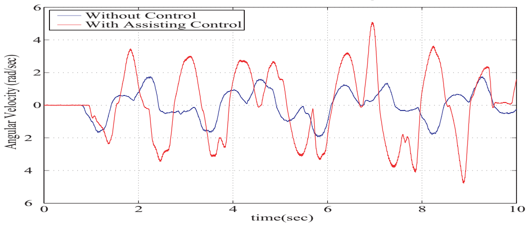
In order to verify the proposed assistance control method, we apply the proposed controller to a robot which has one arm. The experimental setup is described in figure 5.

The robot has one arm and an operator add his force to the arm. By investigating velocities driven by the human force, we can examine the performance of the proposed control method. Figure 6 shows the results.

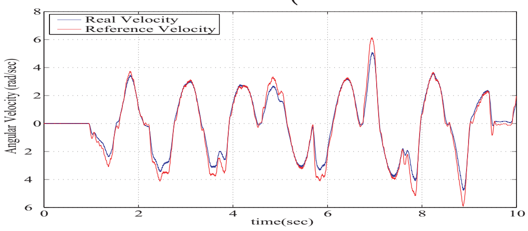
Two experiments were practiced; one without proposed controller, the other with the controller. In both experiments no feedforward torque is supplied, and the arm is driven only by the external human force. Figure (a) shows observed disturbances in both experiments, and the disturbances include human force. We can see the ranges of both force are not so different each other.



(a) observed disturbance (including human force)



(b) velocities of the robot arm (with and without control)



(c) velocity tracking

Fig. 6. Experimental Results

TABLE I
PARAMETER VALUES (NORMALIZED TO MOTOR VOLTAGE)

J	0.024	B	0.1	J_M	0.005	B_M	0.001	A	1

Figure (b) shows the velocities of the robot arm. In spite of the similar ranges of input forces, the ranges of velocities are different each other. Velocity with proposed control is almost two times bigger than the one without control.

Figure (c) shows tracking characteristic of the controller. From this result also suggests choosing appropriate J_M, B_M and A be able to achieve desired disturbance reaction design.

B. 2 Degree of Freedom Characteristic of Proposed Method

This proposed method can be a solution to the revolving door problem. The accident can be analyzed in the viewpoint of disturbance reaction design.

Controlled output will be like:

$$y = \frac{A}{Js+B+A}r + \frac{1}{Js+B+A}\left(\frac{J_M s + B_M + A}{J_M s + B_M}\right)d \tag{3}$$

r is the feedforward motor torque in figure 4 which is necessary to operate a plant in a required way. In the case of a revolving door, this torque will be a constant torque to turn a door at a required speed. d corresponds to human force in figure 4 which acts on the plant such as a door.

In order to clarify this consideration, here we only focus on static forces when motor torque r and human force d make balance with each other. The relationship between two static forces during the balance is described in equation 4.

$$d = -\frac{AB_M}{B_M + A} r \tag{4}$$

This equation means that the motor torque will be confronted by human force with a ratio of $-\frac{AB_M}{B_M+A}$. A simulation was done using the parameters in table III-A to ascertain this fact. Figure 7 shows the result.

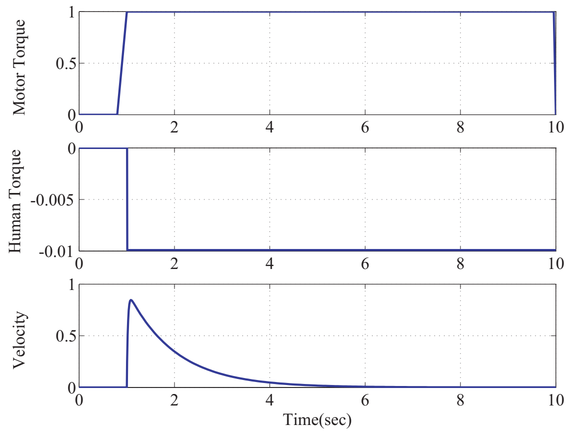


Fig. 7. Simulation for Static Force Comparison

Two torques r, d are chosen according to 4. The upper figure is motor torque, the middle figure is human torque, and the lower figure describes the velocity of a plant. This result explains that man can cope with big motor torque with smaller (here almost $\frac{1}{100}$ times) force. It is interesting that this relationship does not rely on J and B.

C. Application to a Wheelchair

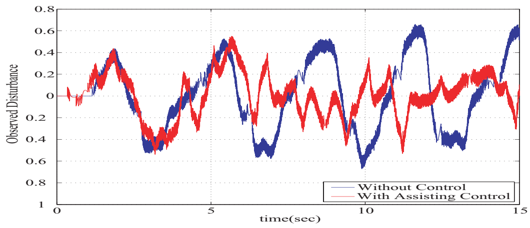
There are many kinds of power assisted wheelchairs, but most of all have some force sensors to measure human force to assist. These sensors which are installed in rims or handles only measure forces that work on limited parts of wheelchair. If sensor is installed in rim, a helper does not benefit from the assisting control, and if sensor is in handle for a helper, a rider will not benefit. Moreover those force sensors are expensive and are one reason that makes the power assisted wheelchairs cost that much.

The proposed controller can work as a power assisting controller that does not need force sensing. Here, the assistance characteristic of the control design is experimented using a wheelchair.

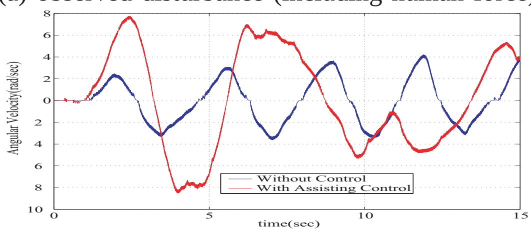
Experiments have been done by the commercial power-assisted wheelchair JW-II (Figure 8). First, a rider has propelled rims of wheels with and without the control. The results are described in figure 9

Figure (a) is the observed disturbances including human force, (b) is the velocities of the robot arm, and (c) shows tracking characteristic of the controller. These results explain almost same things with the robot experiment. The ranges of the observed disturbances are similar in both cases, while the ranges of velocities are different each other. Velocity with proposed control is bigger than the one without control, especially in the first stroke.

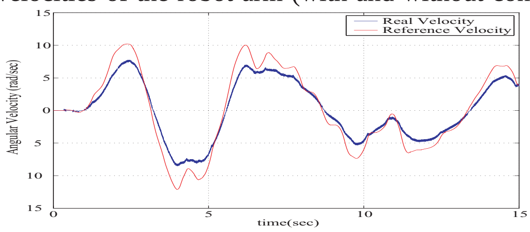
Fig. 8. Experimental Equipment



(a) observed disturbance (including human force)



(b) velocities of the robot arm (with and without control)



(c) velocity tracking

Fig. 9. Experimental Results

One of most important point in this control design is that, even though the observed force is not so precise or smooth enough, the model dynamics for velocity reference will work as some filter that smoothes the observed force. And physical velocity will track the reference velocity with some accuracy that can be modified using the gain A in figure 4

IV. Numerical Consideration of Control Parameters

A novel control design method has been proposed in section II-C, but the parameters left unexplained. In this section, relationship between the parameters and control performance is clarified. To this end, the following discussion is restricted to the application to the power-assisted wheelchairs, and time responses with step torque input to the wheelchair will be checked. Using these time responses, we will find the physical meaning of control parameter.

Dynamics from human force to velocity of a wheelchair can be simplified as:

$$P(s) = \frac{1}{Js + B} = \frac{1}{\tau_b s + 1} \tag{5}$$

For simplicity, DC gain, which was $\frac{1}{B}$ in previous figures, is normalized as 1 here. And the only parameter of the wheelchair will be τ_b which was $\frac{J}{B}$ in previous figures.

This dynamics is converted to the following equation (6).

$$\begin{aligned} P_{c2}(s) &= \frac{1}{Js + B + A}\left(\frac{J_M s + B_M + A}{J_M s + B_M}\right) \\ &= K' \frac{1}{\tau_{b'} s + 1} \frac{\tau_h s + 1}{\tau_l s + 1} \end{aligned} \tag{6}$$

, where $K' = \frac{B_M + A}{(B+A)B_M}$, $\tau_{b'} = \frac{J}{B+A}$, $\tau_l = \frac{J_M}{B_M}$, and $\tau_h = \frac{J_M}{B_M + A}$. We can change any three of the above factors simultaneously by changing J_M, B_M, A.

A. Time constants and DC gain

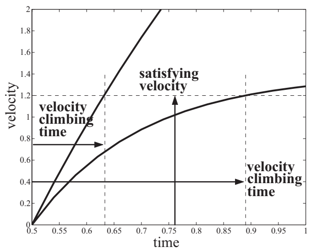
DC gain K' is same as the assistance-ratio in the conventional power assisting control, but in the proposed control method this value is the gain in the low frequency band. In the high frequency band, the gain will be changed.

In equation (2), $\tau_{b'} = \frac{J}{B+A}$, $\tau_l = \frac{J_M}{B_M}$ are two time constants. To investigate the role of these two time constants, step torque is used as input to $P_{c2}(s)$. Then, the velocity of the wheelchair will be,

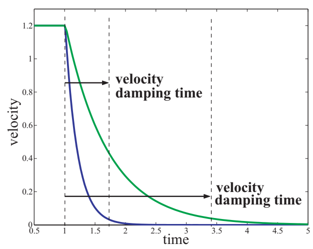
$$v_r(t) = 1 - \frac{\tau_{b'} - \tau_h}{\tau_{b'} - \tau_l} e^{-\frac{1}{\tau_{b'}}t} + \frac{\tau_l - \tau_h}{\tau_{b'} - \tau_l} e^{-\frac{1}{\tau_l}t} \tag{7}$$

τ_h is set smaller then $\tau_{b'}, \tau_l$.

If $\tau_{b'} > \tau_l$ then, $e^{-\frac{1}{\tau_l}t} > e^{-\frac{1}{\tau_{b'}}t}$ and the coefficients will be $\tau_{b'} - \tau_h > \tau_l - \tau_h$. As time goes on, the coefficients $\tau_{b'} - \tau_h$ and $\tau_l - \tau_h$ play important roles, which means the first term has a larger effect on this velocity. But there also can be a period where the effect by $e^{-\frac{1}{\tau_l}t} > e^{-\frac{1}{\tau_{b'}}t}$ is larger than the effect by the coefficients; the second term has a larger effect on this velocity.



(a) when accelerating



(b) when decelerating

Fig. 10. Important parameters in velocity

When a person is riding a wheelchair, he controls the velocity. At the accelerating phase, he adds torque until the velocity reaches a certain level. We call this certain velocity level as 'satisfying velocity', and the time to reach 'satisfying velocity' as 'velocity climbing time'. In figure 10 (a), the two velocity patterns are shown, and the satisfying velocity and climbing time are described. Decrease of this climbing time is related to the power-assistance. To decrease the velocity climbing time, DC gain K' should be high or time constants $\tau_{b'}, \tau_l$ should be small.

At the deceleration phase, the velocity damping time (described in figure 10 (b)) plays an important role in power assistance. It is related to $\tau_{b'}, \tau_l$. To increase the velocity damping time those time constants should be long.

Proposed control can change these parameters, so it can give good assistance.

B. Jerk-peak attenuation

Next, we investigate the jerk of the controlled wheelchair using step torque input.

First, if step torque is used as input to the wheelchair expressed by equation (5), the jerk will be

$$\frac{1}{\tau_b}\delta(t) - \frac{1}{\tau_b^2} e^{-\frac{1}{\tau_b}t} \tag{8}$$

The first term $\frac{1}{\tau_{b'}}\delta(t)$ is mainly concerned with the jerk-peak. If this term is too big, the human will feel unsafe.

If a controller raises the measured force up to K times (,which is the way that many conventional power assisting controllers adopt), jerk will be increased K times, too. This is not good for comfortability.

In the case of the proposed power assisting control, jerk will be like as follows.

$$K'\left(\frac{\tau_h}{\tau_{b'}\tau_l}\delta(t) + \frac{\tau_h - \tau_{b'}}{\tau_{b'}^2(\tau_{b'} - \tau_l)} e^{-\frac{t}{\tau_{b'}}} + \frac{\tau_h - \tau_l}{\tau_l^2(\tau_l - \tau_{b'})} e^{-\frac{t}{\tau_l}}\right) \tag{9}$$

The first term is the jerk-peak term, and it has K' and $\frac{\tau_h}{\tau_l}$. Keeping K' as high as we want for the assistance characteristic, we can also reduce the jerk-peak by setting $\frac{\tau_h}{\tau_l} < 1$. That is, the jerk-peak can be reduced without any loss in DC gain.

The criterion $\frac{\tau_h}{\tau_l} < 1$ means that the gain at high frequency must be lowered to reduce the jerk-peak. In the low frequency, high assistance-ratio is adequate for good assistance performance, and in the high frequency, low assistance-ratio is adequate for the attenuation of the jerk-peak.

Figure 11 shows a jerk pattern when low pass filtered step torque is used as input. Two factors in this figure are important for power assisting control design. First is the peak value of jerk, second is the time span while jerk has a nonzero value.

The peak value is related with how a person feels while accelerating, and the time span is related with the 'velocity climbing time'. Small peak value is good for the comfortability of rider, but a too small peak makes the 'velocity climbing time' longer and worsens the power assistance. But if we have sufficient time span by setting adequate time constants $\tau_{b'}, \tau_l$, the power-assistance will be improved.

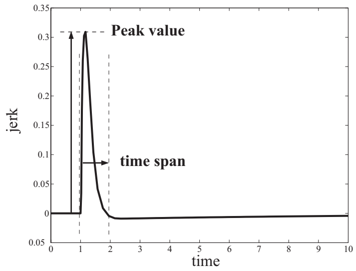


Fig. 11. Important parameters in jerk

V. Analysis of the Effect of Modelling Error

We adopt the disturbance observer to estimate the human torque, which uses the physical model of the wheelchair and the user on it. Error in this model will affect the performance of this assisting controller. In this section, the way in which the error in the model will affect the controller is analyzed. To make the analysis simple, the parametric errors $(\Delta J, \Delta B)$ are considered. The way how these errors affect the controlled system is examined from two points of view: the stabiliyt and the performance.

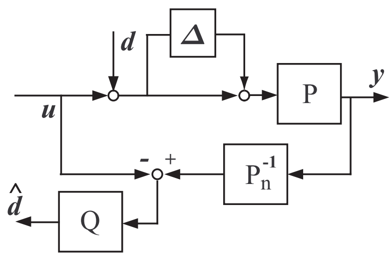


Fig. 12. Disturbance Observer with Modelling Error

A. Stability Analysis

The errors are defined as :

$$\Delta J = J_n - J, \Delta B = B_n - B, P_n(s) = \frac{1}{J_n s + B_n} \tag{10}$$

$$\Delta(s) = \frac{\Delta J s + \Delta B}{Js + B}, P(s) = P_n(s)(1 + \Delta(s)) \tag{11}$$

where J_M, B_n are the inertia and damping values used for the disturbance observer design, and J, B are the real values of inertia and damping.

If there are the errors $\Delta J, \Delta B$ the closed-loop transfer function will change from the equation (2) to

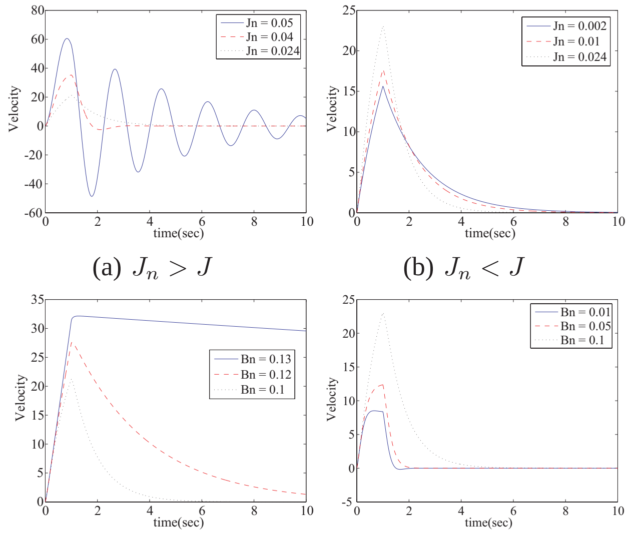
$$\hat{d} = d + (\Delta J s + \Delta B)y \tag{12}$$

$$T(s) = \frac{J_M s + B_M + A}{(Js + B + A)(J_M s + B_M) - A\Delta J s - A\Delta B}. \tag{13}$$

This equation shows that positive ΔJ and ΔB can make the system unstable. This explains the proposed controller can be unstable with the real inertia and damping are less than the nominal value and suggests that the nominal value should not be so large. Error in the inertia (ΔJ) is related to the first-order term and can make the motion oscillatory. This ΔJ is caused by change of user's weight. Error in the damping (ΔB) is related to the constant term so this error will change the power-assist ratio in the low frequency band, and this ΔB is caused by running resistances.

B. Analysis on Assistance Performance

The analysis above can be applied to the performance evaluation. The errors ΔJ and ΔB affect the assistance performance respectively. ΔJ changes the transient response of the assistance, for it is related to the first order term. The response time and oscillation can be changed according to the ΔJ. ΔB has influence on the low frequency bandwidth. This changes the ratio between the peak values of assisting motor torque and the torque exerted by the user. And lasting time of assisting power in one stroke will be influenced by ΔB.



(a) $J_n > J$ (b) $J_n < J$ (c) $B_n > B$ (d) $B_n < B$

Fig. 13. Simulation Results with Modeling Error

This analysis is demonstrated by some simulations. Figure 13 shows the results. In this simulation, the real inertia J is 0.024, and the real damping B is 0.1. The nominal value of the inertia, J_n is changed from 0.01 to 0.05, and the nominal B_n is changed from 0.01 to 0.13. It is found that the stability is weakend when the nominal values are larger than the real values and the assistance performance becomes worse when the nominal values are less. Large ΔJ makes the response rapid and oscillatory, and small ΔJ makes the response slow. On the other hand, large ΔB tends to make offset in the observed disturbance and make the whole system unstable, and small ΔB decreases the assisting torque.

C. To improve the robustness

Proposed controller is the basic linear time invariant system. And the analysis here is constricted to this linear controller. In order to make the assistance more robust to the environmental changes, nonlinear or other advanced estimation can be adopted. There can be many methods to distinguish the human force and it will increase the accuracy of observing the real human force so the controller can amplify only that force.

VI. Conclusion

In this paper, we have suggested that motor systems should be sensitive to disturbance when a person works as disturbance, and propose a control design that will sensitize the plant to the disturbance. It is true that the proposed controller only works well where there is no other disturbance than human force. We may need other disturbance classification method to cope with this case. But as we said in the introduction, the proposed controller is necessary as a basic control unit. Experiments done in this paper tells that the proposed controller's ability as this basic control unit.

From the viewpoint of disturbance response design method, this control design can be compared with the compliance control and the H$^\infty$ control. Compared with compliance control, this method has the characteristic that it removes the stiffness term on purpose to make the reaction more flexible, and compared with the H$^\infty$ control, this has more simple and direct structure.

The idea explained in section IV, V should be demonstrated by experiment, and the interference by other wheel's movement should be considered for improvement of the proposed control design.

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