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Passive Dynamic Control and its Application to Balance Servo

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Abstract— **This paper proposes a new servo control method referred to as "passive dynamic control (PDC)," which is based on the analysis of human walking mechanism. The PDC uses the passive balancing method jointly with the active control, and realizes the purpose control and the disturbance suppression control with much less energy and much more safety than conventional control methods. The servo system, which uses balancing operations, such as mechanical positioning control, is referred to as "balance servo." In this paper, the balance servo by the PDC is described, and its application for the positioning control using the spring balancer and the Magneto-Rheological brake is shown.**

I. INTRODUCTION

SERVO system intends to match the controlled variable with the command signal mechanically. In the case of mechanical positioning control, the balance of force, namely the balance state, is achieved in the steady state. In addition, the unsteady operation (balancing) is executed to achieve the balance of force against the disturbance action by canceling the disturbance. Most of the conventional control systems intend to achieve both the control variable matching control and the disturbance suppression control by using an active method. However, in achieving these purposes, the servo system disregards inefficiency in energy consumption, which is evident from the fact that the power that should be originally unnecessary for controlling the stop operation and the position maintenance is consumed wastefully. For the safety improvement of the actuator, the impedance control [1] and the compliance control [2], [3] are widely used, but it is paradoxical that these controls could be dangerous if they become dysfunctioned due to any trouble. These defects of the conventional control systems are attributable to their inherent characteristics that larger energy is required to generate operating force than to perform the intended work, and that runaway due to trouble cannot be anticipated. If the energy saving can be realized by reviewing the control structure from the viewpoint of energy, it will lead to the improvement of the control safety.

Tomovic' *et al.* [4] analyzed human walking motions, classified the actions produced by the skeletal muscle into 4 elements: Lock, Free, Increasing and Decreasing, and referred to the actuator producing various actions by combining these elements as "cybernetic actuator." It is known that the human flat walking action is extremely efficient. Oguni [5] demonstrated that the above 4 elements of the actions were determined depending on the conditions maximizing the energy efficiency. The authors consider that if this control system can be applied to mechanical systems, the energy- saved control can be realized.

In this paper, the authors propose a new control method referred to as "passive dynamic control (PDC)," and try to apply the PDC to the servo system control. In section II, the authors review the human walking motion analysis presented by Tomovic' *et al.* [4], and demonstrate that applying this control method to a mechanical system is equivalent to a system that introduces passive control (passive balancing) therein and combines the passive control with active control (active balancing) to improve the energy efficiency. Furthermore, paying attention to the safety of the cybernetic actuator, the authors indicate that, the passive balancing is effective for preventing any accidental dangerous condition as to each of the above 4 motions. Then, based thereon, the authors propose the basic principle of the PDC. In section III, the authors show that when the PDC is applied to the mechanical positioning control and then applied to the servo, the servo can have higher energy-saving effect and safety than ever before ("balance servo"). In this case, the passive elements used for the balance servo are the Magneto-Rheological brake ("MR brake") for fixing the position and the spring balancer for achieving free balancing. In section IV, the authors show a model of the balance servo, and examine the effectiveness of the PDC by presenting some experimental results. The sequence is, for example, 1) make the imbalance, 2) release the brake, 3) get the correct position, 4) make the brake on, 5) eliminate the imbalance.

II. PASSIVE DYNAMIC CONTROL

A. Condition of Inherently Safe Design

Generally, in machine safety (ISO12100), priority is given to inherently safe design. The inherently safe design is defined as guarantee that physical conditions, such as force and momentum (kinetic energy), will not cause any hazard to humans even if they are caught or bumped by machines. For example, the maximum force allowed to be applied to a human is specified as 15kgf (ISO10218). When such allowable force limit is shown, reliability is seen in the determination of the safety.

There is a case where the output from a machine is executed to a human by mistake. To avoid this by the inherently safe design, it should be so arranged that the safety is confirmed (no output exceeding the allowable limit) and, if the safety cannot be confirmed, the next motion (next step of

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the sequence) is not started. It is requested to confirm the safety of the function to be executed in next step beforehand in a case where a) the control function of the next step is executed by the passive element having no concept of trouble, b) preparation for executing the control function is carried out in the passive lock state and the passive lock is released only when the normality of the preparation is confirmed, or c) the next sequence is permitted on condition that the system can be locked immediately by passive elements in case of failure on the danger side. However, since the case c) is an approach based on the interlock, the priority should be given to the case a) or b) when the inherently safe design is prioritized.

It seems that in the past research into the theory and method of control, the importance has been attached to the functionality that should be normally executed, and the danger due to failure in control has not been considered. Since many accidents were caused by failure in control, it is necessary to develop the theory and method of control considering the inherently safe design.

B. Cybernetic Actuator

The cybernetic actuator developed by Tomovic' *et al.* [4] creates various output motions by combining 4 states of "Lock," "Free," "Increasing" and "Decreasing." The human joint is constituted by a pair of antagonists. This antagonist takes 2 states of contraction and relaxation, and thereby the joint can be classified into following 4 states:

1) Lock: This is a state with that both the antagonists are contracted holding the joint in place.

2) Free: This is a state with both the antagonists are relaxed leaving the joint at the mercy of external restraints.

3) Increasing: This is a state with the antagonist for driving the joint to rotate in the normal direction is contracted generating the active force in the positive direction.

4) Decreasing: This is a state with the antagonist for driving the joint to rotate in the reverse direction is contracted generating the active force in the negative direction.

For the cybernetic actuator, these are only 4 commands to be inputted. According to the combination of these commands and the order and timing of input, various functions are executed.

C. Interpretation from Viewpoint of Energy

Oguni [5] examined these 4 states from the viewpoint of energy, and showed that they were decided considering the conditions under which the highest energy efficiency was obtained. Here, the above 4 states are considered from the viewpoint of energy as follows:

1) Increasing, Decreasing: The motion command given to the actuator is binary. The state *Increasing* or *Decreasing* is the state "1" with the actuator itself is generating the active force. In this state, the joint moves by the contraction of the antagonist. By setting the state with no load to "1" and the state with load to "0," a large energy-saving effect can be obtained.

2) Free: In this state, the actuator is driven by the external force passively. No energy is supplied to the actuator. Although the human joint is subject to a motion of sagging by the attraction of gravity, this motion is scarcely used for the control of general machines. However, as shown later, the PDC uses this motion for small-energy "Increasing" and "Decreasing."

3) Lock: This state is binarized depending on whether it is active or not. Energy is consumed only for contracting the antagonists. When considering the human walking motions, the lock state is formed alternately by the right and left legs. In this lock state, the knee is completely extended, propping to prevent the center of gravity from falling. This lock state needs no contraction of the antagonists. From the viewpoint of the energy, this lock state is substantially different from that presented by Tomovic' *et al.* [4]. In this paper, this lock state is referred to as "mechanical (passive) lock," and the lock state for maintaining any attitude proposed by Tomovic' *et al.* is referred to as "functional (active) lock." It may be understood that the difference between the mechanical lock and the functional lock is equivalent to the difference between the normally open type and normally closed type of the friction brake. In terms of engineering, it is a passive element using the mechanical friction.

Generally, the mechanical energy is expressed as the product of the force and displacement. Therefore, the energy consumption can be decreased by decreasing the displacement when the force is generated, or weakening the force when the displacement should be increased. Then, when these 2 states are switched with good timing actions, a motion with extremely small energy consumption can be realized.

D. Basic Principle of Passive Dynamic Control

Generally, the balance generation ("balancing") involved in the control has active method and passive method. In the active method, the external force is detected by a sensor and the active force is generated to achieve the balance. However, this method is accompanied by the possibility that the control system could run away due to trouble. Here is a fundamental problem that no error is permitted in the active control for maintaining the balance state. On the other hand, the passive method can prevent any functional loss due to trouble when the balance is achieved by using, for example, a friction brake ("lock"), a passive element.

In the mechanical system, the active control element is the actuator, such as electric motor and hydraulic and pneumatic cylinders, receiving energy in the forms of electricity and pressure and converting the energy into the action of force or rotation. On the other hand, the means for the passive balancing ("passive element") is an element, such as brake, spring and dashpot, consuming, accumulating or discharging the energy. The passing balancing is functional passive element judging from the conditions of the control element ("controllability").

In this paper, the authors propose the *passive dynamic control* (PDC) in which the active method and passive method for the balancing is combined effectively. One of the concepts of the PDC is shown in Fig.1. In the PDC, there are 2 states locked by the passive element as follows:

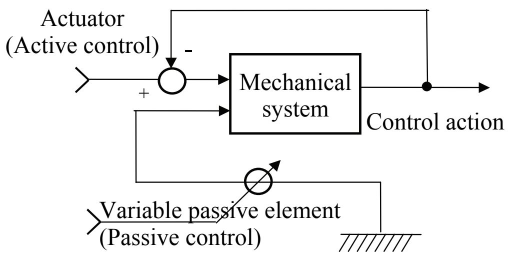

Fig. 1. Concept of the PDC.

1) Free Balance Lock: This is the balancing state in which no action is made even if the lock is released ("free balance") but the lock is still applied forcedly. It may be considered as the state obtained by the execution of the free balance under the passive lock.

2) Imbalance Lock: This is the above free balance state plus the imbalance state, wherein these 2 states are forcedly lock. It may be considered that the imbalance is generated in this state.

The free balancing and the generation of the imbalance are the passive control by means of sensor and actuator. Since they are executed by the free balance lock and the imbalance lock, respectively, in the passive lock state, there is no possibility of dangerous runaway. For example, the "Increasing" and "Decreasing" presented by Tomovic' *et al.* are the generation of the imbalance by the imbalance lock. Here, the release of the lock means the output of force, for which there are safety criteria. The imbalance is compared with the reference value. If the generation of the normal imbalance cannot be confirmed due to failure, the passive lock will not be released. Since the imbalance does not permit any error on the increase side after the release, the imbalance is generated by using the spring balancer (described later) to assure the safety. In this way, the passive lock is an important element for the free balancing and the generation of the imbalance.

III. Balance Servo System by the PDC

A. Control Operation and Balancing

The control had 2 types of actions: the action for meeting the purpose, and action due to disturbance. The action for meeting the purpose is "operation" to be taken in order to meet the purpose, and the action due to disturbance is unfavorable and unexpected, including one due to failure. The servo system intends to match the controlled variable by the action for meeting the purpose. In the mechanical positioning control, the balance of force, i.e., the balance state, is achieved in the steady state. Also in the mechanical positioning control, operation to counteract the disturbance action and achieve balance ("balancing") is required. The conventional control systems intend to achieve both the intentions by the active method.

The main purpose of the control theory is to stabilize the operation to suppress the disturbance. The positional feedback contains the information of the force imbalance, and the stability of the positioning control is decisively dependent on the stability of the force balancing. The PDC regards the mechanical control process basically as the creation of the constant balance state (free balance lock) $\rightarrow$ the creation of the imbalance (imbalance lock) $\rightarrow$ the execution of the purpose control $\rightarrow$ the fixation of the imbalance (imbalance lock) $\rightarrow$ the creation of the new constant balance state (free balance lock), and completes the preparation for the purpose control under the passive lock. Therefore, the PDC can execute the purpose control while securing the energy saving and the safety.

B. Balance Servo and the PDC

The servo that follows the basic process of the PDC is referred to as "balance servo." In this section, the authors consider the application of the balance servo to the mechanical positioning control. The balance servo is not pursued in the cybernetic actuator. In human walking, however, the possibility of the balance servo is implied. For example, in human walking, the left foot is maintaining the passive balance (free balance lock) while the right foot is performing the forwarding motion, and vice versa.

In the positioning by the active control, the balancing is executed through the information of the positional deviation (error). This is the free balance state having no passive lock, and vulnerable to positional deviation due to the external force. The force is generated in the direction of correcting the deviation (imbalance) but this force is apt to become unstable due to delay element. Furthermore, in general, the large energy is consumed to maintain the balance of force.

On the other hand, the positioning control by the PDC starts from the free balance state with the passive lock. First, the operating force for moving to the target position is generated under the passive lock state (imbalance lock). The normal imbalance is confirmed, then passive lock is released, and then the controlled object moves toward the target position. For the positioning, the object is forcedly stopped in the target position by the passive lock. Then, the force is detected in the passive lock maintained state, and the positioning is finished after the free balance is achieved. Although there is no positional feedback from the sensor, since it is under the passive lock, there is no easy occurrence of displacement due to the external force (i.e., the PDC has high robustness.) If the deviation is excessive, the correction motion will be made by using the same procedure. If the operation to slow the speed immediately before the target position is executed, the accurate stop in the target position can be achieved.

Always considering the state of balance with the external force using the passive means with small energy consumption, the PDC realizes the energy saving that cannot be achieved by the conventional active servo. However, a passive dynamic element is still required for the application of the PDC. Such passive dynamic element is referred to as "PDC element."

C. Generation of Imbalance

The generation of the imbalance in the PDC is a step for preparing for the operation force to execute the purpose control. The operation force is generated by using a force sensor and an active actuator (e.g., spring balancer). This operation force is outputted in the free condition in the next step to execute the purpose control. In order for this operation force to satisfy the conditions of the inherently safe design, the imbalance should be generated in the passive lock state. If the operation force is still unable to satisfy the conditions of the inherently safe design, the passive lock should not be released. During the confirmation of the safety of the operation force, the erroneous increases in the operation force cannot be permitted.

D. PDC Element Using MR Fluid

In this study, as one of the important PDC elements, the Magneto-Rheological (MR) brake using MR fluid is used. The MR fluid is suspension dispersed with fine iron particles of the order of several µm in oiliness dispersion medium. The most outstanding feature of the MR fluid is its ability not only to control the phase change from liquid (viscosity) to solid (elasticity) by using magnetic field but also to control the viscosity (for liquid) and the yield stress (for solid) by the intensity of magnetic force. The MR brake is normally in the free state as low-viscosity fluid, and can be in the passive lock state when it is applied with magnetic field. Also, the viscous load on the MR fluid can be adjusted by adjusting the magnitude of the magnetic field. Therefore, the MR fluid can be used not only for generating the passive lock states of the free balance lock and the imbalance lock but also as a passive element for the speed control.

Another important feature of the MR brake as a PDC element and a passive lock element is that the use of the MR brake acts on the deceleration side. For example, the speed can be lowered sufficiently by using the MR brake toward the target position, and then the passive lock is executed in the target position. This allows the positioning control with a small error and high robustness. For the function achieved by the MR brake, the error is negligible for the safety purpose.

IV. Positioning Control of Functionalized Spring Balancer

A. Spring Balancer

The spring balancer is a spring that can supply a constant tensile strength regardless of its elongation within a certain range. The tensile force F of the coil can be varied by the "initial coiling" as far as it is within a certain range. A balance with the gravity can be realized when the load of mass m is adjusted to $F=mg$.

The characteristic of the spring balancer is shown in Fig.2. The initial coiling means the external work applied to obtain the tensile force F. This work is accumulated as a potential energy. Here, the energy E_0 accumulated in the spring by the tensile force F is given by the following equation:

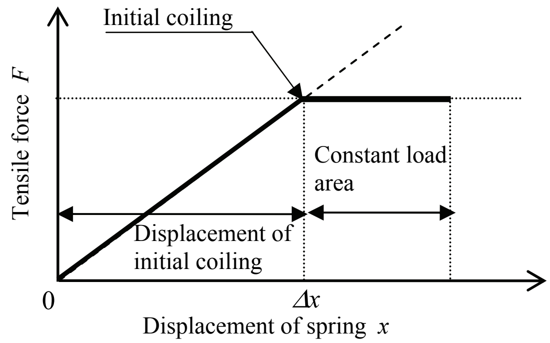

Fig. 2. Principle of spring balancer.

$$Eo = \frac{1}{2} k\Delta x^2 \tag{1}$$

where Δx is the initial displacement of the spring by the initial coiling, and k is the spring constant. The total energy E accumulated in the spring when the load of mass m is lifted by the height L with the tensile force F is given by the following equation:

$$\begin{aligned} E &= Eo + H - \Delta E \\ &= \frac{1}{2} k\Delta x^2 + mgL - FL = \frac{1}{2} k\Delta x^2 + (mg - F)L \end{aligned} \tag{2}$$

where, ΔE is the energy lost by the force of the spring balancer when the mass m is lifted by the height L, and H is the potential energy accumulated in the mass by lifting the mass m by the height L.

Therefore, the external work to lift the load is remarkably reduced by using the spring balancer. The complete balance state $mg=F$ is the free balance condition, where the external work to lift the load is no longer required.

When the spring balancer is used, since the load can be moved up and down without losing the energy supplied initially, the remarkable energy-saving effect can be obtained. Therefore, the spring balancer may be said as a memory device of the energy supplied by the initial coiling.

B. Functionalization for the PDC

The authors have developed a functionalized spring balancer by equipping a commercially available spring balancer with an MR brake and an electric motor. This spring balancer, as shown in Fig. 3, has 2 functions: accumulating the energy in the spring by making the initial coiling, and performing the passive balancing by adjusting the tensile force of the coil. The PDC can be applied by controlling the electric motor as an active element and the MR brake as a passive element.

C. Control Method

Here, the positioning control of an object in the vertical up/down direction by using the functionalized spring balancer is considered. First, the free balance state is realized by making the initial coiling load value equal to the load of the object ($F=mg$). Then, the imbalance is realized in the up (down) direction by using the motor. Now, the object can be moved up (down) only by the imbalance force. The imbalance lock is in the forced lock state realized by using the

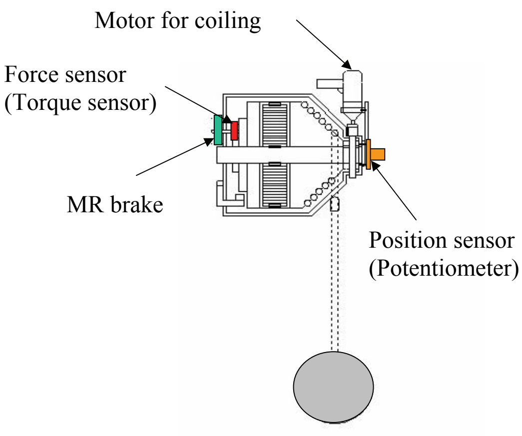

Fig. 3. Functionalized spring balancer.

MR brake. This can be realized only by force strong enough to brake the imbalance force $|F–mg|$. After locking the object at the target point x_p, the balancing is executed to eliminate the internal force (strain) generated by braking the imbalance force ($F=mg$). Then, the free balance lock state is resumed, and the free balance condition is maintained even after the passive lock is released.

The sequence in executing this positioning control by using the PDC is shown in Fig.4. Here, $x(t)$ is the height, x_p is the desired height, $T(t)$ is the torque on the MR brake, T_p is the threshold of the torque, and $V(t)$ is the speed of the load. First, the motor is run in the state locked by the MR brake to realize the imbalance state in the direction of the target position. When the imbalance force detected by the load cell reaches the threshold, the motor is stopped, and the lock state by the MR brake is released. When the load reaches the target value, the lock is applied again, and the motor is driven until the imbalance force becomes zero. When the load exceeds the target value, the motor is activated again to realize the imbalance state in the direction of the target position (opposite direction this time). This process is repeated until the load stops in the target position to realize the free balance state.

As described above, the PDC is a safe servo system substantially different from the conventional servo systems that is subject to the presence of deviation and intend to make the deviation zero.

D. Experiments

Using the functionalized spring balancer, experiments were conducted in the vertical up/down positioning control according to the sequence shown in Fig. 4. The spring balancer was equipped with a potentiometer for detecting the height of the load and a load cell for measuring the torque on the MR brake as shown in Fig. 3. The setting load range of the spring balancer was 50-60 kg, and the electric motor was a DC motor of 50W. The characteristics of the MR brake are shown in Fig.5.

First, an experiment was conducted in position control by moved the load of 55kg from the initial height 15cm to the target height 100cm based only on the basic principle of the PDC. The information of the position used in the control was

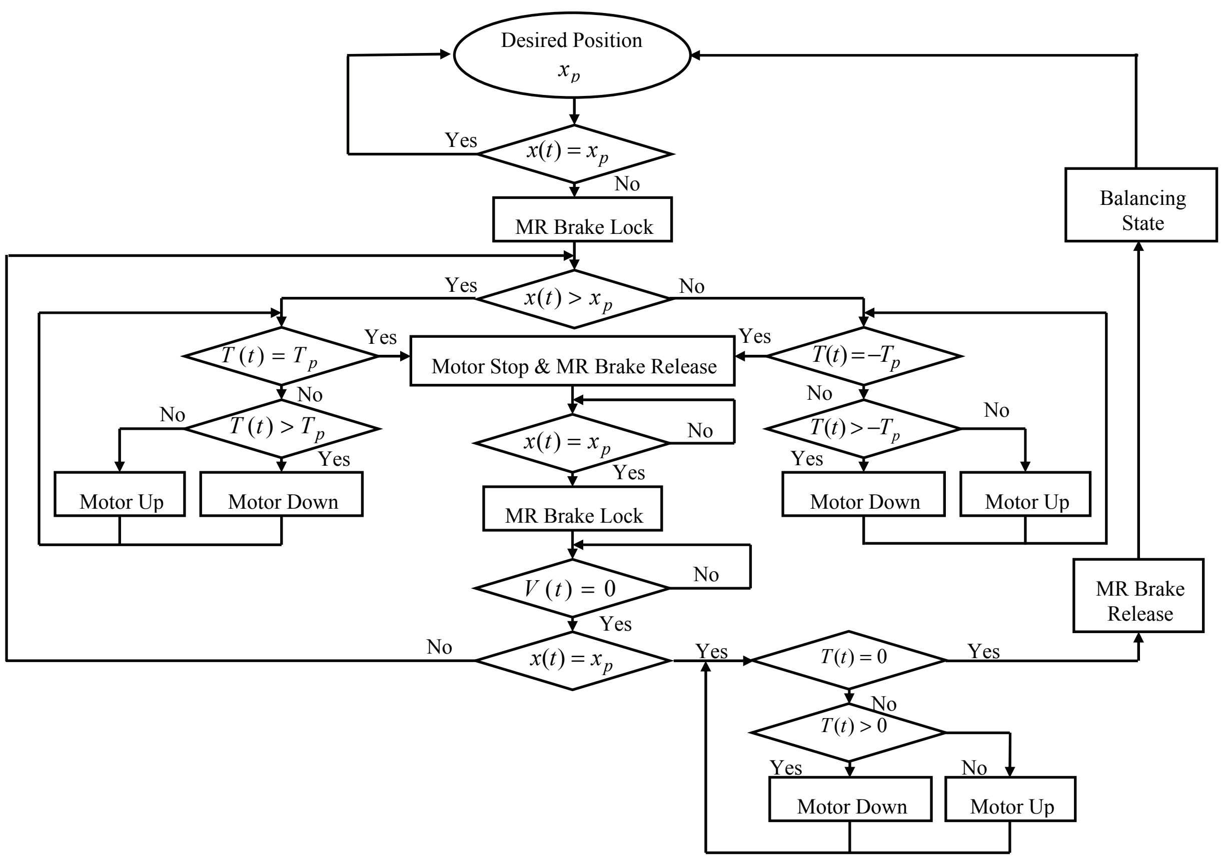

Fig. 4. Flow chart of the basic PDC.

only whether the load was in this side or in the opposite side of the target position. The information of the deviation (difference between the target height and present height) was not used. Next, additional experiments were carried out under the same condition, where the virtual desired value was introduced and the brake was used at that point in order to reduce the overshoot.

The experimental results are shown in Fig.6. Here, "with one VDV" is the case with one virtual desired value, and "with some VDVs" is the case with some virtual desired values. From this figure, it is understood that the basic control by the PDC could not stop the load at the target value at once but could make the stop by repeating convergences. Although it took time, the load of 55kg could be controlled by the motor of 50W. The effectiveness of introducing the brake control was evident. These are the most fundamental experiments of the PDC, and the control performance will be improved by using, for example, the information of the deviation, the speed control, or other techniques, as well.

Matlab and Simulink were used in the above experiments.

V. Conclusions

In this paper, the passive dynamic control (PDC) using the active control and the passive control together was proposed, and the balance servo by the PDC was described. The PDC has advantages summarized as follows:

1) Energy Saving: The purpose control requires no supply of energy, since basically uses the imbalance of force. The only energy that is required for the purpose control is the energy for producing the imbalance. For the mechanical systems, power consumption can be drastically reduced, since the control can be realized by using a small electric motor. Furthermore, there is almost no need of energy to suppress the disturbance, since the target position is held by the brake mechanism. This saves the energy to a great extent compared with the energy required for maintaining the target value and suppressing the disturbance.

2) Safety: Since the energy treated by the PDC is small, even if a runaway is caused due to failure in the control or trouble, the possibility that such runaway would result in a disaster is small, and the possibility of satisfying the conditions of the inherent safety is large. In addition, since the purpose control and the target position holding are achieved by using the passive element (brake mechanism), there is no oscillation due to delay, and there is the safety effect similar to emergency stop.

3) Stability: There is no oscillation due to delay, as described above. Since the position is locked by the passive element when it reaches the target position, the output is free from any adverse effect of disturbance or parameter variation. That is to say, there is no need to analyze the stability against disturbance or parameter variation. Since the adverse effect of disturbance appears as strain, if the strain is detected and reduce it to zero by means of the balancing operation, there will be no possibility of runaway (divergence) even if the lock is released.

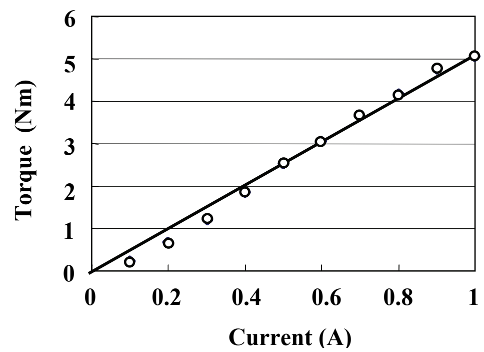

Fig. 5. Torque property of MR break.

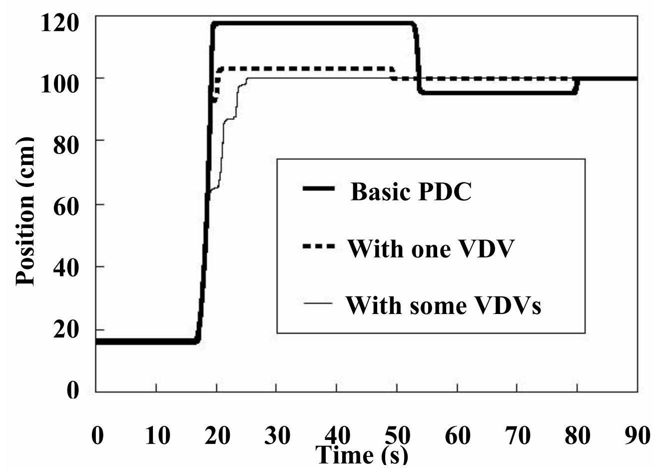

Fig. 6. Positioning control.

The PDC is a control system that does not basically emphasize a quick response. The application range can be widened by using the conventional control methods together or selectively. This is a highly potential, new control method. At present, as the research and development projects with respect to the PDC, the application of the functionalized spring balance is under way to welfare and nursing equipment, amusement equipment, rescue robot systems, material transport systems in production sites, and small elevator systems. Furthermore, a seismic isolator system [6] using the PDC is under development.

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