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Active Control of Self-locking Characteristic of Ultrasonic Motor

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Abstract

This paper discusses a new control method for an Ultrasonic motor (USM). An USM has the capability of generating a resistant torque against an external one even under power-off, which is well known as self-locking characteristic and conveniently utilized to save energy while maintaining rotor position. The goal of the paper is to relax the self-locking characteristic and to widely change it between lock and free states. In order to achieve this, we newly propose the two d.o.f PWM control, in which OFF command is included in addition to CW and CCW commands. By applying this, we can also control the torque of USM in open loop without using any complicated circuit. In this paper, we first demonstrate the basic structure of the two d.o.f PWM control, and then show several experimental results to verify the effectiveness of the scheme proposed.

I. Introduction

By taking advantages of their "light weight", "high torque", and "silent motion" of USMs, recently they have been utilized as actuators for driving joints of articulated robots, especially prosthetic arm and hand [1]-[3].

A typical USM (see Fig.1) is composed of a rotor, a stator made by elastic body and piezo-electric elements for actuation. When sinusoidal signals are sent to the piezo-electric elements in phase, they start stretching and contracting motions alternately. These periodic motions are directly transmitted to the stator connected to the piezo-electric elements in layers. As a result, a sinusoidal wave appears on the surface of the stator, as shown in Fig.2(a). The wave appeared under this condition is a standing one but not a traveling one, and therefore, it does not generate any drive force for the rotor.

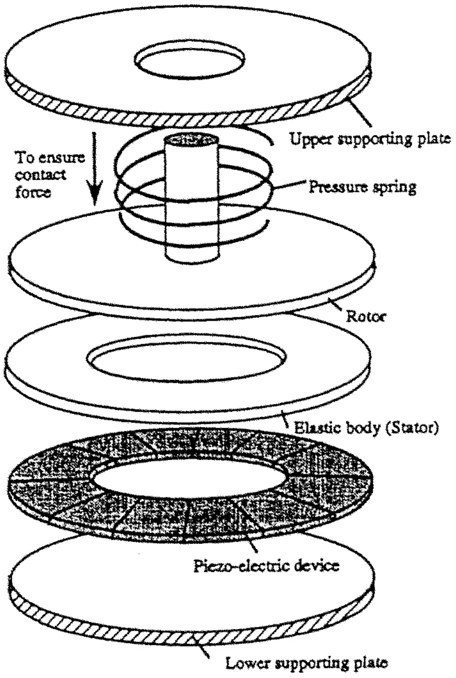

Fig.1 The structure of USM

Now, let us assume that two set of the piezo-electric elements are driven by two sinusoidal signals with a different phase, as shown in Fig.2(b). Under this condition, the wave appeared on the surface of the stator results in a traveling one propagated along the stator ring. This wave eventually generates a drive force through the points of contact between the stator and the rotor, as shown in Fig.2(c). In order for the rotor to receive a high friction torque from the stator, they are normally pressed to each other by a pressure spring.

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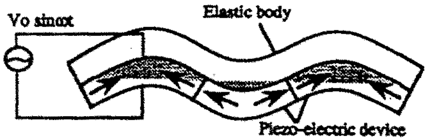
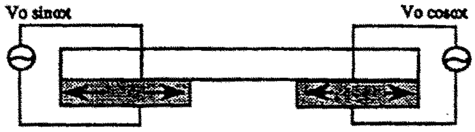
Because of this particular mechanism of USM, it can generate a resistant torque against an environment, even when the power is off. In other words, the actuator itself has the self-braking mechanism. This is well-known as self-locking (or self-braking) characteristic of USM. Owing to this characteristic, the image coming from USM was "stiff" and "rigid" until Nishihori, et. al. [1] had introduced the PWM control, where they combined clockwise (CW) and counter clockwise (CCW) commands with a proper period. By switching from CW to CCW with a high frequency, the drive torque quickly changes from CW to CCW and vice versa, which contributes to reducing the friction between the rotor and the stator, and keeping their contact condition between them in slippage. Under this condition, the rotor can easily rotate by a small external torque. One major advantage of this control is that the PWM control does not require any torque (or force) sensor for making such free phase, because it is based on an open loop control. Thus, the PWM control provided us with a new image, "compliant" to USM in addition to conventional ones. Since both prosthetic arm and hand require compliant motion control in achieving a constrained task, the realization of compliant motion by PWM control brought a great advantage for using USM in such systems. Although the PWM control enables us to realize two extreme phases, namely, the compliant phase and the stiff one where the stiff phase corresponds to self-locking phase, it cannot provide with any intermediate phase between two. Furthermore, the PWM control produces a sever operating condition leading to short life, since the command is switched from one to the completely opposite phase every half cycle.

Our goal in this paper is to change the resistant torque continuously from free phase to locked one by introducing the newly proposed two d.o.f PWM control. The key idea of this control is to insert OFF period between CW and CCW periods in the conventional PWM control. By inserting OFF period, we can acquire two remarkable effects that can not be obtained through the conventional approach. One effect is that by increasing the OFF period gradually from zero, we can change the resistant torque continuously from free phase to locked one. The other one is to suppress the drastic change of the state from CW to CCW phase and vise versa, that was inevitable in the conventional PWM control scheme. By inserting OFF period, the state will change, such as CW→OFF→CCW→OFF→CW. Since the insertion of OFF period makes it possible to avoid a sudden change of state, it is desirable from the viewpoint of increasing the life time of USM. Thus, the two d.o.f contributes to enlarging the capability of USMs and extending its life time.

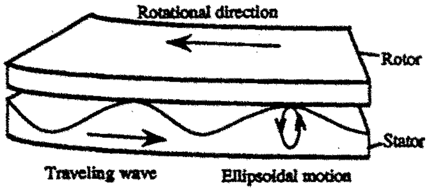
We begin by briefly reviewing the conventional works of USM in section II. In section III, we will discuss the precise structure of the two d.o.f PWM control. Then, we will show several experimental results in section IV to confirm the effectiveness of the control scheme proposed in this paper.



(a) Motions of piezo-electric device and elastic body



(b) Two sinusoidal signals to piezo-electric devices with different phase



(c) The relationship among traveling wave, ellipsoidal motion and rotational direction

Fig.2 The working principle of USM

II. Conventional Works

USM has a long history. In 1973, Barth [4] developed the prototype model of USM, in which the rotor is directly driven by the two piezo-electric elements. As it had many essential problems, such as short life due to the generation of heat by friction and large friction loss at the point of contact, the USM based on this principle has not been accepted in market. In 1982, Sashida [5] designed and developed the traveling wave type USM, as shown in Fig.1, where the rotor receives the driving force through the ellipsoidal motion on the surface of the elastic stators vibrated by the piezo-electric elements. The traveling wave is essential for generating the ellipsoidal motion on the surface of the elastic stator. The utilization of elastic stators contributes to avoiding the sharp increase of the contact force in the contact between the rotor and the stator. As a result, the traveling wave type USM succeeded in relaxing high temperature problem due to the direct contact between the rotor and the piezo-electric devices and improving the life of USM. Since then, many research projects on USM have been started in both universities and private companies especially in Japan [6]-[8], with focusing on traveling wave type USM. Due to these projects, many sophisticated USMs are now commercially available in economic price (for example see [9]). By taking additional advantages into considerations, such as quick response, high torque with compact size, and silent motion, USM is recently implemented into various mechatronics devices, such as the actuator for driving a auto-focus lens [10], and the actuator for drawing a curtain.

On the other hand, there have been a couple of applications for robotics. For example, Scoenwald, et. al. have utilized USM as an actuator for a robot gripper [11]. As far as we know, this is the first application of USM to robotics. Nagata has also utilized USM for actuating a turntable implemented into parallel-jaw gripper [12]. In 1991, Ito, et. al. developed a prosthetic forearm whose joints are actuated by small sized USMs [2]. It has three degrees of freedom driven by the commands based on human's EMG signals. Kato, et. al. [3] have challenged to realize compliant motion in different idea from the PWM control. Shifting the phase corresponds to changing the ellipsoidal motion on the surface of elastic stators. With the zero phase difference, the ellipsoidal motion results in a line motion which does not generate any drive force. As increasing the phase difference from zero to $\pi/2$, the drive force gradually increases. This implies that we can control the output torque by changing the phase between two sine-wave signals. Kato, et. al. have succeeded in achieving the compliance control by using this idea. In order to realize this idea, however, it needs a complicated circuit for phase shifting, while the two d.o.f PWM control does not.

III. Two D.o.f. PWM Control

Fig.3 shows the basic control system for driving an USM, where the drive circuit generates two kinds of pulses having $\pi/2$ phase shift in each other and the frequency coincides with the natural frequency of the piezo-electric devices. The computer sends commands, such as CW, CCW and OFF to the drive circuit with a sufficiently large period compared with that of pulses generated in the circuit. We call one cycle of command given by the computer the control period denoted by T. The control period T is further divided into three periods, t_1: clockwise (CW) period, t_2: counter clockwise (CCW) period, and t_3: OFF period, as shown in Fig.4. Even after determining a proper T, we can change two of three periods freely, while one of them is automatically determined based on the relationship of $T=t_1+t_2+t_3$. So, we have two freedoms for determining three periods for control. This is the reason why we call the control two d.o.f PWM control. The key idea of this control is to put OFF period into the control scheme, which greatly contributes to changing the self-locking torque and extending the working capability of USM. We begin by defining three duty factors of the two d.o.f PWM control.

3.1 Definition of Three Duty Factors

$\alpha=t_1/T$: the ratio of CW period over the control period.
$\beta=t_2/T$: the ratio of CCW period over the control period.
$\gamma=t_3/T$: the ratio of OFF period over the control period.

Three duty factors are not independent upon each other because the relationship $\alpha+\beta+\gamma=1$ always exists. Note that the two d.o.f PWM control results in the conventional PWM control by setting $\gamma=0$.

3.2 Mechanisms for Changing Self-locking Characteristic

Let us assume even ratio for both CW and CCW periods, that means $\alpha=\beta$. Under this condition, the rotor receives exactly same CW and CCW directional torque alternatively.

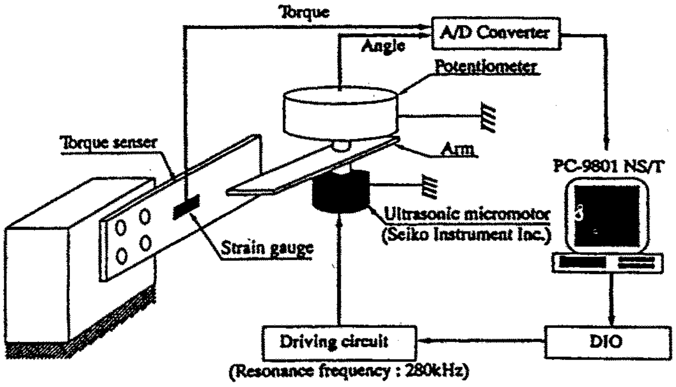


Fig.3 Basic control system for driving USM

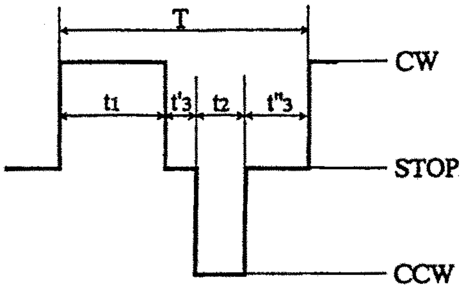


Fig.4 Definition of parameters

For a sufficiently large control period T, CW and CCW motions of the rotor will be observed alternatively. Now, let us assume to decrease T gradually. As T decreases, the amplitude of the reciprocal motion also decreases and eventually results in zero before T reaches zero. This mechanism can be explained as follows: Let us assume that the command is quickly changed from CW to CCW direction. In such a case, the piezo-electric devices also quickly change the oscillation mode and make the opposite directional traveling wave on the surface of stator. This motion change should be quick enough to ensure that we can neglect the time delay, since the concerned mass is sufficiently small. As a result, the rotor starts to receive the CCW directional torque from the stator. Because of the relatively large inertia of the rotor, however, it takes a time for the rotor to change the rotational direction. Due to such delay effect coming from the inertia of rotor, for a quick change of command from CW to CCW direction, the rotor continuously rotates in the CW direction for a while. After the rotor rotates by a certain distance in CW direction, it stops and then starts to rotate in the CCW direction. Now, let us assume to decrease T. When we select a sufficient small T, the command will be switched before the drive torque overcomes the friction torque and the inertia torque. As a result, the rotor will be unable to rotate for such a short time period. Therefore, there should exist the critical time period T_c, where the amplitude of the reciprocal motion results in zero. T_c strongly depends on the size of USM. As the size increases, T_c increases.

Now, assuming T less than T_c, let us discuss the mechanism why the self-locking characteristic is relaxed under $\alpha=\beta$. Under this condition, the rotor can not rotate as explained before. Since the stator generates traveling wave every T/2, slips continuously occur at points of contact between the rotor and the stator. This is just like reducing friction between piston and cylinder by adding a dither signal to the command signal for a hydraulic actuator. The self-locking torque is relaxed through the reduction of friction between the rotor and the stator. The control under $\alpha=\beta$ and $\gamma=0$ is exactly the same as that of the conventional PWM control proposed by Nishihori, et. al. [1], and brings the most frictionless state between rotor and stator.

Now, let us discuss the effect of the insertion of OFF period, namely, $\gamma\neq0$. Inserting OFF period is equivalent to stopping the dither signal intermittently. Therefore, as γ increases, the friction between the rotor and the stator also increases, and eventually results in the self-locked mode with $\gamma=1$, which is the most frictioned state. These discussions can be summarized as follows:

• $\alpha=\beta$, $\gamma=0$	Free state
• $\gamma=1$	Locked state
• $\alpha=\beta$, $0<\gamma<1$	An arbitrary state between free and locked states

Thus, we can change the self-locked torque continuously from free to locked one, which is the most significant characteristic obtained from the two d.o.f PWM control and cannot be achieved using the conventional approaches.

IV. Experimental Evaluation

4.1 Experimental System

Fig.3 shows the experimental system composed of an USM (U-PT0758, resonance frequency 280 kHz: Seiko Co.), a potentiometer for measuring the rotational angle, an arm with the mass of 2.0×10^{-3}[kg] and the moment of inertia of 4.33×10^{-7}[kgm^2], a torque sensor for measuring the self-locking torque, a drive circuit, and a computer for sending CW, CCW and OFF commands to the drive circuit.

4.2 Estimation of T_c

Before precise experiments, we measured the critical time period T_c. Fig.5 shows the potentiometer outputs for various T, where Fig.5 (a), (b), and (c) are executed under T=2.0[ms], 10.0[ms], and 20.0[ms], respectively. In Fig.5, the time axis for the potentiometer is shown in the lower horizontal line and that of command signal from computer is shown in the upper one. Note that distinct oscillating motions are observed for the potentiometer output under T=30.0[ms], while they almost disappear under T less than 10.0[ms]. These preliminary experiments suggest that the critical time period T_c is between 2.0[ms] and 10.0[ms]. Through more precise experiments, we found it about 6.0[ms]. Since the resonance frequency of the piezo-electric device is 280kHz, the rotor receives 840 drive pulses from the stator during the half cycle of the control time period when we set $T=T_c=6.0$[ms]. Even for such a large number of drive pulses, the rotor cannot rotate when the control command is switched in every $T_c/2$.

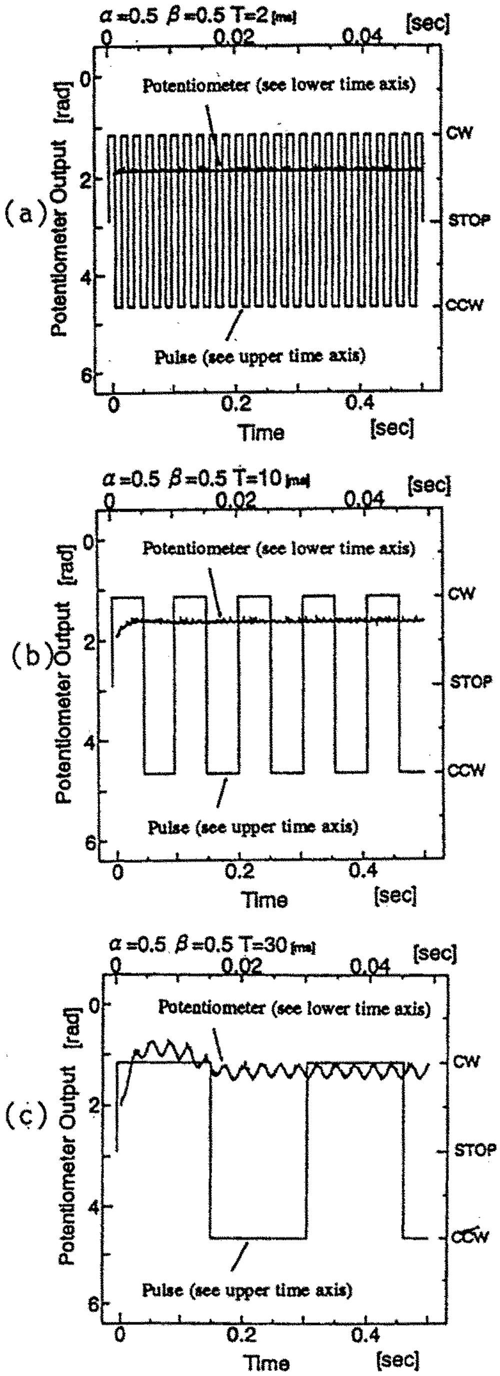


Fig.5 Preliminary experiments to estimate T_c

4.3 Active Control of Self-locking Torque

Fig.6 shows the experimental results of the self-locking torque for various γ, where α=β and OFF period is distributed equally between CW and CCW, $t_3'=t_3''$. In this experiment, we set T=5.0[ms], because we have already confirmed that under this control time period, the rotor remains stationary. It can be seen from Fig.6 that the self-locking torque keeps a small and constant values between γ=0 and γ=0.7, and it sharply increases after γ=0.7. Thus, the self-locking torque does not change linearly with respect to γ, but varies non-linearly. We can regard the phase between γ=0 and γ=0.7 as a free phase and, therefore, the self-locking torque can be actively changed by simply adjusting γ between γ=0.7 and γ=1.0. This characteristic is desirable for providing a mild working condition with the USM and for extending the life time. Under γ=0, the command is quickly switched in every T/2 from CW to CCW and vice versa, which produces a large change of state at points of contact between the stator and the rotor, the moment that the command is switched. By inserting OFF period between CW and CCW command, we can reduce the large change of state between them and avoid such a sever condition expected under γ=0. Thus, the insertion of OFF period is desirable in the sense of avoiding a cruel operating condition for USM.

4.4 Open-loop Torque Control

By introducing the two d.o.f PWM control, we can also control the rotor torque without implementing any torque feedback loop. In this section, we examine how precisely we can control the rotor torque in open-loop.

Fig.7 shows the torque appeared in the arm in contact with the environment, where (a), (b), and (c) are executed under T=1.0[ms], T=2.0[ms], and T=5.0[ms], respectively. In Fig.6, both α and γ are selected as independent parameters. We focus on the CW directional torque characteristic alone, since we can expect the CCW directional characteristic by using symmetrical relationship. It can be seen from Fig.7 that the generated torque increases as T increases. This is because when T is small, the torque increase is blocked by the quick change of command from CW to OFF (or CCW) before the rotor receives sufficiently large torque from the stator.

Now, let us examine the torque response when changing α step by step. Changing α is equivalent to changing torque command. Fig.8 shows the experimental results of the generated torque against an environment when increasing α from 0.0 to 1.0 with 0.2 interval and decreasing with the same interval, where β=0, that means CCW directional command is not included. A remarkable result in Fig.8 is that the torque does not change even when changing α after α=0.6, while it changes between α=0.0 and α=0.4. As seen from Fig.7(c), for example, the generated torque should increase when increasing α from 0.4

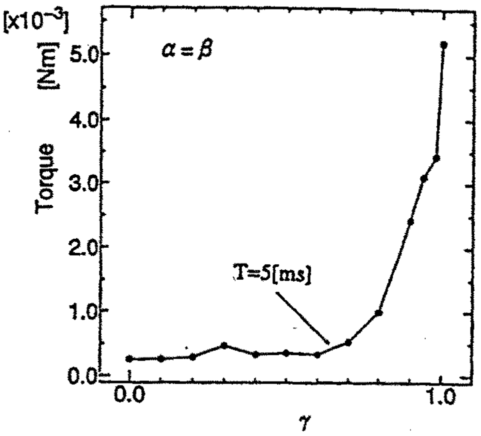
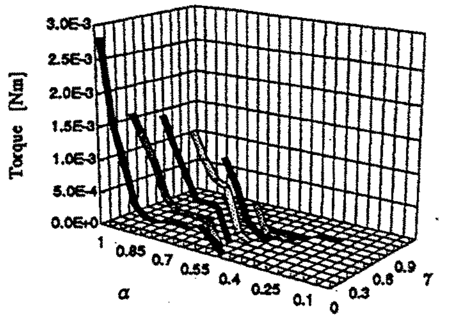
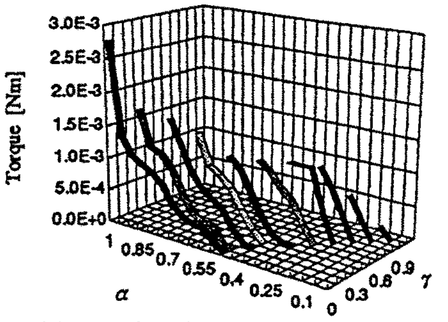


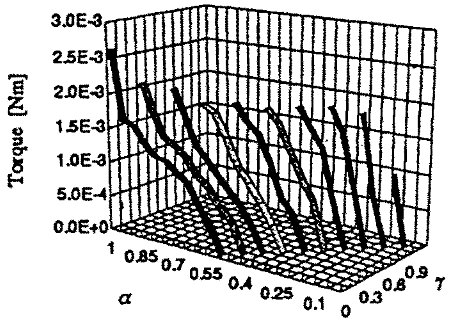
Fig.6 Active control of self-locking torque



(a) T=1.0[msec]



(b) T=2.0[msec]



(c) T=5.0[msec]

Fig.7 Open loop torque control

to 0.6 and from 0.6 to 0.8 and so on. Let us now consider the reason why such a difference appears between two experiments. The major difference between two is the initial condition, namely, the command is changed from $\alpha=0$ to $\alpha=0.6$ in Fig.7, while it from $\alpha=0.4$ to $\alpha=0.6$ in Fig.8. Under $\alpha=0$, initially, the rotor is pressed to the stator firmly by a pressure spring, and then the start command is imparted to the USM. For a step change of command, the rotor efficiently receives the drive torque from the stator. Once the rotor starts to rotate, inertia torque of the rotor contributes to pressing the arm strongly against an environment. When the rotor stops, the inherent self-locking torque of USM takes over supporting the external torque against the environment. As a result, the arm can generate a relatively large torque against the environment. Under $\alpha=0.4$, the arm is already in contact with the environment and, therefore, the rotor is already in supporting external torque. The supported torque may be larger than that appearing when changing α from $\alpha=0.4$ to $\alpha=0.6$. Thus, the rotor fails to generate a larger torque that exceeds the one already produced in the process from $\alpha=0.2$ to $\alpha=0.4$. We believe that this is the main reason for the difference between two results. On the other hand, while decreasing α, the self-locking torque continuously supports the external torque. This is the reason why the torque keeps constant when decreasing α from 1.0 to 0.0 step by step.

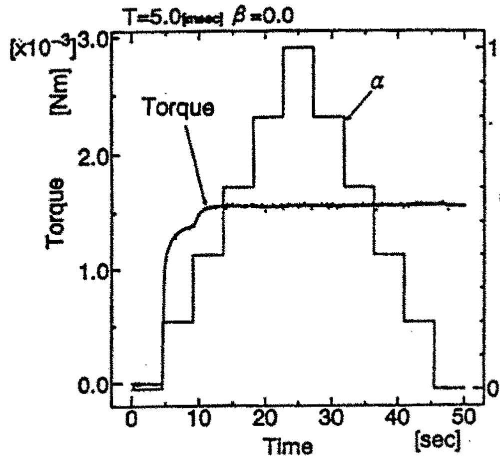


Fig.8 Step response of torque for various α ($\beta=0$)

Fig. 9 shows the torque response when changing α from $\alpha=0.5$ to $\alpha=1.0$ step by step, where $\gamma=0$. Under $\gamma=0$ and $\alpha=\beta=0.5$, the rotor does not generate any torque, because the rotor receives the same torque in both CW and CCW directions in every T/2. As seen from Fig.9, the torque control can be materialized much better under $\gamma=0$ than that under $\beta=0$. This is because we can suppress the friction related effects by combining CW and CCW commands together.

4.5 Consideration on the Position of OFF Period

In 4.3 and 4.4, we distributed OFF period evenly between CW and CCW periods for simplicity. In this section, we experimentally examine the effect of the distribution of OFF period in the time period T.

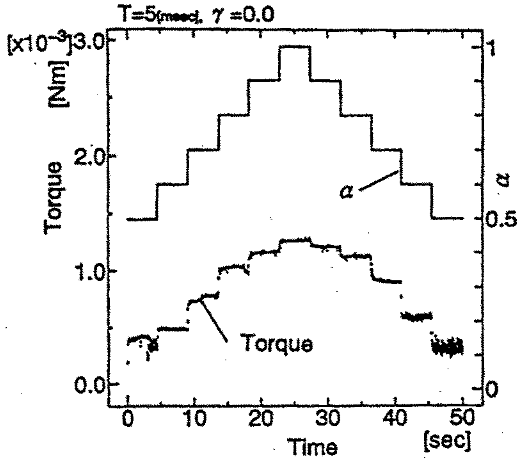
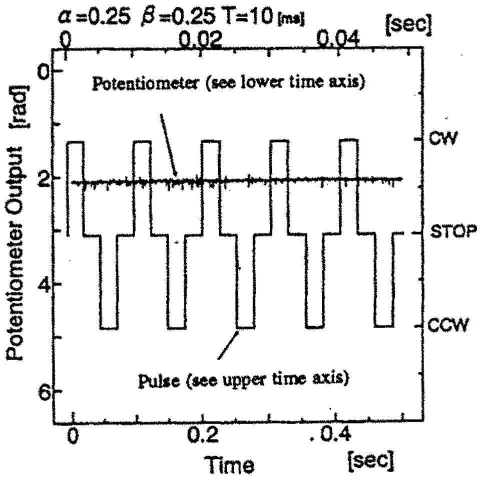
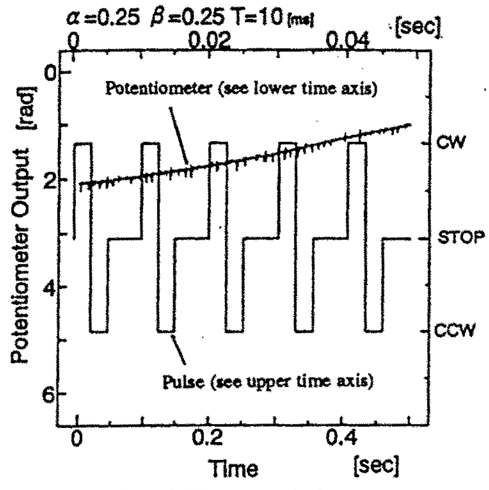


Fig.9 Step response of torque for various α ($\gamma=0$)



(a) $t_3'=t_3''=t_3/2$ and $\gamma=0.5$



(b) $t_3''=t_3$ ($t_3'=0.0$) and $\gamma=0.5$

Fig.10 Influence of the position of OFF period

Fig.10 shows the potentiometer outputs for two different distributions of OFF period, where $\alpha=\beta=0.25$, $\gamma=0.5$, and T=10[ms]. Fig.10 (a) and (b) are executed under $t_3'=t_3''=t_3/2$ and $\gamma=0.5$, and $t_3''=t_3$ ($t_3'=0.0$), respectively. The rotor does not rotate in steady state under even distribution of OFF period as shown in Fig.10(a), while it gradually rotates under uneven distribution as shown in Fig.10(b). This implies that the position of OFF period plays an important role to keep the torque balance between CW and CCW directions. When the whole OFF period is concentrated just after CCW command, the rotor receives small CW directional torque in average and slowly starts to rotate in CW direction. This can be interpreted in the following way. Since there exists OFF period before a CW command, the acceleration of the rotor in CW direction will be smoothly done. On the other hand, since there exists a CW period before a CCW command, it takes more time to start to accelerate the rotor in the CCW direction.

5. Discussion

In 1966, Tomovic and McGhee proposed the concept of Cybernetic Actuator based on the analysis of human muscle system [13]. They showed a couple of new requirements for the actuator which is useful for a robot having interactions with human. The Cybernetic Actuator should have the following four states.

State 1:Free
State 2:Decreasing
State 3:Increasing
State 4:Lock (or Clamp)

The state of decreasing means producing force/power against the direction of applied load. The state of increasing means producing force/power in the same direction of applied load. The state of lock means keeping position against applied load. The state of free means that the actuator easily moves for an external force. The free state is extremely important for a robot which has the possibility to interact with human. Ikuta and others [14], [15] have designed a new type of linear actuator capable of materializing the above four states by combining piezo-electric element for producing propelling force and miniature electromagnetic coil for producing clamp and release.

6. Conclusion

Two d.o.f. PWM control scheme composed of CW, CCW and OFF commands was proposed. We showed that this control is effective for changing the self-locking torque continuously from free to lock states, and for relaxing the sever operating condition utilized in the conventional PWM control. Through precise experiments, we found that under $\alpha=\beta$, there exists the critical time period T_c, where the oscillating motion of the rotor no more appears for a control time period less than T_c. We also found that the inserting position of OFF period changes the torque balance between CW and CCW direction, even under the same α, β, γ and T.

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