Proceedings of the

1996 IEEE IECON

22nd International Conference
on Industrial Electronics,
Control, and Instrumentation

Volume 1 of 3

Ultrasonic Motor with the Capability of Adjustable Self-locking Torque

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Abstract - *This paper discusses a new Ultrasonic Motor (USM) with the adjustable mechanism of self-locking torque. 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 widely change the self-locking torque between lock and free states. In order to achieve our goal, we propose a new type of USM having a pressure adjustable mechanism enabling us to control the contact force between the rotor and the stator. Two d.o.f PWM control, in which OFF command is included in addition to CW and CCW commands, is a good tool for changing the self-locking torque from the viewpoint of control. By combining the new USM with two d.o.f PWM control, we show that the self-locking torque can be largely changed from free to firmly locked states. We also show several experimental results to verify the effectiveness of the idea proposed.*

1. Introduction

An USM has several advantages compared with a DC servo motor. Since a DC servo motor generates a torque based on magnetic force, it needs sufficient volume for generating a large torque. On the other hand, since an USM generates a torque based on friction force between the rotor and the stator, sufficient surface is important for transmitting the driving torque. This is the reason why we can expect a larger torque in USM than in DC servo motor under a small size. In general, an USM can generate a large torque with low speed. Accordingly, we can connect a load directly to the rotor shaft without any reduction gear, while a reduction gear is indispensable for a DC servo motor. Having no use for reduction gear brings both light weight and silent motion. 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].

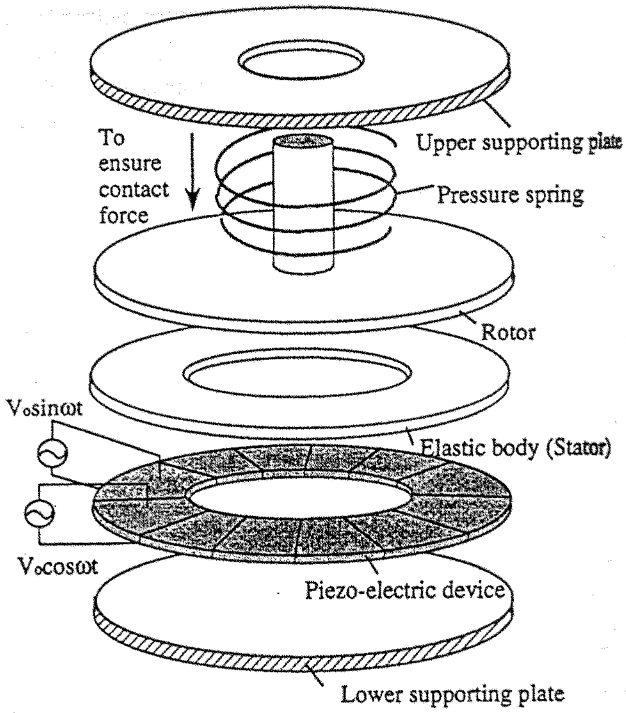

Fig.1 The structure of USM

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.

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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. 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. PWM control has been further extended to two d.o.f PWM control [4], where OFF period is inserted 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 PWM control. 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.

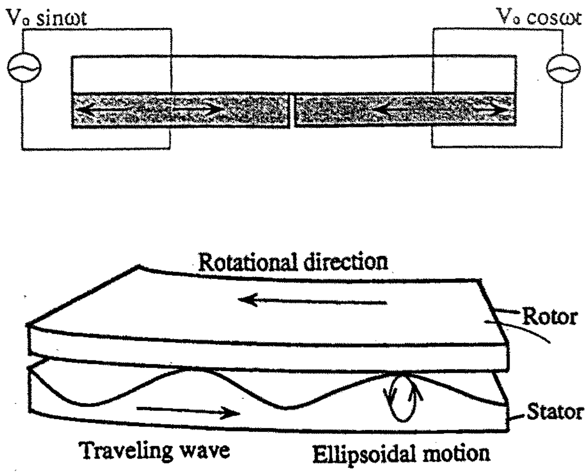


Fig.2 The working principle of USM

In this paper, we pursue a further extension of working region of self-locking torque by adding the adjustable mechanism of the contact force between the rotor and the stator. Since the rotor receives a torque from the stator through friction torque, the contact force between the rotor and the stator plays an important role for determining the maximum torque transmitted from one to another. This suggests that we can change the self-locking torque even by adjusting the contact force in addition to applying an appropriate control. After briefly reviewing the conventional works of USM in section II, we show the basic idea of USM with the adjustable mechanism of contact force between the rotor and the stator in section III. We discuss how to control the newly proposed USM in section IV. Then, we show several experimental results to confirm the effect of variable contact force between the rotor and the stator in section V.

II. Conventional Works

USM has a long history. In 1973, Barth [5] 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 [6] 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 [7]-[9], with focusing on traveling wave type USM. Due to these projects, many sophisticated USMs are now commercially available in economic price (for example see [10]). 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 [11], 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 [12]. 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 [13]. 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 [4] does not.

III. USM with Adjustable Contact Force Mechanism

Fig.3 shows an overview of the proposed USM with adjustable contact force between the rotor and the stator, where the position of the pressure board can be changed by the actuator implemented additionally. According to the position of the pressure board, we can continuously change the contact force between the rotor and the stator. As the pressure board comes down, the contact force increases due to the increase of compression force of spring. On the other hand, the pressure board comes up, it decreases. Since the maximum friction force from the stator to the rotor (or from the rotor to the stator) is proportional to the normal force, we can expect a larger self-locking torque under a larger contact force. Under a smaller contact force, we can expect a smaller self-locking torque. Therefore, by combining two d.o.f. PWM control with this newly proposed USM, we can further extend the operating region of self-locking torque and resultantly the working capability of USM.

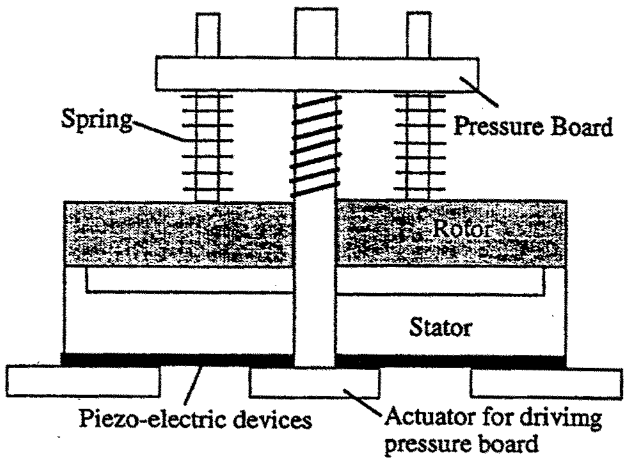


Fig.3 An example of USM with adjustable mechanism of contact force

IV. Two D.O.F PWM Control

Fig.4 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. Three duty factors of the two d.o.f PWM control are defined in the following.

4.1 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 a+b+g=1 always exists. Note that the two d.o.f PWM control results in the conventional PWM control by setting $\gamma=0$.

4.2 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. 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.

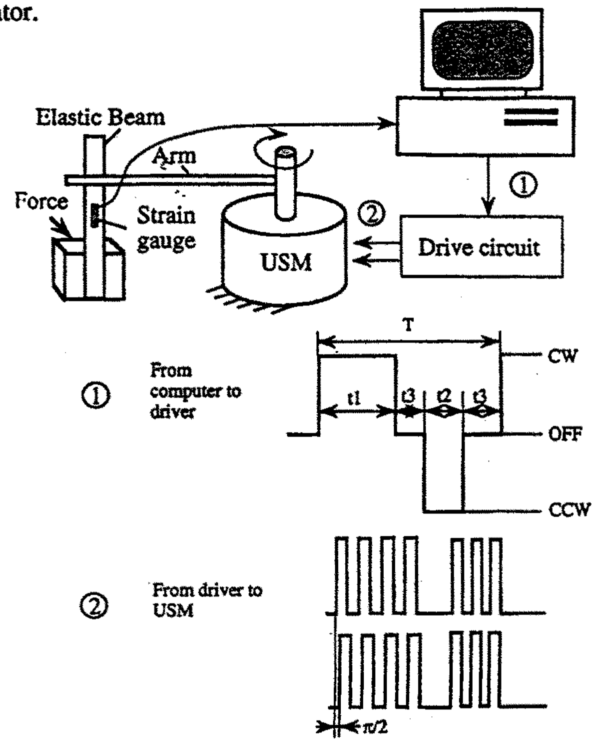


Fig.4 Basic control system for driving USM

Now, let us discuss the effect of the insertion of OFF period, namely, $\gamma \neq 0$. 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 lock

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 [4] and cannot be achieved using the conventional approach [1].

V. Experimental Evaluation

5.1 Experimental System

Fig.4 shows the experimental system composed of an USM, a rigid arm, a torque sensor for measuring the self-locking torque, a drive circuit, a potentiometer, and a computer for sending CW, CCW and OFF commands to the drive circuit. For experimental convenience, the torque sensor (strain gauge) is implemented to an elastic beam whose end is fixed to a cubic block. The block is put on a table so that we can move it freely by our hand. The self-locking torque is measured by pushing the arm by the elastic beam until the rotor finally starts to move. For a small pushing force, the rotor can support the external force due to the friction force between the rotor and stator. For a further large pushing force, however, the rotor can not support such an external force and, eventually, it makes a slip on the stator. The torque sensor output is continuously fed into the computer for monitoring and the maximum torque just before slipping is examined by utilizing the peak point search algorithm.

5.2 Estimation of T_C

Before precise experiments, we measured the critical time period T_C and found that the critical time period T_C is between 10.0[ms] and 30.0[ms]. Based on this fact, we set the time period T less than 10 [ms] in the following experiments.

5.3 Measurements of Self-locking Torque

Fig.5 shows the time history of torque sensor output when the elastic beam is pressed to the arm, where these experiments are done under $\alpha=\beta$ and different γ. $\alpha=\beta$ means that the rotor does not receive any net time average torque from the stator, while it receives CW and CCW directional torque intermittently. $\gamma=0$ means that no input is applied to the USM. The result in $\gamma=0$ tells us the following fact. The rotor can support the external torque until the torque between the rotor and stator becomes the maximum static friction torque. When a torque exceeding the maximum static friction torque is imparted to the arm, the rotor can no more support the external torque, and as a result, it starts to slip. Once the rotor makes slip on the stator, the contact condition drastically changes from static friction to dynamic friction. In general, the dynamic friction torque can support less torque than that of static friction torque. Since the gap between two kinds of friction torque is large in general, we can observe the distinct change of torque before and after making slip.

On the other hand, for experimental results of both $\gamma=0.6$ and $\gamma=0.9$, we can not observe such remarkable jump of torque before and after making slip. In these two cases, the contact condition between the rotor and the stator is already in slipping condition since CCW and CW signals are alternatively applied to the piezo-electric devices. Accordingly, the dynamic friction condition is already kept before and after making slip. This is the reason why the torque does not jump before and after the rotor makes slip. Although it is relatively difficult to measure the exact self-locking torque, we measure it by picking up the first peak of the torque sensor signal. Generally, as γ decreases, the self-locking torque also decreases.

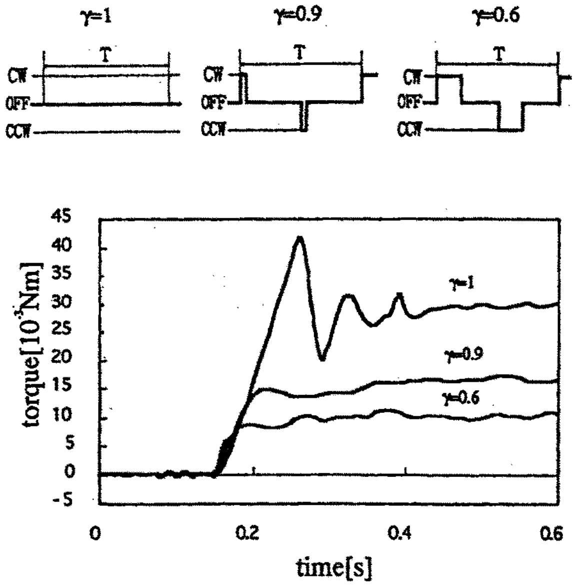
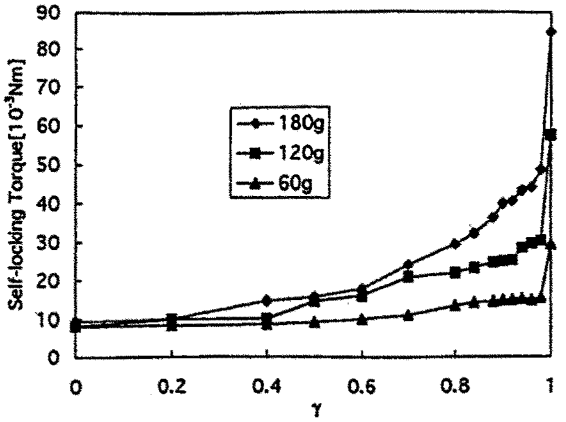
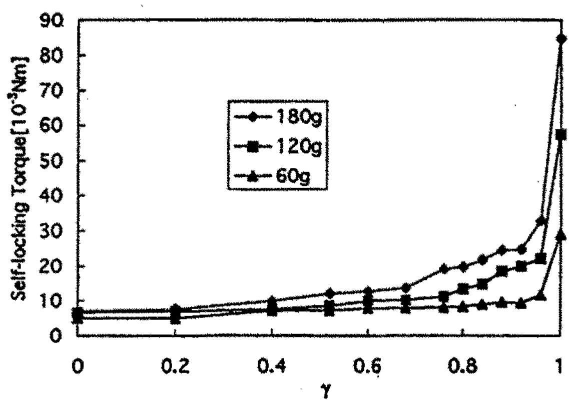


Fig.5 Time history of torque sensor output

Fig.6 shows the experimental results of the self-locking torque for various γ and contact force between the rotor and the stator, where $\alpha=\beta$ and OFF period is distributed equally between CW and CCW, $t_3'=t_3''$. In this experiment, we set (a)T=10.0[ms] and (b)T=5.0[ms], because we have already confirmed that under this control time period, the rotor remains stationary. The contact force is changed by putting the weights on the rotor. It can be seen from Fig.6 that the self-locking torque keeps a small and constant values between $\gamma=0$ and $\gamma=0.8$, and it sharply increases after $\gamma=0.8$. Thus, the self-locking torque does not change linearly with respect to γ, but varies non-linearly. We can regard the phase between $\gamma=0$ and $\gamma=0.8$ as a free phase and, therefore, the self-locking torque can be actively changed by simply adjusting γ between $\gamma=0.8$ and $\gamma=1.0$. This characteristic is desirable for providing a mild working condition with the USM and for extending the life time. Under $\gamma=0$, 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 $\gamma=0$. Thus, the insertion of OFF period is desirable in the sense of avoiding a cruel operating condition for USM.



(a) T=10.0[ms]



(b)T=5.0]ms]

Fig.6 Self-locking torque

Another interesting observation in Fig.6 is the behavior for the contact force. The self-locking torque also varies in proportion to the contact force imparted to the rotor. This fact is quite naturally accepted, because the friction force is proportional to the normal force (contact force). From Fig.6, it is obvious that changing the contact force greatly contribute to extending the working condition of USM, especially from the viewpoint of adjusting self-locking torque.

VI. Conclusion

A new USM with the adjustable mechanism of contact force between the rotor and the stator was proposed to extend the working region of self-locking torque. We showed that the combination of the proposed USM with two d.o.f. PWM control is effective for changing the self-locking torque continuously from free to locked states. By increasing the contact force, we could increase the self-locking torque almost in proportion to the contact force applied. We also showed that the self-locking torque sharply increases between γ=0.8 and γ=1.0, while it almost keeps constant. Through precise experiments, we found that 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.

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1996 IECON 22ND International Conference on Industrial Electronics, Control and Instrumentation (IECON'96)

IEEE Catalog Number: 96CH35830
Library of Congress Number: 95-77996

ISBN Softbound: 0-7803-2775-6
ISBN Casebound: 0-7803-2776-4
Microfiche: 0-7803-2777-2

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