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Velocity Profile Generation Methods for Industrial Robots and CNC Machine tools

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Abstract: We propose software algorithms which provide the characteristics of acceleration/deceleration essential to high dynamic performance at the transient state where industrial robots or CNC machine tools start and stop. The path error, which is one of the most significant factors in performance evaluation of industrial robots and CNC machine tools, is analyzed for linear, exponential, and parabolic acceleration/deceleration algorithms in case of circular interpolation. The analysis shows that the path error depends on the acceleration/deceleration routine and the servo control system. In experiments, the entire control algorithm including the proposed acceleration/deceleration algorithms is executed on the motion control system with a floating point digital signal processor(DSP) TMS320C30 as a CPU. The experimental results demonstrate that the proposed algorithms are very effective in controlling axes of motion of industrial robots or CNC machine tools with the desired characteristics.

I. INTRODUCTION

The new era of automation, which started with the introduction of industrial robots and CNC machine tools, was undoubtedly stimulated by digital computers. Especially, digital control technology and high performance microprocessors enabled control systems for industrial robots and CNC machine tools to be designed flexibly. As a consequence, they can be adapted to the changes in production, so it has become possible to produce new products in a short time. In addition, the limitations in function and performance which could not be resolved in analog control systems have been overcome [1].

In the control system of industrial robots and CNC machine tools, the most important factor is to make the end effector or the machine tool follow the desired machining or contouring path within the permissible accuracy. To achieve this, the desired path data are generated and the servo motors, which actually drive the axes of motion, are controlled on the basis of them. The path data are usually obtained from acceleration/deceleration and interpolation routines. In practice, industrial robots and CNC machine tools require interpolations in order to coordinate the motion of machine axes to generate the required machining or contouring paths. Linear and circular interpolations are basic techniques in generating signals which prescribe the desired path, but other interpolation techniques such as helical, hypothetical axis, polar coordinate, and cylindrical interpolations are adopted in case of more complex paths. On the other hand, acceleration/deceleration techniques are essential to industrial robots and CNC machine tools for the smooth movement without vibration or jerks at the transient state. Linear, exponential, and parabolic acceleration/de- celeration techniques are most widely used in industry.

The sequence of operations which is needed for carrying out the desired job is programmed and interpreted to provide the decoded instructions to interpolation and acceleration/deceleration routines. Then, industrial robots and CNC machine tools are controlled by the servo control systems which use the output of the acceleration/deceleration routine as the input. Practically, there exists the path error which appears as the distance difference between the interpolated path and the actual path. This error depends on the kind of both acceleration/deceleration techniques and control methods of the servo control system, so the optimal selection is required in order to reduce the error to the desirable degree. Recently, feedforward control, fuzzy control, and neural control technologies are being used so as to reduce the error below the permissible limit [2],[3].

The flexibility in programming without change of hardware is one of the significant factors in the controller design of industrial robots and CNC machine tools. Especially, the performance in tracking the desired path and the maximum attainable tracking speed depend on the computing speed of the control algorithm. These practical requirements impose a heavier load on the microprocessor CPU, making the use of DSPs mandatory.

In this paper, we propose software acceleration/deceleration algorithms which are essential to high dynamic performance of industrial robots or CNC machine tools at the transient state in the repeated motion or movement along a desired path. In addition, we analyze the path error for linear, exponential, and parabolic acceleration/deceleration algorithms in case of circular interpolation. The analyses show the path error depends on the acceleration/deceleration routine and the servo control system. To illuminate the performance of the proposed acceleration/deceleration algorithms, we present experimental results performed on the motion control system with a floating point DSP TMS320C30 as a CPU. The experimental results show the effectiveness of the proposed algorithms in controlling axes of motion of industrial robots or CNC machine tools with the desired performances.

II. SOFTWARE ACCELERATION/DECELERATION

Software acceleration/deceleration algorithms can be obtained from digital convolution. First, let us assume that the input f_i, which is the desired path data, to software acceleration/deceleration algorithms is given by Fig.1. Fig.1 shows that the input f_i is a pulse train whose frequency is f_c. The physical meaning of each pulse in the pulse train is unit position increment in the movement along a desired path.

1. Linear acceleration/deceleration

The convolution of f_i and the sequence in Fig.2 yields the output f_o which has the characteristic of linear acceleration/deceleration. From Fig.2, the impulse transfer function $H(z)(F_o(z)/F_i(z))$ is given by

$$H(z) = (1-z^{-m})/m(1-z^{-1}). \quad (1)$$

Then, the relationship between f_i and f_o is expressed as the following recursive equation:

$$f_o(k) = [f_i(k)-f_i(k-m)]/m + f_o(k-1). \quad (2)$$

If the sampling time is given by T_s, then the acceleration/deceleration time $t_{acc/dec}$ can be written as

$$t_{acc/dec} = mT_s. \quad (3)$$

(2) provides the basic information for the software linear acceleration/deceleration algorithm. Based on (2), we can design the hardware system for linear acceleration /deceleration shown in Fig.3, where buffer registers act as delay elements [4],[5].

2. Parabolic acceleration/deceleration

The characteristic of parabolic acceleration/deceleration is
obtained from the cascade connection of the linear acceleration /deceleration algorithms:

$$f_{o1}(k) = [f_i(k)-f_i(k-m_1)]/m_1 + f_{o1}(k-1),$$

$$f_{o2}(k) = [f_{o1}(k)-f_{o1}(k-m_2)]/m_2 + f_{o2}(k-1), \quad (4)$$

$$f_{op}(k) = [f_{o(p-1)}(k)-f_{o(p-1)}(k-m_p)]/m_p + f_{op}(k-1),$$

where m_j, $j=1,\ldots,p$ represent the number of buffer registers in each linear acceleration/deceleration block. For $p=2$, the characteristic of parabolic acceleration/deceleration is obtained.

3. Exponential acceleration/deceleration

The convolution of f_i and the sequence in Fig.5 yields the output f_o which has the characteristic of exponential acceleration /deceleration. The impulse transfer function H(z) for exponential acceleration /deceleration is given by

$$H(z) = z(1-a)/(z-a). \quad (5)$$

From (8), it follows that

$$f_o(k) = (1-a)[f_i(k)-f_o(k-1)] + f_o(k-1). \quad (6)$$

(6) becomes the basic equation for the software exponential acceleration/deceleration algorithm, from which the equivalent hardware system can be derived as in the case of linear acceleration /deceleration.

4. Arbitrary acceleration/deceleration

The characteristics such as linear acceleration/parabolic deeceleration, exponential acceleration/parabolic deceleration, and etc. can be obtained by combinations of the previous acceleration /deceleration methods. However, there may exists the case where the general algorithm is required which provides characteristics of arbitrary acceleration/deceleration except the foregoing ones. Now, we discuss such a general algorithm and the simultaneous control method of multiple axes of motion based on it.

Let f_o be the output which has the characteristic of desired acceleration/deceleration for the input f_i, then f_o can be generated from the following convolution [8]:

$$f_o(k) = \sum_{n=0}^{k} f_i(n)a_{k-n}, \quad (7)$$

where a_k represents the slope of the velocity profile $f_o(k)$ at the instant k. The characteristic of desired acceleration/deceleration can be generated by the appropriate choice of a_k, $k=1\ldots q$, which are uniquely determined provided that the desired waveform of $f_o(k)$ is selected.

Now, we describe the practical implementation of (7) in the motion control system which controls the multiple axes of motion of industrial robots or CNC machine tools. First, let us define the variables:

f_{ij}	position displacement of the j-th axis,
f_{oj}	acceleration/deceleration output of the j-th axis,
V_{jmax}	maximum speed of the j-th axis,
$Q(a,b)$	quotient of a divided by the integer b,
$R(a,b)$	remainder of a divided by the integer b,
K_{ap}	number of sampling periods needed for the completion of acceleration/deceleration,

and assume that q, the discrete time duration of a_k, is the same as K_{ap} and Σa_k is equal to 1.

In order to obtain the velocity command which provides the characteristic of desired acceleration/deceleration, the position displacement of the j-th axis is divided by V_{jmax} to generate the quotient $Q(f_{ij},V_{jmax})$ and the remainder $R(f_{ij},V_{jmax})$. Based on these values, the position displacement except $R(f_{ij},V_{jmax})$, which is denoted as $f_q(k)$, is distributed over $Q(f_{ij},V_{jmax})$ sampling periods as follows:

$$f_q(k) = V_{jmax}[u(k)-u(k-Q(f_{ij},V_{jmax}))] \quad (8)$$

where u(k) is the unit step function. The convolution of $f_q(k)$ and a_k yields

$$\begin{aligned} f_{oj}(k) &= \sum_{n=0}^{k} f_q(n)a_{k-n}, \\ &= \sum_{n=0}^{k} V_{jmax}(a_{k-n}-a_{k-n-g}), \quad g = Q(f_{ij},V_{jmax}) \quad (9) \\ &= f_{oj}(k-1)+V_{jmax}(a_k-a_{k-g}). \end{aligned}$$

In (9), a_k and $f_{oj}(k)$ represent the profiles of acceleration, that is torque, and velocity of the j-th axis, respectively. As a consequence, the path command of the j-th axis for $f_q(k)$ is given by

$$P_{oj}(k) = \sum_{n=0}^{k} f_{oj}(n),$$

$$= P_{oj}(k-1)+f_{oj}(k), \quad f_{oj}(0) = 0. \tag{10}$$

Finally, the remained $R(f_{ij}, V_{jmax})$ is divided by $Q(f_{ij}, V_{jmax})+K_{ap}$ to generate $Q(R(f_{ij}, V_{jmax}), Q(f_{ij}, V_{jmax})+K_{ap})$ and these resultant values are distributed evenly over the whole range of acceleration/deceleration in the discrete time domain. As a consequence, we can see that f_{ij} has been transformed into the velocity command with the characteristic of desired acceleration /deceleration, whose integral over the whole range of acceleration /deceleration is equal to the position displacement of the j-th axis.

The simultaneous control of multiple axes of motion can be easily obtained on the basis of the above procedure. If the maximum value among the position displacements of axes of motion is defined as f_{max} and divided by V_{max}, $Q(f_{max}, V_{max})$ will be obtained. Division of the displacements of other axes by this value generates signals whose maximum values are less than or equal to V_{max} and ranges of acceleration/deceleration are $Q(f_{max}, V_{max})$. The convolutions based on these values provide the velocity commands with the characteristic of desired acceleration /deceleration for the simultaneous control of multiple axes of motion.

It can be easily shown that the aforementioned acceleration /deceleration algorithms can be considered as the special cases of this one. The equivalent hardware system which provides the same characteristic of acceleration/deceleration as that given by (7) can be designed as Fig.6.

III. PATH ERROR ANALYSIS FOR THE CIRCULAR INTERPOLATION

1. Circular Interpolation

Now, we discuss briefly the well-known 2 dimensional circular interpolator before the analysis of the path error in industrial robots and CNC machine tools [1], [5], [9]. In circular interpolation, the end effector of the industrial robot or the tool of the CNC equipment tracks the circular arc with a constant tangential velocity or feedrate. For simplicity of analysis, simultaneous control of two axes, that is x and y axes, is only taken into consideration. In this case, the circular interpolator generates the axial velocities V_x and V_y which are transferred to the acceleration/deceleration algorithms.

Each iteration of the interpolation algorithm, which corresponds to the incremental angle α, generates the axial velocity commands for x and y axes as follows:

$$V_x(k) = -[2R\sin(\alpha/2)/T_s]\sin(\omega T_s k+\omega T_s/2),$$

$$V_y(k) = [2R\sin(\alpha/2)/T_s]\cos(\omega T_s k+\omega T_s/2), \tag{11}$$

where R is the radius of the circular arc, V is a constant tangential velocity or feedrate, and ω is given by

$$\omega = V/R. \tag{12}$$

$V_x(k)$ and $V_y(k)$ become the inputs to the acceleration/deceleration algorithm, from which f_o with the desired characteristic is generated resultantly.

2. Path Error Analysis

The sequence of operations which is needed for carrying out the desired job is programmed and interpreted to provide the decoded instructions to interpolation and acceleration/deceleration routines. Then, industrial robots and CNC machine tools are controlled by the servo control system with the output of the acceleration/deceleration routine as the input. Practically, there exists the inevitable path error between the interpolated path and the actual path. The path error consists of two factors. One results from acceleration/deceleration while the other from the servo control system. The magnitude of each error depends on the kind of the acceleration/deceleration techniques or the servo control methods.

Now, we discuss the path errors for linear, exponential, and parabolic acceleration/deceleration algorithms in case of circular interpolation. Actually, the steady state accuracy in contouring or machining is very important in performance evaluation of industrial robots and machine tools, so the path error is only analyzed in the steady state.

2.1. Path error due to acceleration/deceleration

V_x and V_y calculated from (11) are the inputs to the acceleration/deceleration routine. There is the distance difference between the interpolated path and the generated path from the acceleration/deceleration routine. We call this difference the path error due to acceleration/deceleration. For the analysis of this error, we define R_c as $2R\sin(\alpha/2)/T_s$, R_c' as the radius of the circular arc generated from Y_x, Y_y, which are the outputs of acceleration/deceleration to the inputs V_x, V_y, and $\Delta R_{a/d}(\infty)$ as $R_c(\infty) - R_c'(\infty)$. The path errors due to acceleration/deceleration are summarized as follows:

A) Linear acceleration/deceleration

The outputs Y_x, Y_y to V_x, V_y are calculated as follows:

$$Y_x(k) = -[2R\sin(\alpha/2)/T_s][\cos(\omega T_s/2)Y_s(k) + \sin(\omega T_s/2)Y_c(k)],$$

$$Y_y(k) = [2R\sin(\alpha/2)/T_s][\cos(\omega T_s/2)Y_c(k) - \sin(\omega T_s/2)Y_s(k)], \tag{13}$$

where

$$Y_c(k) = [(\cos(\omega T_s k+\phi_w)/(\sqrt{2-2c_o})+(1-c_o)/(2-2c_o))u(k) -(\cos(\omega T_s k-\omega T_s m+\phi_w)/(\sqrt{2-2c_o})+(1-c_o)/(2-2c_o))u(k-m)]/m,$$

$$Y_s(k) = [(\sin(\omega T_s k+\phi_w)/(\sqrt{2-2c_o})+s_i/(2-2c_o))u(k) -(\sin(\omega T_s k-\omega T_s m+\phi_w)/(\sqrt{2-2c_o})+s_i/(2-2c_o))u(k-m)]/m, \tag{14}$$

$$c_o = \cos(\omega T_s), \quad s_i = \sin(\omega T_s),$$
$$\phi_w = \mathrm{atan}[-s_i/(1-c_o)].$$

As k tends to the infinity, it follows that

$$Y_x(\infty) = -[2R\sin(\alpha/2)/T_s][2\sin(m\omega T_s/2) \sin(\omega T_s k+\omega T_s/2+\phi_w+\pi/2-\omega T_s m/2)/m(\sqrt{2-2c_o})],$$

$$Y_y(\infty) = [2R\sin(\alpha/2)/T_s][2\sin(m\omega T_s/2) \cos(\omega T_s k+\omega T_s/2+\phi_w+\pi/2-\omega T_s m/2)/m(\sqrt{2-2c_o})]. \tag{15}$$

Then, the path error is expressed as

$$\Delta R_{a/d}(\infty) = R_c[1-P_1/mP_2], \quad (16)$$

where

$$P_1 = \sin(m\omega T_s/2), \; P_2 = \sin(\omega T_s/2). \quad (17)$$

B) Exponential acceleration/deceleration

By the same way, it follows that

$$Y_x(\infty) = -[2R\sin(\alpha/2)/T_s][G_w\sin(\omega T_s k+\omega T_s/2+\phi_w),$$

$$Y_y(\infty) = [2R\sin(\alpha/2)/T_s][G_w\cos(\omega T_s k+\omega T_s/2+\phi_w), \quad (18)$$

where

$$G_w = (1-a)/(\sqrt{a^2-2ac_o+1}). \quad (19)$$

The path error is given by

$$\Delta R_{a/d}(\infty) = R_c[1-1/\sqrt{1+2a(1-c_o/(a-1)^2}]. \quad (20)$$

C) Parabolic acceleration/deceleration

For p = 2, the path error is given by

$$\Delta R_{a/d}(\infty) = R_c[1-(P_1/mP_2)^2] \quad (21)$$

If the sampling time is assumed to be negligibly small, then the path error due to acceleration/deceleration is expressed as the equation based on the time constant of the acceleration/deceleration routine [10].

2.2. Path error due to the servo control system

Before the analysis, we assume that the disturbance torques due to the frictions in the gears, Coriolis, gravity loading, and centrifugal effects of the link are suppressed to the desirable degree by precomputing them and feeding the computed values into the servo control system. Under this assumption, we consider the servo control system in Fig.7 which is one of the typical systems widely used in industry. These servo control systems make the end effector of the industrial robot or the tool of the CNC equipment track the desired path in order to carry out contouring or machining.

The output of the acceleration/deceleration routine is transmitted to the servo control system as the input. In this case, there exists the distance difference between the actual path of the end effector or the tool and the generated path from acceleration/deceleration. For the analysis of this difference due to the servo control system, we define the radius of the actual circular arc as R_{sv} and the path error $\Delta R_{sv}(\infty)$ as $R_c'(\infty) - R_{sv}(\infty)$.

The transfer function of the system in Fig.7 in z-domain is expressed as

$$H_{sv}(z) = \frac{c_1 z+c_2}{z^3+b_1 z^2+b_2 z+b_3}, \quad (22)$$

where

$$b_1 = d_1K_P[d_2T_s-1+\exp(-d_2T_s)]-\exp(-d_2T_s)-2,$$

$$b_2 = 1+2\exp(-d_2T_s)+d_1(K_I-K_P)[d_2T_s-1+\exp(-d_2T_s)] +d_1K_P[1-(1+d_2T_s)\exp(-d_2T_s)],$$

$$b_3 = d_1(K_I-K_P)[1-(1+d_2T_s)\exp(-d_2T_s)]-\exp(-d_2T_s), \quad (23)$$

$$c_1 = d_1K_I[d_2T_s-1+\exp(-d_2T_s)],$$

$$c_2 = d_1K_I[1-(1+d_2T_s)\exp(-d_2T_s)],$$

$$d_1 = JK_{pw}K_T/(B+K_{pw}K_T)^2, \; d_2 = (B+K_{pw}K_T)/J,$$

K_I and K_P are the integral and proportional gains in the position control loop, respectively, K_{pw} is the proportional gain in the velocity control loop, J is the equivalent momentum of inertia of the axis, K_T is the motor torque constant, B is the damping coefficient, and T_L is the disturbance torque [11]. In Fig.7, θ_r^* and ω_r^* represent the position and velocity commands, respectively, and θ_r and ω_r the actual position and velocity, respectively.

Now, we discuss the path error due to the servo control system in Fig.7. The path error is calculated as follows:

$$\Delta R_{sv}(\infty) = R_c'(1-A/B), \quad (24)$$

where

$$A = \sqrt{[\cos(3\omega T_s)+b_1\cos(2\omega T_s)+b_2\cos(\omega T_s)+b_3]^2 +[\sin(3\omega T_s)+b_1\sin(2\omega T_s)+b_2\cos(\omega T_s)]^2},$$

$$B = \sqrt{[c_1\cos(\omega T_s)+c_2]^2+[c_1\sin(\omega T_s)]^2}. \quad (25)$$

It can be seen from (24) and (25) that the path error due to the servo control system depends on the sampling period T_s and control gains K_I, K_P, K_{pw}. However, we can not obtain the explicit information about the effect of control gains on the path error without the help of computer simulations because of the complexity of (24) and (25). Practically, the control gains are adjusted for the output response of the servo control system to the unit step input to be critically damped, that is to make it act as the first order system. In this case, the path error can be approximately expressed on the basis of the time constant of the servo control system, which is varied by the change of control gains. Though not exact one, such an expressions provides the efficient solution to the problem of optimal control gains which guarantee the minimum path error [10].

The total path error between the interpolated path and the actual path is given by the sum of path errors in (16), (20), or (21) and (24). For more strict and accurate analyses, the numerical analysis and nonlinear modelling of industrial robots and CNC machine tools are required.

IV. EXPERIMENTAL RESULTS

The control algorithm including the proposed acceleration /deceleration algorithms is executed on the motion control system with a floating point DSP TMS320C30 as a CPU.

As a test bed, a cartesian type robot FARA-C2 of Samsung Electronics is utilized and encoders whose resolution is 4096 pulses/rev. are used. The actual photograph of the FARA-C2 is shown in Fig.8.

In experiments, 122880 pulses are given as the position command of the X-axis of FARA-C2 in the -X direction in each case of linear, exponential, and parabolic acceleration/deceleration. The waveforms of velocity feedback, velocity command with the characteristic of desired acceleration/deceleration, and motor torque for each case are shown in Fig.8. In Fig.8, ω_r^*, ω_f, and T_e represent velocity command, velocity feedback, and motor torque, respectively. It is shown in Fig. 8 that velocity feedback is identical to velocity command and motor torque is almost the same as differentiation of the velocity feedback. This fact indicates that the control gains were adjusted for the servo control system to act as the first order system.

The experimental results demonstrate that the proposed software acceleration/deceleration methods are very effective in controlling axes of motion of industrial robots or CNC machine tools with the desired characteristics.

V. CONCLUSION

This paper proposes software algorithms which provide characteristics of acceleration/deceleration essential to high dynamic performance in industrial robots or CNC machine tools at the transient state in the repeated motion or movement along a desired path. Based on software acceleration/deceleration algorithms, the equivalent hardware structures are designed. Moreover, a more general method which provides the characteristics of arbitrary acceleration/deceleration is derived from the basic ideas for typical acceleration/deceleration which are widely used in industry.

The mathematical analyses show that the path error, which is one of the most significant factors in performance evaluation of industrial robots and CNC machine tools, results from the acceleration/deceleration routine and the servo control system. The analyses of the path errors due to the acceleration/deceleration routine and the servo control system provide the information which is available for reducing the magnitude of the path error.

In experiments, the entire control algorithm including the proposed acceleration/deceleration algorithms was executed on the motion control system with a floating point DSP TMS320C30 as a CPU and a cartesian type robot FARA-C2 used as a test robot. The experimental results demonstrate that the proposed software acceleration/deceleration methods and the motion control system are very effective in controlling axes of motion of industrial robots or CNC machine tools with the desired characteristics

Further researches should be directed toward the development of the servo control method which minimizes the path error and the actual analysis of the produced part by the measurement devices.

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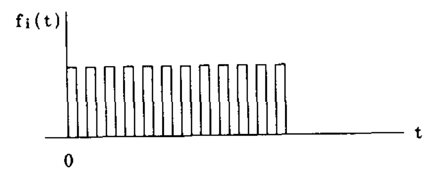


Fig.1. The input to the software acceleration/deceleration algorithms.

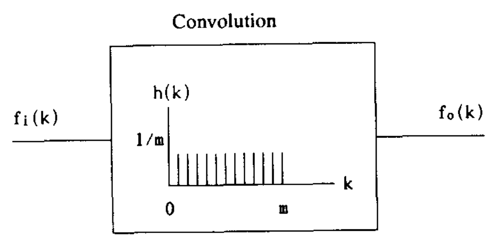


Fig.2. The block diagram of linear acceleration/deceleration.

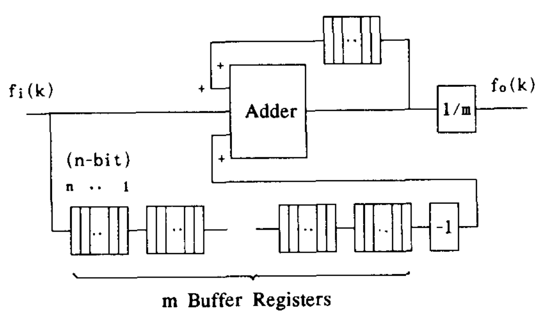


Fig.3. The hardware structure of linear acceleration/deceleration.

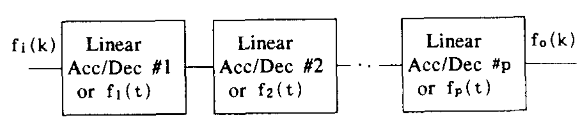


Fig.4. The block diagram of parabolic acceleration/deceleration.

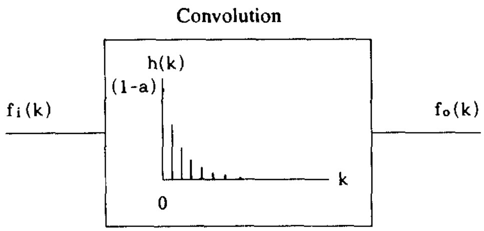


Fig.5. The block diagram of exponential acceleration/deceleration.

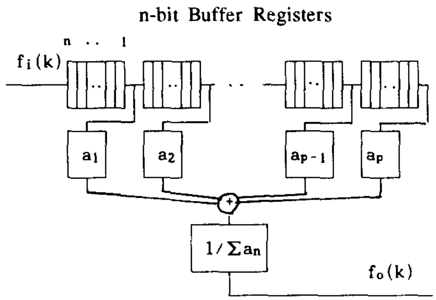
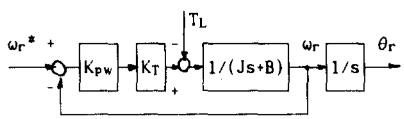
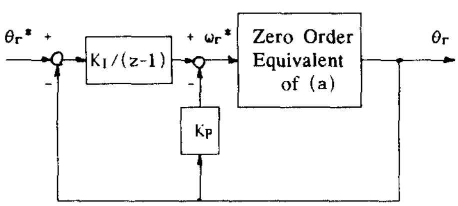


Fig.6. The hardware structure of arbitrary acceleration /deceleration based on DDA method.

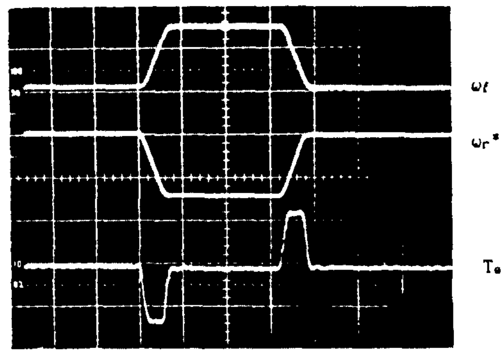


(a) Velocity control system.

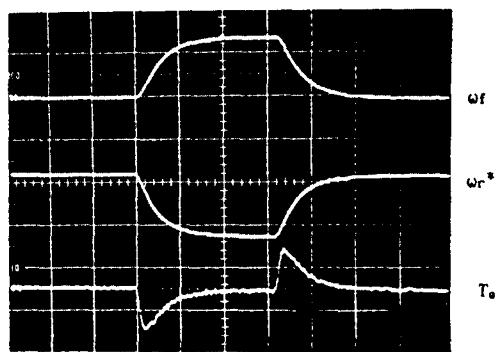


(b) Servo control system.

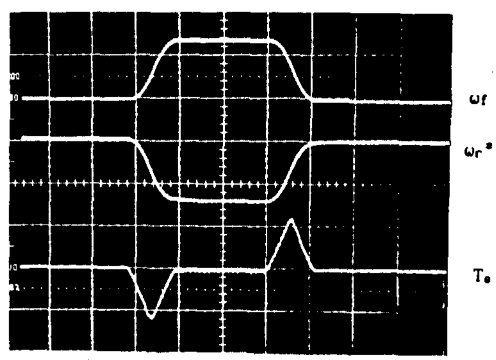
Fig.7 The servo control system for industrial robots and CNC machine tools.



(a) The experimental result for linear acceleration/deceleration.



(b) The experimental result for exponential acceleration /deceleration.



(c) The experimental result for parabolic acceleration/deceleration.

Fig 8. The experimental results for software acceleration/decelera- tion algorithms. (x-axis:0.5 sec, y-axis:upper,middle:57kpps/div., lower:3.9kgf-cm)