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A Feasible Approach for the Unified PID Position Controller Including Zero-Phase Error Tracking Performance for Direct Drive Rotation Motor

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ABSTRACT

The design and implementation of a high performance PID (Proportional Integral & Differential) style controller with zero-phase error tracking property is considered in this article. Unlike a ball screw driven system, the controller in a direct drive system should provide a high level of tracking performance while avoiding the problems due to the absence of the gear system. The stiff mechanical element in a direct drive system allows high precise positioning capability, but relatively high tracking ability with minimal position error is required. In this work, a feasible position controller named 'Unified PID controller' is presented. It will be shown that the function of the closed position loop can be designed into unity gain system in continuous time domain to provide minimal position error. The focus of this work is in two areas. First, easy gain tunable PID position controller without speed control loop is designed in order to construct feasible high performance drive system. Second, a simple but powerful zero phase error tracking strategy using the pre-designed function of the main control loop is presented for minimal tracking error in all operating conditions. Experimental results with a s-curve based position pattern commonly used in industrial field demonstrate the feasibility and effective performance of the approach.

Keywords: Direct drive rotation motor, Unified position controller, Zero-phase error tracking control

1. Introduction

Recently, the development and commercialization of improved electromechanical components has progressed rapidly. Particularly noteworthy from a system design viewpoint are DDR(Direct-Drive Rotation) motors. In comparison to traditional gear-reduced systems, the technical advantages of direct-drive systems are widely known in the industrial field: friction is reduced, backlash is eliminated, and the mechanical stiffness is very high[1][2]. The disadvantages, on the other hand, usually do not get as much attention: the system is more sensitive to disturbance torque, mechanical resonance is more critical and mechanical stability tends to be low due to the absence of the damping element. Furthermore, since the DDR motor is commonly applied to an exceedingly high-end application field, extremely accurate tracking performance is required in the drive system. Therefore, more complicated control algorithms should be applied for the positioning system, which leads to terrible gain tuning work in the actual field. To fully exploit the potential

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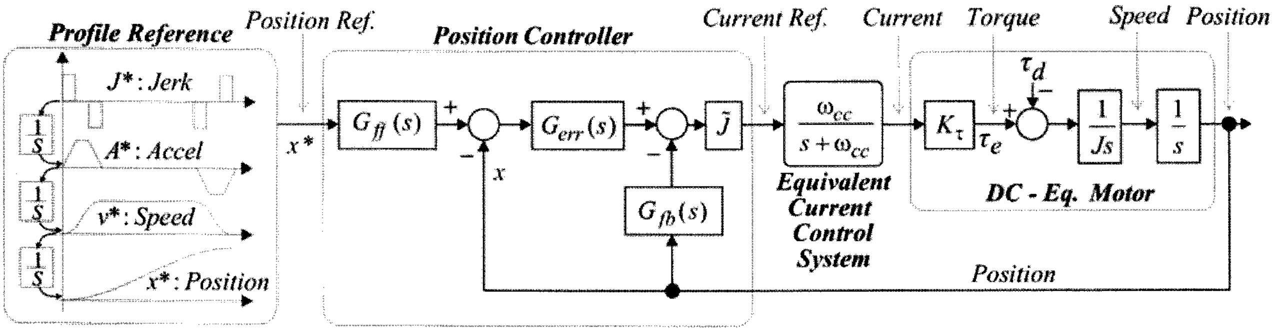


Fig. 1 The block diagram of the DDR motor drive system with the PID position controller including feedforward feedback controller

advantages of direct-drive actuators, all of these factors should be explicitly accounted for in the controller design. Concerning the viewpoint of the field implementation, a simpler, but more powerful position control algorithm is needed to construct a successful positioning system.

In the last decades, there were various works about the closed loop for the positioning system[3]-[14]. One study worthy of notice is the PID position loop based on the TDOF (Two Degrees Of Freedom) scheme[5]-[8]. These works utilized the state feedback controller through classical control approaching and showed that the whole control system can be modeled into a stable time invariant transfer function without internal speed control block. Research on discrete-time tracking controllers includes [9]–[14], which all combine feedback and feedforward controllers. Another noteworthy previous work is the zero phase error tracking controller (ZPETC) based on approximate inversion of the closed-loop system[10]-[13]. In a positioning system with inherent dynamics, phase-delay would occur between the position reference and actual position in transient state, which directly results in the tracking errors. In the ZPETC scheme, although more complicated analysis and high-end control equipments were required, the phase delay effect was rejected in the positioning system.

The general structure of the whole positioning control system for standard industrial applications is shown in Fig. 1. The position reference generating block provides pre-designed position reference pattern based on jerk. Jerk means the impact to moving part of the motor and it's dimension is $\mathrm{rev/s^3}$ (or $\mathrm{rad/s^3}$). In the reference generating block, the allowed acceleration and speed are fully considered in order to guarantee that a continuous position pattern is provided and the impact toward load object is minimized. A typical position controller consists of feedforward controller, main compensation controller and feedback controller. In a position control block of the figure, $G_{ff}(s)$, $G_{err}(s)$ and $G_{fb}(s)$ represent feedforward controller, error compensator and feedback controller, respectively. The error compensator combined with the feedback controller acts as a main position controller. The notation $\hat{J}$ means the inertia information for the controller. Furthermore it will be assumed that $\hat{J}$ has the same value of the actual motor throughout this work. The uncertainty about inertia information will be treated in the advanced work about inertia identification. The motor is modeled into the DC-equivalent form which consists of a single inertia, J, and a disturbance element denoted as τ_d. The dynamics of the torque disturbance is not the focus of this work. The influence from torque disturbance could be rejected by well-designed load torque observers as in [1][2]. The notation K_τ means the torque constant to produce torque from the machine current in a DC-equivalent model. Between the position controller and the motor, an equivalent current control system including power amplifier stage is placed. In common cases, the current loop can be modeled into a function of simple low-pass filter with cut-off frequency ω_{cc}. If the bandwidth of inner current loop is much higher than that of the outer position loop, the equivalent current block does not affect global dynamics of the position loop. With the above assumption, the dynamics of the current block will not appear in this presentation.

The focus of this work is in two areas. First, a feasible position controller design which accounts for easy gain tuning strategy for actual application is proposed. All designs in this work are done in continuous time domain for clear functional implementation. A function of low-pass filter is chosen for the main controller to achieve stable dynamics of the whole positioning system. The method here proposes a first-order filter function which lends itself to easy gain tuning and straightforward implementation. Second, a feedforward controller is designed to give zero-phase error tracking property to the positioning system. Advances in the industrial field pose a new control challenge for field engineers: nearly zero tracking errors should be guaranteed during a full motion in direct drives. This challenge could be accomplished by the previous researches which need complex computational work based on the discrete time model. In this work, without hard computational processing, the simplest way to get the zero tracking error performance is presented. From the analysis of the main position loop, a simple PD (Proportional & Differential) style feedforward controller only for position reference is designed in continuous time to compensate the phase error. This proposed feedforward controller provides a convenient method for assuring the global position loop while providing zero tracking error performance without damage of the feedback control loop related to stiffness.

Simulation and Experimental results for s-curve based position reference trajectories, which are commonly used in industrial drives, demonstrate the effectiveness of the approach.

2. Unified PID Position Controller

The proposed work, basically motivated by difficulties posed by the low dynamics of the conventional positioning loop, in which the position controller is connected to the inner speed controller in cascade form as shown in Fig.2. As described above, the current control loop is designed to have the highest dynamics as a basic inner control loop in general drive applications. The dynamics of current loop is not involved in the outer control loop, i.e. speed control loop, only while the outer control loop has relatively lower dynamics than that of the inner loop. When the dynamics of outer loop exceeds that of the inner loop, total design process would fall in tremendous complexity and can hardly be applied to the actual field. In the same sequence, the position control loop has the lowest dynamics in cascade control style. So the whole dynamics of the positioning system would be too poor to satisfy the industrial requirements for DDR motor drives.

Although the previous works in the TDOF scheme score a success in removing the inner speed control loop, hard work for adjusting each gain still remains.

Fig.3 shows the structure of the proposed position

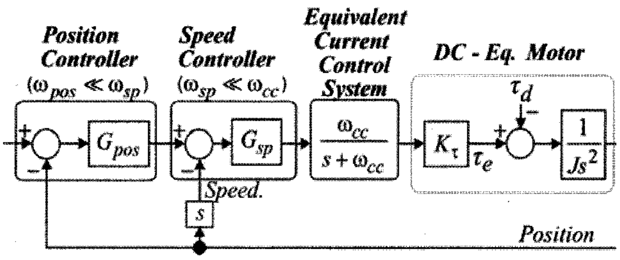


Fig. 2 Block diagram of the conventional cascade-style position

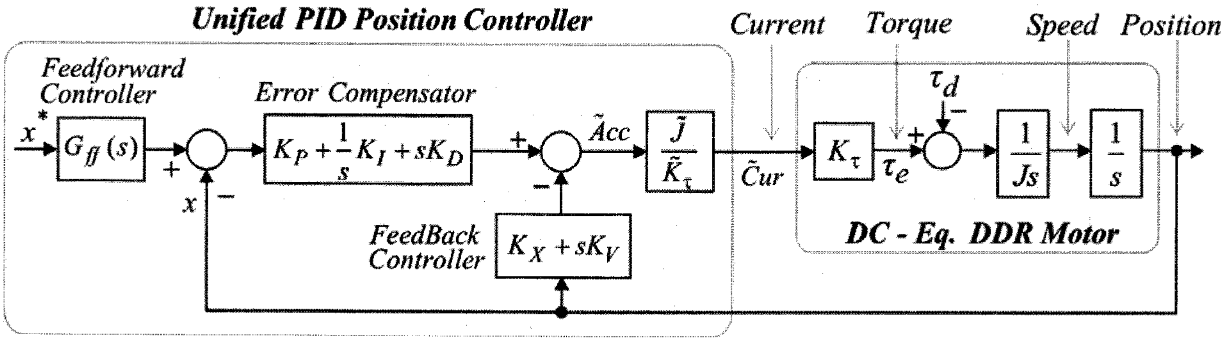


Fig. 3 Block diagram of the proposed unified PID position controller including feedforward controller

controller named 'Unified PID'. The position control loop is directly connected to the inner current loop without speed loop. The dynamics of the current control loop is passed as mentioned above. Removing the inner speed controller could lead the positioning system into an unstable state because there are double-poles in the plant model. To build a stable positioning system, a PD style controller is introduced for the feedback controller $G_{fb}(s)$. Before the error compensator, a feedforward controller $G_{ff}(s)$ for zero-phase error tracking control is located. The function for the feedforward controller is not considered in earlier design time and the choice for this function will be presented in a sequential section.

A conventional well-known PID (Proportional, Integral & Differential) controller is adopted for the error compensator. This approach gives various freedoms in design process since many variations for desired functions are possible. In Fig.3, K_P, K_I and K_D in error compensation loop represent the proportional gain, the integral gain and the differential gain, respectively. Also, in the feedback controller for position state feedback, K_X and K_V mean the proportional gain and the differential gain. In order to give a physical meaning for the positioning loop, the outputs of each controller are treated as acceleration terms for motor driving. It is another advantage of this approach that a close research about parameter uncertainty is done in simple way. All acceleration terms are combined and converted to a current reference by multiplication with compound constant, $\hat{J}/\hat{K}_\tau$. $\hat{J}$ and $\hat{K}_\tau$ are the inertia and torque-constant information for the drive system. The issue about the uncertainties for these parameters will be focused in the advanced work for parameter identification.

2.1 Main positioning loop design

In the industrial application field for DDR motors, such as semi-conductors or machine tools, the required conditions for the positioning loop can be summarized as follows: the tracking phase error should be minimized, no-overshoot is guaranteed and stiffness toward load disturbance must be high. Moreover, for actual implementation on the industrial fields, a simple structure with easy gain tuning property is strongly recommended. From these viewpoints, a function of the low pass filter will be suitable for the global dynamics of the positioning loop. The reasons for choosing the low pass filter function are condensed into three points: First, a low pass filter function has good predictable dynamics of itself. The bandwidth of the whole position loop can be defined clearly by the cut-off frequency of the filter. In addition, the overshot can be suppressed perfectly in a low pass filter with less effort. Second, a stable feature of the low pass filter corresponds closely with the requirement for industrial fields. Last, without formidable efforts, all gains related to the error compensator and the feedback controller can be easily defined in a unified manner.

The desired global dynamics in a low pass filter function can be easily obtained through the pole-zero cancellation method. In Fig.3, the dynamics of the closed position loop except feedforward controller can be represented as the next form.

$$
\begin{aligned}
x &= \frac{K_\tau}{\hat{K}_\tau}\frac{\hat{J}}{J}\frac{1}{s^2}\left(G_c(s)(x^*-x) - G_{fb}(s)x\right) \\
&= \frac{1}{s^2}\left((K_P + K_I\frac{1}{s} + K_D s)(x^*-x) - (K_X + K_V s)x\right) \quad (1) \\
&(\hat{K}_\tau \cong K_\tau,\ \hat{J} \cong J)
\end{aligned}
$$

Thus, the closed loop function of the proposed control system can be obtained from the above equation.

$$
G_c(s) \equiv \frac{x}{x^*} = \frac{K_D s^2 + K_P s + K_I}{s^3 + (K_D + K_V)s^2 + (K_X + K_P)s + K_I} \quad (2)
$$

The notations of x and x^* mean the position of the motor and position reference for the drive system.

Moreover, from the relationship between the closed loop function and the open loop function, the open loop dynamics can be deduced as follows from Eq.2.

$$
G_o(s) = \frac{K_D s^2 + K_P s + K_I}{s^3 + K_V s^2 + K_X s} = \frac{K_D\left(s^2 + \frac{K_P}{K_D}s + \frac{K_I}{K_D}\right)}{s\left(s^2 + K_V s + K_X\right)} \quad (3)
$$

As shown above, the open loop function of the whole position loop can be simplified to a single integral function by the pole-zero cancellation method. Let us introduce some variables for the cancellation process. A notation ω_c is chosen for the gain K_D. Then two hidden variables denoted by ω_n and ξ are selected for cancellation as follows.

$$\begin{aligned} \omega_c &= K_D \\ 2\xi\omega_n &= K_V = \frac{K_P}{K_D} \\ \omega_n^2 &= K_X = \frac{K_I}{K_D} \end{aligned} \tag{4}$$

Then, the open loop function is represented as,

$$G_o(s) = \frac{\omega_c\left(s^2 + 2\xi\omega_n s + \omega_n^2\right)}{s\left(s^2 + 2\xi\omega_n s + \omega_n^2\right)} = \frac{\omega_c}{s}. \tag{5}$$

So, a closed loop function in the first-order low pass filter form can be represented from Eq.5.

$$G_c(s) = \frac{G_o(s)}{1+G_o(s)} = \frac{\omega_c}{s+\omega_c} \tag{6}$$

In the above equation, ω_c acts as a cut-off frequency of the low pass filter. And the bandwidth of the global position controller is defined by ω_c consequently. Note that the whole dynamics of the proposed position controller is determined by the cut-off frequency only, while the hidden variables denoted by ω_n and ξ don't appear on it. These hidden variables are not related to the global dynamics of the positioning loop directly, but they will play an important role to obtain a required stiffness because they are deeply related on the gains for the feedback loop.

Now, the whole gains can be yielded easily from Eq.4.

$$\begin{aligned} K_D &= \omega_c \\ K_P &= 2\xi\omega_n\omega_c \\ K_I &= \omega_n^2\omega_c \\ K_V &= 2\xi\omega_n \\ K_X &= \omega_n^2 \end{aligned} \tag{7}$$

Using above gains in a designed step provides a simple but extremely stable operation to the position loop and the system has -20dB roll-off due to the natural property of the first-order filter.

On the other hand, the whole closed loop transfer function might have a function of the second-order filter for -40dB roll-off property. In the proposed controller, the second-order filter function can be obtained directly by removing the gain K_D in Eq.2. In this case, the full closed loop function is described as below by introducing two explicit variables ω_n' and ξ' from the filter theory.

$$\begin{aligned} &G_c'(s) = \frac{\omega_n'^2}{s^2 + 2\xi'\omega_n' s + \omega_n'^2} \\ &\text{while} \begin{cases} K_P = \omega_n'^2, \ K_I = \omega_n'^2\omega_o, \ K_D = 0. \\ K_V = 2\xi'\omega_n' + \omega_o, \ K_X = 2\xi'\omega_n'\omega_o \end{cases} \end{aligned} \tag{8}$$

In the above equation, the notation of ω_o is a hidden none-zero variable for pole-zero cancellation. And variables denoted by ω_n' and ξ' mean the natural frequency and damping ratio of the conventional second-order low pass filter.

It is clear that the second-order filter function has more powerful roll-off property rather than that of the first-order, but the second-order filter function does not necessarily give the best performance in the global operating area. First of all, removing the differential loop in the error compensation controller degrades the dynamic performance while the reference is varied widely in a short time. Thus, it is strongly recommended to implement the first-order filter function for the position loop although this function has poor phase-error dynamics in high frequency band. A feasible solution about the problem related to the phase-error is presented in the next design step for the feedforward controller.

2.2 Feedforward controller for ZPETC

In the earlier works, there were interesting controller design methods for a zero-phase error tracking control scheme. The main issue arises from the phase delay between the reference signal and the actual position in the tracking control area. Whether the controller is designed in continuous time or discrete time, the phase delay is inevitable problematic thing in a tracking system. Even if the higher gains for the controller reduce the phase error strictly, there would be realistic high limitation of the gains in actual fields. One of the attractive ideas to solve the problem is the phase compensation method for the reference signal. A phase-shift function like as the lead-lag function ($(Bs+1)/(As+1)$) can be a good choice for phase compensation. This function can be founded in some control structure from a commercial controller. In any case, however, it should be guaranteed that the dynamics of the reference signal is well known to minimize the phase delay. Although the reference signal comes along with a pre-designed pattern, it is formidable work to adjust the phase delay online.

Another approach to eliminate the phase error is the ZPETC scheme based on the inversion model of the system. In general, to achieve an inversion model is very hard work because common position loops have complex structure. Thus, all of the previous works for the ZPETC were done in discrete time to overcome the complexity by calculating power of the high-end drive system. However, these approaches result in only making another tortuous system.

In this work, fully predictable dynamics of the proposed position controller is utilized to get the zero-phase error tracking performance. As described above, when each of the controller gains is properly adjusted according to the rules in Eq.7, the proposed controller has the function of a first-order low-pass filter. As the function continues working, a significant phase-delay would take place due to the interaction between the frequency band of the reference signal and the cut-off frequency of the position controller. In the proposed system, this phase-delay cannot be avoided while an easy gain tuning strategy is maintained. On the other hand, a feedforward controller just acts on the reference signal without the influence on the feedback loop. However, the global dynamics can be changed dramatically by this controller. When a feedforward controller is involved in a control loop as shown in Fig.3, the closed transfer function in Eq.6 can be represented as shown.

$$G_c(s) = \frac{x}{x^*} = \frac{\omega_c}{s+\omega_c} G_{ff}(s) \tag{9}$$

In order to remove the phase delay perfectly, another PD style controller is designed for the feedforward controller.

$$G_{ff}(s) \equiv 1 + \frac{1}{\omega_c} s \tag{10}$$

The differentiation for position reference does not make any trouble since a pattern generator provides a continuous position reference in tracking control. The speed reference form pattern generator could also be used instead of the differentiation for position reference.

As a result, the overall transfer function for the position loop can be converted as below.

$$G_c(s) = \frac{\omega_c}{s+\omega_c}(1 + \frac{1}{\omega_c} s) \equiv 1. \tag{11}$$

As shown above, the whole transfer function for the position loop is strictly changed to 1. This means there is no theoretical phase-delay in all frequency bands. All these are available due to the simplest pre-designed function of the main position controller. A noteworthy point of this approach is that the dynamics related to the stiffness or load disturbance still follows the stable property of the first-order low pass filter. Since the feedforward controller does not affect the behavior of the feedback loop, the issues which arise from the feedback loop can be separated from the feedforward controller. Furthermore, the performance of this controller is not influenced by white or gray noise from the actual fields. Strictly speaking, this approach is one of the design methods based on the inversion model of the system. However, the most essential thing of this work is the complete fulfillment of the actual requirements; easy gain tuning with stable dynamics and zero-phase error tracking performance with simple implementation.

2.3 Comments on Implementation

For implementation, there are some considerable components about the proposed positioning loop. One of the important components is the calculation method for the proportional loop in the feedback controller. The structural drawback of the main position controller causes a problem when the motor always rotates to one direction continuously.

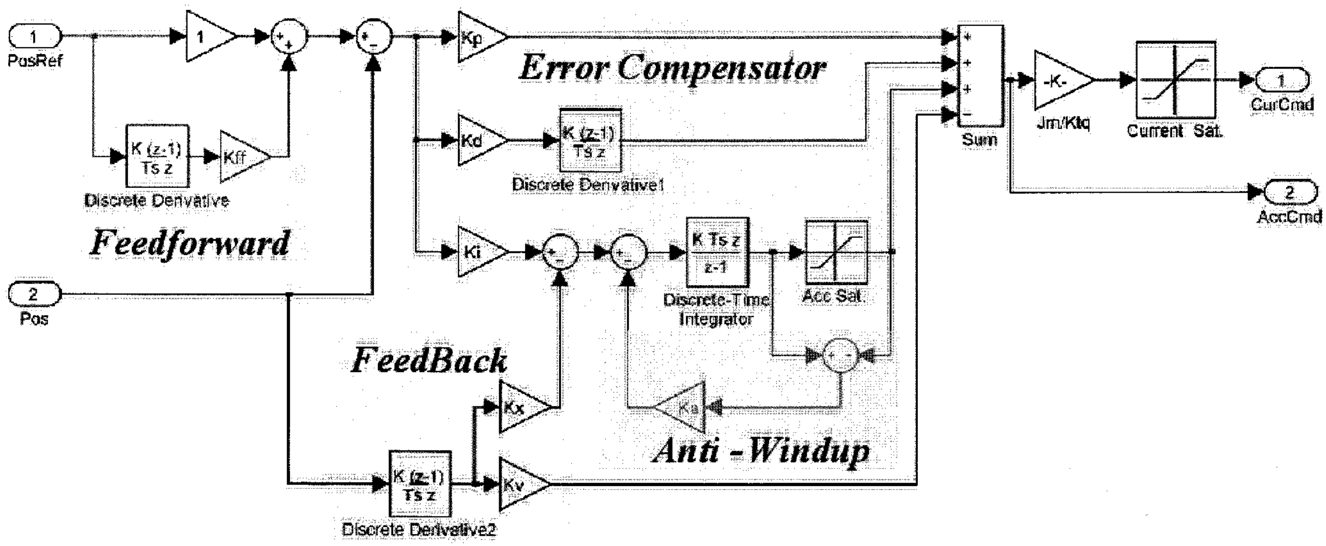


Fig. 4 Actual implementation of the proposed zero-phase error unified PID position controller in descrete time model(MATLAB function)

Since the output of the proportional term in feedback loop is increased relative to the real position, it would openly exceed a maximum value which the general digital controller can count without the loss of precision. The next functional modification clears this problem.

$$\begin{aligned} Out_I &= K_I \frac{1}{s}(x^* - x) \\ Out_X &= K_X x = K_X \frac{1}{s} \cdot (sx) \\ Out_{I+X} &= \frac{1}{s}\left(K_I(x^* - x) + K_X sx\right) \end{aligned} \tag{12}$$

The notations, Out_I and Out_X, mean the outputs of the integral loop in error compensator and the output of the proportional loop in feedback controller. As shown in the last line of Eq.12, Out_I and Out_X can be combined into one integral operator, and this combination enables us to design the anti-windup scheme for the proposed controller.

In general, the output of an integrator should be limited to some reasonable value when the motor current reaches above the absolute limitation. This current limitation might be decided by some external conditions, such as the motor ratings or the capacity of the power amplifier.

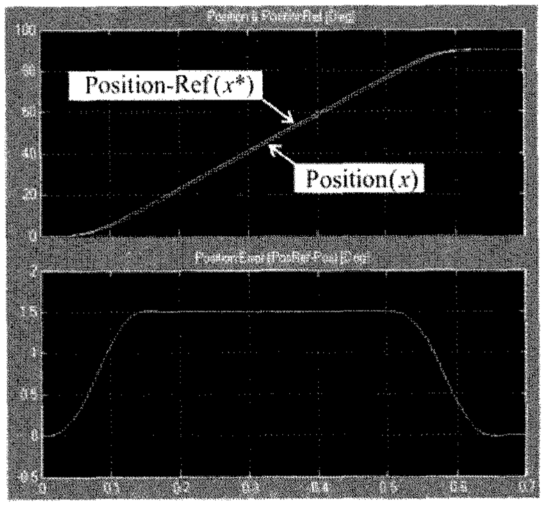
In Fig.4, a functional implementation example of the position controller is shown in MATLAB function. All functions are designed in sampling based discrete form and 0.5msec sampling time is chosen for this example. On the left side, feedforward block for the zero-phase error tracking is shown. The notation K_{ff} in this block means the gain of the discrete derivative function. From Eq.11, it is obvious that $1/\omega_c$ should be chosen for the gain K_{ff} to match up the condition for minimizing tracking error. On the middle top side of the figure, the modified PID main error compensator is shown. The main difference between this one and the traditional PID is the modified integral function including the feedback term of the differentiation of the position to implement the modification for feedback loop as explained in Eq.12. On the left bottom side of the figure, the modified implementation of the feedback block is presented. Also, to prevent the integral loop from going into windup state in abnormal conditions, a commonly used anti-windup controller is attached to the main integrator. In common operating conditions, this anti-windup function is hardly activated.

Another comment for implementation is located on the sampling rate of the digitalized controller. As widely known, the performance of the positioning system highly depends on the sampling rate. Generally higher sampling rate yields higher performance. However, concerning the actual operation of the inner current control loop would restrict the sampling rate for external position loop to a certain maximum rate. Also, to satisfy the required bandwidth of the positioning loop, the sampling frequency should be over the maximum bandwidth more than twenty times. According to a realistic workout for implementation, a 2~4kHz sampling rate is appropriate for the position loop while the sampling rate for the current loop is 20~40kHz. With a 2kHz sampling rate, a 100Hz (628rad/s) bandwidth can be achieved in a positioning system under noise-free conditions. However, the actual condition of the industrial fields normally bounds the maximum bandwidth to 200rad/s.

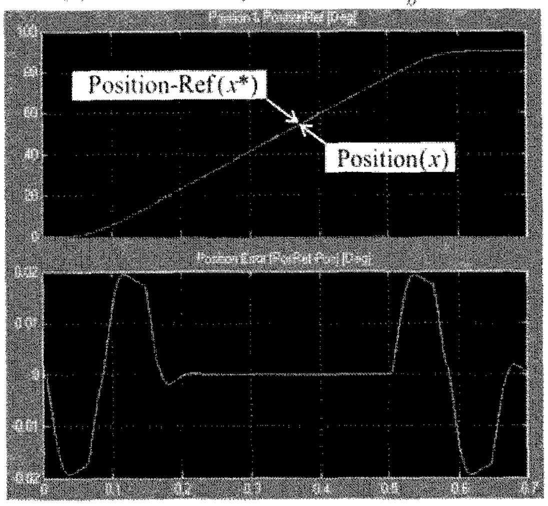
3. Simulation Results.

Fig.5 demonstrates some simulation results about the proposed position controller using the MATLAB model shown in Fig.4. The position reference is provided from a conventional pattern generator based on jerk. The conditions for the position profile here is: the final position is 90Deg, the maximum speed is 0.5rev/s, the maximum acceleration is 6 $\mathrm{rev/s^2}$ and the jerk is 300 $\mathrm{rev/s^3}$. These are commonly used conditions in the DDR applications for LCD (Liquid Cristal Display) industry. A 0.5ms sampling rate and 120rad/s bandwidth are chosen for the position loop. A commercial DDR motor is modeled in DC-equivalent form as a plant. The parameters and ratings of the motor are listed in Table.1.

The simulation results vividly demonstrate the phase error response of the proposed controller vividly. The result without feedforward controller is shown in the upper plots of the figure. Since the position loop acts as the first-order filter, the tracking position errors reach to 1.5Deg while the move trajectory traverses 90Deg from 0Deg. On the contrary, when the feedforward controller is utilized for the same controller, greatly reduced tracking errors are shown in the lower plots. The steady state position errors are almost zero while the motor speed keeps constant value. In the transient state, peaking tracking error on the order of 0.02Deg can be seen. The origin of these is not known certainly, but digitalizing error in the controller and imperfect transient changes of the reference pattern are suspected.



(a) Phase error response without $G_{ff}(s)$



(b) Phase error response with $G_{ff}(s)$

Fig. 5 Simulation results for pahse error response

Table 1 Parameter and ratings of DDR Motor

Parameter	Value	
J_m	0.013[$\mathrm{Kg\cdot m^2}$]	Motor Inertia
J_{load}	0.04[$\mathrm{Kg\cdot m^2}$]	Load Inertia
K_{tq}	25[Nm/A]	DC model
I_{max}	3[A]	DC model
$Speed_{max}$	1[rev/s]	

4. Experimental Results

This section illustrates the feasibility of the presented unified-PID algorithm with zero-phase error tracking property. The experimental tests are performed in the positioning control plant using a commercial DDR motor drive system. A test load with inertia of 0.04 $Kg \cdot m^2$ is attached on the motor to imitate the actual field condition. The position information is obtained by a high resolution rotary encoder of 655,360pulse/rev. The power amplifier stage consists of a PWM based 3-phase inverter system with 300V rail voltage and two current sensors for current feedback. Whole control algorithm is implemented on a full digital motion driver using 32bit DSP processor. The sampling rates for the position loop and the current loop are 0.5ms and 0.05ms, respectively. The sampling rate of the current loop is basically related to the synchronous PWM scheme for the switching device in a power amplifier and the switching frequency is settled to 20kHz automatically in the servo driver. The dynamics of the inner current loop is fixed to 3000rad/sec. As described above, the dynamics of the position loop is not affected by the inner current loop while a low cut-off frequency under about 300~500rad/s is chosen for the position loop. The position reference has the same pattern used in the simulation study.

Fig.6 shows the typical positioning performance of the proposed position controller without the feedforward controller. It seems that the motor position would follow the reference well and the whole closed position loop works as a first-order low pass filter as expected. In the lower plots of the figure, actual speed follows the speed reference provided by the pattern generator with some phase delay. This result dictates that a large amount of tracking errors takes place in the moving instance. The corresponding tracking errors are shown in Fig.7. In the lower plots of the figure, peak tracking errors of roughly 1.5Deg can be seen as shown in the simulation works. In the lower side, the tracking errors enclosed by a dashed circle are enlarged to closely show the tracking performance. It is obvious that the proposed position controller has a stable positioning performance, but shows poor tracking performance in itself. Of course, adopting higher cut-off frequency for the position controller reduces the tracking errors to a lower level.

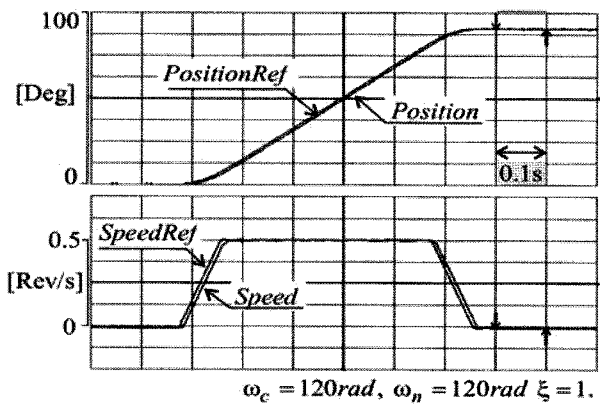
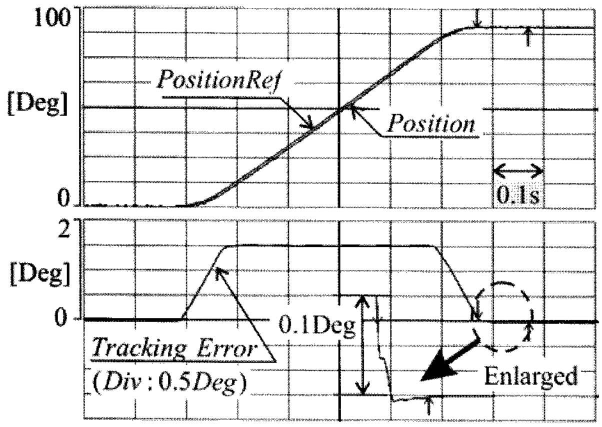


Fig. 6 Experimental result for the positioning performance of the proposed controller. (Upper plots: Position-Ref & Position, Lower plots: Speed-Ref & Speed)

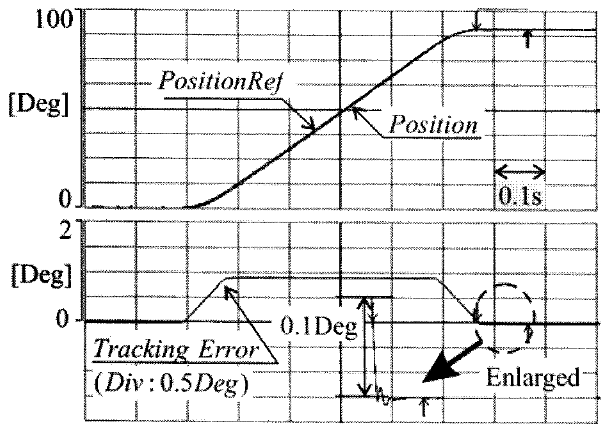
Fig.8 shows the tracking error response of the position controller with a 200rad/s cut-off frequency (a hidden gain ω_n is set to 200rad/s according to the gain tuning rule not presented here). As shown in the figure, the peak tracking error is reduced to 0.9Deg as expected. However, high gain tuning approach is not appropriate in the actual field, since there is always realistic limitation owing to the system noise and the system resonance frequency.

Fig.9 and Fig.10 demonstrate the tracking errors response with the feedforward controller. Fig.9 shows the tracking error response with the same conditions applied for Fig.7. As shown in the lower plots, the tracking errors are greatly reduced as compared with the previous results. Note that the division for a plot of the tracking error is 0.025Deg only. The peak tracking error is roughly 0.025Deg in transient state, and this level is similar to that of the simulation result. Unlike the simulation results, some ripple patterns can be seen in steady state. It is guessed that some disturbances have influence upon the positioning loop, and they might derive principally from the air gap flux distortion. This influence can be suppressed by increasing the cut-off frequency of the main position controller. An improved tracking error response is shown in Fig.10. When the cut-off frequency is increased to 200rad/s, the tracking errors do not exceed 0.01Deg in all speed range. These results strongly satisfy a required level of tracking performance, 0.05Deg, currently in use in semiconductor processing applications.



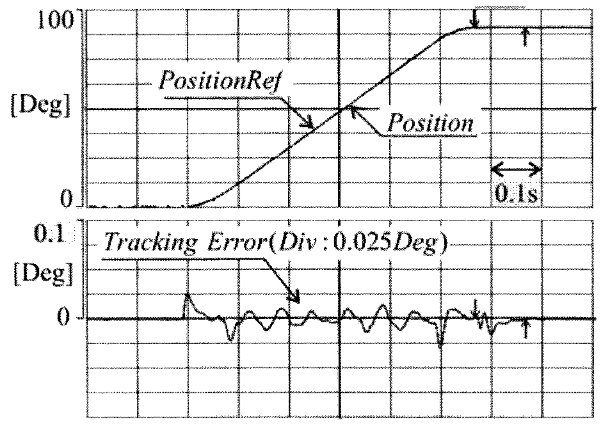
$\omega_c = 120rad$, $\omega_n = 120rad$ $\xi = 1$.

Fig. 7 Experimental result for the tracking error response of the proposed controller without feedforward #1. (Upper plots: Position-Ref & Position, Lower plots: tracking error & enlarged)



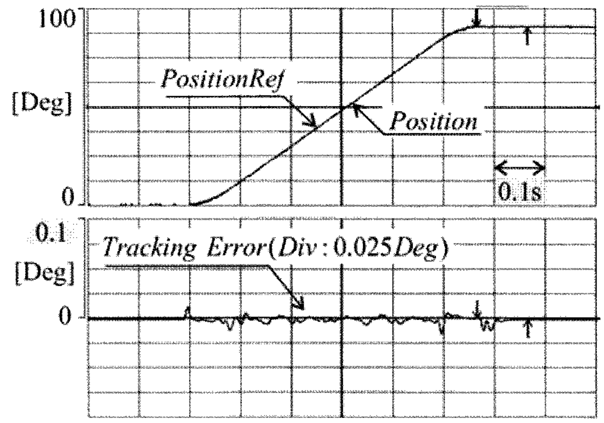
$\omega_c = 200rad$, $\omega_n = 200rad$ $\xi = 1$.

Fig. 8 Experimental result for the tracking error response of the proposed controller without feedforward #2. (Upper plots: Position-Ref & Position, Lower plots: tracking error & enlarged)



$\omega_c = 120rad$, $\omega_n = 120rad$ $\xi = 1$.

Fig. 9 Experimental result for the tracking error response of the proposed controller with feedforward #1. (Upper plots: Position-Ref & Position, Lower plot: tracking error)



$\omega_c = 200rad$, $\omega_n = 200rad$ $\xi = 1$.

Fig. 10 Experimental result for the tracking error response of the proposed controller with feedforward #2. (Upper plots: Position-Ref & Position, Lower plot: tracking error)

5. Conclusion

A position controller including feedback controller and feedforward controller was designed and applied to high resolution DDR motor drives. To stabilize the positioning system without speed control loop, a PD type controller was introduced for a state feedback controller. It was shown that the closed position loop can be transformed to a first-order low pass filter by smart gain modification strategy and this approach clears the formidable gain tuning problem in a simple way. Moreover, a feedforward control algorithm which accounts for the phase error property of the main position loop was designed. It was effective in minimizing the tracking errors presented in a DDR motor drive with arbitrary position reference pattern, assuring a stable dynamics related to the feedback loop. A computationally simple structure of the proposed position loop was adequate to obtain a dramatic improvement in reducing tracking error with less effort. The implementation results clearly demonstrate the effectiveness of the proposed approach. With a commonly used position pattern, this control method greatly reduces the tracking errors in the order of 0.01Deg in all speed ranges. Although developed for a specific case, these design techniques are applicable to common direct-drive systems used in a variety of other manufacturing applications.

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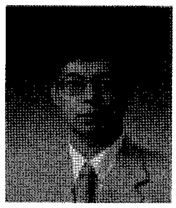

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