Trajectory Tracking Control Method Based on Zero-Phase Minimum-Phase Factorization for Nonminimum-Phase Continuous-Time System

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***Abstract*—The purpose of this paper is development of high-precision trajectory tracking control for nonminimum-phase continuous-time systems with unstable zeros. This paper proposes a two degree of freedom control system design method that is based on a novel factorization method for nonminimum-phase continuous-time systems. First, nonminimum-phase continuous-time systems is factorized to minimum-phase system and zero-phase system in continuous-time domain. The feedforward controller is constructed from inverse system of each factorized system. The inverse system of the minimum-phase system is designed by multi-rate perfect model following control theory, and the inverse system of zero-phase system is designed by zero-phase FIR filter. Finally, This paper shows the effectiveness of proposed method by simulation and experimental results.**

I. Introduction

In motion control, two-degree-of-freedom control system is known as effective method in trajectory tracking control, and is applied to many industrial equipments. The inverse system of the plant is well used for the feedforward controller of the two-degree-of-freedom control system. In the design of the inverse system of the plant, it is very important where the zero of the plant is located, because, the unstable zero becomes unstable pole in the inverse system of the plant. The system which has dead time and an unstable zero is non-minimum phase system. Since the control design is difficult for nonminimum-phase continuous-time system, the design which does not generate unstable zero in mechanical design is proposed [1].

There are two kinds of unstable zeros in continuous-time domain and discrete-time domain. Even if minimum-phase continuous-time system, when the relative degree is larger than three, the discrete time system has unstable zero. Moreover, when the plant is nonminimum-phase continuous-time system, the discrete time system also has unstable zero. Some effective methods are proposed by unstable zero which is related to discretization. In single rate discrete time system, there are zero phase error tracking control [2] and zero magnitude error tracking control [3] which can realize perfect inverse characteristic to phase characteristic or amplitude characteristic. In multi-rate discrete time system, there is perfect tracking control [4] which realizes stable and perfect inverse characteristic. By these methods, the unstable zero which generated in discretization does not become the problem in control system design. The unstable zero of continuous-time generates undershoot as shown in figure 1. As the result, the improvement of trajectory tracking characteristics is difficult. According to [5], the response of two-degree-of-freedom control system can be arbitrarily chosen in the range maintaining unstable zero to this nonminimum phase continuous time system. As the method of improving trajectory tracking characteristics using the analog controller, the plant of continuous system is factored by inner outer factorization, and the method used for two-degree-of-freedom control system as the extended inverse function which related the inner function to lag time is reported in [6].

In fact, it is common to use discrete-time controller. Therefore, control performance will deteriorate, when the controller designed by the continuous system is digital re-designed, although we would like to realize these methods by digital controller. There is delayed inverse filter which realizes approximately the inverse characteristic with nonminimum-phase discrete-time system unstable as the method of improving trajectory tracking characteristic using FIR filter [7] [8]. The method does not have the consideration with regard to the cause of generating of the unstable zero of discrete-time system.

In this paper, the two-degree-of-freedom control system which has the feedforward controller designed have high trajectory tracking characteristic is proposed to the plant which has unstable zero in continuous time. Moreover, the proposed

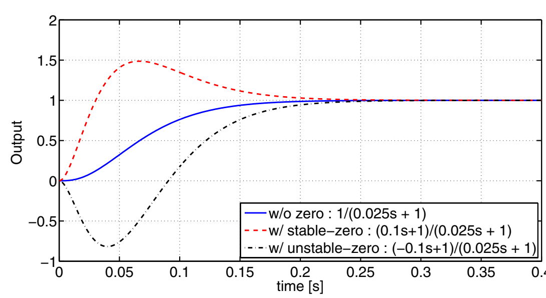


Fig. 1. Difference of time response by location of zero.

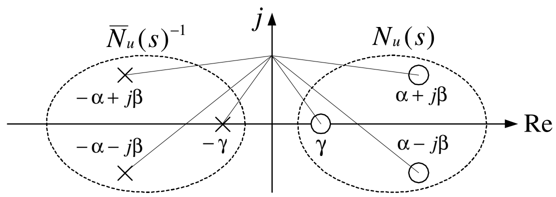


Fig. 2. Poles-zeros location of $P_{AP}(s)$

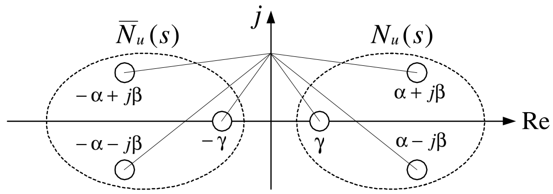


Fig. 3. Poles-zeros location of $P_{ZP}(s)$

control system is implemented with digital controller.

II. Factorization of Plant

In this paper, the plant is LTI and nonminimum-phase continuous-time system. The transfer function of the plant is expressed with

$$P(s) = \frac{N_p(s)}{D_p(s)} = K\,\frac{N_s(s)N_u(s)}{D_p(s)}, \tag{1}$$

where $N_p(s)$ and $D_p(s)$ are lth and nth order numerical polynomial equations, K is constant value, $N_s(s)$ and $N_u(s)$ are numerical polynomial equations that have m stable-zeros, and q unstable-zeros. $N_p(s)$, $N_s(s)$ and $N_u(s)$ is represented as follows.

$$N_p(s) = b_{p_l}s^l + b_{p_{l-1}}s^{l-1} + \cdots + b_{p_1}s + b_{p_0}, \tag{2}$$
$$N_s(s) = b_{s_m}s^m + b_{s_{m-1}}s^{m-1} + \cdots + b_{s_1}s + 1, \tag{3}$$
$$N_u(s) = b_{u_q}s^q + b_{u_{q-1}}s^{q-1} + \cdots + b_{q_1}s + 1. \tag{4}$$

Note that no zeros of the plant exist on the imaginary axis with origin included. An example of $N_u(s)$ is shown as

$$N_u(s) = (s-\gamma)(s-z_0)(s-\bar{z}_0) \tag{5}$$

when γ is real zero, z_0, $\bar{z}_0$ are complex zeros as $z_0 = \alpha + j\beta$, $\bar{z}_0 = \alpha - j\beta$. $\gamma, \alpha, \beta > 0$. Generally, arbitrary stable transfer functions can be expressed by the product of minimum-phase system and an all pass system. This factorization is known as inner-outer factorization. In the control system design to nonminimum-phase system, inner-outer factorization is used well. Factorization description of Eq. (4) is shown as

$$P(s) = K\,\frac{N_s(s)\bar{N}_u(s)}{D_p(s)} \cdot \frac{N_u(s)}{\bar{N}_u(s)}, \tag{6}$$

where $\bar{N}_u(s)$ is the reflection of $N_u(s)$ as

$$\bar{N}_u(s) = (s+\gamma)(s+z_0)(s+\bar{z}_0). \tag{7}$$

Furthermore, $N_u(s)/\bar{N}_u(s)$ is all-pass characteristics, which is expressed $P_{AP}(s)$ in this paper. Fig. 2 shows the poles-zeros location of $P_{AP}(s)$. In this paper, the control system is designed based on not this inner-outer factorization but novel factorization. The plant can be expressed with

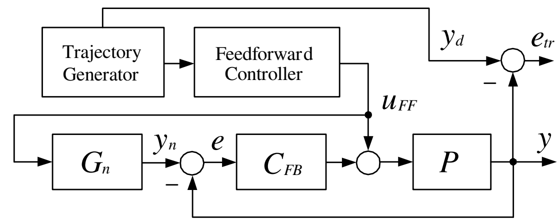


Fig. 4. Proposed control system.

$$P(s) = \frac{K\,N_s(s)}{D_p(s)\bar{N}_u(s)} \cdot \bar{N}_u(s)N_u(s), \tag{8}$$

where the right side are represented

$$P_{MP}(s) = \frac{K\,N_s(s)}{D_p(s)\bar{N}_u(s)}, \tag{9}$$
$$P_{ZP}(s) = \bar{N}_u(s)N_u(s). \tag{10}$$

First, $P_{MP}(s)$ is clearly proper and minimum-phase system. Then, $P_{ZP}(s)$ is described as follows. The location of the zeros of $P_{ZP}(s)$ is shown in Fig. 3. $P_{ZP}(s)$ is clearly non-proper system, and this phase characteristic is zero-phase in all frequency domain. Therefore, description of Eq.(8) shows factorization into minimum-phase system and zero-phase system for nonminimum-phase system.

III. Control System Design

A. Outline of Proposed Control System

Feedforward controller is designed to the plant, which is factorized into the minimum-phase system and the zero-phase system. The continuous-time inverse system of Eq.(8) is expressed with

$$C_{FF}(s) = P_{MP}(s)^{-1}P_{ZP}(s)^{-1}. \tag{11}$$

First, inverse system $P_{MP}(s)^{-1}$ of minimum-phase system is designed. In this paper, although perfect tracking control is used for the design of an inverse system, other methods (e.g. ZPETC, ZMETC) can be used. Then, the inverse system of the zero-phase system is designed. $P_{ZP}(s)^{-1}$ is the zero-phase low pass characteristic. Since this filter has an unstable pole, it should not consist of continuous systems. However, in discrete-time system, the zero-phase filter which used the FIR filter exists. In particular, according to [10], the method of approximating the gain characteristic of IIR filter with the zero-phase FIR filter is proposed. In this paper, the approximation inverse system of the zero-phase system is designed based on the design method of this zero-phase FIR filter.

B. Feedforward Controller for Zero-phase System

Zero-phase filter is used as feedforward controller for zero-phase system. The detailed design method of the zero-phase

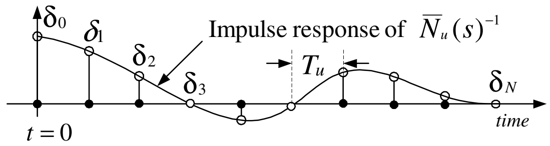


Fig. 5. Impulse response of $\bar{N}_u(s)^{-1}$.

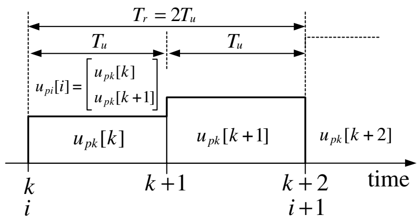


Fig. 6. Multirate-sampling (case of n+q=2).

filter used in this paper is described in [10]. Zero-phase filter is a kind of FIR filter as

$$G_{ZPF}[z, z^{-1}] = \alpha_0 + \sum_{k=1}^{N} \alpha_k (z^k + z^{-k}). \tag{12}$$

The calculation way of the coefficient $\alpha_n (n = 0, 1, \cdots, N)$ is described as follows. First, the impulse response of IIR filter with the desired gain characteristic is calculated. Then, the impulse response at $t = nT_u$ is expressed as δ_n as shown in Fig. 5. The coefficient α_k can be derived from using δ_n as

$$\tilde{\alpha}_k = \sum_{n=k}^{N} \delta_n \delta_{n-k} \tag{13}$$

$$\alpha_k = \frac{\tilde{\alpha}_k}{\tilde{\alpha}_0 + 2(\tilde{\alpha}_1 + \tilde{\alpha}_2 + \cdots + \tilde{\alpha}_N)}. \tag{14}$$

The gain characteristics of the obtained zero-phase filter can be approximated $P_{ZP}(s)^{-1}$ one. From Eq.(12), since the obtained zero-phase filter $G_{ZPF}[z, z^{-1}]$ is non-proper system. Thus, in practice, zero-phase filter is implemented with time-shift operator as

$$C_{ZP}[z] = G_{ZPF}[z, z^{-1}] z^{-(2N+1)}. \tag{15}$$

Furthermore, the approximation accuracy of FIR filter is decided by how many IIR characteristics are included in the acquired impulse response. Basically, if filter length N increases, approximation accuracy will improve, but in the case of the impulse response which hardly changes, the improvement in approximation accuracy is small. Moreover, when change of an impulse response is too quick as compared with sampling time, approximation accuracy deteriorates. In consideration of the above, it is determined that sampling time and filter length will satisfy control specification.

C. *Feedforward Controller for Minimum-phase System*

Vibration suppression perfect tracking control is used as an inverse system to minimum-phase system $P_{MP}(s)$. The state equation of minimum-phase continuous-time system $P_{MP}(s)$ is represented by

$$\dot{\boldsymbol{x}}_p(t) = \boldsymbol{A}_p \boldsymbol{x}_p(t) + \boldsymbol{b}_p \boldsymbol{u}_p(t), \tag{16}$$

where the state equation is realized by controllable canonical form. The degree is $(n+q)$. Then, the discretized state equation by zero-order hold method at sampling time T_u is expressed as

$$\boldsymbol{x}_{pk}[k+1] = \boldsymbol{A}_{pk} \boldsymbol{x}_{pk}[k] + \boldsymbol{b}_{pk} \boldsymbol{u}_{pk}[k]. \tag{17}$$

Furthermore, the plant of Eq.(17) is discretized with multi-rate sampling. As an example, the control input in case the degree $n + q = 2$ is shown in Fig. 6. The multi-rate discretized state equation of the minimum-phase system is represented by

$$\boldsymbol{x}_{pi}[i+1] = \boldsymbol{A}_{pi} \boldsymbol{x}_{pi}[i] + \boldsymbol{b}_{pi} \boldsymbol{u}_{pi}[i]. \tag{18}$$

$$\boldsymbol{A}_{pi} = \boldsymbol{A}_{pk}^{(n+q)}$$

$$\boldsymbol{b}_{pi} = \begin{bmatrix} \boldsymbol{A}_{pk}^{(n+q-1)} \boldsymbol{b}_{pk} & \cdots & \boldsymbol{A}_{pk} \boldsymbol{b}_{pk} & \boldsymbol{b}_{pk} \end{bmatrix}$$

Thus, the control input $\boldsymbol{u}_{pi}[i]$ which realizes desired state variable $\boldsymbol{x}_d[i]$ is derived as

$$\boldsymbol{u}_{pi}[i] = \boldsymbol{b}_{pi}^{-1} (\boldsymbol{I} - z\boldsymbol{A}_{pi}) \boldsymbol{x}_d[i+1] \tag{19}$$

where $\boldsymbol{x}_d[i]$ is the state variable at $\boldsymbol{x}_d(iT_r)$ which is calculated by

$$\boldsymbol{x}_d(t) = \frac{1}{N_s(s)} \begin{bmatrix} 1 & s & \cdots & s^{n+q} \end{bmatrix}^T y_d(t). \tag{20}$$

Here, $y_d(t)$ is the desired trajectory of the output. The multi-rate feedforward controller which is realized (19) is represented by

$$C_{MP}[z] = \left[\begin{array}{c|c} \boldsymbol{O} & \boldsymbol{I} \\ \hline -\boldsymbol{b}_{pi}^{-1} \boldsymbol{A}_{pi} & \boldsymbol{b}_{pi}^{-1} \end{array} \right]. \tag{21}$$

IV. Simulation and Experimental Result

The effectiveness of the proposed method is verified by the simulation and experiment. Furthermore, in simulation and experiment, the condition that using sampling time, FB controller, and desired trajectory are fixed.

A. *Plant*

The experimental device is precision linear stage which is the mock model of XY gantry stage. Fig. 7 shows the physical model of the plant whose parameter are shown in table I.

The plant is two inertia systems which consist of the carriage and the table. Here, The transfer function from force f to position x_2 is represented by

$$P(s) = \frac{x_2(s)}{f(s)} = \frac{b_{22}s^2 + b_{21}s + b_{20}}{a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s} \tag{22}$$

where the parameters of Eq.(22) are shown as

$$\begin{aligned} I_y &= m(b^2 + h^2)/12, \ a_4 = MmL^2 + MI_y, \\ a_3 &= (M+m)\mu_\theta + (mL^2 + I_y)C_x, \\ a_2 &= (M+m)k_\theta - mgL(M+m) + \mu_\theta C_x, \\ a_1 &= (k_\theta - mgL)C_x, \ b_{22} = mL^2 + I_y - mLl, \\ b_{21} &= \mu_\theta, \ b_{20} = k_\theta - mgL. \end{aligned}$$

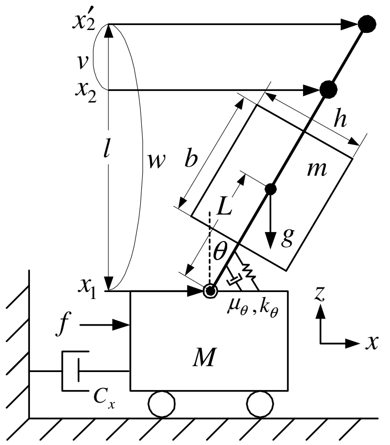


Fig. 7. Physical model of high precision stage.

TABLE I
STAGE PARAMETERS.

M	Carriage Mass [kg]	5.5
m	Table Mass [kg]	7.7
b	Widths of table [m]	0.1
h	Heights of table [m]	0.14
L	Length from pivot to CG [m]	0.09
I	Length from pivot to x_2 [m]	-
μ_θ	Viscous coefficient of pivot [Nms/rad]	0.21
μ_θ	Stiffness coefficient of pivot [Nms/rad]	1336
C_x	Viscous coefficient of air bearing [Ns/m]	24

According to [1], if length l increases, the unstable zero in continuous-time domain will generate in $x_2(s)/f(s)$. Practically, the sensor-position cannot set to any position due to all sensor-position of the stage is fixed. Thus, we use the imaginary position x_2' instead of the real position x_2 in this paper. x_2' is externally dividing point as $x_2' = (-vx_1 + wx_2)(w-v)$. Fig. 8 shows the frequency responses of the plant $P(s) = x_2'(s)/f(s)$ and its nominal plant $P_n(s)$. The transfer function of the nominal plant is expressed as

$$P_n(s) = \frac{-7.071(s+101.7)(s-103.3)}{s(s+1.818)(s^2+8.74s+3.92\times10^4)}. \tag{23}$$

From Eq. (eq:Pn(s)) above equation, the plant has the unstable zero in continuous-time domain. Each terms of Eq. (23) is shown as

$$\begin{cases} D_p(s) = s^4 + 9.92s^3 + 3.92\times10^4 s^2 \\ \qquad\qquad +4.63\times10^4 s \\ N_p(s) = -7.071s^2 + 11.31s + 7.429\times10^4 \\ N_s(s) = 9.833\times10^{-3}s + 1 \\ N_u(s) = 9.681\times10^{-3}s - 1 \\ K = -7.429\times10^4. \end{cases} \tag{24}$$

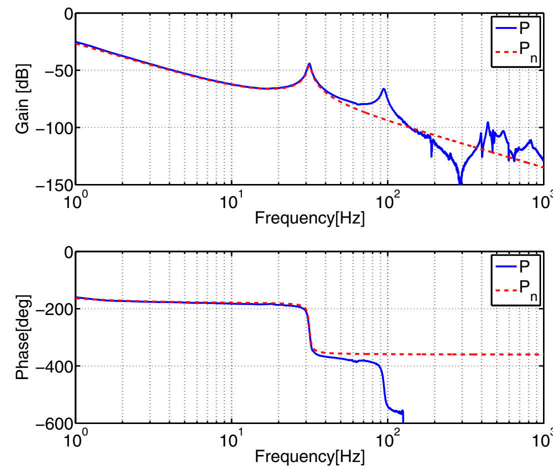


Fig. 8. Frequency response of $P(s)$ and $P_n(s)$.

B. Feedback Controller

The FB controller which is PID with notch-filter is represented by

$$C_{FB}(s) = C_{PID}(s)\cdot C_{notch}(s) \tag{25}$$

$$C_{PID}(s) = \frac{p_2 s^2 + p_1 s + p_0}{s(s+l_1)} \tag{26}$$

$$C_{notch}(s) = \frac{s^2 + Q_1 s + \omega_0^2}{s^2 + Q_2 s + \omega_0^2} \tag{27}$$

$$p_2 = 4.69\times10^4,\quad p_1 = 8.26\times10^5,$$
$$p_0 = 5.19\times10^6,\quad l_1 = 98.68,$$
$$Q_1 = 5.048,\quad Q_2 = 201.9,\quad \omega_0 = 202.0$$

This FB controller $C_{FB}(s)$ is discretized by tustin method at sampling time T_u.

C. Desired Trajectory

The desired trajectory $y_d(t)$ is the step response of reference model $M(s)$ which response has no overshoot. The distance of reference r is 8 mm.

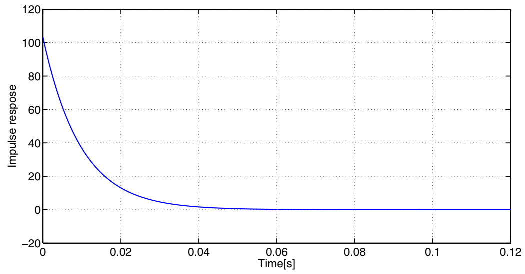
$$M(s) = \left(\frac{\omega_d}{s+\omega_d}\right)^4,\ \omega_d = 2\pi 200 \tag{28}$$

$$y_d(t) = \mathcal{L}^{-1}\left[M(s)\cdot\frac{r}{s}\right],\ r = 0.008 \tag{29}$$

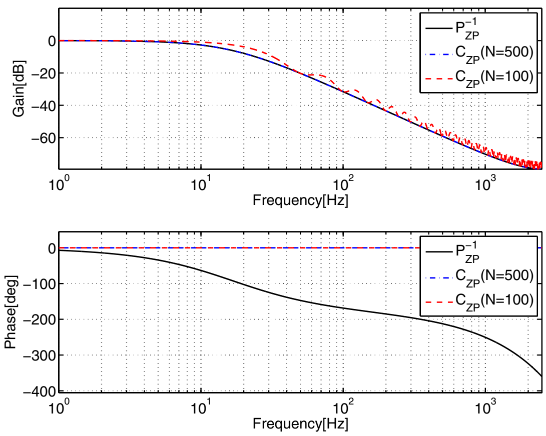
D. Conventional Method

It is known that the response of two-degree-of-freedom control system can be arbitrarily set when maintains unstable zero for nonminimum-phase continuous-time system [5]. From some knowledge, in this paper, the conventional method is VSPTC which is designed for reference model with the same unstable zero as the plant. VSPTC is a kind of PTC when the plant has resonance peak [9]. The nominal plant in conventional method is expressed as

$$P_n(s) = K\frac{N_s(s)}{D_p(s)}. \tag{30}$$



(a) Impulse response of $N_u(s)^{-1}$.



(b) Frequency responses of $C_{ZP}(s)$ and $P_{ZP}(s)^{-1}$.

Fig. 9. Impulse response and Frequency response.

Note that the order of the plant $P_n(s)$ is not n but $(n+q)$. The transfer function $G_n(s)$ which generates the nominal output y_n is represented by

$$G_n(s) = K\frac{N_s(s)N_u(s)}{D_p(s)}. \quad (31)$$

E. Proposed Method

In this section, the proposed method is described without part of the design method of the inverse system for minimum-phase system.

1) Design of zero-phase filter: Fig. 9(a) shows the impulse response of $\bar{N}_u(s)^{-1} = 1/(96.81\times 10^{-3}s+1)$. The frequency responses of designed filter $C_{ZP}[z]$ and desired filter $P_{ZP}[z]^{-1}$ as shown in Fig. 9(b). To evaluate the approximate accuracy with respect to filter length, $C_{ZP}[z]$ is designed in case of $N=100$ and 500.

F. Simulation results

In order to evaluate the characteristics of each feedforward path. Fig. 10 shows the frequency responses which are the feedforward path from y_d to u_{FF}, and $P(s)^{-1}$. From this figure, the inverse system of the plant can be approximated with sufficient accuracy by the proposed method. On the other hand, the conventional method has the modeling error with regard to unstable zero $N_u(s)$.

The time response of trajectory tracking is shown in Fig. 11. Figure 11(a), Fig. 11(b), and Fig. 11(c) are desired output y_m, tracking error e, and control input u, respectively. In those figures, the solid line and the dashed line are the proposed method and the conventional method. Filter length N of the zero-phase FIR filter is 500 which the impulse response sufficiently converged. Furthermore, in order to compare the proposed method and the conventional method clearly, the rise timing of both output is coincided. It can be verified that the proposal method can be suppressing the tracking error greatly in the standup of an output as compared with the conventional method from Fig. 11(a) and Fig. 11(b). Moreover, both most different point is the control input shown in Fig. 11(c). The control input of the proposed method is applied before an output rises, and it is smooth as compared with the conventional method. The effect which this control input gives to an output can be verified from the behavior of the state variable. The output equation when the plant is realized by controllable canonical form is expressed by

$$y(t) = b_{p_2}x_3(t) + b_{p_1}x_2(t) + b_{p_0}x_1(t) \quad (32)$$

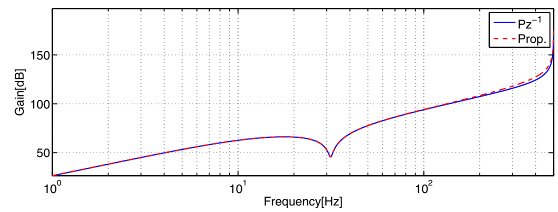
where $x_3 = \dot{x}_2$, $x_2 = \dot{x}_1$. The response of right-hand side each item of Eq. (32) and an output is shown in Fig. 13. From the figure, most sums of right-hand side each item serve as zero in the time before rising of an output. In the time after rising of an output, the trajectory of the state variable which corresponds with the request response mostly is obtained.

G. Experimental results

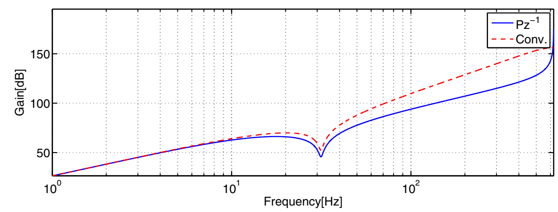
Fig. 12 shows the experimental result. Fig. 12(a), 12(b) and 12(c) are the desired trajectory y_d, the tracking error e and the control input u, respectively.

V. Conclusion

In this paper, two-degree-of-freedom control system which achieves good following characteristics for nonminimum-phase continuous-time system was developed. By proposed method, nonminimum continuous-time system was factored into the minimum-phase system and the zero-phase system,

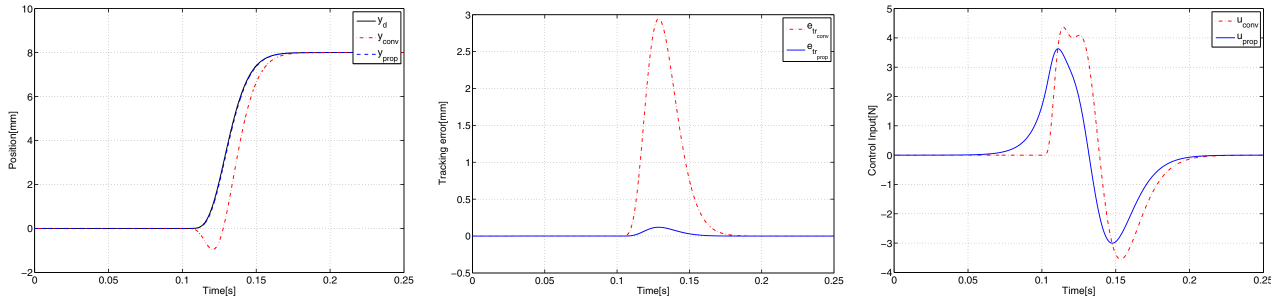


(a) Proposed method.



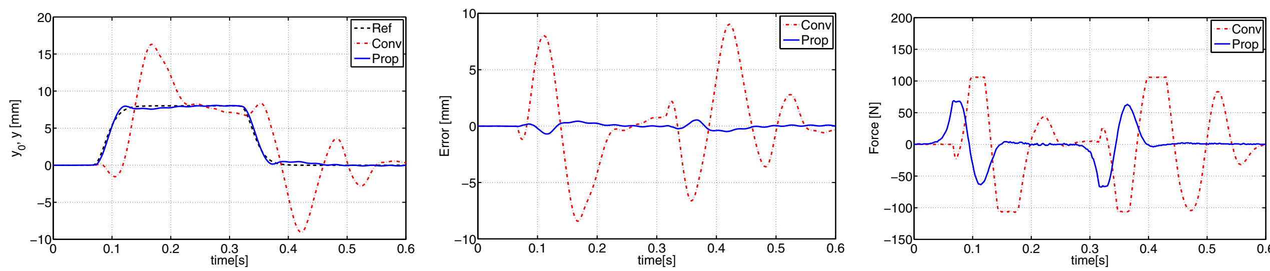
(b) Conventional method.

Fig. 10. Frequency responses u_{FF}/y_d and $P(s)^{-1}$



(a) Reference y_m and output y. (b) Tracking error e_{tr}. (c) Control input u.

Fig. 11. Simulation results (N = 500).



(a) Reference y_m and output y. (b) Tracking error e_{tr}. (c) Control input u.

Fig. 12. Experimental results.

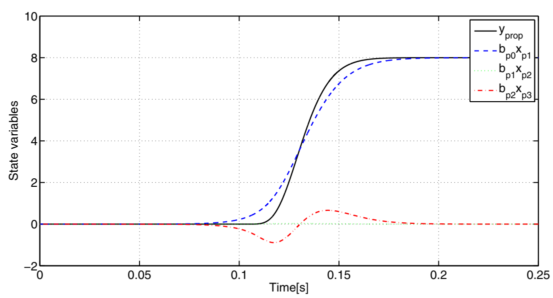


Fig. 13. Trajectory of $b_{p_2}x_3$, $b_{p_1}x_2$, $b_{p_0}x_1$, and y.

and the inverse system of each system was designed. Accordingly, the approximated inverse system of the highly precise plant has been developed. The undershoot was greatly suppressed. Note that, the proposed method uses the approximated inverse system, therefore perfect tracking is not able to achieved. However, the approximate error can be reduced by a designer.

In the trajectory tracking control of nonminimum-phase continuous-time system, although the trajectory of the state variable to obtain the desired output is discussed, consideration of initial state variables is required. On the other hand, the proposed method can be designed without the consideration to an initial value. Thus, since the design plan of the design method is clear, many application is expectable.

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