New Target Transfer Functions with No Overshoot

Dae-Jeong Yang, Young-Chol Kim

Abstract - To design a controller based on the pole placement method, it is necessary to obtain either a target transfer function or a desired characteristic equation which results in the closed-loop response. Specially, a step response in which no overshoot occurs is highly desirable in many applications. In this paper, we present two new prototypes of Type I target transfer functions whose step responses have an overshoot of less than 0.1%. One prototype is obtained by Taylor's approximation of a Gaussian function. It is, however, observed that the response delays increase with increasing order, while the rise times are nearly constant. The other prototype is a modification of the first prototype, so that their transfer function coefficients have particular values in terms of specific parameters γ_i and τ (see section 2). The second prototype gives very useful properties in which step responses are almost the same shape, irrespective of the order. It, also, has no overshoot. Some other properties of the two prototypes and an application example are given.
Key Words - target transfer function, stability index, time constant, Gaussian function

1. Introduction

In many cases, the classical controller design for linear time invariant systems boils down to the problem of properly selecting the target closed-loop model so that it satisfies stability requirements as well as prespecified performances. Specific methods are relevant, when the controller must meet time-domain specifications such as the maximum overshoot, rise time, and settling time etc. These are the ITAE, ISE, Bessel filter prototype[1]. Comparing the transient responses, it is well known that both ISE and ITAE prototypes have some overshoots, whereas the Bessel prototype has almost none. However, response rates of all these prototypes become slower as their order increases.

This parer will suggest two new prototypes of target transfer function with an overshoot of less than 0.1% and the difference of transient responses of less than 1.5% without regard to system order. Furthermore the settling time of the prototypes can be set arbitrarily. We consider only the Type I model as a target transfer function. Since the type I system has no zero, the problem is the same as finding a set of target characteristic polynomials. To do this, some specific parameters, γ_i and τ (see ch.2) which was first defined by Naslin[2] are introduced. These parameters play an important role in a derivation of a new prototype. We start by approximating a function that normalizes Gaussian magnitude characteristics and linear phase properties. A set of finite order polynomials can be developed by using Taylor's series expansion for the magnitude function. From this procedure, we get the interim prototype which gives very similar step responses as those of the Bessel prototype. But the coefficients and the pole locations of the two prototypes ar quite different from each other. Modifying this prototype, a new form can be obtained. In order to know how much each pole (or pole pair) has any effect on the step response, we define a special function D which is called the dominance function. It is said that either a real pole or a complex pole pair that has a large D value corresponds to the dominant pole(or pole pair). Through step responses, pole location patterns, and the dominance function, some properties of the proposed two prototypes are represented. As an example, a new prototypes will be applied to the pole placement design problem for the controller and then will be compared with the results designed by the ITAE and the dominant second order pole placement methods, which are mostly used in the classical control designs.

In the second chapter, we define a Gaussian function, necessary parameters, and a dominance function. In chapter 3, we suggest two new target transfer functions. In chapter 4, some properties of the new target transfer functions will be given. To show the practicality of the new target transfer functions, chapter 5 provides an example. Finally, the conclusion follows.

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2. Definitions

Consider the following Gaussian function.

$$|G(j\omega)| = e^{(-a\omega^2)} \tag{1}$$

where, a is a positive real number. It is known that this function has no overshoot in step response[3]. We can write a target transfer function of Type I as

$$T(s)=\frac{Y(s)}{R(s)}=\frac{a_n}{s^n+a_1 s^{n-1}+\cdots+a_{n-1}s+a_n} \qquad (2)$$

The characteristic polynomial is

$$\Delta(s)=a_0 s^n+a_1 s^{n-1}+\cdots+a_{n-1}s+a_n \text{ ,}(a_0=1) \qquad (3)$$

The definition of system types is referred to in [1]. It is noted that a system of Type I has a closed-loop DC gain of 1, that is, $T(0)=1$. Now, define the following parameters in terms of only polynomial coefficients.

$$\gamma_{n-i}=\frac{a_i^2}{a_{i+1}a_{i-1}} \quad , \quad i=1,2,\cdots,n-1 \qquad (4)$$

$$\tau=\frac{a_{n-1}}{a_n} \qquad (5)$$

We call γ_i and τ as the stability index and the equivalent time constant, respectively. The characteristic polynomial (3) can be written by γ_i's and τ below.

$$\Delta(s)=a_n\left[\left\{\sum_{i=2}^{n}\left(\prod_{j=1}^{i-1}(1/\gamma_{i-j}^{j})(\tau s)^i\right)\right\}+\tau s+1\right] \qquad (6)$$

$$\Delta(s)=s^n+\frac{\prod_{j=1}^{n-1}\gamma_j^{(n-j)}}{\tau^n}\times\left\{\sum_{i=2}^{n}\left(\prod_{j=1}^{i-1}(1/\gamma_{i-j}^{j})(\tau s)^i\right\}+\frac{\prod_{j=1}^{n-1}\gamma_j^{(n-j)}}{\tau^{n-1}}s+\frac{\prod_{j=1}^{n-1}\gamma_j^{(n-j)}}{\tau^n} \qquad (7)$$

Naslin[2] first suggested that the stability index, γ_i, very closely relates to the damping ratio and for some given values γ_i's, the shape of the step response does not change much with increasing order. Manabe[4] found a set of γ_i's, $\gamma_1=2.5$, $\gamma_2=\gamma_3=\cdots=\gamma_{n-1}=2$. These value have favorable characteristics which have almost no overshoot for system Type I and almost equal response forms irrespective of the system order. Even though the Manabe form was found heuristically, its properties are empirically true.

As a measure of indication how much each complex pole pair (or real pole) effects the step response, we are going to, newly, define the dominance function. We rewrite (2) as

$$T(s)=\frac{Y(s)}{R(s)}=\frac{a_n}{\prod_{i=1}^{n}(s-p_i)}. \qquad (8)$$

Assume that $T(s)$ has $2m$ complex conjugate poles with $p_j=\beta_j+j\omega_j$ and $n-2m$ real poles. Then the unit step response can be written as

$$Y(s)=\frac{1}{s}+\prod_{i=1}^{n-2m}\frac{K_i}{(s-\alpha_i)}+\sum_{j=1}^{m}\left\{\frac{C_j}{(s-p_j)}+\frac{C_j^*}{(s-p_j^*)}\right\} \qquad (9)$$

Taking the inverse Laplace transform, we have

$$y(t)=1+\prod_{i=1}^{n-2m}K_i e^{\alpha_i t}+\sum_{j=1}^{m}2|C_j|e^{\beta_j t}\cos(\omega_j t+\theta_j) \qquad (10)$$
$$\theta_j=\arg(C_j)$$

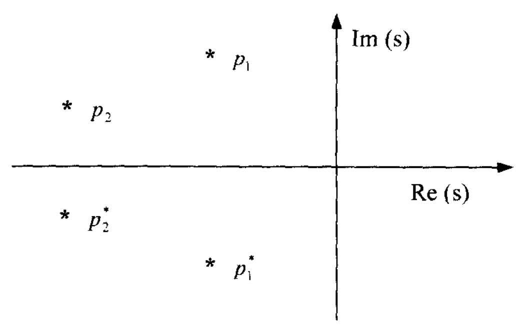
Let us now define the dominance function D.

$$D_i:=\int_0^T|A_i|e^{\lambda_i t}dt=\frac{|A_i|}{\lambda_i}(e^{\lambda_i T}-1), \qquad (11)$$
$$i=1,2,\cdots,(n-m)$$

where $A_i=K_i$ or $2|C_i|$, $\lambda_i=\alpha_i$ or β_i. The T is the time $y(t)$ reaches in the steady state. It is sufficient to choose $T\geq 4\tau$. The dominance function D_i equals the area of envelope of each damped sinusoid of $y(t)$. Thus, it means that the larger D_i a certain pole pair has, the more dominant the pole pair effects on the step response. For analysis and design purposes, it is important to sort out the poles that have a dominant effect on the transient response. In most textbook, it is usual to qualitatively sectionalize the s-plane into two regions in which the dominant and insignificant poles can lie. The two regions are recognized by merely how far or close to the imaginary axis the poles are. We must point out that such definitions may not be proper for the analysis. Let us see an example.

Example 1 : Consider the following fourth order transfer function.

$$T(s)=\frac{145.28}{(s+2.7\pm j2.5)(s+3.2\pm j0.7)}=\frac{145.28}{(s-p_1)(s-p_1^*)(s-p_2)(s-p_2^*)}$$



	poles	Damping ratio	D_i(%)
p_1, p_1^*	$-2.7 \pm j2.$	0.734	22.8
p_2, p_2^*	$-3.2 \pm j0.$	0.977	77.2

We see that though $p_2 - p_2^*$ pair lies farther from the imaginary axis than $p_1 - p_1^*$ pair, $p_2 - p_2^*$ pair has a much more dominant effect than $p_1 - p_1^*$. ▽▽▽

3. New target transfer functions

In this section, two new prototypes of Type I transfer function will be presented.

3.1 G-type

Taking the Taylor series expansion of (1) at $\omega = 0$,

$$|G(jw)| = e^{(-aw^2)} = \frac{1}{\sum_{n=0}^{\infty} \frac{(a\omega^2)^n}{n!}} \qquad (12)$$

Since the denominator of (12) is a infinite series, we need to approximate it to n-th order of a polynomial.

$$D^2(j\omega) = 1 + a\omega^2 + \frac{(a\omega^2)^2}{2!} + \frac{(a\omega^2)^3}{3!} + \cdots + \frac{(a\omega^2)^n}{n!} \qquad (13)$$

Let $w = s/j$, and substituting this into (13),

$$D(s)D(-s) = (-1)^n \frac{a^n s^{2n}}{n!} + \cdots + \frac{a^2 s^4}{2!} - as^2 + 1. \qquad (14)$$

Solving (14), we obtain $D(s)$ as shown in Table 1.

Table 1 A new target function by approximation Gaussian function

order	$T(s) = \frac{a_n}{s^n + a_1 s^{n-1} + \cdots + a_{n-1}s + a_n}$
2	$s^2 + 2.1974/\sqrt{a}s + 1.4142/a$
3	$s^3 + 3.5615/\sqrt{a}s^2 + 4.8423/as + 2.4495/(a\sqrt{a})$
4	$s^4 + 5.0729/\sqrt{a}s^3 + 10.867/as^2 + 11.423/(a\sqrt{a})s + 4.899/a^2$
5	$s^5 + 6.714/\sqrt{a}s^4 + 20.062/as^3 + 32.778/(a\sqrt{a})s^2 + 28.951/a^2 s + 10.954/(a^2\sqrt{a})$
6	$s^6 + 8.4845/\sqrt{a}s^5 + 32.993/as^4 + 74.313/(a\sqrt{a})s^3 + 101.23/a^2 s^2 + 78.438/(a^2\sqrt{a})s + 26.833/a^3$
7	$s^7 + 10.366/\sqrt{a}s^6 + 50.225/as^5 + 145.90/(a\sqrt{a})s^4 + 272.10/a^2 s^3 + 323.54/(a^2\sqrt{a})s^2 + 225.78/a^3 s + 70.993/(a^3\sqrt{a})$
8	$s^8 + 12.354/\sqrt{a}s^7 + 72.316/as^6 + 259.63/(a\sqrt{a})s^5 + 620.73/a^2 s^4 + 1005.9/(a^2\sqrt{a})s^3 + 1073.3/a^3 s^2 + 686.56/(a^3\sqrt{a})s + 200.8/a^4$

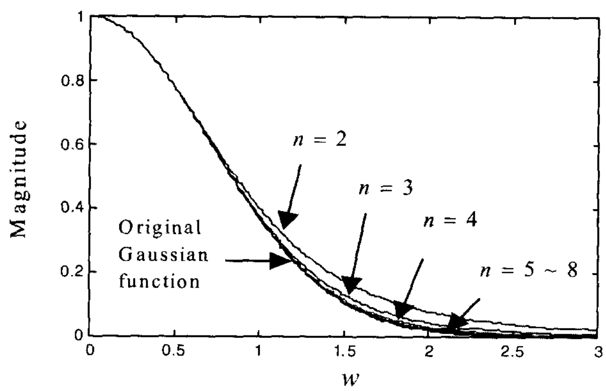


Fig. 1 Comparisons of frequency magnitudes of the original Gaussian function and target transfer functions.

This standard transfer function is called the G-type target transfer function. Fig.1 shows frequency magnitude responses of the original Gaussian function and target transfer functions in Table 1 when $a = 1$. When $n \geq 5$, we see that the maximum difference of two functions is 0.1%.

Substituting values of coefficient, in Table 1 into (4), it is evident that γ_i's are independent upon the parameter a in (1). The γ_i's that are calculated by coefficients in Table 1 are shown in Table 2.

Though some algebraic calculations, we obtained converting equations relating between τ and a, and, also between t_s and a, which are shown in Table 3. These two tables are very useful for designing a controller so that it satisfies the no overshoot requirement and the desired settling time[4].

Table 2 Stability index of G-type target transfer function

order	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7
3	2.6878	2.6195					
4	2.4508	2.0380	2.3681				
5	2.3342	1.8499	1.8279	2.2492			
6	2.2651	1.7580	1.6535	1.7265	2.1819		
7	2.2194	1.7038	1.5685	1.5576	1.6679	2.1394	
8	2.1871	1.6682	1.5186	1.4754	1.5016	1.6304	2.1106

Table 3 Relations of between a and τ , t_s

order	Equivalent time constant τ	Settling time t_s (Approx. values)
3	$1.9768\times\sqrt{a}$	$4.78\times\sqrt{a}$
4	$2.3317\times\sqrt{a}$	$5.01\times\sqrt{a}$
5	$2.643\times\sqrt{a}$	$5.25\times\sqrt{a}$
6	$2.9232\times\sqrt{a}$	$5.50\times\sqrt{a}$
7	$3.1803\times\sqrt{a}$	$5.74\times\sqrt{a}$
8	$3.419\times\sqrt{a}$	$5.96\times\sqrt{a}$

3.2 Y-type

Kim et al.[5] found that when the magnitude pattern of γ_i's, $[\gamma_1, \gamma_2, \cdots, \gamma_{n-1}]$ with respect to the number of order looks like an "S" curve as shown in Fig.2, it has the almost same response shapes irrespective of the number of orders.

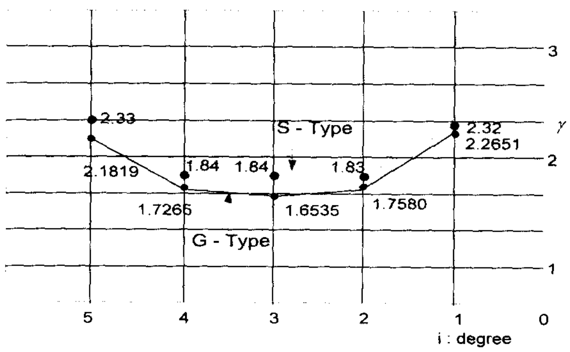


Fig. 2 γ_i patterns of S and G prototypes($n=6$)[5].

Based on this fact, we choose the γ_i's of the 4th order case in Table 2 as reference values and, subsequently, set the γ_i's of higher orders so that these γ_i's has the same behavior as the S-type pattern above. The results are laid out in Table 4. Substituting each γ_i in Table 4 into (7), a new prototype of target transfer function are obtained as shown in Table 5. This standard transfer function is called the Y-type target transfer function. We have calculated

Table 4 Stability index of Y-type target transfer function

order	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7
4	2.4508	2.0380	2.3681				
5	2.4508	2.0380	2.0380	2.3681			
6	2.4508	2.0380	2.0380	2.0380	2.3681		
7	2.4508	2.0380	2.0380	2.0380	2.0380	2.3681	
8	2.4508	2.0380	2.0380	2.0380	2.0380	2.0380	2.3681

$t_s=2.2857\tau$. For example, assume that if we want to design a controller satisfying the settling time $t_s=1$ sec, then $\tau=0.4375$.

Table 5 Target transfer functions of Y-type

order	$T(s)=\dfrac{a_n}{s^n+a_1s^{n-1}+\cdots+a_{n-1}s+a_n}$
4	$s^4+11.828/\tau s^3+59.078/\tau^2 s^2+144.79/\tau^3 s+144.79/\tau^4$
5	$s^5+24.106/\tau s^4+245.38/\tau^2 s^3+1225.6/\tau^3 s^2+3003.7/\tau^4 s+3003.7/\tau^5$
6	$s^6+49.127/\tau s^5+1019.2/\tau^2 s^4+10374/\tau^3 s^3+51817/\tau^4 s^2+126990/\tau^5 s+126990/\tau^6$
7	$s^7+100.12/\tau s^6+4233/\tau^2 s^5+87815/\tau^3 s^4+893890/\tau^4 s^3+4464800/\tau^5 s^2+10942000/\tau^6 s+10942000$
8	$s^8+204.05/\tau s^7+17582/\tau^2 s^6+743330/\tau^3 s^5+(1.5421\times 10^5)/\tau^4 s^4+(1.5697\times 10^8)/\tau^5 s^3+(7.8403\times 10^8)/\tau^6 s^2+(1.9215\times 10^9)s+(1.9215\times 10^9$

Thus, we can select a desired characteristic polynomial with the predetermined system order n. Then we can set up the Diophantine equation with the target polynomial. Finally, solving the equation, the controller will be obtained.

4. Properties of the new target transfer functions

This section deals with some properties relative to the two prototypes in the previous section. To do this, we will investigate the step responses, the poles patterns, and the dominance of each pole pair of both prototypes.

4.1 G-type

The step responses of the G-type functions in Table 1 are shown in Fig.3. All these give rise to no overshoot, whereas their response delays increase as the order becomes larger.

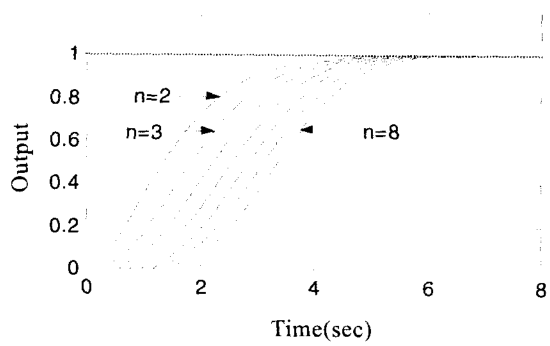


Fig. 3 Step responses of G-type transfer functions

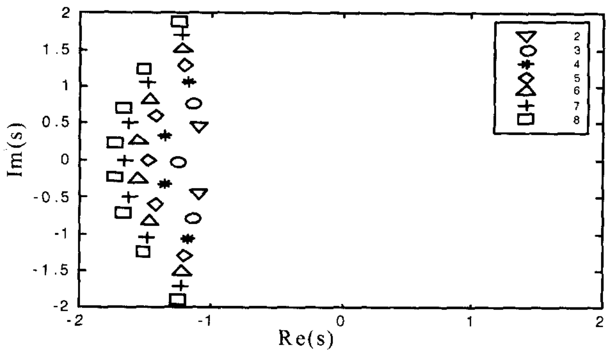


Fig. 4 Root location of G-type transfer functions

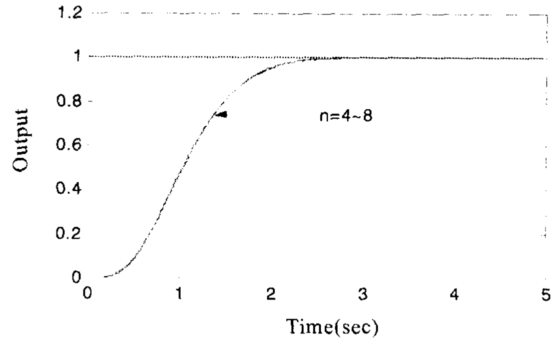


Fig. 5 Step responses of the Y-type transfer function

The pole locations of the G-type transfer functions are depicted in Fig.4. We can see that all the roots seem to be located on the arc of an ellipse. When $n=4\sim6$, the damping ratios and the dominance function D_i relative to the G-type transfer functions are given in Table 6. It is observed that the G-type has the dominance property of which the pole pair(or real pole) that results in the largest damping ratio is superior to the others.

Table 6 Dominance functions of G-type($n=4\sim6$)

n	p_i	ζ_i	D_i
4	$-1.1811\pm j1.0604$	0.744	23.77
	$-1.3554\pm j0.328$	0.972	76.231
5	$-1.2034\pm j1.2989$	0.679	10.66
	$-1.4193\pm j0.5993$	0.921	49.66
	-1.472	1	39.69
6	$-1.2207\pm j1.5145$	0.628	4.53
	$-1.4614\pm j0.833$	0.869	29.42
	$-1.5601\pm j0.2687$	0.985	66.05

4.2 Y-type

Fig.5 and Fig.6 show the step responses and their pole locations of Y-type standard transfer functions given in Table 5, respectively. This new prototype requires that the overshoot is less than 0.12% and the difference in transient responses for $n=4\sim8$ is less than 1.1%. It is obvious that the Y-type with this property will be very useful in dealing with design problems.

As shown in Fig.6, the Y-type has a quite different root pattern from that of the G-type. It is observed that the Y-type has always two pairs of the complex conjugate poles and the $n-4$ real poles when $n\geq4$. Table 7 shows that the three poles close to the imaginary axis much more dominant than the remainder.

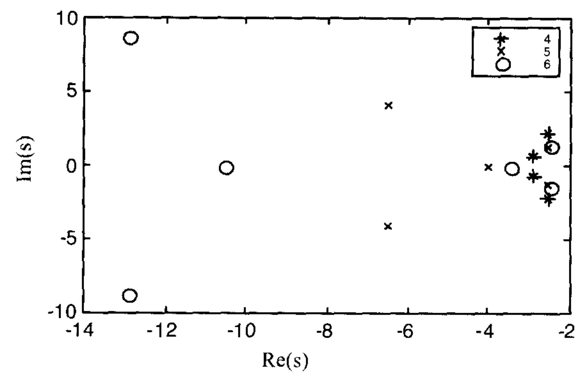


Fig. 6 Root location of the Y-type transfer function

Table 7 Dominance functions of Y-type($n=4\sim6$)

n	p_i	ζ_i	D_i
4	$-2.7538\pm j2.4725$	0.744	25.77
	$-3.1602\pm j0.7644$	0.972	74.23
5	$-2.753\pm j1.4322$	0.887	70.19
	-4.4196	1	28.47
	$-7.0902\pm j4.5161$	0.843	1.34
6	$-2.747\pm j1.5437$	0.872	60.835
	-3.8048	1	38.745
	-11.507	1	0.379
	$-14.161\pm j9.5707$	0.829	0.0417

5. Example

We attempt to compare the controller design using Y-type and G-type transfer functions with those of the dominant second order pole-placement, the ITAE, which are generally well known. Consider a feedback system as shown in Fig.7 and the plant below ;

$$G(s)=\frac{N(s)}{D(s)}=\frac{2}{s(s^2+0.25s+6.25)}$$

For the purpose of simple comparison, the following two specifications are considered.

- The order of both the numerator and the denominator of the controller are of the second order.
- Settling time($\pm 1\%$) should be less than 2.5sec.

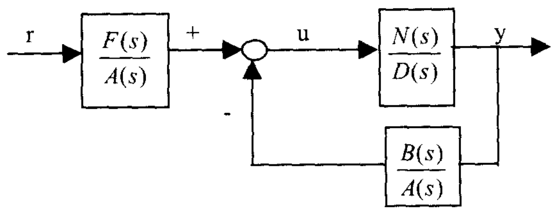


Fig. 7 Feedback system

From the above conditions, the closed-loop system must be of the fifth order. In the dominant second order pole placement design, we choose three poles as main roots at $-2\pm j1.9$, -10 such that it satisfies the given settling time. We place the rest of the poles at -15 and -25, which correspond to the observer poles, here. With the desired poles, the resulting controllers are shown in Table 8. When the ITAE prototype[1] is applied, we first have to denormalize the standard values to have the desired settling time.

Table 8 Controllers designed by pole-placement, ITAE, Y-type

Control Method	Controller
Pole Placement	$\frac{B(s)}{A(s)}=\frac{8.871s^2+19.84s+38.05}{0.0027s^2+0.143s+2.5678}$ $F(s)=38.05(1+s/15)(1+s/25)$
ITAE	$\frac{B(s)}{A(s)}=\frac{157.89s^2+281.89s+653.46}{s^2+11.51s+79.0725}$ $F(s)=653.4562$
G-type	$\frac{B(s)}{A(s)}=\frac{98.657s^2+35.392s+223.69}{s^2+13.849s+78.761}$ $F(s)=223.69$
Y-type	$\frac{B(s)}{A(s)}=\frac{376.0653s^2+444.98s+959.451}{s^2+21.7896s+193.418}$ $F(s)=959.4507$

The ITAE controller with a denormalizing parameter $\omega_n=4.2$ are given in Table 8. Finally, in order to use the Y-prototype, we first calculate $\tau=1.093$ from the algebraic relation $t_s=2.2857\tau$. Similarly, in G-prototype, we obtain $\tau=1.2585$. Substituting this τ into the fifth order form in Table 1 and Table 5, we have the desired characteristic polynomial. Then, it is easy to find a controller.

$$C_G(s)=s^5+14.1055s^4+88.4606s^3+303.5s^2+562.8835s+447.24$$
$$C_Y(s)=s^5+22.04s^4+205.115s^3+936.67s^2+2098.8s+1918.9$$

All controllers result from 4 different design methods which appear in Table 8.

Fig.8 shows the step responses of the closed-loop system with each controller. Four controllers satisfy the given specifications. Both the Pole-placement and the ITAE have overshoots, but Y-type and the G-type have no

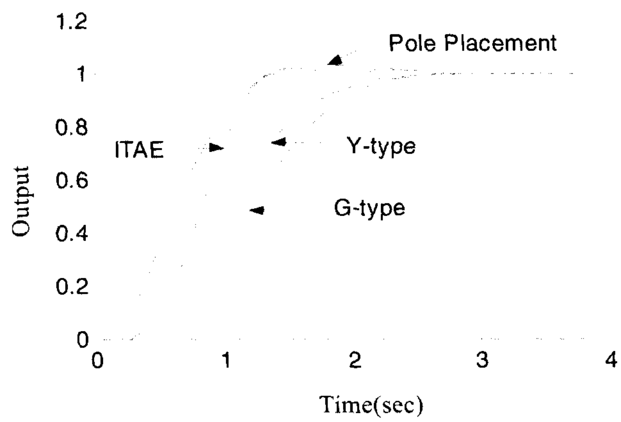


Fig. 8 Step responses of each controller

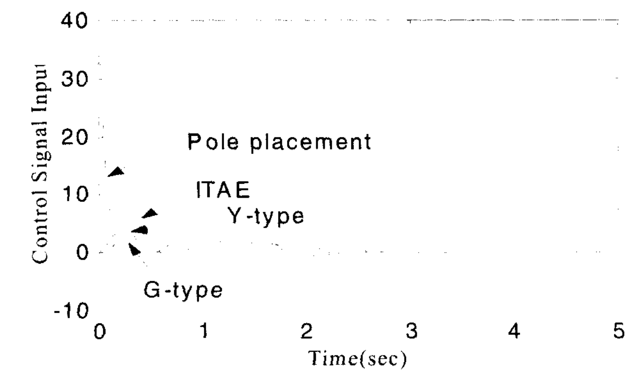


Fig. 9 Control input signals of each controller

Table 9 Comparisons of control input energy and stability margin

Control Method	Control signal margin			Stability margin	
	Max.	Min.	Energy	Gain[dB]	Phase [degree]
Pole Placement	37.58	-3.42	59.22	6.81	50.4
ITAE	6.56	-3.21	20.12	2.103	24.6
G-type	2.28	-0.0015	4.258	5.186	52.42
Y-type	3.96	-0.10	6.047	4.89	47.2

overshoot. Next, the control input of each controller will be compared. The magnitude of the control input is one of the important factors in design because it relates to the capability of the input actuator. Fig.9 and Table 9 show the control input magnitude, and energy of each case. Note that the control input of the Y-type and the G-type are much smaller than the others.

6. Conclusions

We present two new prototypes of Type I target functions which have no overshoot. The step response in which no overshoot occurs is required in many control applications. Based on the Gaussian function, we obtained target characteristic polynomials. This first prototype gives no overshoot but its response delay increases as the order becomes large. By using specific parameters, γ_i and τ which are defined from the coefficients of characteristic polynomials, and based on the Kim's prototype[5], we proposed a second prototype for target transfer functions. This one has three major characteristics; (i) no overshoot, (ii) the same transient response shapes irrespective of the order n, and (iii) the arbitrary settling time is easily met. We defined a dominance function which means how much each complex conjugate pole pair(or a real pole) effects the step response. Using the dominance function, the pole dominancy property of two prototypes has been analyzed. Finally, we show through a classical control design example that the proposed target transfer functions are very useful for this purpose.

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