Transient Response Analysis and Compensation of the Second Order System with One RHP Real Zero

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Abstract: In this paper, the magnitude of undershoot and overshoot in a prototype second order system with one positive real zero is computed by the analytic methods. Also, it will be shown that the peak times of the undershoot and overshoot can be calculated using the impulse and step response of the second order system. Three different cases are investigated : underdamped($0 < \zeta < 1$), critically damped($\zeta = 1$) and overdamped($\zeta > 1$) cases. We deal with the undamped($\zeta = 0$) case as a special case of the underdamped. And a compensation method is proposed to reduce undershoots of the nonminimum phase system using feedforward compensator.

Keywords: Nonminimum phase system, right half plane (RHP) zero, second order system, undershoot, overshoot, transient response, feedforward compensator

I. Introduction

It is well-known that zeros of the system can affect the transient response to the step type reference input. The left half plane (LHP) zeros of the system may cause problems like the overshoot, and the right half plane (RHP) zeros may depress the overshoot at the price of the undershoot[1]. Specially, the RHP zeros which are nearer to the imaginary axis than poles cause worse transients, like the undershoots, oscillations and time delay, in the step response. The occurrence of these phenomena to the step type reference input is usually undesirable in the controlled system outputs. But, it might be impossible to acquire response without these phenomena because there exist fundamental limitations on the achievable transient response of the system with RHP zeros[2][5]. Generally, these limitations can be characterized completely by the number and location of the RHP zeros[5]. In particular, it is well established that the continuous time systems with an odd number of the real RHP zeros have the initial undershoot on the step input, i.e., the initial response is in the opposite direction from the steady state response[3][6]-[9]. Besides, when the system has even positive real zeros including conjugate complex zeros which have positive real parts and absolute values of these zeros are not so large as compared to absolute values of the poles, the output has so-called Type B undershoot, i.e., the initial response is in the same direction of the steady state response, but the mid-term transient response is in the opposite direction of the steady state response[6].

The case of a second order system with one real zero has been well-studied since there exists analytic relation to the location between one real zero and two poles. Also, using some examples of the system with zeros it has been illustrated that the maximum overshoot and peak undershoot increase significantly when the LHP and RHP zeros approach to the origin, respectively[1][3][10][11]. However, there is no control methods proposed such that reduce the magnitude of the undershoot. Despite the progress of the modern control techniques, which provide for pole placement or minimization of a cost functional, the undershoot problem still remains open[3]. One reason is that there is little analytic relationship presented between location of the zeros and characteristics of the system response. Another reason is that the modern feedback control schemes can not move the zeros of the system even though they are able to place the poles of the system arbitrarily.

In this paper, as an initial attack on this problem, the magnitude of undershoot and overshoot of a prototype second order system with one RHP real zero is analyzed in the time domain and explicitly presented by some analytic equations. Also, we will show that the peak times of the undershoot and overshoot can be calculated using the impulse and step response of the system. Analytic results in the time domain would be a useful understanding about the effect of the RHP zeros. Based on these analyses, we propose a feedforward compensator design method which decreases the amount of undershoots. That is the main contribution of the current paper.

The layout of this paper is organized as follows : In Section 2, we deal with the influence of one RHP real zero on a second order system. In Section 3, we will study feedforward compensator which decreases amount of undershoots at the price of rise time. In Section 4, performances of the proposed compensator are shown via computer simulation. The concluding remarks are given in Section 5.

II. Influence of one RHP real zero on a 2nd order system

Consider a prototype second order system with one RHP real zero as follows:

$$G(s) = \frac{-\frac{\omega_n^2}{a}(s-a)}{s^2 + 2\zeta\omega_n s + \omega_n^2}\ , \tag{1}$$

where a is a positive real value. Note that the DC gain of the system (1) is 1. Assume that the prototype second order system is stable, and that the initial value of the system is zero. The system (1) will show an initial undershoot on the step type reference input because of one RHP real zero. We will consider three different cases : underdamped($0 < \zeta < 1$), critically damped($\zeta = 1$), and overdamped($\zeta > 1$) cases. And, the

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undamped($\zeta = 0$) case is taken as a special case of the underdamped.

1. Underdamped case $(0 < \zeta < 1)$

In this case, the system (1) can be rewritten by

$$G(s) = \frac{-\frac{\omega_n^2}{a}(s-a)}{(s-p_1)(s-\bar{p}_1)} = \frac{-\frac{\omega_n^2}{a}(s-a)}{(s+\zeta\omega_n)^2+\omega_d^2} \tag{2}$$

with two poles and one RHP zero as follows:

$$\begin{array}{rcc} \text{poles} & : & p_1, \bar{p}_1 = -\zeta\omega_n \pm j\omega_d \,, \\ \text{RHP zero} & : & a \,, \end{array} \tag{3}$$

where $\omega_d = \omega_n\sqrt{1-\zeta^2}$ is the damped natural frequency. For $t \geq 0$, the impulse response of the system (2) is given by the inverse Laplace transform as follows:

$$\begin{aligned} g(t) &= \frac{\omega_n^2}{a} e^{-\zeta\omega_n t}\left[\frac{a+\zeta\omega_n}{\omega_d}\sin\omega_d t - \cos\omega_d t\right] \\ &= A_1 e^{-\zeta\omega_n t}\sin(\omega_d t - \phi_1), \end{aligned} \tag{4}$$

where

$$A_1 = \frac{\omega_n}{a}\sqrt{\frac{a^2+2a\zeta\omega_n+\omega_n^2}{1-\zeta^2}}\,, \tag{5}$$

and

$$\phi_1 = \tan^{-1}\theta_1,\ \theta_1 = \frac{\omega_d}{a+\zeta\omega_n}\,. \tag{6}$$

The impulse response (4) will be zero at time *t* such that

$$\omega_d t - \phi_1 = i\pi, \tag{7}$$

where $i = 0, 1, 2, \cdots$. Since the impulse response is the time derivative of the unit step response, the peak undershoot of the system (2) can be found at the peak undershoot time t_p such that

$$t_p = \frac{\phi_1}{\omega_d}, \tag{8}$$

in the unit step response. Since the unit step response of the system (2) is represented by

$$Y(s) = \frac{-\frac{\omega_n^2}{a}(s-a)}{s(s^2+2\zeta\omega_n s+\omega_n^2)} \tag{9}$$

in the frequency domain, the unit step response in the time domain is explicitly written by

$$\begin{aligned} y(t) &= 1 - e^{-\zeta\omega_n t}\left[\cos\omega_d t + \left(\frac{a\zeta+\omega_n}{a\sqrt{1-\zeta^2}}\sin\omega_d t\right)\right] \\ &= 1 - \frac{A_1}{\omega_n}e^{-\zeta\omega_n t}\sin(\omega_d t + \phi_2), \end{aligned} \tag{10}$$

where

$$\phi_2 = \tan^{-1}\theta_2,\ \theta_2 = \frac{a\sqrt{1-\zeta^2}}{a\zeta+\omega_n}\,. \tag{11}$$

Now, we can find the peak undershoot as follows:

Lemma 1: The peak undershoot of the system (2) is formulated as follows:

$$\begin{aligned} Y_{pu} &= y(t_p) \\ &= 1 - \frac{e^{-\frac{\zeta\phi_1}{\sqrt{1-\zeta^2}}}}{a}\sqrt{a^2+2a\zeta\omega_n+\omega_n^2}\,. \end{aligned} \tag{12}$$

Proof: The unit step response of the system (2) is expressed at time t_p as follows:

$$y(t_p) = 1 - \frac{1}{a}\sqrt{\frac{a^2+2a\zeta\omega_n+\omega_n^2}{1-\zeta^2}}e^{-\zeta\omega_n t_p}y_1(t_p), \tag{13}$$

where

$$\begin{aligned} y_1(t_p) &= \sin(\omega_d t_p + \phi_2) \\ &= \sin(\phi_1)\cos\phi_2 + \cos(\phi_1)\sin\phi_2 \\ &= \frac{\theta_1+\theta_2}{\sqrt{(1+\theta_1^2)(1+\theta_2^2)}}\,. \end{aligned} \tag{14}$$

Denominator and numerator of the $y_1(t_p)$ can be rewritten as follows:

$$\theta_1+\theta_2 = \frac{\sqrt{1-\zeta^2}\left(a^2+2a\zeta\omega_n+\omega_n^2\right)}{(a+\zeta\omega_n)(a\zeta+\omega_n)}\,, \tag{15}$$

and

$$\sqrt{(1+\theta_1^2)(1+\theta_2^2)} = \frac{a^2+2a\zeta\omega_n+\omega_n^2}{(a+\zeta\omega_n)(a\zeta+\omega_n)}\,, \tag{16}$$

which gives the relation

$$y_1(t_p) = \sqrt{1-\zeta^2}\,. \tag{17}$$

Hence we have the Eq. (12). ■ ■

It can be shown from Eqs. (6) and (8)

$$\lim_{a\to+\infty} t_p = 0\,, \tag{18}$$

which says that if the real RHP zero approaches infinitely to the right on the complex plane, the undershoot phenomenon will vanish, and $y(0^+) = 0$. It can be also shown that

$$\lim_{a\to+\infty} Y_{pu} = 0. \tag{19}$$

On the other hand, we can show that

$$\lim_{a\to 0^+} Y_{pu} = -\infty, \tag{20}$$

i.e., when the real RHP zero approaches the origin on the complex plane, the peak undershoot becomes infinitely large.

From Eq. (7), the maximum overshoot occurs at the time point $t_m = \dfrac{\phi_1+\pi}{\omega_d}$, and it is explicitly formulated by

$$Y_m = 1 + \frac{e^{-\frac{\zeta(\phi_1+\pi)}{\sqrt{1-\zeta^2}}}}{a}\sqrt{a^2+2a\zeta\omega_n+\omega_n^2}\,. \tag{21}$$

Thus it can be seen that

$$\lim_{a\to 0^+} Y_m = \infty, \tag{22}$$

which says that when the real RHP zero is getting close to the origin on the complex plane, the maximum overshoot becomes infinitely large. It can be also shown that

$$\lim_{a\to\infty} t_m = \frac{\pi}{\omega_d}, \tag{23}$$

(a) Impulse response

(b) Step response

Fig.1. Impulse response and step response of underdamped system.

(a) Impulse response

(b) Step response

Fig.2. Impulse response and step response of undamped system.

and

$$\lim_{a\to\infty} Y_m = 1 + e^{-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}} . \tag{24}$$

That is to say that although the real RHP zero is infinitely far from the origin on the complex plane, the system (2) always has the overshoot in the unit step response. Fig. 1 summarizes the characteristics of the system (2) in the impulse and unit step responses.

If the damping ratio ζ is zero, the response becomes undamped and the poles of the system (2) lie on the imaginary axis. Hence, the impulse response, the peak undershoot time and the unit step response of the system (2) for the undamped case may be obtained by substituting $\zeta = 0$ in Eqs. (4), (7) and (10), respectively:

$$g(t) = A_2 \sin(\omega_n t - \phi_3), \tag{25}$$

$$t_{p_i} = \frac{\phi_3 + i\pi}{\omega_n},\ i = 0, 1, 2, \cdots, \tag{26}$$

$$y(t) = 1 - \frac{A_2}{\omega_n}\sin(\omega_n t + \phi_4), \tag{27}$$

where

$$A_2 = \frac{\omega_n}{a}\sqrt{a^2 + \omega_n^2}, \tag{28}$$

$$\phi_3 = \tan^{-1}\frac{\omega_n}{a}, \tag{29}$$

and

$$\phi_4 = \tan^{-1}\frac{a}{\omega_n}, \tag{30}$$

for $t \geq 0$. Thus, Eqs. (25) and (27) imply that the system (2) with zero damping ratio has a peak to peak values of $\pm A_2$ and $1 \pm A_2/\omega_n$ in the impulse and unit step response, respectively. From Eq. (28), it can be seen that

$$\lim_{a\to 0^+} A_2 = \infty . \tag{31}$$

Hence, like the underdamped case, peak to peak values of the impulse and unit step response become infinitely large when the real RHP zero is getting close to the origin on the complex plane. And since

$$\lim_{a\to\infty} A_2 = \omega_n, \tag{32}$$

the undamped system with one RHP infinite zero has the same bounds in the impulse and step response as those of the undamped system without zero as follows:

$$-\omega_n \leq \lim_{a\to\infty} g(t) \leq \omega_n, \tag{33}$$

$$0 \leq \lim_{a\to\infty} y(t) \leq 2. \tag{34}$$

Fig. 2 summarizes the characteristics of the undamped system in the impulse and unit step response.

2. Critically damped case ($\zeta = 1$)

In the critical damping case ($\zeta = 1$), the second order system (1) can be written as follows:

$$\begin{aligned} G(s) &= -\frac{\frac{\omega_n^2}{a}(s-a)}{s^2 + 2\omega_n s + \omega_n^2} \\ &= -\frac{\frac{\omega_n^2}{a}(s-a)}{(s+\omega_n)^2} . \end{aligned} \tag{35}$$

Using the inverse Laplace transform, the impulse response of the system (35) can be written by

$$g(t) = \omega_n^2\left[\left(1 + \frac{\omega_n}{a}\right)t - \frac{1}{a}\right]e^{-\omega_n t} . \tag{36}$$

From (36), we can compute the peak undershoot time t_p as follows:

$$t_p = \frac{1}{\omega_n + a} . \tag{37}$$

Also, we can show that the unit step response of the system (35) is given by

$$y(t) = 1 - \left[1 + \frac{\omega_n}{a}(\omega_n + a)t\right]e^{-\omega_n t} . \tag{38}$$

Thus, the peak undershoot is expressed as follows:

$$\begin{aligned} Y_{pu} &= y(t_p) \\ &= 1 - \left(1 + \frac{\omega_n}{a}\right)e^{-\frac{\omega_n}{\omega_n + a}} . \end{aligned} \tag{39}$$

Eqs. (36) and (38) imply that the system (35) has no overshoot to the unit step response. Eqs. (37) and (39) give the results as follows :

$$\lim_{a\to 0} t_p = \frac{1}{\omega_n}, \tag{40}$$

$$\lim_{a\to\infty} t_p = 0, \tag{41}$$

$$\lim_{a\to 0} Y_{pu} = -\infty, \tag{42}$$

$$\lim_{a\to\infty} Y_{pu} = 0 . \tag{43}$$

Typical plot of the critically damped system is shown by Fig. 3.

(a) Impulse response

(b) Step response

Fig.3. Impulse response and step response of critically damped case.

(a) Impulse response

(b) Step response

Fig.4. Impulse response and step response of overdamped case.

3. Overdamped case ($1 < \zeta$)

In this case, the second order system (1) is represented by

$$G(s) = \frac{-\frac{\omega_n^2}{a}(s-a)}{(s-p_3)(s-p_4)} , \tag{44}$$

which means that the system has two distinct real poles and one RHP real zero as follows:

$$\begin{array}{rcl} \text{poles} & : & p_3, p_4 = -\zeta\omega_n \pm \omega_n\sqrt{\zeta^2-1} \, , \\ \text{RHP zero} & : & a \, . \end{array} \tag{45}$$

Thus, the impulse response of the system (44) is derived by the inverse Laplace transform as follows:

$$g(t) = \frac{\omega_n}{2a\sqrt{\zeta^2-1}} \left[(a-p_3)\, e^{p_3 t} - (a-p_4)\, e^{p_4 t} \right] . \tag{46}$$

From the condition $g(t) = 0$, the peak undershoot time t_p is satisfies the relation

$$e^{2\omega_n\sqrt{\zeta^2-1}t_p} = \frac{a-p_4}{a-p_3} . \tag{47}$$

Therefore, the peak undershoot time t_p is formulated as follows:

$$t_p = \frac{1}{2\omega_n\sqrt{\zeta^2-1}} \ln \frac{a-p_4}{a-p_3} . \tag{48}$$

Since the unit step response of the system Eq. (44) is given by

$$\begin{aligned} y(t) \;=\; 1 + \frac{1}{2a} \Bigg[& \frac{a-p_3}{\zeta^2 - \zeta\sqrt{\zeta^2-1} - 1} e^{p_3 t} \\ & + \frac{a-p_4}{\zeta^2 + \zeta\sqrt{\zeta^2-1} - 1} e^{p_4 t} \Bigg] , \end{aligned} \tag{49}$$

we can get the following expression for the peak undershoot:

$$\begin{aligned} Y_{pu} \;=\; 1 + \frac{1}{2a} \Bigg[& \frac{a-p_3}{\zeta^2 - \zeta\sqrt{\zeta^2-1} - 1} \left(\frac{a-p_4}{a-p_3} \right)^{\frac{p_3}{p_3-p_4}} \\ & + \frac{a-p_4}{\zeta^2 + \zeta\sqrt{\zeta^2-1} - 1} \left(\frac{a-p_4}{a-p_3} \right)^{\frac{p_4}{p_3-p_4}} \Bigg] . \end{aligned} \tag{50}$$

It is noted from Eq. (46) that the overdamped system (44) has no overshoot to the unit step response like the critically damped system. Typical plot of the overdamped system is shown by Fig. 4.

III. Design of feedforward compensator

In this chapter, we will propose a feedforward compensator in order to decrease the amount of undershoot owing to the RHP zero. The main idea is that small input gives rise to small amount of undershoot at the price of rise time. Let us consider the feedforward compensator as follows:

$$C(s) = \frac{1}{\alpha}\frac{1}{s}(1 - e^{-\alpha s}), \tag{51}$$

where α is a positive real value which it is selected by designer. Note that this compensator makes the step type input be a ramp input with saturation as shown in Fig. 5. When a unit step function is applied to this compensator, its output has the shape of Fig. 5. We will investigate the characteristic of this compensator concentrated on a undershoot phenomenon.

Let t_z be the time point that the unit step response crosses over the zero level and M is the area of step response from 0 to t_z. The graphical representation of these parameters is given by Fig. 6. Note that the compensated system to have a smaller peak undershoot than the system without the compensator, since the system input is smaller than the unit step input for $0 \leq t < \alpha$. Then the remaining problem is how to select the design parameter α. The undershoot compensating effect of the compensator by adjusting the design parameter α is demonstrated in the Lemma 2 below.

Lemma 2: Let Y_{pu} and t_p be the peak undershoot and the peak undershoot time of the system without compensator (51), respectively. And let Y_{pc} and t_{pc} be the peak undershoot and the peak undershoot time of the compensated system, respectively. Then they have the relations as follows:

1) In the case of $\alpha < t_z$,

$$\max(\alpha, t_p) < t_{pc} < t_z . \tag{52}$$

$$-\frac{1}{\alpha}\int_0^{\alpha} y(t)dt < |Y_{pc}| < |Y_p| . \tag{53}$$

2) In the case of $\alpha \geq t_z$,

$$t_{pc} = t_z , \tag{54}$$

$$Y_{pc} = \frac{1}{\alpha}\int_0^{t_z} y(t)dt < Y_{pu} . \tag{55}$$

Proof: Let $Y_c(s)$ be the unit step response of the system (1) with the compensator (51) and $Y(s)$ be the step response of system (1) without the compensator. Then $Y_c(s)$ is given as follows:

$$Y_c(s) = \frac{1}{\alpha} \frac{-\frac{\omega_n^2}{a}(s-a)}{s^2(s^2 + 2\zeta\omega_n s + \omega_n^2)} (1 - e^{-\alpha s}) . \tag{56}$$

Fig.5. The compensator response to the unit step input.

Fig.6. M and t_z in the unit step response.

The peak undershoot time t_{p_c} of the unit step response with the compensator (51) can be derived from the derivative of the response (56), which gives

$$\begin{aligned} sY_c(s) &= \frac{1}{\alpha}\frac{-\frac{\omega_n^2}{a}(s-a)}{s(s^2+2\zeta\omega_n s+\omega_n^2)}(1-e^{-\alpha s}) \\ &= \frac{1}{\alpha}Y(s)(1-e^{-\alpha s})\,. \end{aligned} \quad (57)$$

Eq. (57) can be converted to the time domain expression as follows:

$$\dot{y}_c(t) = \frac{1}{\alpha}\left[y(t)1(t) - y(t-\alpha)1(t-\alpha)\right], \quad (58)$$

where $y(t)$ is the step response of the system (1) in time domain without compensator and $1(t)$ is the unit step function. Also for $0 \le t < \alpha$, the Eq. (58) is written as follows :

$$\dot{y}_c(t) = \frac{1}{\alpha}y(t). \quad (59)$$

Thus, from Eq. (59), if the peak undershoot time t_p appears in $0 \le t < \alpha$, then t_{pc} is the time point that $y(t)$ is equal to zero. Conversely, from Eq. (58), if the peak undershoot time t_p appears in $t \ge \alpha$, then t_{pc} is the time point that $y(t) = y(t-\alpha)$. Hence, we can obtain Eq. (54) and (55).

Also, t_{pc} does not exist on $0 \le t < \alpha$ in the case of $\alpha < t_z$ because the step response $y(t)$ is not equal to zero on $0 \le t < t_z$. And the peak undershoot time t_{pc} exists anywhere between t_p and t_z. Thus t_{pc} and Y_{pc} satisfy the inequality (52) and (53). ■ ■

For $0 \le t < \alpha$, the compensated step response $Y_c(s)$ has $1/\alpha$ times value of the ramp response of the system (1), i.e., $Y_c(s)$ is $1/\alpha$ times integral of the step response of the system (1). And we can see that if $\alpha = 0$, then t_{pc} and Y_{pc} are equal to t_p and Y_{pu}, respectively. It is noted that the absolute value of Y_{pc} is always smaller than that of Y_{pu} and these results are holding in the stable system with odd real RHP zeros.

From Lemma 2, it is note that the peak undershoot Y_{pc} and peak undershoot time t_{pc} of the system with the feedforward compensator are determined by M, t_z and α. To make it Shortly, if the design parameter α is too large, then peak undershoot is very small at the price of rise time and *vice versa*. Thus, from advanced information of M and t_z in the step response of the system without compensator, we can properly select the value of α.

IV. Simulation

In order to exemplify the undershoot compensating effect of the compensator by adjusting the design parameter α, a simulation is performed in this chapter. Let $\omega_n = 2$, $\zeta = 0.75$ and $a = 1$ in the second order system (1). The system has poles at $\{-1.5 \pm 1.323j\}$, and zero at $\{1\}$ in the complex plane. Since the RHP zero is nearer to the imaginary axis than poles, the system has a large peak undershoot shown in the solid curve of Fig. 7. From Eq. (8) and (12), it can be seen that the peak undershoot has the value $Y_p \simeq -0.6288$ and appears at $t_p \simeq 0.3679$ in the unit step response. Fig. 7 also shows the unit step responses of the system with the feedforward compensator according to variation of α as a design parameter. Note that the case of $\alpha = 0$ is the same to the case of system without compensator. We can see that as the α increases, the peak undershoot decreases at the price of rise time. Also, the maximum value of t_{pc} is shown to be the time t_z.

Fig.7. Step responses.

V. Conclusion

In this paper, we have analyzed the characteristics of a second order system with one RHP zero, and have calculated the peak undershoot Y_{pu}, peak undershoot time t_p, maximum overshoot Y_m, maximum overshoot time t_m, etc, in the unit step response of the system. Also, we have shown that the overshoot phenomenon is not appeared in critically damped and overdamped case, but that the undershoot phenomenon is appeared in all cases. Using the feedforward compensator, we have seen that the unit step response has a reduced peak undershoot at the price of rise time. And, the usefulness of the feedforward compensator is shown via an example applied to the second order system with one RHP real zero.

Although the RHP zeros effect upon the system step response is analytically calculated in the second order system with one RHP real zero, the global characterization of the RHP zeros effect still remains as an open problem. Thus, it is difficult to control systems with RHP zeros, and it will require the further research.

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