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# 4차 시스템의 최대오버슈트에 관한 유의 성질

## Some Remarks on the Maximum Overshoot of a Fourth-order System

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(Young Chol Kim · Jong Geon Lee)

**Abstract** – Consider a linear fourth-order system with no zero that is represented in terms of four specific parameters: two damping ratios and two natural frequencies. We investigate several interesting questions about the maximum overshoot of the system with respect to the four-tuple parameters. Some remarkable results are presented.

**Key Words** : Maximum overshoot, Damping, Fourth-order system, Maximum overshoot contours

### 1. Introduction

The problem of designing controllers with transient response specifications is very important for practical applications. Several results on the problem of achieving non-overshooting step response have been provided in [1-3]. Jayasuriya [1] and Lin [4] presented some necessary and sufficient conditions on the pole-zero configurations for a class of systems to have a non-overshooting step response. However, the maximum overshoot of the fourth-order system with respect to the variation of pole locations has been seldom discussed in literature.

In this paper, we consider a fourth-order SISO linear system with no zero and attempt to investigate a certain damping characteristics of the system. In physics and engineering, the damping is generally defined by an effect that reduces the amplitude of oscillations in an oscillatory system. In other words, this means the dissipation of energy from a vibrating structure. For a second-order system, the damping is exactly characterized by only damping ratio irrespective of its natural frequency. Whereas various types of damping can be defined in multiple degree of freedom systems [5, 6]. There are many systems expressed by a fourth-order transfer function model, for example, any feedback systems of second-order process with a second-order controller and any third-order processes fed back by a first-order controller. The most popular one of the fourth-order systems is a 2 DOF vibrating structure, which consists of two mass-spring-damper models [5, 6]. There are also many other fourth-order models in robot manipulators and flight dynamic systems.

For the fourth-order system without zero, the maximum overshoot can be regarded as a measure of the damping of a high-order system even though the relationship between the two are not linearly proportional. In general, the decay ratio of oscillatory response relative to the change of parameters may be quite different from the effects of their maximum overshoots, and furthermore the maximum overshoot highly depends on the zeros of the system.

We here concentrate on the maximum overshoot relative to the pole locations. The poles are represented in terms of four-tuple parameters such as two damping ratios and two natural frequencies. Main concerns in this paper are to investigate what the maximum overshoot of the 4th-order system will be going as the four-tuple parameters are changed. For examples, can we say that if both damping ratios increase, the maximum overshoot of the step response will be always reduced? It is well known that this problem cannot be analytically solved because the step response of 4th-order system is a highly nonlinear function of the four parameters.

In Section 2, three questions will be given and followed by answers to these questions in the Section 3.

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### 2. Problem statements

#### 2.1 Step response of the firth-order system

A fourth-order transfer function model is represented by

$$T(s)=\frac{a_0}{s^4+a_3s^3+a_2s^2+a_1s+a_0}$$
$$=\frac{\omega_{n1}^2\omega_{n2}^2}{(s^2+2\zeta_1\omega_{n1}s+\omega_{n1}^2)(s^2+2\zeta_2\omega_{n2}s+\omega_{n2}^2)}, \quad (1)$$

where $\omega_{ni}$ and $\zeta_i$ for $i=1,2$, are the undamped natural frequencies and damping ratios, respectively.

The response of the fourth-order system (1) to the unit step input is expressed by

$$y(t)=1-\sum_{i=1}^{2}\omega_{n1}^2\omega_{n2}^2\{2A_ie^{-\zeta_i\omega_{ni}t}\cos(\omega_{ni}\sqrt{1-\zeta_i^2}\,t)$$
$$+2B_ie^{-\zeta_i\omega_{ni}t}\sin(\omega_{ni}\sqrt{1-\zeta_i^2}\,t)\}, \quad (2)$$

where

$$A_i=\frac{\alpha_i}{\alpha_i^2+\beta_i^2},\qquad B_i=-\frac{\beta_i}{\alpha_i^2+\beta_i^2}, \quad (3)$$

$$\alpha_i=-10\zeta_i^2\omega_{ni}^4+8\zeta_i^4\omega_{ni}^4+2\omega_{ni}^4-2\omega_{ni}^2\omega_{nj}^2$$
$$+2\zeta_i^2\omega_{ni}^2\omega_{nj}^2+8\zeta_i\zeta_j\omega_{ni}^3\omega_{nj}-8\zeta_i^3\zeta_j\omega_{ni}^3\omega_{nj}, \quad (4)$$

$$\beta_i=4\zeta_j\omega_{ni}^3\omega_{nj}\sqrt{1-\zeta_i^2}-8\zeta_i^2\zeta_j\omega_{ni}^3\omega_{nj}\sqrt{1-\zeta_i^2}$$
$$-6\zeta_i\omega_{ni}^4\sqrt{1-\zeta_i^2}+8\zeta_i^3\omega_{ni}^4\sqrt{1-\zeta_i^2}+2\zeta_i\omega_{ni}^2\omega_{nj}^2\sqrt{1-\zeta_i^2},$$
$$\text{for}\quad i=1,2\quad\text{and}\quad j=1\quad\text{or}\quad 2\quad(j\neq i). \quad (5)$$

As a special case, if $\omega_n:=\omega_{n1}=\omega_{n2}$, (2) is simplified as follows;

$$y(t)=1-\overline{A_1}e^{-\zeta_1\omega_nt}\sin(\omega_n\sqrt{1-\zeta_1^2}\,t+\phi_1)$$
$$+\overline{A_2}e^{-\zeta_2\omega_nt}\sin(\omega_n\sqrt{1-\zeta_2^2}\,t+\phi_2), \quad (6)$$

where

$$\sin(\phi_i):=\frac{A_i}{\sqrt{A_i^2+B_i^2}},\quad \cos(\phi_i):=\frac{B_i}{\sqrt{A_i^2+B_i^2}},$$
$$\overline{A_i}:=\frac{1}{2(\zeta_1-\zeta_2)\sqrt{1-\zeta_i^2}},\qquad \text{for}\ i=1,2. \quad (7)$$

### 2.2 Problem statements

As seen in (2), the unit step response of the fourth-order system in (1) is the sum of four cosine functions having time varying magnitudes, which is a highly nonlinear function of the four parameters. It is not possible to determine the peak time as well as the maximum value of the response algebraically. Main concern of this paper is investigate how the maximum overshoot of the fourth-order system varies as the parameters, $\omega_{ni}$ and $\zeta_i$ for $i=1,2$ are changed.

Assume that four parameters, $\{\zeta_1,\omega_{n1}\}$ and $\{\zeta_2,\omega_{n2}\}$, in (1) are all positive, for which the system is stable. The problems of interesting here are as follows:

(i) For a fixed $\zeta_1$ and $\zeta_2$, what is the relationship between the maximum overshoot of (1) and the undamped natural frequencies?

(ii) Suppose that $\zeta_1$ and $\zeta_2$ are simultaneously changed in the opposite direction but the sum of both, $\zeta_1+\zeta_2$, increases, while $\omega_{n1}$ and $\omega_{n2}$ are constants and the same each other, that is, $\omega_{n1}=\omega_{n2}$. As expected, will the maximum overshoot of (1) be reduced for every set $\{\zeta_1,\zeta_2\}$ that the condition holds?

On the contrary to this, will the maximum overshoot of (1) increase if the sum $\zeta_1+\zeta_2$ is reduced?

(iii) For any constant $\omega_{n1}$ and $\omega_{n2}$, will the maximum overshoot of (1) monotonically decrease only if both $\zeta_1$ and $\zeta_2$ are increased?

On the contrary, will the reduction of both $\zeta_1$ and $\zeta_2$ make the maximum overshoot of (1) monotonically increase?

## 3. Main Results

The following theorem states that the maximum overshoot of the system in (1) with fixed $\zeta_1$ and $\zeta_2$ remains unchanged irrespective of the values of $\omega_{n1}$ and $\omega_{n2}$ if two complex poles are moved along the individual $\zeta_i$-line at the same rate.

**Theorem 1**: Consider the fourth-order system in (1) of which the parameters, $\zeta_1$ and $\zeta_2$, are fixed. Then the maximum overshoots of the system to the step input remain unchanged for any $\omega_{n1}$ if their $\omega_{n1}$ and $\omega_{n2}$ are changed with a constant ratio, that is, $\omega_{n2}=c\,\omega_{n1}$ (where c is a positive constant).

**Proof**: For a given set of parameters $\{\zeta_1,\omega_{n1},\zeta_2,\omega_{n2}\}$ with $\omega_{n2}=c\,\omega_{n1}$, the step response of (1) can be written by from (2),

$$y(t)=1-B_1e^{-\zeta_1(\omega_{n1}t)}\sin(\sqrt{1-\zeta_1^2}\,(\omega_{n1}t)+\psi_1)$$
$$+B_2e^{-c\zeta_2(\omega_{n1}t)}\sin(c\sqrt{1-\zeta_2^2}\,(\omega_{n1}t)+\psi_2) \quad (8)$$

Let $\bar{t}:=\omega_{n1}t$ and substituting this into (8}) yields

$$y(\bar{t})=1-B_1e^{-\zeta_1\bar{t}}\sin(\sqrt{1-\zeta_1^2}\,\bar{t}+\psi_1)$$
$$+B_2e^{-c\zeta_2\bar{t}}\sin(c\ \sqrt{1-\zeta_2^2}\,\bar{t}+\psi_2) \quad (9)$$

It is obvious that the maximum values of (8) and (9) are the same because (9) is nothing but a time-scaled function of (8) by a factor $\omega_{n1}$. Therefore, the maximum overshoot of the fourth-order system under the above condition remains unchanged without regard to the value of $\omega_{n1}$. ♣

In order to give the answers to the questions (ii) and (iii), we now introduce the maximum overshoot contours. We compute the set of $\{\zeta_1, \zeta_2\}$ numerically for which the corresponding fourth-order systems with a fixed $\{\omega_{n1}, \omega_{n2}\}$ result in the same maximum overshoots. Then the maximum overshoot contours ranged over from zero to 90% can be depicted on the $\zeta_1-\zeta_2$ plane. Fig.1 shows the maximum overshoot contours for the case of $\omega_{n2}=c_{45}\omega_{n1}$ (where $c_{45}:=\tan 45^o=1$). It is seen that the contours of this case are symmetric with respect to the diagonal line, $\zeta_2=\zeta_1$. In particular, it is also remarkable that the maximum overshoot contours less than about 10 % are concave curves, whereas the contours higher than about 10 % are convex ones.

For the purpose of comparisons, we present the maximum overshoot contours for different cases: (a) $\omega_{n2}=c_{15}\omega_{n1}$, (b) $\omega_{n2}=c_{30}\omega_{n1}$, (c) $\omega_{n2}=c_{60}\omega_{n1}$ (where $c_\theta:=\tan\theta^o$), as shown in Fig. 2. According to the Theorem 1, the maximum overshoots of (1) depend on only $\{\zeta_1, \zeta_2\}$ for any $\omega_{n1}$ provided that $\omega_{n2}=c_\theta\omega_{n1}$. It allows us to obtain all the contours in Figs. 1 and 2 by letting $\omega_{n1}=1\,[rad/s]$ arbitrarily. Through these figures, we can see that the maximum overshoot contours of (1) are drastically changed depending on the rates of $\omega_{n2}/\omega_{n1}$. From Fig.2, the contours for the case where $\omega_{n2}=c_{30}\omega_{n1}=0.577\omega_{n1}$ (see Fig. 2(b)) are identical to those of the case of $\omega_{n2}=c_{60}\omega_{n1}=1.732\omega_{n1}$ if the parameters of two axes, $\zeta_1$ and $\zeta_2$, are exchanged each other. This implies that the maximum overshoot contours for the case of $\omega_{n2}=c_{15}\omega_{n1}=0.268\omega_{n1}$ are identical to those for $\omega_{n2}=c_{75}\omega_{n1}=3.732\omega_{n1}$ if $\zeta_2$ is replaced by $\zeta_1$ and $\zeta_2$ instead of $\zeta_1$ in Fig. 2(a).

Here is the answer to the question (ii) mentioned in the Section 2.

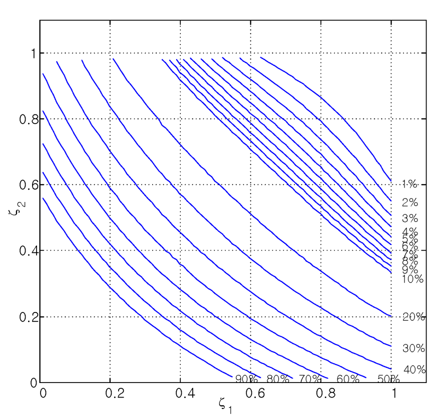
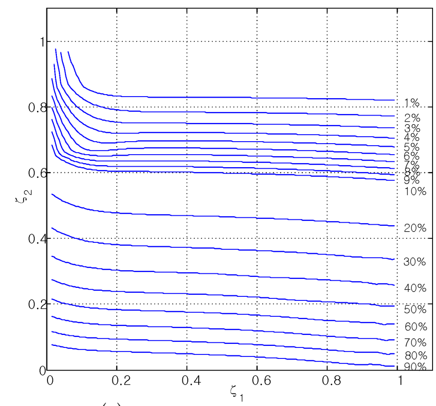
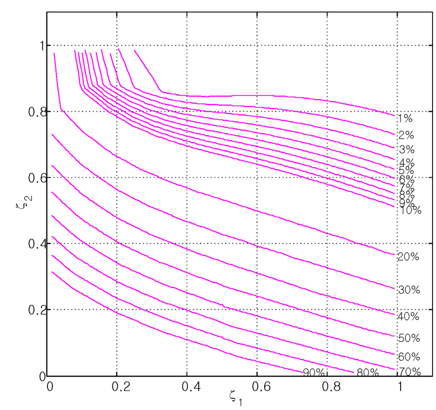


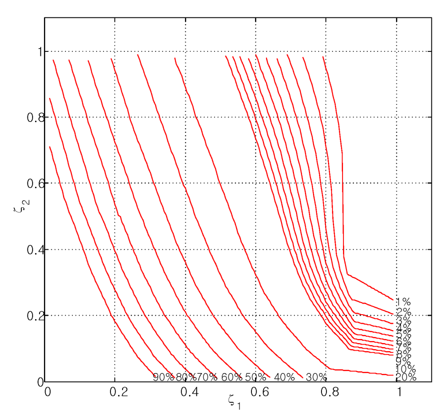

**Fig. 1** The maximum overshoot contours of the fourth-order systems on the $\zeta_1-\zeta_2$ plane when $\omega_{n2}=\omega_{n1}$.




(a) $\omega_{n2}=c_{15}\omega_{n1}=0.268\omega_{n1}$




(b) $\omega_{n2}=c_{30}\omega_{n1}=0.577\omega_{n1}$




(c) $\omega_{n2}=c_{60}\omega_{n1}=1.732\omega_{n1}$

**Fig. 2** The maximum overshoot contours of the fourth- order systems on the $\zeta_1-\zeta_2$ plane: when $\omega_{n1}=1\,[rad/s]$, (a) $\omega_{n2}=c_{15}\omega_{n1}$, (b) $\omega_{n2}=c_{30}\omega_{n1}$, and (c) $\omega_{n2}=c_{60}\omega_{n1}$.

**Fact 1:** For the fourth-order system in (1) with $\omega_{n1} = \omega_{n2} = \omega_n$, it follows that

(a) there exist some sets of $\{\zeta_1, \zeta_2\}$ in which the maximum overshoot of $T(s, \zeta_1, \zeta_2)$ rather grows even though the sum, $\zeta_1 + \zeta_2$, is increased, and

(b) on the contrary, there are some sets of $\{\zeta_1, \zeta_2\}$ in which the maximum overshoot of $T(s, \zeta_1, \zeta_2)$ rather decreases even though the sum, $\zeta_1 + \zeta_2$, is reduced.

**Proof: (a)** On the Fig.1, we can make a tangent line at a point on any convex shape contours. For example, let $C_1(\zeta_{11}^*, \zeta_{12}^*)$ be a point on the 50 % maximum overshoot contour (briefly, 50 % contour hereafter), where the contour and the diagonal line intersect, as shown in Fig. 3.

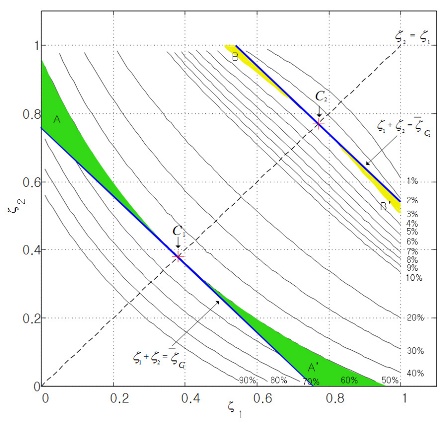



**Fig. 3** Region A and B supporting the Fact 1 in the $\zeta_1 - \zeta_2$ plane.

The tangent line is given by the equation $\zeta_1 + \zeta_2 = \bar{\zeta}_{C_1}$, where $\bar{\zeta}_{C_1}$ is an intercept constant on the $\zeta_2$ axis. The green regions, A and A', are the patches composed by the tangent line and the 50 % contour. Let $L_{50\%}$ be the subset consisting of $\{\zeta_1, \zeta_2\}$ lower than the 50 % contour. According to the observation results shown in Fig.1 and Fig.2, it is true that the maximum overshoot of $T(s, \zeta_1, \zeta_2)$ for any $\{\zeta_1, \zeta_2\} \in L_{50\%}$ becomes larger than 50%. On the other hand, it follows that

$$\zeta_1 + \zeta_2 \geq \bar{\zeta}_{C_1} = \zeta_{11}^* + \zeta_{12}^*, \text{ for all } \{\zeta_1, \zeta_2\} \in A \text{ or } A'.$$

The regions A and A' belong to the set $L_{50\%}$. Therefore the regions like A and A' are the sets satisfying the part (a).

**(b)** Similarly, we can draw a tangent line at a point on any concave shape contours in Fig. 3. For example, let $C_2(\zeta_{21}^*, \zeta_{22}^*)$ be a point on the 3 % contour, where the contour and the diagonal line intersect. This tangent line is expressed by the equation $\zeta_1 + \zeta_2 = \bar{\zeta}_{C_2}$, where $\bar{\zeta}_{C_2}$ is an intercept constant on the $\zeta_2$ axis. The regions, B and B', are also the parches composed by the tangent line and the 3 % contour. Let $U_{3\%}$ be the subset consisting of $\{\zeta_1, \zeta_2\}$ upper than the 3 % contour. Similar to the proof of (a), it is true that the maximum overshoot of $T(s, \zeta_1, \zeta_2)$ for any $\{\zeta_1, \zeta_2\} \in U_{3\%}$ becomes smaller than 3 %. However, it follows that

$$\zeta_1 + \zeta_2 \leq \bar{\zeta}_{C_2} = \zeta_{21}^* + \zeta_{22}^*, \text{ for all } \{\zeta_1, \zeta_2\} \in B \text{ or } B'.$$

The regions B and B' belong to $U_{3\%}$. Therefore the regions like B and B' are the sets satisfying the part (b). ♣

Now, let us consider the question (iii) in Section 2.

**Fact 2:** For the fourth-order system in (1) with the fixed $\omega_{n1}$ and $\omega_{n2}$, it follows that

**(a)** there exist some sets of $\{\zeta_1, \zeta_2\}$ in which the maximum overshoot of $T(s, \zeta_1, \zeta_2)$ rather grows even though both $\zeta_1$ and $\zeta_2$ increase, and

**(b)** on the contrary, there are some sets of $\{\zeta_1, \zeta_2\}$ in which the maximum overshoot of $T(s, \zeta_1, \zeta_2)$ rather decreases even though both $\zeta_1$ and $\zeta_2$ are reduced.

**Proof: (a)** The proof will proceed by finding such a region in the $\zeta_1 - \zeta_2$ plane. Fig. 4 indicates the 6 % maximum overshoot contour (briefly, 6 % contour hereafter) of the fourth-order system with the constants $\omega_{n1} = 2$ and $\omega_{n2} = 0.5$. According to the results shown in Fig. 2, recall that for any point $\{\zeta_1, \zeta_2\}$ under the 6 % contour in the $\zeta_1 - \zeta_2$ plane, the corresponding systems $T(s, \zeta_1, \zeta_2)$ have smaller overshoots than those of the other points either on the curve or above. As shown in Fig. 4, we draw a horizontal line of $\zeta_2 = 0.674$ passing through the 6 % contour and mark the points with $X_1$, $X_2$ and $X_3$ at which the 6 % contour intersects with the horizontal line. The models $T(s, \zeta_1, \zeta_2)$ corresponding to these points have the same values of the maximum overshoot. The regions, C and D, are the sets of $\{\zeta_1, \zeta_2\}$ composed by the graphs of the horizontal line and the 6 % contour. It is evident that both $\zeta_1$ and $\zeta_2$ are greater than or equal to the point $X_2(\zeta_{21}, \zeta_{22})$ if the point $\{\zeta_1, \zeta_2\}$ is chosen in the region D. Since any points $\{\zeta_1, \zeta_2\}$ in the region D are under the 6 % contour, the maximum overshoot of the corresponding fourth-order systems are larger than 6 %. Therefore the region D is the set satisfying the part (a).

(b) Similarly, the part (b) can be proved. Both $\zeta_1$ and $\zeta_2$ are lower than or equal to the point $X_2(\zeta_{21}, \zeta_{22})$ if the point $\{\zeta_1, \zeta_2\}$ is chosen in the region C. However, since any points $\{\zeta_1, \zeta_2\}$ in the region C are over the 6 % contour, the maximum overshoot of the corresponding fourth-order systems are smaller than 6 %. Therefore the region C is the set satisfying the part (b). ♣

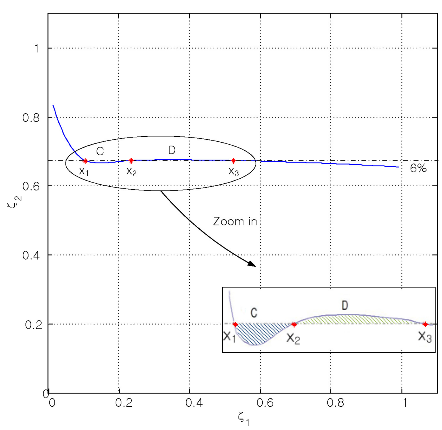



Fig. 4 The 6 % maximum overshoot contour of the fourth-order system when $\omega_{n1}=2$ and $\omega_{n2}=0.5$.

Table 1 The Max. overshoots $(M_{ov})$ of the systems corresponding to four points chosen in Fig. 3 when $\omega_{n1}=\omega_{n2}$.

| Points | $\zeta_1$ | $\zeta_2$ | $\zeta_1+\zeta_2$ | $M_{ov}$ (%) | Remark |
|---|---|---|---|---|---|
| $C_1$ | 0.38 | 0.38 | 0.76 | 50.23 | See Fig. 3 |
| $C_{A'1}$ | 0.78 | 0.05 | 0.83 | 56.45 | A point inside A' |
| $C_2$ | 0.77 | 0.77 | 1.54 | 2.995 | See Fig. 3 |
| $C_{B2}$ | 0.54 | 0.98 | 1.52 | 2.781 | A point inside B |

**Example 1.** Let us demonstrate the Fact 1. We first pick two points $C_1$ and $C_{A'1}$ inside A' in the Fig. 3. As shown in Table 1, the system $T(s, \zeta_1, \zeta_2)$ corresponding to $C_{A'1}$ has larger $\zeta_1+\zeta_2$ than that of $C_1$ but its maximum overshoot rather increases. For $C_2$ and $C_{B2}$ inside B, $T(s, C_{B2})$ has smaller overshoot than $C_2$ although its $\zeta_1+\zeta_2$ is reduced.

**Example 2.** As an example for the Fact 2, we choose five points such as $X_1$, $X_2$ and $X_3$ on the 6 % contour, and $C_3$ inside the region C, $D_3$ inside the region D, respectively. Table 2 shows that the maximum overshoot of $T(s, C_3)$ decreases even though two damping ratios of $C_3$ become lower than those of $X_2$, while $T(s, D_3)$ has a little larger overshoot although both damping ratios of $D_3$ are increased from $X_2$.

Table 2 The Max. overshoots $(M_{ov})$ of the systems corresponding to five points chosen in Fig. 4 when $\omega_{n1}=2$ and $\omega_{n2}=0.5$.

| Points | $\zeta_1$ | $\zeta_2$ | $M_{ov}$ (%) | Remark |
|---|---|---|---|---|
| $X_1$ | 0.1678 | 0.6740 | 6.00 | See Fig. 4 |
| $C_3$ | 0.200 | 0.6738 | 5.97 | A point inside C |
| $X_2$ | 0.269 | 0.6740 | 6.00 | See Fig. 4 |
| $D_3$ | 0.350 | 0.6741 | 6.018 | A point inside D |
| $X_3$ | 0.432 | 0.6740 | 6.00 | See Fig. 4 |

## 4. Conclusion

We have derived some remarkable results about the maximum overshoot of a fourth-order system without zero which is represented by the four-tuple parameter $\{\zeta_1, \omega_{n1}, \zeta_2, \omega_{n2}\}$. For this fourth-order system, the following results are obtained:

(i) The maximum overshoot of the system to the step input remains unchanged with respect to the value of $\omega_{n1}$ as long as their two natural frequencies are changed with a constant ratio, that is, $\omega_{n2}=c\,\omega_{n1}$.

(ii) An insightful chart indicating the maximum overshoot contours on the $\zeta_1-\zeta_2$ plane is proposed.

(iii) The maximum overshoot of the fourth-order system does not have monotonicity with respect to either increase or decrease of $\zeta_1+\zeta_2$, and both $\zeta_1$ and $\zeta_2$ as well.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