Design of Low Frequency and Decoupling Compensator for MIMO System Including Time-delay Elements and Interferences

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Abstract

The aim of this research is to compensate the multivariable system's Tele-control performance and preserve the stability of closed-loop system. Generally, in Tele-control systems, it contains two time-delay elements that have influence on design of the input signals and processing of output signals. Therefore, the closed-loop performance of the system is unstable and tracking characteristic of the output becomes worse due to time-delay elements. Moreover, in multivariable system, the interferences cause harmful influence against the desired output signals. In this research, we propose the new effective compensator for the plant that has time-delay elements and interferences. The designed compensator is consists of low frequency and decoupling controller. Therefore, closed-loop system is stabilized and reduced the interference. Furthermore, the effectiveness of the proposed compensator is verified by carrying out the control of pitch angle and angular velocity of wind-turbine simulator system.

Keywords: *Low frequency Compensator, Decoupling Compensator, Time-Delay System*

1. Introduction

The purpose of this paper is to stabilize the closed-loop of multivariable system and realize a good performance and cancel the interference signals. Generally, time-delay occurs when plant has input delay, output delay or internal delay. But, in Tele-control systems, there are two time-delay elements due to utilization of communication systems. Therefore, closed-loop system contains with delays, one is input delay and the other is feedback delay or output delay [1]-[3]. Stabilization of time-delay system was considered in many schemes and methods such as PID (Proportional Integrator Derivative) controller for classical method [4]-[8], and LQI (Linear Quadratic Integration) for modern method. However, improvement of system's performance is quite hard due to existence of time-delay elements. Therefore, in this research, tracking performance of system is improved by using low frequency and decoupling compensator. It is well known that time-delay element has a large phase lag which drops suddenly. This may cause instability in the closed-loop system, even though the plant itself is stable. Therefore, it is required that the internal stability of the closed-loop system. To this end, the parameters of the low frequency compensator are adjusted in order to assure improvement of the performance. For interferences cancellation, there are two methods, one is general scheme of diagonalizing the plant by compensator, and the other scheme is diagonalized the plant over low-frequency bands that the scheme has better performance comparing to general schemes. Therefore, in this paper, the internal stability of the closed-loop and performance of output of the system is improved by low frequency and decoupling compensator. And then, evaluation of proposed method is simulated to confirm the stability of closed-loop and output performance. In following, we discuss about validity of the low frequency and decoupling compensator against time-delay element and interferences by numerical analysis. Furthermore, the effectiveness of the proposed compensator is verified by carrying out the control of pitch angle and angular velocity of wind-turbine simulator system.

2. Time-Delay System

In this research, we consider a round trip time-delay system that one is input signal including time-delay element to reach plant, and the other is output signal of the plant or a feedback signal of the system. The central aim of this control problem is to reduce the adverse effect of the time-delay elements and to eliminate the error signals between reference and control outputs. Fig. 1 shows the illustration of the Tele-control system. Also, the equivalent system of Fig. 1 has been shown in Fig.2, it shows that the block diagram of a round trip time-delay system includes with controller.

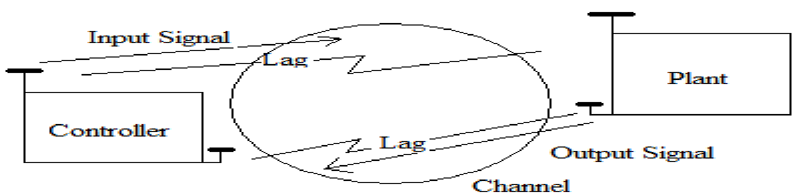

Fig. 1: Illustration of Tele-Control system

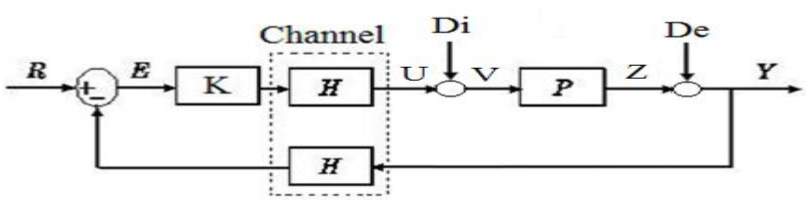

Fig. 2: Tele-control system with compensator

There are various transfer functions in Fig. 2. This is inputs vector of $[R\ Di\ De]^T$ that transfers to output vector of $[Y\ Z\ V\ U\ E]^T$, where “K” is controller, “P” is plant, “H” is time-delay elements and “Di” and “De” are internal and external disturbances, respectively. Here, controller has the role of stabilization of the closed-loop system and tracking for a better performance. By minimizing the error, the characteristics of closed-loop of the transfer function from “R” to “E” can be improved. For instance, when the system has less error, then we have better performance. However, necessary condition of improving the performance is to assure the internal stability of the closed-loop system. Furthermore, the necessary and sufficiently condition of internal stability in eq. (1) is to guarantee the stability of the gang of four transfer function which contains the complementary sensitivity signal from R to Y, load sensitivity signal from Di to Z, disturbance sensitivity signal from U to R and sensitivity signal from R to E. [7]-[10]. The gang of four function is shown in Table 1. And the transfer function of Fig. 2 is shown in equation (1).

Table 1 Gang of Four

Complementary Sensitivity: (I + PKH2)−1PKH	Load Sensitivity: $(I + PKH^2)^{-1}P$
Disturbance Sensitivity: $(I + PKH^2)^{-1}KH$	Sensitivity: $(I + PKH^2)^{-1}$

$$\begin{bmatrix} Y \\ Z \\ V \\ U \\ E \end{bmatrix} = \begin{bmatrix} \Delta PKH & \Delta P & \Delta \\ \Delta PHK & \Delta P & -\Delta KHPH \\ \Delta KH & \Delta & -\Delta KH \\ \Delta KH & -\Delta PHKH & -\Delta HKH \\ \Delta & -\Delta PH & -\Delta H \end{bmatrix} \begin{bmatrix} R \\ Di \\ Do \end{bmatrix} \quad (1)$$

where, $\Delta = (I + PKH^2)^{-1}$ is sensitivity function.

Here, bode diagram of time-delay element of $H(s) = e^{-sL}$ is shown in Fig. 3. It is clear that it contains 0 dB gain and for phase suddenly drops by increasing frequency. If we express phase of time-delay mathematically, then we have $\text{phase}(H) = -L\omega$ which is proportionally decreasing with L. That is, if L is large then phase decrease rapidly with respect to frequency. Therefore, this may cause the instability of closed-loop system. Because, if cross gain frequency is larger than cross phase frequency, then gain margin will be less than 1, hence closed-loop become unstable.

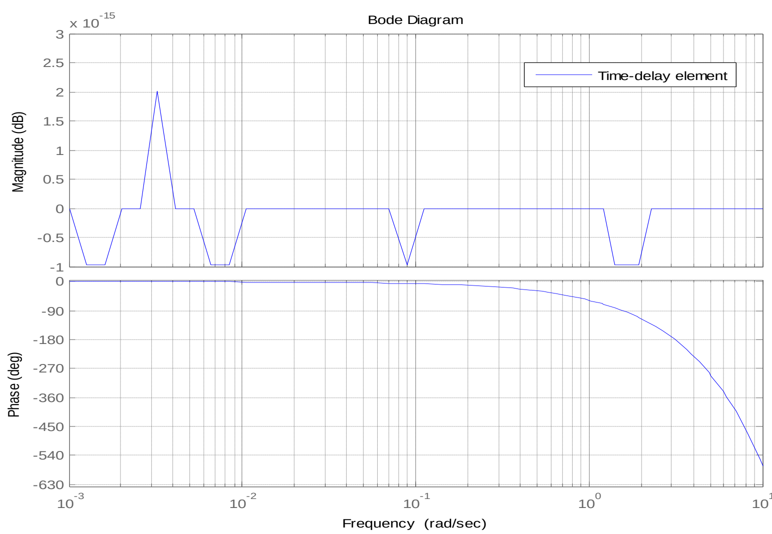

Fig. 3: Bode Diagram of Time-delay element e^{-sL} $(L = 1)$

Here, we consider an open loop transfer function for stable case. Cross gain frequency is the frequency at which gain of open loop becomes 1(0 [dB]) and also cross phase frequency is the frequency at which phase of open loop becomes -180°. The condition of stability of closed-loop system is the case that phase margin larger than 0°and gain margin larger than 1 (0[dB]). Let us approach in mathematical expression. Supposed that the open loop transfer function is $G(j\omega)=|G(j\omega)|e^{j\gamma(\omega)}$, where $\gamma(\omega)$is phase of $G(j\omega)$. When $\omega = \omega_{cg}$ where ω_{cg} is cross gain frequency, then for stability condition, we have $\varphi_{margin} = 180 - \gamma(\omega_{cg}) > 0$. For gain margin we have $\omega = \omega_{cp}$ where ω_{cp} is cross phase frequency, then we have gain margin $G_{margin} = G(\omega_{cp})^{-1}$ and stability condition is $G_{margin} > 1$.

For example, we take two open loop transfer functions in which G_1 is stable and G_2 is unstable which has been shown in Nyquist diagram in Fig. 4.

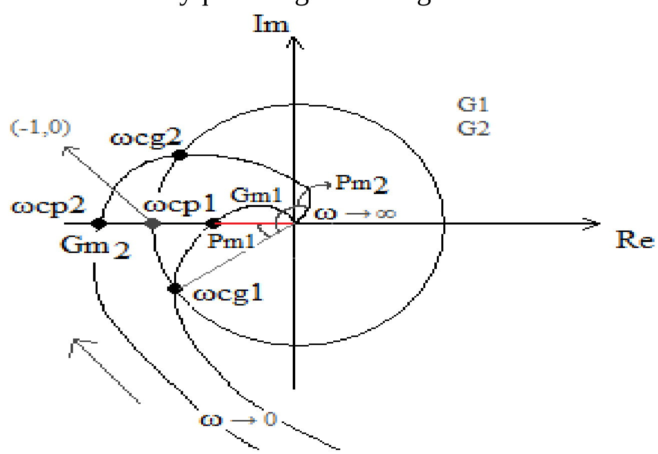

Fig .4: Nyquist diagram of G1 and G2
Gm : Gain margin Pm: Phase margin

As it is clear that in Fig. 4, in the case of G_1 we have $\omega_{cg1} < \omega_{cp1}$, therefore, the closed-loop of G_1 is stable. However, in the case of G_2 we have $\omega_{cp2} < \omega_{cg2}$ that means gain margin is less than 1 and closed-loop system is unstable. Therefore, the existence of time-delay element may occurs the instability of the closed-loop system as the same as G2's conditions.

Here, the stability condition of controller is well-posed that has been shown in the following equation:

$$I + P(j\omega)K(j\omega)H^2(j\omega) \neq 0 \quad \text{for } \forall\omega \qquad (2)$$

The equation (2) means that singular values of open loop system in high frequency must have small values. However, for good performance of system with time-delay, singular values of open loop in low frequencies should have large values. Therefore, by using the low frequency compensator, we can increase the singular values in low frequencies. This is because of low frequency compensator has the roll of increasing the singular values in low frequencies. Also the performance of system is adjustable by tuning the controller's parameters in order to avoid the overshoots in output signals.

3. Low Frequency Compensator

As we discussed previously, the system including time-delay elements, has large phase lag especially in high frequency. Therefore, controller is required to reduce the gain in high frequency. In other words, if and only if open loop has large gain in low frequencies and small gain in high frequencies, the time-delay has no influence in the closed-loop system. To confirm this fact, we give the next theorem and to prove by a scalar transfer function from R to Y in Fig. 2.

In this case, polar expression of "P","K" and "H" are given as below.

.$P = r_P e^{j\theta_P}$, $K = r_K e^{j\theta_K}$ and $H = e^{-j\omega L}$, where "L" is time-delay.

[Theorem 1]

The necessary and sufficient conditions for a closed-loop system to be internally stable is that it possess the characteristics of open loop transfer function, HPKH, which has large gain in low frequencies and small one in high frequencies. This condition will improve the performance of the closed-loop system, and robust disturbances.

The necessity conditions are explained below:

From Fig. 2, the transfer function from R to Y is given by

$$Y = \frac{PKH}{1+PKH^2}R \rightarrow \frac{Y}{R} = \frac{PKH}{1+PKH^2} = \frac{r_P e^{j\theta_P} r_K e^{j\theta_K} e^{-j\omega L}}{1+r_P e^{j\theta_P} r_K e^{j\theta_K} e^{-j2\omega L}} .$$

$$= \frac{r_P r_K e^{j(\theta_P+\theta_K-\omega L)}}{1+r_P r_K e^{j(\theta_P+\theta_K-2\omega L)}} = \frac{R_{ol} e^{j\varphi}}{1+R_{ol} e^{j\theta}} .$$

Here, we take $R_{ol} = r_P r_K$, $\theta = \theta_P + \theta_K - 2\omega L$ and $\varphi = \theta_P + \theta_K - \omega L$

Then, we have closed-loop function for complementary sensitivity function which given by

$$\frac{R_{ol} e^{j\varphi}}{1+R_{ol} e^{j\theta}} = \frac{R_{ol}}{\sqrt{R_{ol}{}^2+2R_{ol}\cos\theta+1}} e^{j\left(\varphi-\tan^{-1}\frac{R_{ol}\sin\theta}{1+R_{ol}\cos\theta}\right)} = R_{cl} e^{j\theta_{cl}} .$$

In this case, we assume that the open-loop system has monotony decreasing transfer function in frequency domain. Then, we consider two cases, one is for low frequencies and the other is for high frequencies. This means that for any $\omega \ll 1$, then, we have $R_{ol} \gg 1$ and for any $\omega \gg 1$, then, we have $R_{ol} \ll 1$.

From the above assumption, the summation of the phase of plant and controller is given by $\theta_P + \theta_K \approx -90°$ for $\forall\omega$.

Then we have 2 cases,

- For $\omega \ll 1$, we have $R_{cl} \approx 1$, and $\theta_{cl} \approx 0$, therefore, here we have $R_{cl} = 1$. Such that Y=R, hence, the error is reduced, then the performance is improved.
- For $\omega \gg 1$ we have $R_{cl} \approx 0$ and $\theta_{cl} = -90° - \omega L \approx -\infty$ that means there is not any influence of time-delay element in high frequencies and it is robust to disturbances.

The Sufficient condition is indicates as following:

The sufficient condition of stabilization of closed-loop is axiomatic in small gain theorem given by following.

$$\|PKH^2\|_\infty < 1 \qquad (3)$$

This theorem is expanded to multivariable case, by evaluation of singular values as shown in below.

$$\bar{\sigma}(KHPH) < 1 \qquad (4)$$

Where, $\bar{\sigma}(.)$ indicate the maximum singular values.

From these conditions, the controller for MIMO system can be chosen as following for the stability:

$$K(s) = \mathrm{diag}\{\frac{1+\alpha Ts}{Ts}, \dots, \frac{1+\alpha Ts}{Ts}\} \quad (5)$$

Here, α and T are tuning parameters of the controller.

4. Decoupling Compensator for multivariable system

Generally, in multivariable control system, there are interferences in output signal. In order to cancel the interference, diagonalizing of control plant matrix is required by decoupling compensator. In this paper, two schemes of diagonalization of control plant are approached, one is general scheme and the other is diagonalization over low frequency bands. Here, we assume 2 by 2 multivariable system:

Control Plant: $P = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix}$

Decoupling Compensator: $G_C = \begin{bmatrix} G_{C11} & G_{C12} \\ G_{C21} & G_{C22} \end{bmatrix}$

(1) General Diagonalization (All frequency band decoupling compensator)

Serial connection between control plant and compensator is:

$$PG_C = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \begin{bmatrix} G_{C11} & G_{C12} \\ G_{C21} & G_{C22} \end{bmatrix}$$

$$= \begin{bmatrix} P_{11}G_{C11} + P_{12}G_{C21} & P_{11}G_{C12} + P_{12}G_{C22} \\ P_{21}G_{C11} + P_{22}G_{C21} & P_{21}G_{C12} + P_{22}G_{C22} \end{bmatrix}$$

By eliminating the undiagonal elements, the interferences effects are cancelled:

$$\begin{cases} P_{11}G_{C12} + P_{12}G_{C22} = 0 \\ P_{21}G_{C11} + P_{22}G_{C21} = 0 \end{cases}$$

That compensator becomes as follows:

$$G_C = \begin{bmatrix} P_{21}^{-1} & -P_{11}^{-1} \\ -P_{22}^{-1} & P_{12}^{-1} \end{bmatrix} Q \quad (6)$$

Where, Q is proper stable and minimum phase filter that can be called as free parameter. Also, by using these free parameters, the stability and performance of system is adjustable.

(2) Diagonalization over low frequency band

As it is clear, for general case of diagonalization, interference cancellation for all band frequency is quite not suitable due to existence of inverse system in compensator. Because, even one element of plant is non-minimum phase, then the inverse of itself become unstable. Therefore, the stability of general scheme of diagonalization is not always guaranteed.

To solve this problem, low band frequency decoupling compensator is considered to avoid the instability. The low band frequency decoupling compensator can be shown as follows:

$$P(0) = \lim_{\omega \to 0} \begin{bmatrix} P_{11(j\omega)} & P_{12(j\omega)} \\ P_{21(j\omega)} & P_{22(j\omega)} \end{bmatrix} \quad \text{When } P_{22}(0)P_{11}(0) - P_{12}(0)P_{21}(0) \neq 0$$

$$P(0)G_C = I \rightarrow G_C = P^{-1}(0) \qquad (7)$$

As it is clear, in equation (7) the decoupling compensator is the inverse of system plant with its DC component only and is a constant gain. Comparing to general scheme, the low frequency decoupling compensator is simplified. However, by comparing these two different schemes, we evaluate the decoupling compensator in next section.

5. Simulation and Results

In order to evaluate the Low frequency and decoupling compensator, we have simulated for a wind turbine system (WTS) which is multivariable. The simulation process is first to simulate the low frequency compensator using general scheme of diagonalization and low frequency band diagonalization. Next, we compare the performances of different schemes. Here, we assume that system has 2 seconds delay for each time-delay element. Here, the dynamics of WTS is shown as follows:

Dynamics for angular velocity of blade: $J_\omega \dfrac{d\omega}{dt} = \dfrac{1}{2} C_T \rho A V^2 R - \dfrac{1}{2} I\omega^2 - f_r \omega$

Dynamics of pitch of angle: $J_\theta \dfrac{d^2\theta}{dt^2} = MR^2\omega^2\theta^2 - \theta k - c\dot{\theta}$

Following tables shows the parameters values.

Table 2: Parameters of WTS Dynamics

Parameters	Factors	Values
Inertia of Power Generator	I	0.1 kg
Air density	ρ	1.2kg/m^3
Area of WTS (blade)	A	πR^2 7.06m^2
Length of blade	R	1.5m
Torque factor	C_T	0.1
Friction of blade	f_r	0.1
Weight of Rotor	M	42kg
Damper factor	c	5000kgm/s
Spring factor	k	10000kgm
Angular Velocity of blade	ω	Variable
Pitch angle of blade	θ	Variable
Moment Inertia of pitch	J_θ	1.6kgm^2
Moment Inertia of blade	J_ω	0.8kgm^2

The linear system of WTS become as follows:

$$P = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} = \begin{bmatrix} P_\omega & P_{Interference1} \\ P_{Interference2} & P_\theta \end{bmatrix}$$

$$= \begin{bmatrix} \dfrac{1}{16s+1} & \sum_{i=1}^{n} \dfrac{0.2s}{s^2 + 2\zeta_i \omega_{n_i} s + \omega_{n_i}^2} \\ \dfrac{1}{s^2+0.1s+1} & \dfrac{1}{5s^2+10s+1} \end{bmatrix} \quad (8) \quad , \text{ Delay element: } H = \begin{bmatrix} e^{-1s} & 0 \\ 0 & e^{-1s} \end{bmatrix}$$

Case (1) General Diagonalization

All frequency band Decoupling Compensator:

$$G_C = \begin{bmatrix} P_{Interference2}^{-1} & -P_\omega^{-1} \\ -P_\theta^{-1} & P_{Interference1}^{-1} \end{bmatrix} Q \quad , \text{where } Q(s) = \frac{1}{s^2 + 0.2s + 1}$$

$$\text{LFC: } K(s) = \begin{bmatrix} \dfrac{1+10s}{1000s} & 0 \\ 0 & \dfrac{1+10s}{1000s} \end{bmatrix}$$

Case (2) Low Frequency Band Diagonalization

Decoupling Compensator: $G_C = P^{-1}(0)$

$$\text{LFC: } K(s) = \begin{bmatrix} \dfrac{1+12.5s}{25s} & 0 \\ 0 & \dfrac{1+12.5s}{25s} \end{bmatrix}$$

From above theorem, we can provide a new controller which is combination of LFC and DC. LFC is to cancel the effects of time-delay element and DC is to cancel the effects of interference signal which is disturbance for system. It is shown Fig. 5, the block diagram of LFC+DC controller in Tele-Control System.

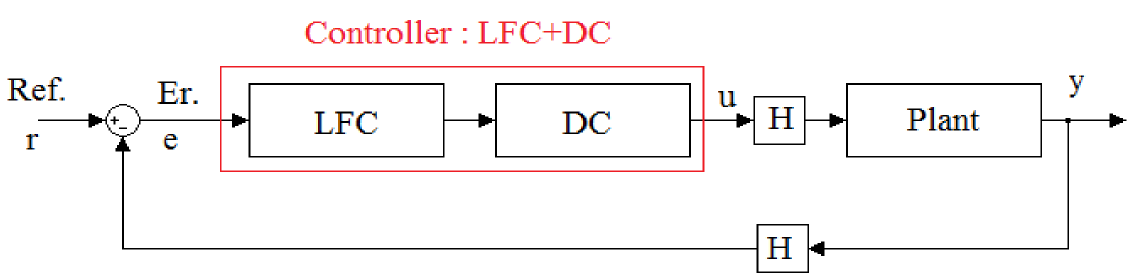

Fig. 5: Combination of LFC and DC Controller

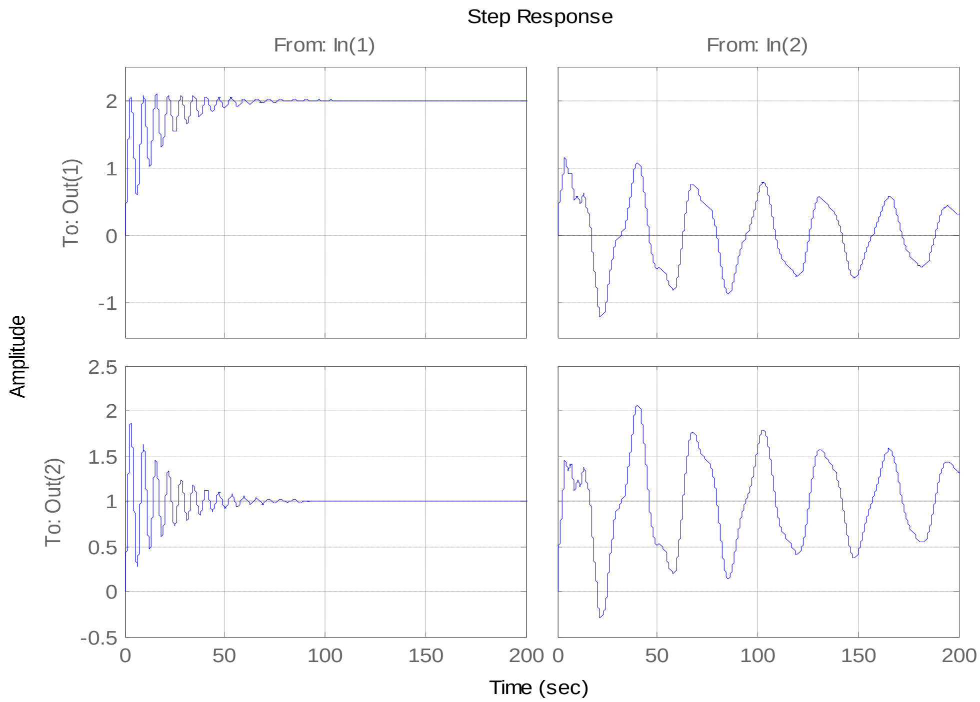

Fig.6: Step Response of System without Controller (Equation (8))

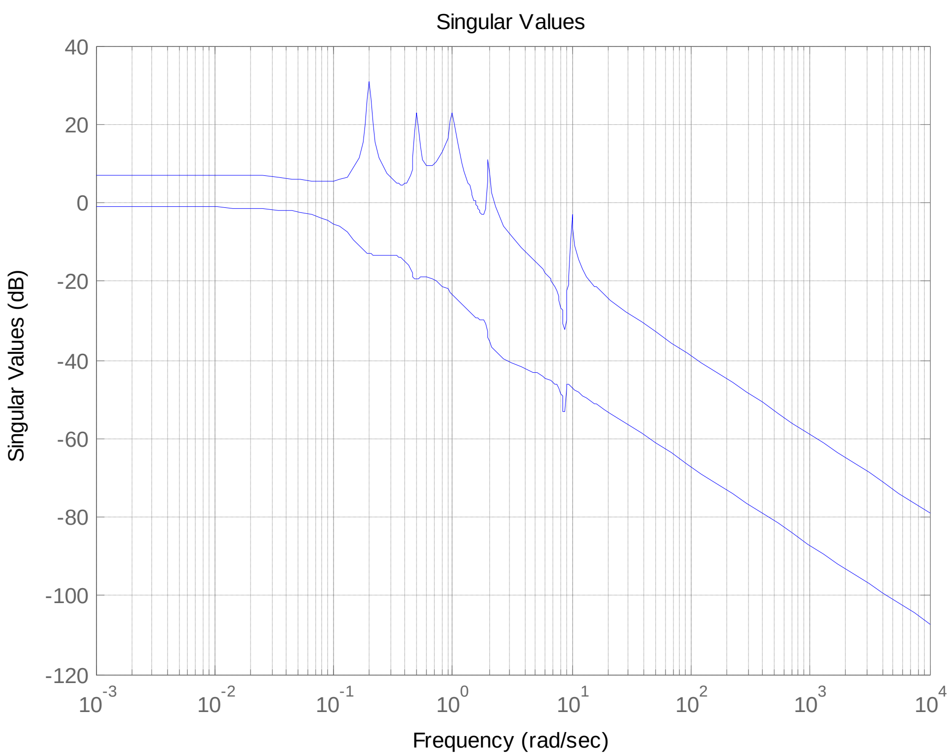

Fig. 7: Singular Values of System without Controller

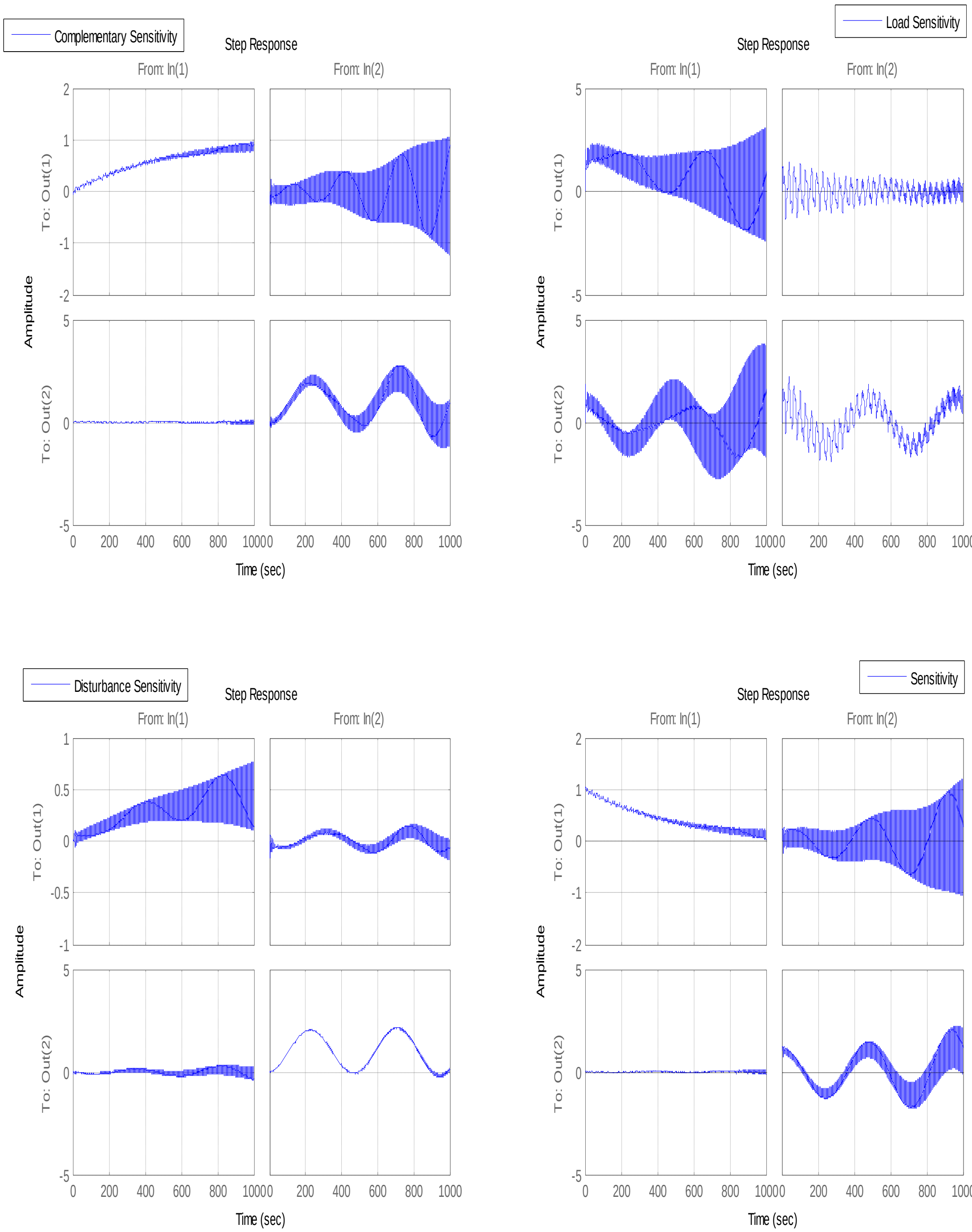

Fig.8: Step Response of Gang of Four (case 1)

Results (Step Response of gang of four and singular values with Controller case 1)

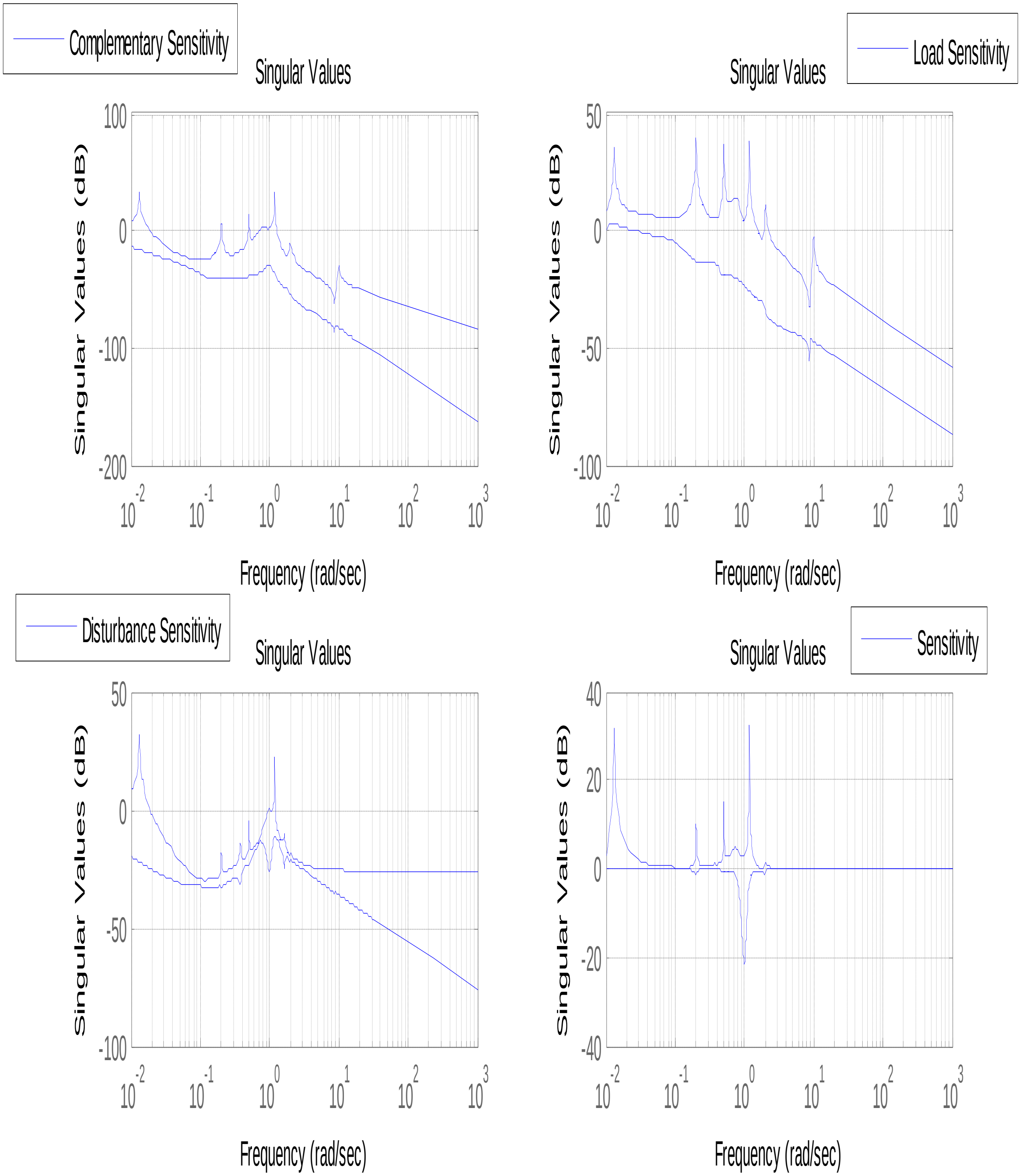

Fig.9: Singular Values of Gang of Four (case 1)

Results (Step Response of gang of four and singular values with Controller case 1)

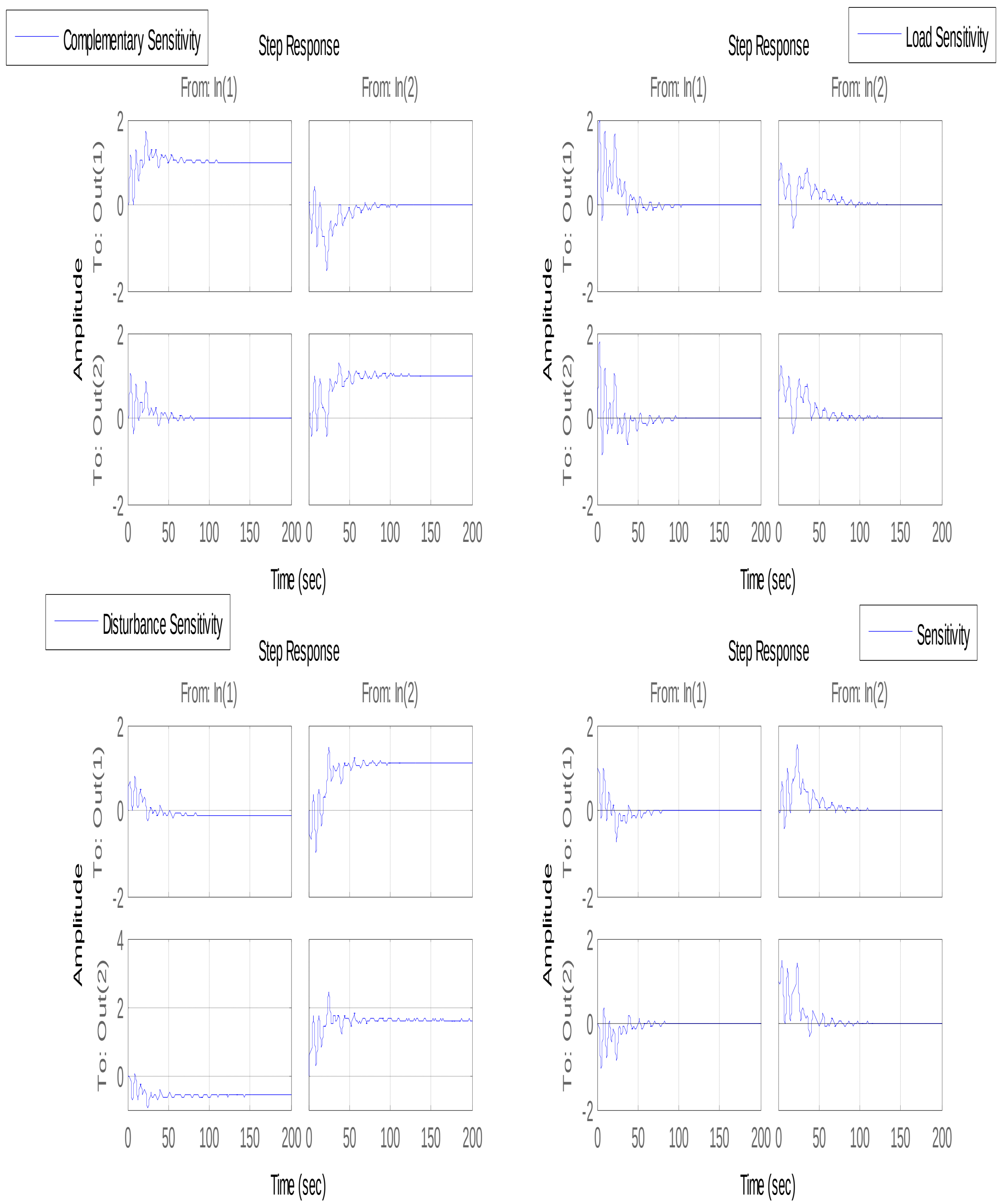

Fig.10: Step Response of Gang of Four (case 2)

Results (Step Response of gang of four and singular values with Controller case 2)

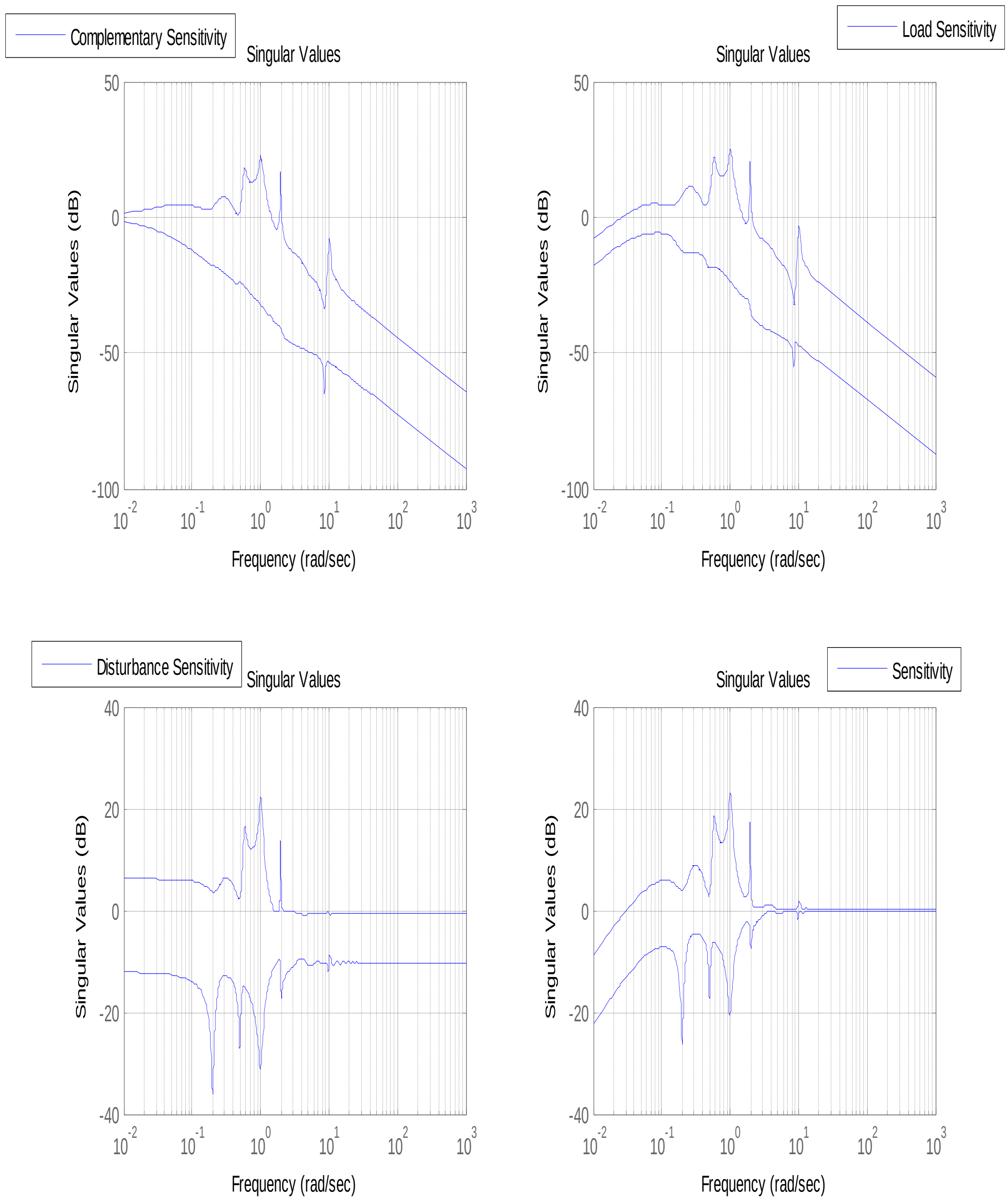

Fig. 11: Singular Values of Gang of Four (case 2)

Results (Singular Values of gang of four and singular values with Controller case 2)

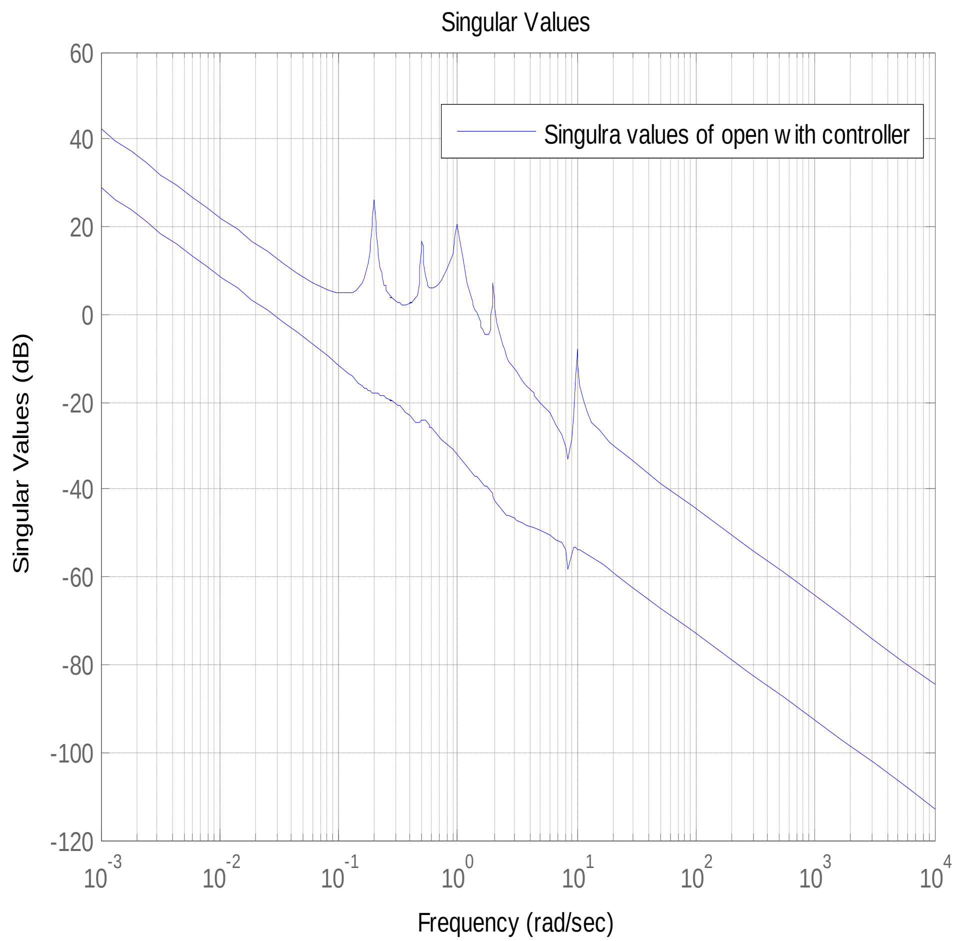

Fig.12: Singular Values of Open Loop with Controller

From in Fig. 6, it is clear that the step response of system without controller converges to undesired values due to interferences. And from Fig.7, the gain of the open loop without controller is low and it contains several peaks due to existence of time-delay elements and interferences. Therefore, interferences cancellation and improvement of performance of the system must be approached with low frequency and decoupling compensator. For case 1 (General decoupling compensator), as we can see in Fig.8, the singular values of complementary sensitivity function drops in low frequency, in other words the frequency cut is located in low frequency. Furthermore, the sensitivity function contain with large gain in low frequencies. Thus, the system becomes unstable as it is clear in Fig. 9. However, for with controller case 2, from Fig.10, we can see that the step responses are stable and converge to reference signals. Furthermore, sensitivity function is converges to 0, and from Fig.11, we can see that the singular values of sensitivity function in low frequencies, it contains with small gain. Finally, comparing Fig.7 and Fig. 12, the singular values of system with controller, in low frequency band, it contains large gain which means system has better performance and reduced the gain in high frequency in order to stabilize the closed-loop system.

5. Conclusion

In this paper, we consider a round trip time-delay and interferences in system. Time-delay may cause the instability in closed-loop system. Moreover, in MIMO system, interferences may adverse effect the output signal. Therefore, we used low frequency (LFC) and decoupling compensator (DC) in order to reduce the effects of time-delay by LFC and eliminate the effects of interferences by DC. Finally, we combine these two compensators in order to create a new controller. In decoupling compensator, there are two methods, one is general decoupling compensator and the other is low frequency decoupling compensator. However, there is non-minimum phase system or vibrator interference to the general decoupling compensator in the system; it becomes unstable due to construct the interference of inverse system. Therefore, it is open problem to design the low frequency decoupling compensator for non-nominal and vibration interferences system to avoid the instability.

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