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Control Systems Protection in Case of Uncertainties and Disruptions Affecting their Operations

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Abstract

This research contributes in the design and application of a robust controller capable of suppressing the effects of external disturbances, noise and parameters uncertainties of the control system. It also contributes to the analysis of system's robustness by examining its sensitivity in terms of all variable and disturbing factors. The method of the D-partitioning is applied in the course of design of the robust controller to achieve system's desired performance and stability. The performance of the robust system is demonstrated in terms of its improved stability and transient response. The recommended design and analysis of robust control systems is beneficial for the advancement of control theory in this field.
Keywords: **Parameters Uncertainties, Disturbance, Noise, Regions of stability, D-Partitioning, Robust control;**

1. Introduction

This research demonstrates the unique property of a robust controller in suppressing the effects of any parameters uncertainties as well as any external disturbances and noise on a control system's performance.

An extensive literature review reveals that there is a shortage in the analysis on this matter.

A method for a design of a robust controller is suggested, following a number of unique steps. The controller enforces desired system stability, damping and time response. [1]. The method of the Advanced D-Partitioning [2], [3], further developed and simplified by the author in previous published work [4], [5], [6], is used for the design of the robust controller and for the stability analysis of the compensated system.

System's sensitivity analysis is applied in terms of the effects of the external disturbances, noise and parameters uncertainties. The results for the system sensitivity are compared for the cases before and after the robust compensation.

2. Disturbing and Variable Factors in a Control System

A control system is robust when it has low sensitivities and maintains certain properties like stability and performance in spite of plant parameter uncertainties or external disturbances, noise. The view of a feedback robust control system, incorporating a robust controller, is demonstrated in Figure 1, where disturbing factors are entering the system in three different locations. In effect, there is always parameters uncertainty in the model of the plant. Also, it is assumed that disturbances appear at the system's output and are additive to the system's output signal. In addition there is noise affecting the control system which is usually measured on the sensor inputs. Each of these different types of disturbing factors can have an additive component [7], [8].

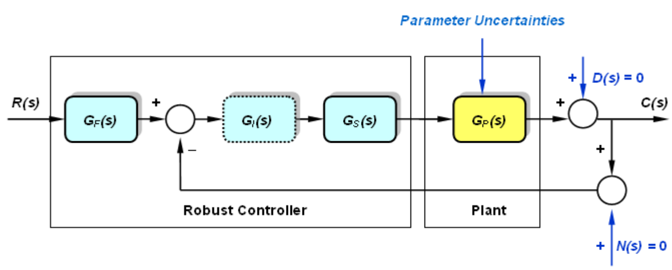

Fig. 1. Robust control system subjected to parameters uncertainties, disturbances, noise

3. Design of a Robust Control System

The forward transfer function [1], [9],[10] of a tracker control system is:

$$G_P(s) = \frac{K}{0.0001s^3 + 0.025s^2 + s} \qquad (1)$$

In this case, the system's gain K is considered a variable and uncertain parameter. A robust controller, incorporated into the system, consists of a series and a forward stage $G_S(s)$, $G_F(s)$, as seen in Figure 1. This controller will have the purpose of forcing the control system into an insensitive state in terms of uncertainties and variation of its parameters, as well as insensitive to external disturbances and noise.

The following successive steps are taken to design the system's robust controller:

Step 1: It is assumed that the closed-loop transfer function of G_P(s) is involved in a unity feedback system as a stand-alone block. Then the transfer function of the closed-loop system is:

$$G_{CL}(s) = \frac{K}{0.0001s^3 + 0.025s^2 + s + K} \quad (2)$$

Step 2: In accordance with the ITAE criterion, the optimal value of K that satisfies the condition of a relative damping ratio ζ = 0.707 is determined by the code:

```
>>K=[15:0.01:25]
>> for n=1:length(K)
G_array(:,:,n)=tf([10000*K(n)],[1 250 10000 10000*K(n)]);
end
>> [y,z]=damp(G_array);
>> plot(K,z(1,:))
```

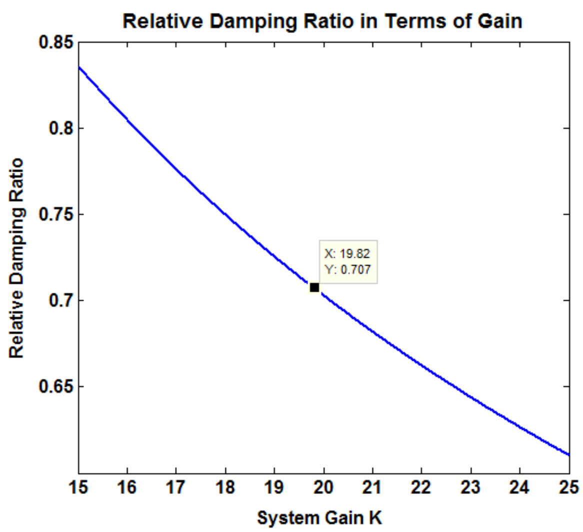

Figure 2. Gain value corresponding to relative damping ratio $\zeta = 0.707$

Step 3: As seen from Figure 2, the optimal gain is K = 19.82. By substituting this value in equation (2), the transfer function of the closed-loop system is modified to:

$$G_{CL}(s) = \frac{198200}{s^3 + 250s^2 + 10000s + 198200} \quad (3)$$

This condition corresponds to the desired closed-loop poles −21.9 ± j21.9, determined as seen from the code:

```
>> GCL1=tf([198200],[1 250 10000 198000])
>> damp(GCLo)
```

Eigenvalue	Damping	Freq. (rad/s)
-2.19e+001 + 2.19e+001i	7.07e-001	3.10e+001
-2.19e+001 - 2.19e+001i	7.07e-001	3.10e+001
-2.06e+002	1.00e+000	2.06e+002

Step 4: Following the ITAE criterion, the design strategy for constructing the series controller stage G_S (s) is to place its two zeros near the desired dominant closed-loop poles, corresponding to optimal value of K.

Therefore, the two series controller zeros can be placed also at −22 ± j22 and its transfer function is:

$$G_S(s) = \frac{(s+22+j22)(s+22-j22)}{968} = \frac{s^2+44s+968}{968} \quad (4)$$

Step 5: Further, the series stage is connected in series with the plant as follows:

$$G_{OL}(s) = G_S(s)G_P(s) = \frac{0.001K(s^2+44s+968)}{0.0001s^3+0.025s^2+s} \quad (5)$$

Step 6: If G_{OL}(s) is involved in a unity feedback system, its closed-loop transfer function is determined as:

$$G_{CLS}(s) = \frac{0.001K(s^2+44s+968)}{0.0001s^3+0.025s^2+s+0.001K(s^2+44s+968)} \quad (6)$$

Step 7: As seen from the equation (6), the closed-loop zeros will cancel the closed loop poles of the system, being in their vicinity. To avoid this problem, a forward controller G_F (s) is added to the system.

The poles of G_F (s) should cancel the zeros of G_{CLS} (s). Therefore, the transfer function of the forward controller is designed as follows:

$$G_F(s) = \frac{968}{s^2+44s+968} \quad (7)$$

Step 8: Finally, the transfer function of the total compensated system that includes the two controller stages is derived considering the block diagram in Figure 1:

$$G_T(s) = G_F(s)G_{CLS}(s) = $$
$$= \frac{K}{0.0001s^3+0.025s^2+s+0.001K(s^2+44s+968)} \quad (8)$$

4. Control System Analysis

The characteristic equation of the original closed-loop system is determined from equation (2) as follows:

$$G(s) = 0.0001s^3 + 0.025s^2 + s + K = 0 \tag{9}$$

The D-partitioning in terms of the variable parameter *K*, as shown in Figure 3, is obtained from equation (10) and is plotted with the aid of following the code:

$$K(s) = -\frac{0.0001s^3 + 0.025s^2 + s}{1} \tag{10}$$

```
>> K=tf([0.0001 0.025 1 0],[0 1])
Transfer function:
 -0.0001 s^3 - 0.025 s^2 – s
>>dpartition(K)
```

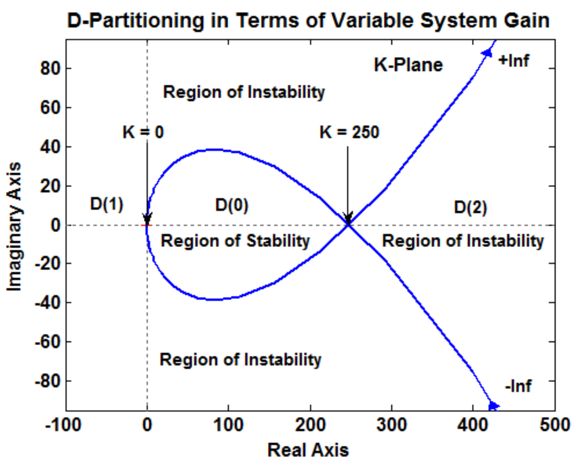

Fig. 3. D-Partitioning in terms of the variable system gain

The D-partitioning curve in terms of one variable parameter can be plotted in the complex plane within the frequency range $-\infty \leq \omega \leq +\infty$, facilitated by MATLAB the "nyquist" m-code. The procedure can work on any computer where the MATLAB program is installed. To avoid any misinterpretation of the D-Partitioning procedure, the "nyquist" m-code is modified into a "dpartition" m-code with the aid of the MATLAB Editor and a proper formatting. The "dpartition" m-code will plot the curve of a specific system parameter in terms of the frequency variation from $-\infty$ to $+\infty$.

The D-partitioning analysis of the original system determines three regions on the *K*-plane: D(0), D(1) and D(2). Only D(0) is the region of stability, being the one, always on the left-hand side of the curve for a frequency variation from $-\infty$ to $+\infty$.
It is seen that the original system is stable within the gain range $0 \leq K \leq 250$.

The D-partitioning analysis of the robust compensated system is shown in Figure 4. It is determined from the equation (11), where the D-partitioning curve is plotted with the aid of following the code:

$$K = -\frac{0.0001s^3 + 0.025s^2 + s}{0.001s^2 + 0.044s + 1} \tag{11}$$

```
>> K = tf([-0.0001 -0.025 -1 0],[0.001 0.044 2])
>> dpartition(K)
```

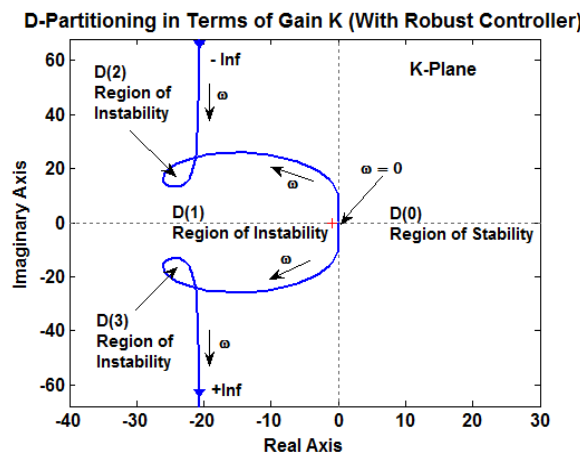

Fig. 4. D-Partitioning in Terms of *K* with the Robust Controller

As seen from Figure 4, the D-partitioning determines four regions in the *K*-plane: D(0), D(1), D(2) and D(3). Only D(0) is the region of stability, being always on the left-hand side of the D-partitioning curve for a frequency variation from $-\infty$ to $+\infty$. From the analysis is obvious that the robust compensated system is stable for any value of $K > 0$, since this corresponds to the region D(0).

Step responses of the original feedback system for different gain values are shown in Figure 5 and are obtained by the code below. They vary considerably for different gains *K*, demonstrating system's sensitivity in terms of one of its parameters uncertainty.

```
>> Gp20=tf([0 20],[0.0001 0.025 1 0])
>> Gp50=tf([0 50],[0.0001 0.025 1 0])
>> Gp100=tf([0 100],[0.0001 0.025 1 0])
>> Gpfb20=feedback(Gp20,1)
>> Gpfb50=feedback(Gp50,1)
>> Gpfb100=feedback(Gp100,1)
>> step(Gpfb20,Gpfb50,Gpfb100)
```

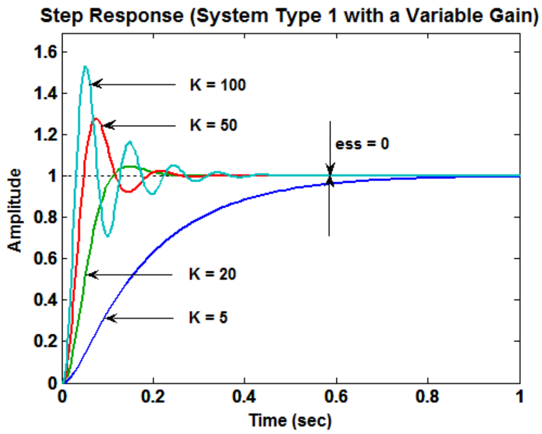

Fig. 5. Step responses of the original system with a Variable Gain

The compensated closed-loop system is examined for robustness in the time-domain, by substituting random values for the system's gain K = 100, K = 200, K = 500:

$$G_T(s)_{K=100} = \frac{100}{0.0001s^3 + 0.125s^2 + 5.4s + 96.8} \quad (12)$$

$$G_T(s)_{K=200} = \frac{200}{0.0001s^3 + 0.225s^2 + 9.8s + 193.6} \quad (13)$$

$$G_T(s)_{K=500} = \frac{500}{0.0001s^3 + 0.525s^2 + 23s + 484} \quad (14)$$

The step responses are plotted by the code:

```
>> GT100 = tf([100],[0.0001 0.125 5.4 96.8])
>> GT200 = tf([200],[0.0001 0.225 9.8 193.6])
>> GT500 = tf([500],[0.0001 0.525 23 484])
>> step(GT100,GT200,GT500)
```

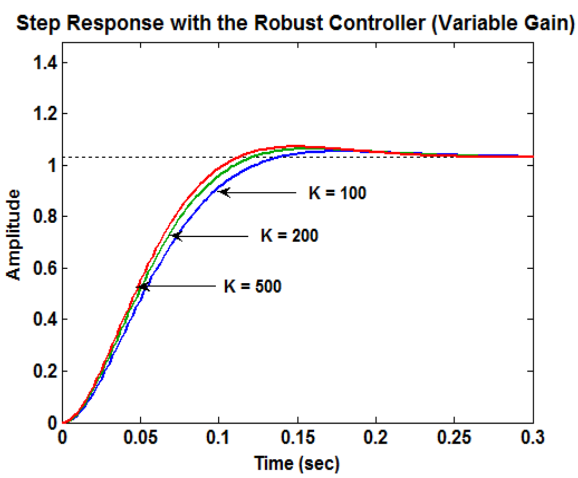

Fig. 6. Robust system responses (K = 100, K = 200, K = 500)

Due to the effect of the applied robust controller, the system becomes quite insensitive to considerable variation of the gain K, as seen from Figure 6.

5. Sensitivity of the Robust Control System

5.1 Sensitivity in Case of Parameter Uncertainties

The sensitivity interpretation of a system with respect to parameter variations can be easily achieved with the aid of the frequency-domain plots.

Considering that the original control system with a unity feedback has a general transfer function of the type:

$$W(s) = \frac{G_P(s)}{1 + G_P(s)} \quad (15)$$

If taking into account the variation of any of the parameters of the original open-loop system, represented by the transfer function $G_P(s)$, the sensitivity of $W(s)$ with respect to any variations of $G_P(s)$ is determined as follows [11], [12]:

$$S_G^W(s) = \frac{dW(s)/W(s)}{dG(s)/G(s)} = \frac{G_{P1}(s)^{-1}}{1 + G_{P1}(s)^{-1}} = \frac{1}{1 + G_{P1}(s)} \quad (16)$$

The best sensitivity value is considered as $S_G^W(s) = 0$.

By substituting equation (1) into equation (15) and further into equation (16) for the cases K = 100, K = 200 and K = 500, the sensitivities of the original system are:

$$S^W_{G1\,Original\ K=100}(s) = \frac{0.0001s^3 + 0.025s^2 + s}{0.0001s^3 + 0.025s^2 + s + 100} \quad (17)$$

$$S^W_{G1\,Original\ K=200}(s) = \frac{0.0001s^3 + 0.025s^2 + s}{0.0001s^3 + 0.025s^2 + s + 200} \quad (18)$$

$$S^W_{G1\,Original\ K=500}(s) = \frac{0.0001s^3 + 0.025s^2 + s}{0.0001s^3 + 0.025s^2 + s + 500} \quad (19)$$

Similarly, taking into account the total robust control system described by equation (8) and substituting it in (16), the sensitivities for the cases K = 100, K = 200 and K = 500, are determined as:

$$S^W_{G1\,Robust\ K=100}(s) = \frac{0.0001s^3 + 0.125s^2 + 5.4s + 96.8}{0.0001s^3 + 0.125s^2 + 5.4s + 196.8} \quad (20)$$

$$S^W_{G1\,Robust\ K=200}(s) = \frac{0.0001s^3 + 0.225s^2 + 9.8s + 193.6}{0.0001s^3 + 0.225s^2 + 9.8s + 393.6} \quad (21)$$

$$S^W_{G1\,Robust\;K=500}(s) = \frac{0.0001s^3 + 0.525s^2 + 23s + 484}{0.0001s^3 + 0.525s^2 + 23s + 984} \qquad (22)$$

The sensitivity assessment of the original and the robust compensated system in terms of frequency variation is determined by the following code and shown in Figure 7:

```
>> G1OriginalK100=tf([0.0001 0.025 1 0],[0.0001 0.025 1 100])
>> G1OriginalK200=tf([0.0001 0.025 1 0],[0.0001 0.025 1 200])
>> G1OriginalK500=tf([0.0001 0.025 1 0],[0.0001 0.025 1 500])
>> G1RobustK100=tf([0.0001 0.125 5.4 96.8],[0.0001 0.125 5.4 196.8])
>> G1RobustK200=tf([0.0001 0.225 9.8 193.6],[ 0.0001 0.225 9.8 393.6])
>> G1RobustK500=tf([0.0001 0.525 23 484],[ 0.0001 0.525 23 984])
>>bode(G1OriginalK100,G1OriginalK200,G1OriginalK500,
        G1RobustK100,G1RobustK200,G1RobustK200)
```

As seen from Figure 7, the sensitivity of the original control system at cases K = 100, K = 200 and K = 500 is $S^W_G(s) \geq 0\,\text{dB}$ in the frequency range 65 rad/sec < ω < 400 rad/sec, reaching $S^W_G(s) = 21.6\,\text{dB}$ for the case of K = 200.

The robust system sensitivity for the case of K = 100, coincide with the cases of K = 200 and K = 500. The sensitivity of the robust control system is $S^W_G(s) \leq 0\,\text{dB}$ for ω < 30 rad/sec and for ω > 400 rad/sec, while it is $S^W_G(s) \geq 0\,\text{dB}$, but is with an insignificant value in the frequency range of 30 rad/sec < ω < 200 rad/sec. The robust system is with considerably lower sensitivity compared with the original one.

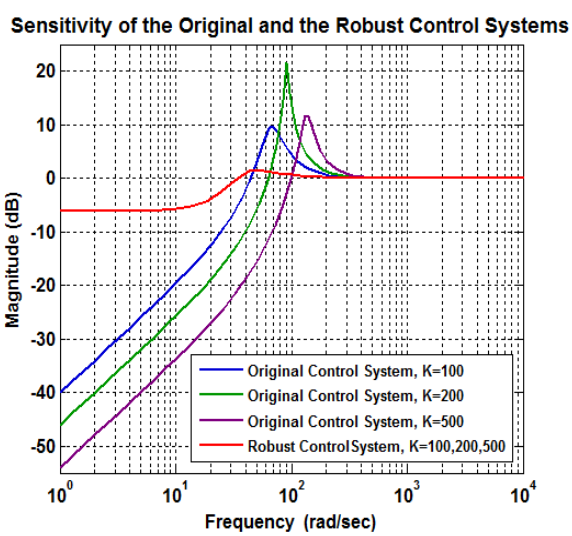

Fig.7. Sensitivity of original and robust control system (Variable gain K)

5.2 Sensitivity in Case of System's Disturbance

Both disturbances and noise are additive to the system's output signal. If the values of the disturbance and noise are $D(s)$ = 0 and $N(s)$ = 0, the system's input-output transfer function is determined from the block diagram of Figure 1:

$$W_{Robust}(s) = \frac{C(s)}{R(s)} = \frac{G_F(s)G_S(s)G_P(s)}{1 + G_S(s)G_P(s)} \qquad (23)$$

It is suggested that the series controller $G_S(s)$ is to be designed with the objective, the output signal $C(s)$ to be insensitive to the disturbance $D(s)$ or to the noise $N(s)$ over the frequency range in which the disturbance or the noise are dominant. At the same time the forward controller $G_F(s)$ is to be designed to achieve the desired transfer function $W_{Robust}(s)$ between the input $R(s)$ and the output $C(s)$ of the system. The sensitivity of $W_{Robust}(s)$ with respect to any variations of $G_P(s)$ is:

$$S^{WR}_{GP}(s) = \frac{dW_{Robust}(s)/W_{Robust}(s)}{d[G_P(s)G_S(s)]/[G_P(s)G_S(s)]} = \frac{1}{1 + G_S(s)G_P(s)} \qquad (24)$$

In the ideal case the sensitivity should be $S^{WR}_{GP}(s) = 0$.

If the input is $R(s)$ = 0 and the noise is $N(s)$ = 0, the disturbance-to-output transfer function is presented as:

$$Q_{Robust\,D}(s) = \frac{C(s)}{D(s)} = \frac{1}{1 + G_S(s)G_P(s)} \qquad (25)$$

The ideal case of disturbance suppression would be if $Q_{Robust\ D}(s)$ = 0. The disturbance-to-output transfer functions for the original and the robust control systems are represented as follows:

$$Q_{Original\,D}(s) = \frac{C_{Original}(s)}{D(s)} = \frac{1}{1 + G_P(s)} = \qquad (26)$$
$$= \frac{0.0001s^3 + 0.025s^2 + s}{0.0001s^3 + 0.025s^2 + s + 200}$$

$$Q_{Robust\,D}(s) = \frac{1}{1 + G_S(s)G_P(s)} = \qquad (27)$$
$$= \frac{0.0001s^3 + 0.025s^2 + s}{0.0001s^3 + 0.2316s^2 + 10.1s + 200}$$

The improvement in terms of the disturbance rejection is analyzed by comparing the transfer functions $Q_{OriginalD}(s)$ and $Q_{RobustD}(s)$ in the frequency domain. The functions (26) and (27) are plotted as Bode magnitudes in the

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frequency domain with the aid of the following code and shown in Figure 8:

```
>> Q1OriginalK200=tf([0.0001 0.025 1 0],[0.0001 0.025 1 200])
>> Q1RobustK200=tf([0.0001 0.025 1 0],[0.0001 0.231 10.1 200])
>> bode(Q1OriginalK200,Q1RobustK200)
```

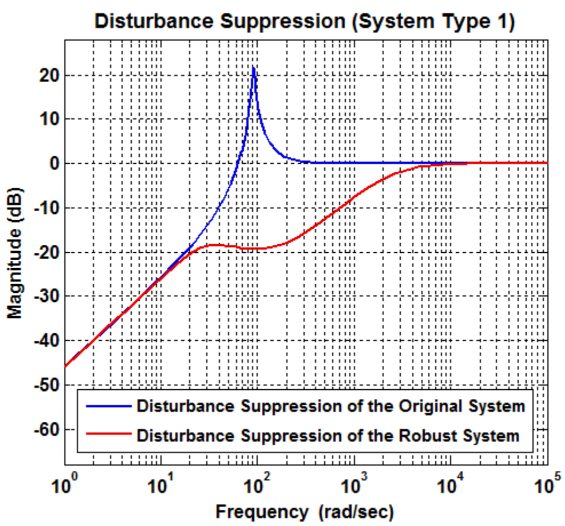

Fig. 8. Disturbance suppression of the original and robust control systems

The plot shown in Figure 8 reveals that the disturbance suppression of the original control system is $Q_{OriginalD1} \geq 0$ dB in the frequency range 60 rad/sec < ω < 300 rad/sec, reaching $Q_{OriginalD1}$ = 21.6 dB at 90.6 rad/sec.

By applying the robust controller, the disturbance rejection is significant. The magnitude Bode plot of disturbance-to-output function is $Q_{RobustD1} \leq 0$ in the full frequency range.

5.3 Sensitivity in Case of System Subjected to Noise

If the input is $R(s) = 0$ and the disturbance is $D(s) = 0$, the noise-to-output transfer function is:

$$Q_{Robust\ N}(s) = \frac{C(s)}{N(s)} = -\frac{G_S(s)G_P(s)}{1+G_S(s)G_P(s)} \quad (28)$$

The ideal case of noise suppression is considered when $Q_{Robust\ N}(s) = 0$.

The noise-to-output transfer functions for the original and the robust control systems are represented as follows:

$$Q_{Original\ N1}(s) = \frac{C_{Original\ 1}(s)}{N(s)} = -\frac{G_{P1}(s)}{1+G_{P1}(s)} = -\frac{300}{0.0001s^3 + 0.025s^2 + s + 300} \quad (29)$$

$$Q_{RobustN1}(s) = \frac{C_{Robust1}(s)}{N(s)} = -\frac{G_{S1}(s)G_{P1}(s)}{1+G_{S1}(s)G_{P1}(s)} = -\frac{0.031s^2 + 13.64s + 300}{0.0001s^3 + 0.3356s^2 + 14.64s + 300} \quad (30)$$

The improvement of the noise rejection is analyzed by comparing the transfer functions $Q_{OriginalN1}(s)$ and $Q_{RobustN1}(s)$ in the frequency domain. The functions (29) and (30) are plotted in the frequency domain with the aid of the following code and shown in Figure 9.

```
>> Q1OriginalK300N=tf([-300],[0.0001 0.025 1 300])
>> Q1RobustK300N=tf([-0.031 -13.64 -300],[0.0001 0.335 14.64 300])
>> bode(Q1OriginalK300N,Q1RobustK300N)
```

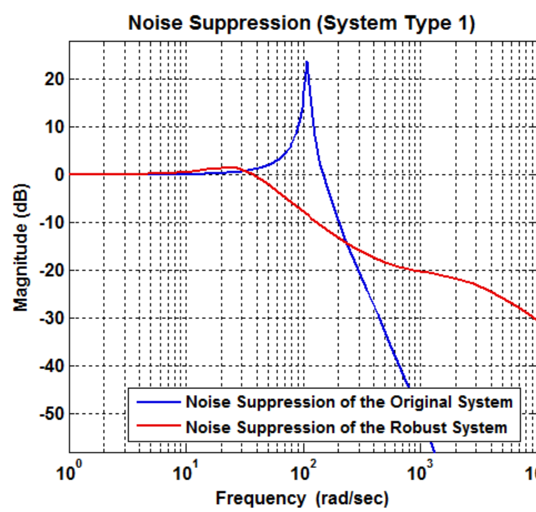

Fig. 9. Noise suppression of the original and robust control systems

As seen from Figure 9, the noise suppression of the original control system is $Q_{OriginalN} \geq 0$ dB in the frequency range 20 rad/sec < ω < 147 rad/sec and is reaching $Q_{OriginalN}$ = 23.6 dB at 108 rad/sec. By applying the robust controller, the noise rejection is significant. The magnitude Bode plot of the noise-to-output function is $Q_{RobustN} \geq 0$ dB in the frequency range 5 rad/sec < ω < 38 rad/sec dB is reaching $Q_{RobustN}$ = 1.4 dB at 24 rad/sec, but it is insignificant compared with the one of the original system, while $Q_{RobustN} \leq 0$, for the rest of the frequency range.

6. Conclusions

The main achievement of this research is the design of a robust controller, capable of suppressing the effects of all distressing factors to the system. In addition, performance and sensitivity analysis in terms of parameter variations, disturbances and noise is another contribution to the subject.

The design strategy of a robust controller proves that by implementing desired dominant system poles, the controller enforces the required relative damping ratio and system performance. The robust controller has an effect of bringing the system to a state of insensitivity to the variation of its parameters within specific limits of the parameter variations. Previously published work by the author [6], [9] is demonstrating that the designed robust controller is equally effective for uncertainties of any of the system's parameters. The results from the sensitivity analysis also confirm that the introduction of the designed robust controller considerably reduces the system sensitivity to parameters uncertainties and therefore improves the robustness of the system. It is also seen that the robust controller has the effect of considerable rejection of the disturbance and noise, bringing their additive components to the system's output signal close to zero.

The achievements in this research are believed to lead to the advancement of the knowledge in the field of robust systems analysis and putting additional light to the efficiency of suppressing the effects of any parameters uncertainties, external disturbances and noise on the system's performance. This area was worth researching not only because it advances knowledge. It has a considerable practical aspect as well. It can be used to improve the performance of a lot of industrial control systems that have unstable and variable parameters due to different ambient conditions or are subjected to noise and disturbance.

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