Hydraulic Servo System Control Using Differential Evolution Based Robust Structure Specified H∞ Controller

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Abstract: Synthesis of an H∞ controller usually gives a very high order of controller. The order of the controller is much higher than the plant. Hence, it makes the controller become very hard to be implemented in practical application especially using small microcontroller. However, disturbances and un-modeled dynamics always exist in the system. This research introduced modeling and simulation of lower order structure specified H∞ robust controller to control a hydraulic servo system. A low order controller shortens the gap between the complicated H∞ controllers to the practical embedded control system application. Simulation showed that the proposed controller give satisfactory result as the responses have small settling times and no steady state error. The resulted controller also gave better responses compared to the responses of a full order H∞ controller generated using Matlab Robust Control Toolbox.

Keywords: Servo Hydraulic; Closed Loop Control; H-Infinity Control

Introduction

Servo system powered by hydraulic actuator is called hydraulic servo system. Hydraulic position servo system is widely used in many applications such as in industries, construction, military, transportation, and so on. However, there are challenges in controlling a hydraulic servo system. Non-linearity, un-modeled dynamics, and some uncertainties due to variations in fluid volumes and leakage may appear in the system. Tadese et.al [1] modeled and simulated fuzzy-PID position controller for a hydraulic servo system. Skarpetis et.al [2] proposed robust position tracking for a hydraulic servo system. They solved using Internal Model Principle modified with a Hurwitz invariability technique and a Simulated Annealing Algorithm. A loop shaping based robust controller for hydraulic servo system also presented by Zhang et.al [3]. Robust optimization in H∞ control has been studied in the last of few years [4,5,6,7] Basically it can be solved in frequency domain [4,7] or time domain [6] point of view. However, both methods generate controller that has order much higher than the plant itself. It makes the implementation of H∞ robust controller is far from being practical. This research proposed a lower order of robust structure specified H∞ controller based on parameter optimization to get the H∞ performance requirements are achieved. To guarantee the optimum parameter is achieved, Differential Evolution was applied to avoid the search trapped in local optimum. Differential Evolution is an evolution based optimization [8]. Sutyasadi [9] showed that DE-based H∞ controller has better performance than PID controller under uncertainties. The remainders of this paper are organized as follows. In section II modeling of the hydraulic servo system is presented. H∞ controller and n-modeled dynamics and uncertainties of the system are explained in section III. Simulation result of the proposed controller responses under uncertainties is presented in section IV. A full order of H∞ controller is synthesized using robust control Matlab Toolbox and compared to the proposed controller in section V. Conclusion is given in section VI.

Hydraulic Model

In this chapter, derivation of the hydraulic servo system is provided. The hydraulic servo system consists of hydraulic actuators, electronic drives, and position transducer [13,14]. Mathematical model of the system provides relationship between displacement output of the load and voltage input to the solenoid that moves the spool. Figure 1 shows a hydraulic actuator with four way valve configuration.

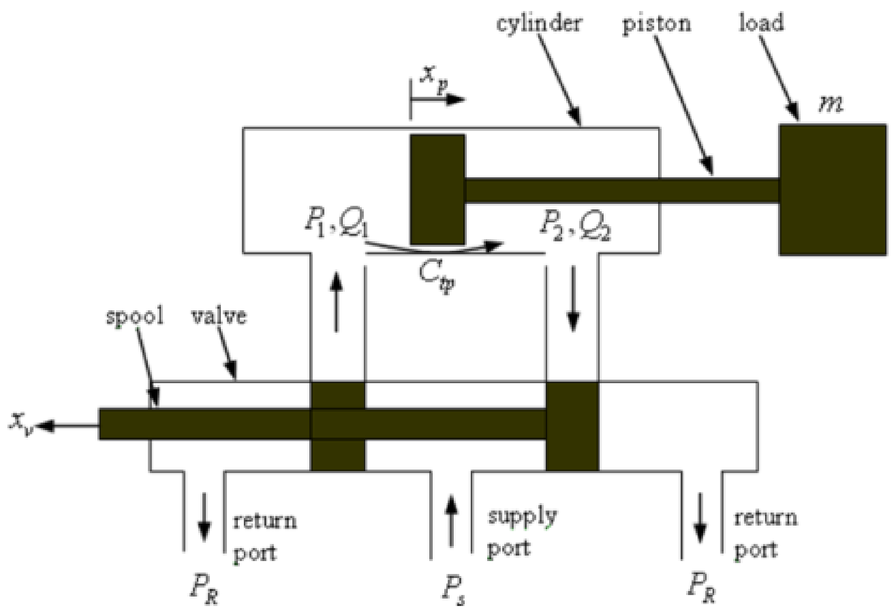

Figure 1. A hydraulic actuator with four-way valve configuration.

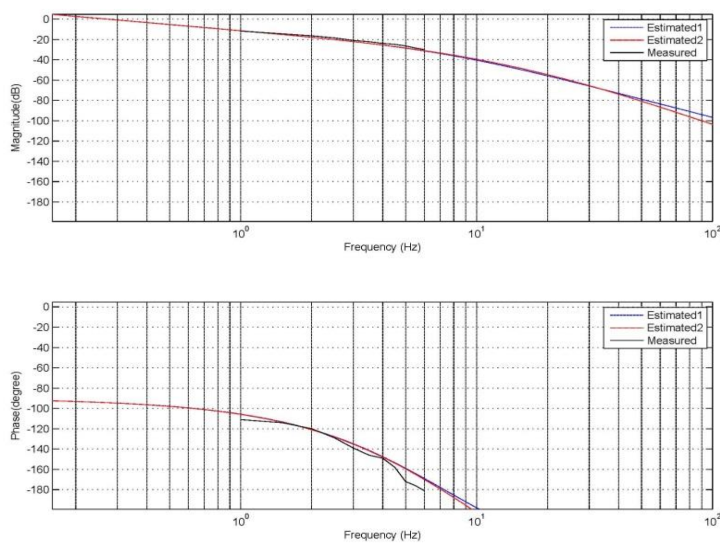

Figure 2. Bode plot of the open loop transfer function: (estimated 1) second order.

The objective for developing the actuator system dynamics is to construct a strict - feedback control with fixed boundary layer to obtain precise position control of a nonlinear electro-hydraulic servo system [15]. In order to represent servo valve dynamics through a wider frequency range, transfer function is used as approximation of the valve dynamics.

The data is separated into estimation data, which is used for identifying unknown system parameters and measurement data. In order to excite all the relevant frequencies of the systems and to construct a good model; the frequencies are set the sinusoidal inputs with range of 1 to 6 Hz and pressure of 5 Mpa. In conventional design of a hydraulic servo system, third order transfer function is generally used, as given in (1) below

$$G(s)=\frac{K_q\frac{\omega_n^2}{A_1}}{s(s^2+2\delta\omega_n s+\omega_n^2)} \quad (1)$$

In frequency response analysis, we measure the amplitude of oscillations at the signal frequency. At first, we carried out a set of experiments using the open loop system to determine the amplitudes of oscillations, which occur at the signal frequency. In order to observe the signal frequency component of the response only, experiments are carried out using signal frequencies of 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5 and 6 Hz at 5 Mpa pressure. Overall, the system identification is done by fitting a third order polynomial. The system transfer function is found to be:

$$G(s)=\frac{9272}{s^3+205.5s^2+105560s} \quad (2)$$

From Figure 2, The correspondence levels between predicted model and the experimental data for second order and the third order models are about 74.16% and 80.77 %, respectively. In this experiment, the input test signal during 1 to 6 Hz is applied as the estimation data. Then the parameter values are varied by optimization until best fitting is reached. Matlab identification toolbox software is used to create the mathematical model of the system. The process -modeling tool is selected to customize the structure of identified model based on the knowledge of the second order and third order of hydraulic plant. Finally, comparison between the experimental outputs and its predicted model using estimation data is obtained as shown in Figure 2.

Structure Specified H∞ Robust Controller

System uncertainties

Multiplicative uncertainties on a system are shown in Figure 3. *$G_n(s)$* is the nominal system, *ΔG(s)* is the system perturbation, *K(s)* is the controller, *r(t)* is the reference input, *e(t)* is the tracking error, *d(t)* is the external disturbance, and *y(t)* is the output of the system.

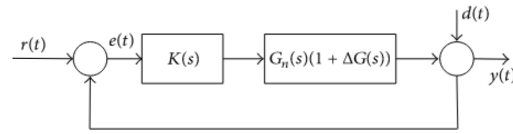

Figure 3. Single-input single-output controlled system with perturbation.

The perturbed system is expressed by

$$\tilde{G}(s)=G_n(s)(1+\Delta(s)) \quad (3)$$

Thus, the multiplicative system perturbation is determined from

$$\Delta(s)=\left(\frac{\tilde{G}(s)}{G_n(s)}-1\right) \quad (4)$$

Nominal transfer function of the hydraulic servo system is shown in (1). Refers to (2) the equation can be re-written as:

$$G(s)=\frac{0.878\omega_n^2}{s^3+2\delta\omega_n s+\omega_n^2} \quad (5)$$

with $\delta=0.999$ and $\omega_n=102.76$ in the nominal plant. Uncertainties was included as the variation of ω_n and δ. Singular value of the uncertainties is shown in Figure 4.

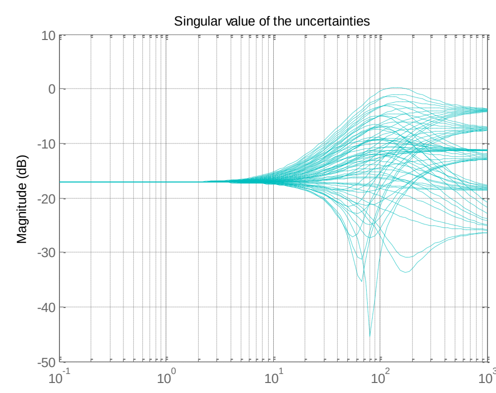

Figure 4. Single value of uncertainties.

Mixed sensitivity H∞ control

If a controller K(s) is achieved so the close loop system is stable, then robust stability performance will follow inequality:

$$J_{\infty,b} = \left\| W_T(s) T(s) \right\|_{\infty} < 1 \qquad (6)$$

and the robust stability against system perturbation will follow inequality:

$$J_{\infty,a} = \left\| W_s(s) S(s) \right\|_{\infty} < 1 \qquad (7)$$

where *S(s)* and *T(s)* are the sensitivity and complementary sensitivity function respectively. *Ws* is the sensitivity weight that attenuate the external disturbance and W_T is the complementary sensitivity that upper bound the multiplicative perturbation. The control block diagram is shown in figure 5.

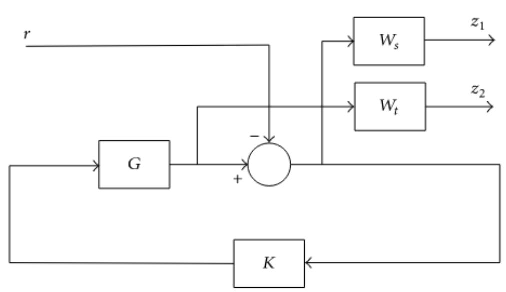

Figure 5. Mixed sensitivity control block diagram.

Following Skogestad's method [9], the sensitivity weight is:

$$W_s(s) = \frac{0.5s + 1}{s + 0.001} \qquad (8)$$

Weight to the bounded uncertainties was set with the help of Matlab software. It was designed so that the weight upper bound the uncertainties in all frequency ranges. The complementary sensitivity is set as:

$$W_t = \frac{1.148s^2 + 78.84s + 858.8}{s^2 + 118.4s + 5378} \qquad (9)$$

Figure to the uncertainties with the weight is shown in Figure 6.

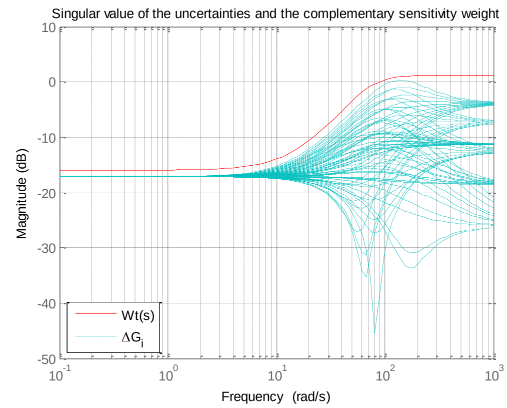

Figure 6. Singular value of the uncertainties and the complementary sensitivity weight.

Differential Evolution Optimization

When we have the nominal plant transfer function, sensitivity function, complementary sensitivity function, and the structure of the controller, the parameters of the controller can be achieved using Differential Evolution (DE). DE is a new heuristic approach to minimize nonlinear and non-differentiable functions [10]. DE search in parallel and begin with a random population. Through mutation, recombination, and selection it will retain good individuals and reject bad individuals [11].

Parameters of DE are set as follows: number of population = 50, differential weight = 0.8, and crossover probability = 0.7. Figure 7 to Figure 9 show the searching of controller parameter during the evaluation process.

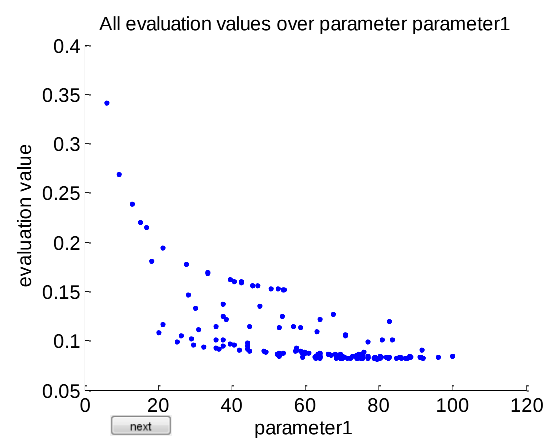

Figure 7. Evolution of parameter 1.

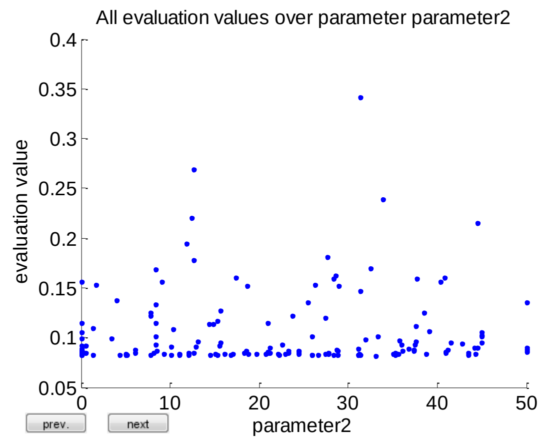

Figure 8. Evolution of parameter 2.

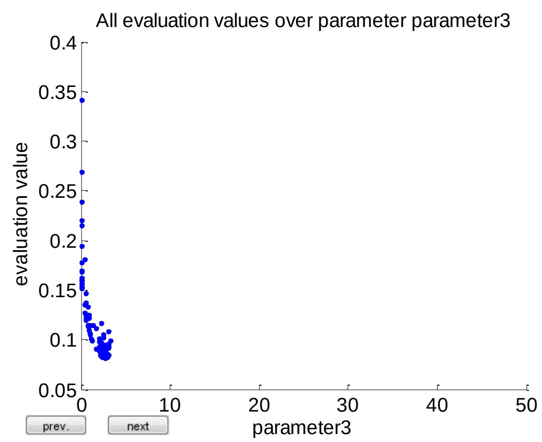

Figure 9. Evolution of parameter 3.

Structure specified mixed sensitivity H∞ controller which the parameters derived using DE [12] is:

$$K(s) = 79.4786 + \frac{33.0537}{s} + 2.6622s \qquad (9)$$

Hardware System Architecture

The HSS must follow the control theory guidelines, Which is the main purpose to improve the velocity of piston in HSS. The hardware system of HSS is divided into two parts, which are explained below.

Hardware Design

Firstly, which construct the mechanical model of an electro-hydraulic system. The simulated response of the model provides insight into the behavior of electrohydraulic system.

As shown in Fig 10, (1) is the linear potentiometer; (2) is double cylinder; (3) is servo valve; (4) pressure relief valve represent fluid flows in out of the valve; (5) pressure unit is the input and output line pressures and (6) is the microcontroller to control system.

The HSS consists of a hydraulic pump, servo valve, actuator, transducer, power supply, and microcontroller. Hydraulic system model is shown in Fig.11.

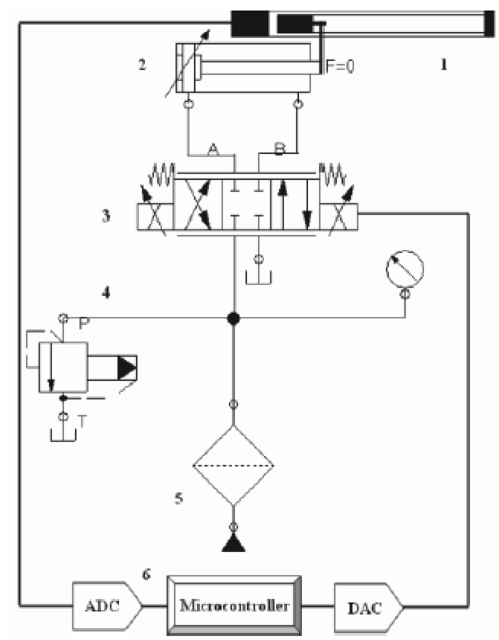

Figure 10. schematic diagram of the electro-hydraulic position control system.

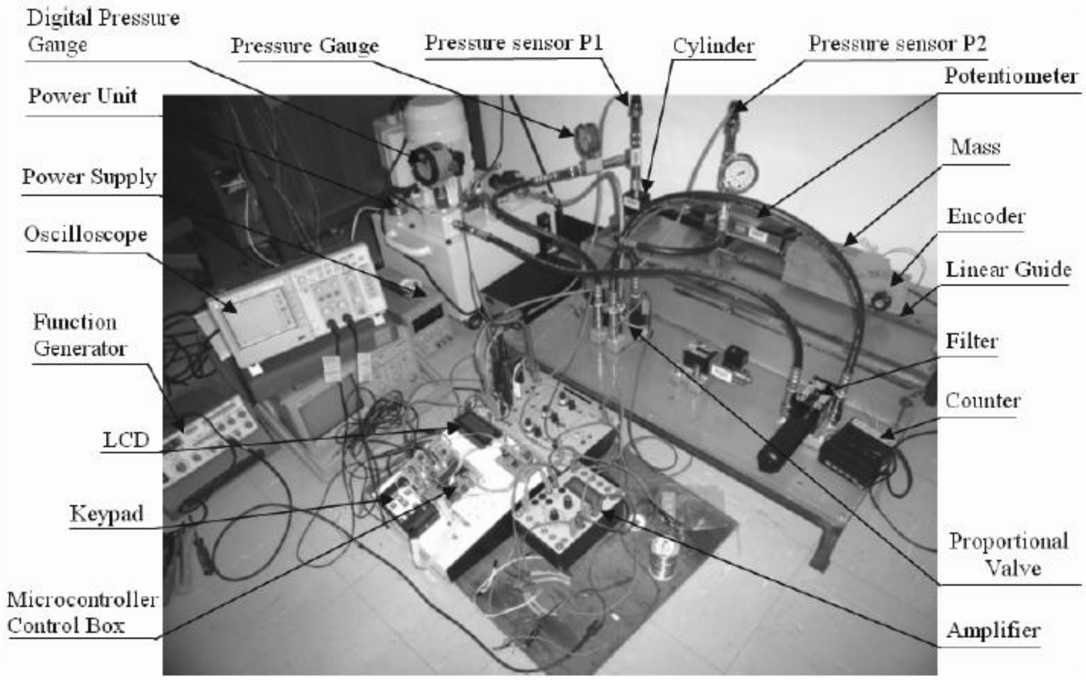

Figure 11. Electro-hydraulic servo system model.

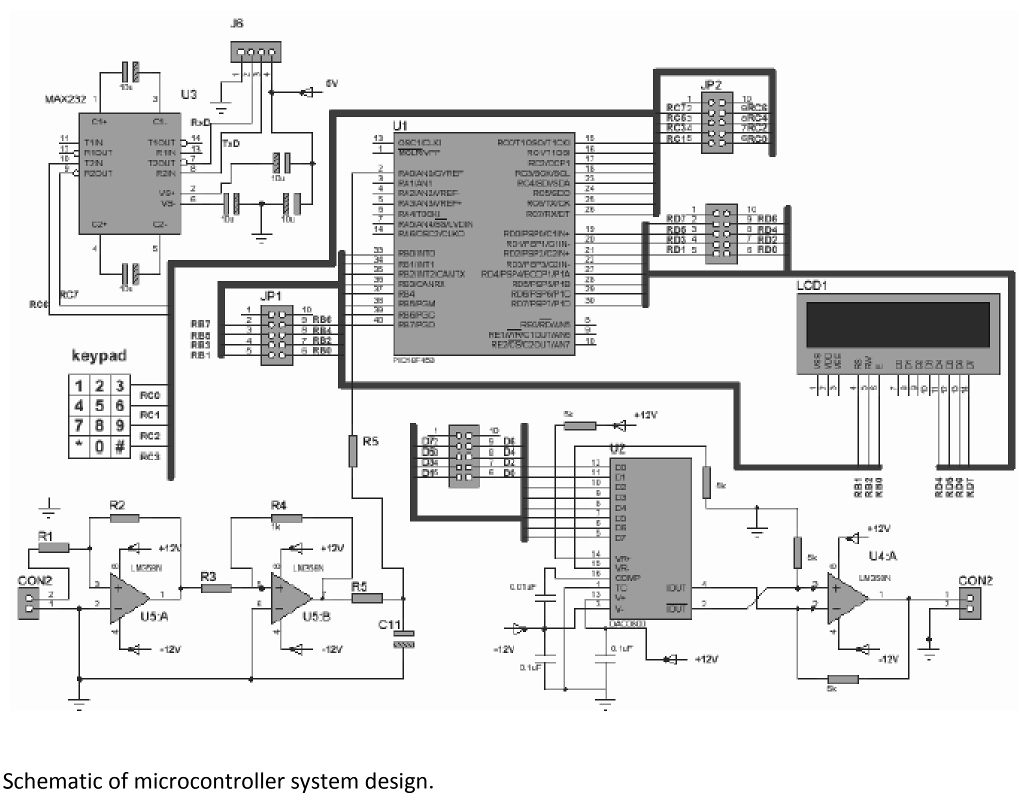

Figure 12. Schematic of microcontroller system design.

A microcontroller based control system has been developed and used to control the hydraulic servo system. We used microcontroller PIC 18F458 to control the hydraulic servo system, in conjunction with the data acquisition processor. The schematic of microcontroller system design is shown in Fig. 12. The mass flow rate across the five-port valve is controlled by manipulating the spool offset, by controlling the current supplied to the solenoid.

Simulation Result

Figure 13 shows the simulation result of the proposed controller under uncertainties. With the nominal plant without uncertainty, the system response has oscillation but no overshoot. Settling times in nominal mode is small, almost 0.1 second. However, under uncertainties, some responses in some conditions have overshoot although still less than 20%. Settling times around 0.05 to 0.1 for any possibility among the uncertainties is considerably small.

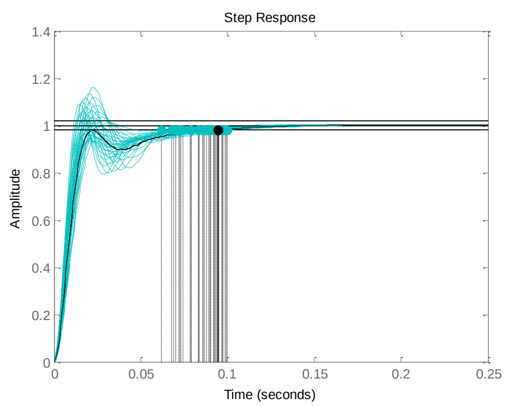

Figure 13. System responses under uncertainties using structure specified controller.

To check whether the resulted controller is satisfies the requirement or not is by plot the sensitivity, complementary sensitivity, and inverse of their weights. Figure 14 shows that the sensitivity and the complementary sensitivity singular plot are less than the inverse of their weights.

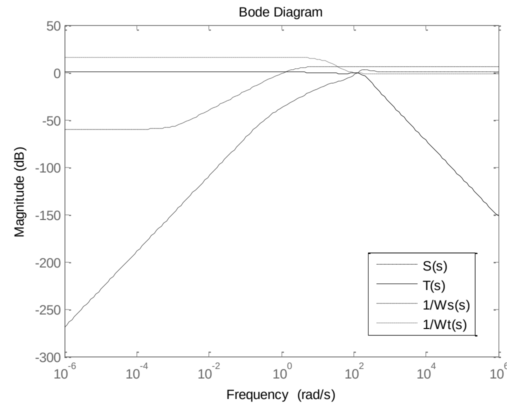

Figure 14. Sensitivity, Complementary Sensitivity, and inverse of their weights using structure specified controller.

Full Order H∞ Robust Controller

Matlab, using its robust control toolbox actually provides method to synthesis a mixed sensitivity robust controller. To validate the proposed controller, a high order mixed sensitivity H∞ robust controller is derived. The resulted controller is (10).

The controller is simulated using the same plant and the same range of uncertainties. Figure 14 shows system responses of the system under uncertainties. Under uncertainties all system responses are stable and there are no overshoot and oscillation. However, settling times of all the responses is considerably long.

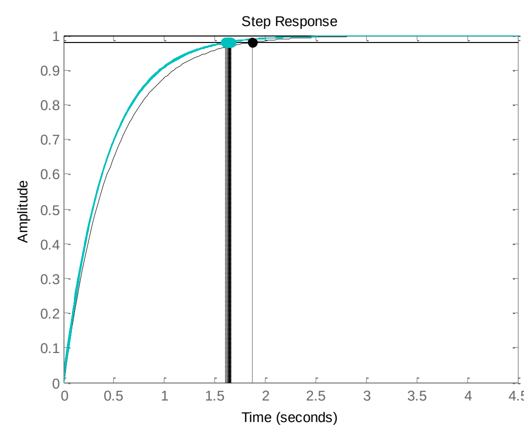

Figure 14. System responses under uncertainties using high order controller.

$$K(s) = \frac{3.431e07s^5 + 1.111e10s^4 + 1.382e12s^3 + 8.081e13s^2 + 1.948e15s + 3.742e06}{s^6 + 1.071e04s^5 + 5.278e07s^4 + 1.469e11s^3 + 1.771e13s^2 + 8.118e14s + 8.118e11} \quad (10)$$

The singular value plot of the sensitivity, complimentary sensitivity, and their weight shows that all the requirements are fulfilled already. Figure 15 shows that the singular plot of the sensitivity, complementary sensitivity, and its weights satisfy the requirements.

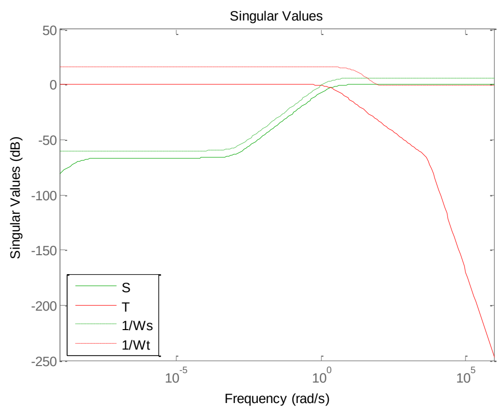

Figure 15. Sensitivity, Complementary Sensitivity, and inverse of their weights using high order controller.

Simulation Result

Structure specified mixed sensitivity H∞ robust controller were successfully derived. System responses under uncertainties show that the proposed controller successfully worked. The controller has much simpler structure than the conventional H∞ robust controller. However, it has overshoot and oscillation in some condition but much smaller settling time. Maximum overshoot was 18%, the higher overshoot the smaller is the settling time. Overshoot did not occur in all condition of uncertainty. Settling times varies between 0.05 to 0.1 second. The conventional high order controller gave better response in term of overshoot and oscillation. However, the smallest settling time was 1.65 second, and the maximum settling time is almost 2 second which is much bigger than the proposed controller settling times. Overall, it can be concluded that the structure specified mixed sensitivity H∞ robust controller has satisfactory performance. Moreover, its structure in the form of PID controller gives much benefit due to its popularity in industries. The structure also makes it possible to be programmed into a small microcontroller. Even though, it still provide robust performance that a robust controller usually provides.

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