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Robustness of the Feedback PD Compensator used with Second-Order and Third-Order Processes

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Abstract
Robustness is one of the requirements used in controllers and compensators design. The designs presented in the previous papers did not consider the robustness of the controller or compensator. Therefore, the objective of this paper is to investigate the robustness of the feedback compensator used to control second-order and third-order processes against uncertainty in the process parameters. A variation of ± 20 % in process parameters is considered through simulation to study its effect on the system performance parameters using the tuned compensators. With a feedback PD compensator controlling an underdamped second order process, the variation in process natural frequency and damping ratio has small effect on the maximum percentage overshoot , settling time and the phase margin of the control system. The phase margin is above 103 degrees for all the changes in the process parameters providing robust compensator characteristics. With feedback PD compensator controlling a third-order process of bad characteristics, the variation in the process four parameters is investigated. The variation of the process numerator parameter has neglected effect on the performance functions of the control system. The variation of the process denominator parameters has remarkable effect of the performance functions as large as 282 %. However, for all the changes in the process parameters the phase margin of the control system is 51 degrees which is acceptable. This indicates the robustness of the used feedback PD compensator when used with the difficult third-order process.

Keywords
Second-order and third-order processes – feedback PD compensator – Robustness of feedback compensators - Compensator with notch filter plus gain – control system performance.

I. Introduction

Processes are subject to uncertainty in their parameters during operation. Therefore, it is worth to investigate the effectiveness of the used controllers or compensators with such certainty.

Hu, Chang, Yeh and Kwatny (2000) used the H∞ approximate I/O linearization formulation and µ-synthesis to design a nonlinear controller for an aircraft longitudinal flight control problem and address tracking, regulation and robustness issues [1]. Gong and Yao (2001) generalized a neural network adaptive robust control design to synthesize performance oriented control laws for a class of nonlinear systems in semi-strict feedback forms through the incorporation of backstepping design techniques [2]. Lee and Na (2002) designed a robust controller for a nuclear power control system. They used the Kharitonov and edge theorem in the determination of the controller which was simpler than that obtained by the H∞ [3]. Arvanitis, Syrkos, Stellas and Sigrimis (2003) analyzed PDF controllers designed and tuned to control integrator plus dead time processes in terms of robustness. They performed the robustness analysis in terms of structured parametric uncertainty description [4]. Lhommeau, Hardouin, Cottenceau and Laulin (2004) discussed the existence and the computation of a robust controller set for uncertain systems described by parametric models with unknown parameters assumed to vary between known bounds [5]. Dechanupaprittha, Hongesombut, Watanabe, Mitani and Ngammroo (2005) proposed the design of robust superconducting magnetic energy storage controller in a multimachine power system by using hybrid tabu search and evolutionary programming. The objective function of the optimization problem considered the disturbance attenuation performance and robust stability index [6].

Chin, Lau, Low and Seet (2006) proposed a robust PID controller based on actuated dynamics and an unactuated dynamics shown to be global …….. bounded by the Sordalen lemma giving the necessary sufficient condition to guarantee the global asymptotic stability of the URV system [7]. Vagja and Tzes (2007) designed a robust PID controller coupled into a Feedforward compensator for set point regulation of an electrostatic micromechanical actuator. They tuned the PID controller using the LMI-approach for robustness against the switching nature of the linearized system dynamics [8]. Fiorentini and Bolender (2008) described the design of a nonlinear robust/adaptive controller for an air-breathing hypersonic vehicle model. They adapted a nonlinear sequential loop-closure approach to design a dynamic state-feedback control for stable tracking of velocity and altitude reference trajectories [9]. Labibi, Marquez and Chen (2009) presented a scheme to design decentralized robust PI controllers for uncertain LTI multi-variable systems. They obtained sufficient conditions for closed-loop stability of multi-variable systems and robust performance of the overall system [10]. Matusu, Vanekova, Porkop and Bakosova (2010) presented a possible approach to design simple PI robust controllers and demonstrate their applicability during control of a laboratory model with uncertain parameters through PLC [11].

Kada and Ghazzawi (2011) described the structures and design of a robust PID controller for higher order systems. They presented a design scheme combining deadbeat response, robust control and model reduction techniques to enhance the performance and robustness of the PID controller [12]. Surjan (2012) applied the genetic algorithm for the design of the structure specified optimal robust controllers. The parameters of the chosen controller were obtained by solving the nonlinear constrained optimization problem using IAE, ISE, ITAE and ITSE performance indices. He used constraints on the frequency domain performances with robust stability and disturbance rejection [13]. Jiao, Jin and Wang (2013) analysed the robustness of a double PID controller for a missile system by changing the aerodynamic coefficients. They viewed the dynamic characteristics as a two-loop system and designed an adaptive PID control strategy for the pitch channel linear model of supersonic missile [14]. Pradham, Ray, Sahu and Moharana (2014) proposed a control strategy to improve the power factor and voltage regulation at disturbance supply system for more robustness [15]. Hao and Yang (2014) studied a robust adaptive fault-tolerant compensation control problem using sliding-mode output feedback for uncertain linear systems with actuator faults [16].

II. Feedback PD Compensator Tuning

The feedback PD compensator was suggested by the author to control underdamped second-order processes [17]. Consider a second-order-like process having:

- Natural frequency: 5 rad/s.
- Damping ratio: 0.2

The tuned compensator parameters are [17]:

- Proportional gain: $K_{pc} = 0.005025$
- Derivative gain: $K_d = 0.285020$

The control system performace measures are:

$OS_{max} = 0.1001$ %
$T_s = 0.8152$ s
GM = ∞ dB
PM = 107 degrees

Process Uncertainty

Due to the change in the operating conditions during operation, the process is subjected to parametric changes. It is assumed that this change can be as large as ± 20 % of the assigned process parameters.

Compensator Robustness

The control system is robust when it has acceptable changes in its performance due to model changes or inaccuracy [18]. On the other hand Lee and Na added the stability requirement to the robustness definition besides the plants having uncertainty [3]. Toscano added that the controller has to be able to stabilize the control system for all the operating conditions [19].
In this work, the robustness of the controller and hence of the whole control system is assessed as follows:

- A nominal process parameters are identified.
- The compensator is tuned for those process parameters.
- A variation of the process parameters is assumed within a certain range.
- Using the same compensator parameters, the step response of the system using the new process parameters is drawn and the control system performance is evaluated through the maximum percentage overshoot and settling time.
- The frequency based relative stability parameters are also evaluated using the open-loop transfer function of the control system.
- The variation in process parameters is increased and the procedure is repeated.

Application of the above procedure results in the fact that with the feedforward Notch compensator almost all the performance parameters change with changing the process natural frequency.

- The control system is stable for all the changes in the process parameters.
- The settling time increases by 7 %.
- The maximum percentage overshoot increases from 0.1 to 2.3 %.
- The phase margin decreases by 3.7 %.
- In general, the phase margin with all the changes in the process parameters is greater than 103 degrees.
- Fig.1 shows the variation of the settling time against the variation in the process parameters.

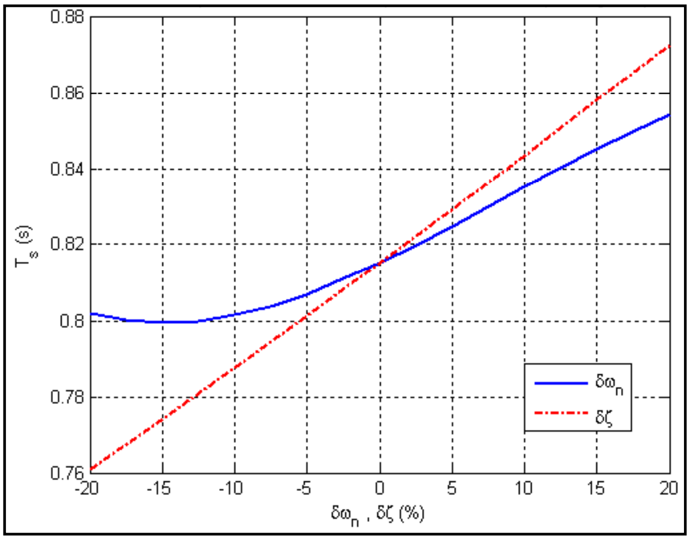

Fig.1: Effect of process parameters change onsystem settling time (Feedback PD compensator for a second order process).

- Fig.2 shows the variation of the maximum percentage overshoot against the variation in the process parameters.

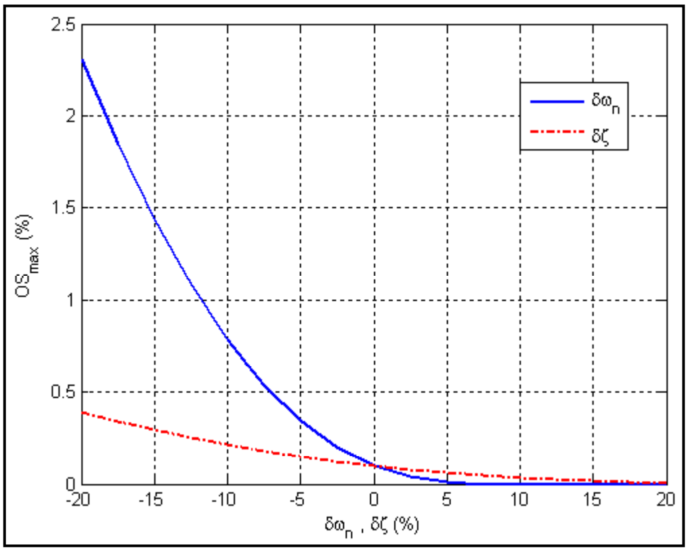

Fig. 2: Effect of process parameters change on system maximum overshoot (Feedback PD compensator for a second order process).

- Fig.3 shows the variation of the phase margin against the variation in the process parameters.

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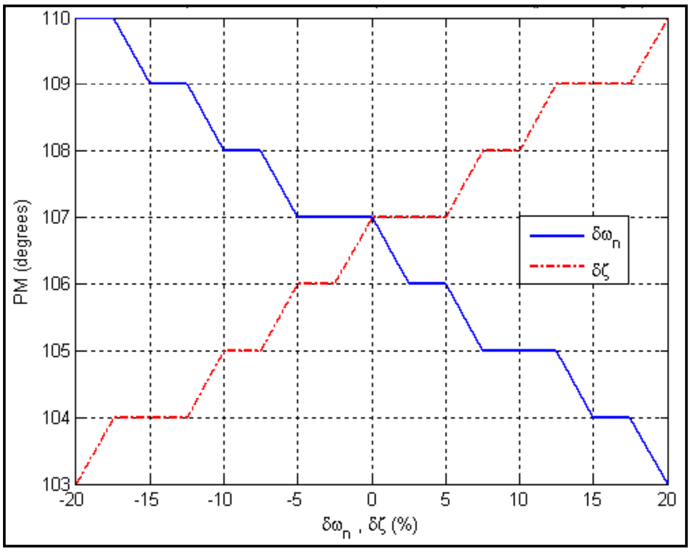

Fig.3: Effect of process parameters change on system phase margin (Feedback PD compensator for a second order process).

III. Feedback Compensator For A Third-Order Process

Hassaan used a feedback PD compensator to control a highly oscillating third-order process with large settling time [20].

The compensator parameters and the system performace measures are:

K_{pc} =	0.022738	
K_d =	2.671408	
Maximum percentage overshoot:	4.9983	%
Settling time:	6.2671	s
Gain margin:	∞	dB
Phase margin:	63.6	degrees

The robustrness investigation procedure is applied on the resulting control system for process variation in the range ± 20 % from the nominal values. The results are as follows:

- The change in numerator parameter (one parameter) of the process transfer function does not affect the settling time , maximum percentage overshoot of the control system and decreased the phase margin by 3.6 %.
- The change in the first parameter of the process denominator increased the settling time and maximum percentage overshoot by 88.1 % and 59.1 % respectively. This change decreased the phase margin by 19.3 %.
- The change in the second parameter of the process denominator increased the settling time and maximum percentage overshoot by 82.2 % and 282.5 % respectively. This change decreased the phase margin by 5.5 %.
- The change in the third parameter of the process denominator increased the settling time and maximum percentage overshoot by 56.3 % and 138.2 % respectively. This change decreased the phase margin by 6.3 %.
- Fig.4 shows the effect of the transfer function numerator parameter change on the system settling time.

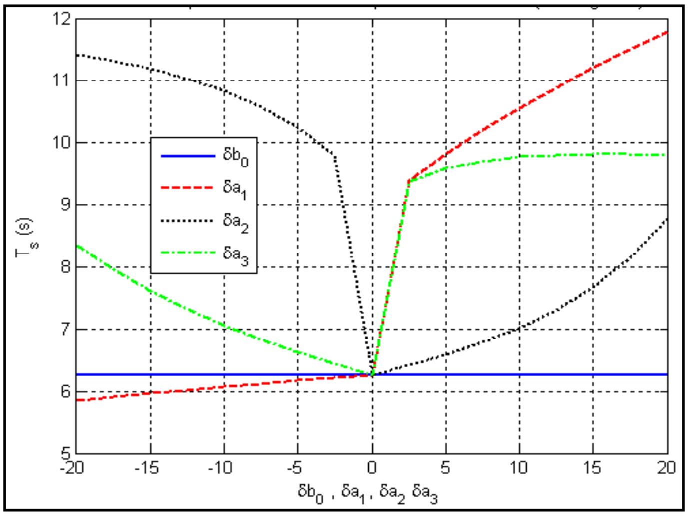

Fig. 4: Effect of process parameters change on system settling time (Feedback PD compensator for a third order process).

- Fig.5 shows the variation of the maximum percentage overshoot against the variation in the process parameters.

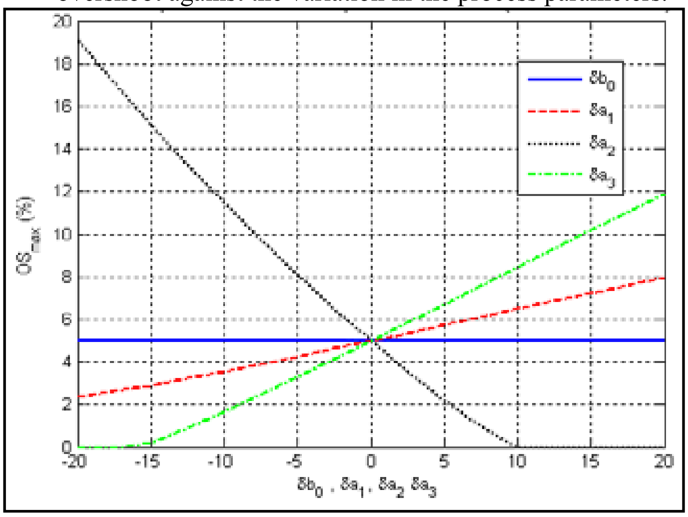

Fig. 5: Effect of process parameters change on system maximum overshoot (Feedback PD compensator for a third order process).

- Fig.6 shows the variation of the phase margin against the variation in the process parameters.

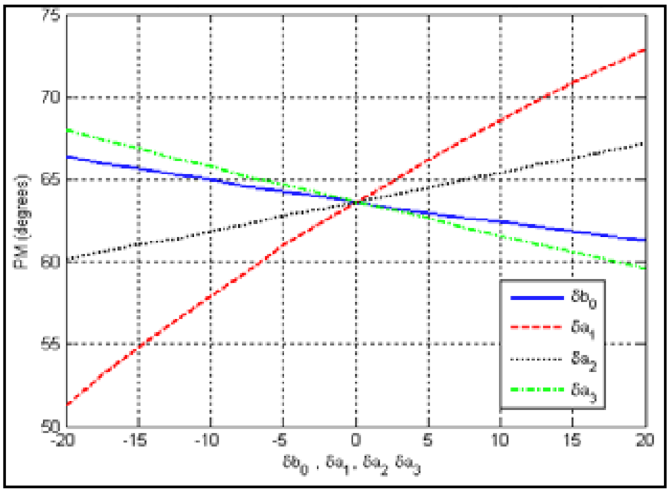

Fig.6 : Effect of process parameters change on system phase margin (Feedback PD compensator for a third order process).

IV. Conclusions

- Variation in second-order process parameters within ± 20 % was considered.
- The judgment on the robustness condition of a controller is based on an accepted range of both gain margin and phase margin of the closed-loop control system.
- According to Ogata [21], a recommended range is: GM ≥ 6 dB and 30 ≤ PM ≤ 60 degrees.
- According to Lei and Man [22], the phase margin range can be widened to be:
  30 ≤ PM ≤ 90 degrees.
- Tuned feedback PD compensator used to control an oscillating second-order and third-order processes is robust for all the changes in the process parameters.
- The settling time is more sensitive to the changes in process damping ratio of the second-order process.
- The maximum percentage overshoot is more sensitive to the changes in process natural frequency of the second-order process.
- The phase margin is sensitive to the changes in both parameters of the second-order process.
- The settling time is more sensitive to the changes in parameters of the of the denominator of the third-order process.
- The maximum percentage overshoot and phase margin are more sensitive to the changes in second parameter of the denominator of the third-order process.

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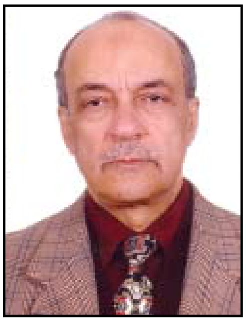

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