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Robust Controller Design for Boiler Burning Process Using RBode Plot

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ABSTRACT: This paper presents a robust controller design for boiler burning process using Robust Bode (RBode) plot. The boiler plant is modeled as a first-order dynamic lag with time-delay. The designed controller is compared with a traditional Cohen-Coon controller. The significance of using RBode plot method in case of time-delay systems is twofold: (i) RBode method has not been applied on time-delay systems previously. Through this paper, applicability of RBode technique with time-delay systems is established, which, in turn, widens the scope of application of this technique. (ii) Successful implementation of RBode method on time-delay systems indicates its potential in case of higher order systems (as many practical higher order systems may be approximated as a lower order system with time delay).

Keywords—Controller design; robust control; structured uncertainty; time delay.

I. INTRODUCTION

Based on robust performance criterion, Robust Bode (RBode) plot method creates allowable and forbidden regions on the open-loop Bode plot of the compensated SISO (Single-Input-Single-Output) system. The design objective is to shape the open-loop response to avoid entering the forbidden regions defined by the boundary functions on magnitude and phase subplots [1].

Other automated methods (for example, H-infinity and μ-synthesis) exist for designing controllers to achieve robust performance in the presence of plant uncertainties. These tools require that the performance specifications and uncertainties be described by transfer functions, which are often hard to construct and may result in conservative designs.

RBode plot method (in its modified form) is of current interest [1-3]. RBode plot method had been previously applied to systems such as a head- positioning control system in a hard disk drive [2], and a dynamic non-linear butterfly valve system [3].

All those systems have somewhat small time constants with little or no time-delay. On the other hand, industrial chemical processes are generally slow and often have large time-delays, which deteriorate control quality. We consider the typical case of industrial boiler control, where the control objective is to ensure constant steam pressure by regulating the amount of fuel and air in the burning system.

Large values of time constant and time-delay lead to several control problems – such as increased maximum error of controlled variable, decreased dynamic quality of the control system and decreased stability of the closed-loop system. All of these call for a robust control strategy.

II. SYSTEM MODEL

The boiler burning process was approximately modeled as a first-order dynamic lag with time-delay. The nominal transfer function was taken as:

$$P(s) = \frac{3e^{-700s}}{1+1200s}$$

i.e. T=700 s and τ=1200 s.

For conducting the simulations and necessary calculations, Padé approximation was applied on the nominal transfer function, resulting in:

$$P(s) = \frac{3(1-350s)}{(1+1200s)(1+350s)} = \frac{-1050s+3}{420000s^2+1550s+1}$$

The Bode plot (magnitude and phase) of the nominal plant model is shown in Fig. 1.

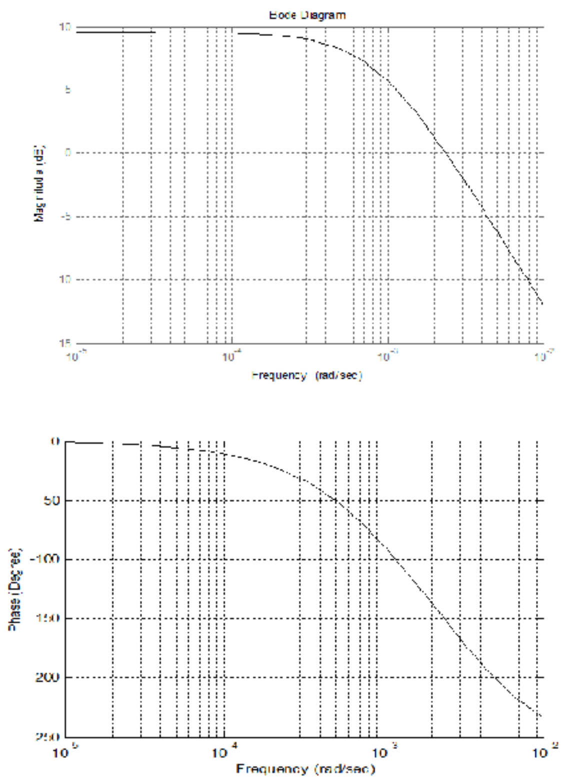

Fig. 1. Bode plot (magnitude and phase) of the nominal plant model.

III. STRUCTURED UNCERTAINTY

To simulate structured uncertainty, ±10% variations in T and τ were considered.

i.e. $630\ s \leq T \leq 770\ s$ and $1080\ s \leq \tau \leq 1320\ s$

IV. INITIAL CONTROLLER DESIGN

The initial PI controller was designed using Zeigler-Nichols tuning method.

Controller transfer function:

$$C_{ZN}(s) = 0.386\left(1 + \frac{1}{2333.333s}\right) = \frac{900.666s + 0.386}{2333.333s}$$

All the simulations and calculations were carried out considering the frequency range in-between 10^{-5} & 10^{-2} rad/s. This range covers the corner frequencies of the nominal plant transfer function and the initial controller transfer function. 500 logarithmically spaced points within this range was considered for the MatLab simulations and plots.

V. DETERMINATION OF WEIGHTING FUNCTIONS

The weighting functions $W_s(\omega)$ and $W_u(\omega)$ were determined using the relations

$$\left|\frac{1}{1+\widetilde{P}(j\omega)C(j\omega)}\right| < |W_s(\omega)|^{-1} \text{ and}$$

$$\left|\frac{\widetilde{P}(j\omega)}{P(j\omega)} - 1\right| \leq |W_u(\omega)| \quad \text{, for all } \omega,$$

where $\widetilde{P}(j\omega)$ is the plant transfer function including the structured uncertainties.

In accordance with the above conditions, the weighting functions were selected as:

$|W_u|=0.1739$ and $|W_s|=0.0001$.

VI. RBODE PLOT

The RBode magnitude boundary functions were calculated. For most part of the frequency range under consideration, the upper and lower magnitude boundaries were found out to be infinity & zero respectively.

Approximately between $2.75\text{x}10^{-3}$ & $3.79\text{x}10^{-3}$ rad/s frequencies, the upper and lower magnitude boundary functions define a semi-circular forbidden region. The |L| curve did not enter the forbidden region in that frequency range (where L is the open-loop transfer function i.e. cascaded system of controller and plant transfer function). Even when the extremities of the structured uncertainties were considered, the forbidden region remained untouched.

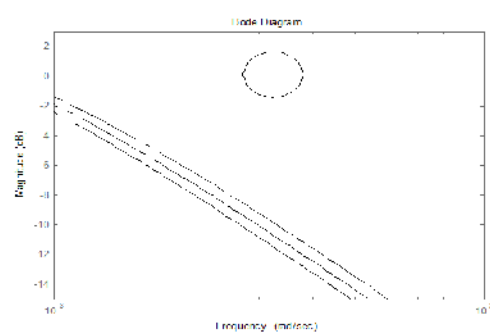

Fig. 2. RBode magnitude plot - the circular forbidden region is successfully avoided.

The phase boundary conditions were met by satisfying the Inequality relation:

$$\left(\frac{|W_s|^2 - 1 + 2|W_s W_u||L| + \left(|W_u|^2 - 1\right)|L|^2}{2|L|}\right) < -1$$

(Inequality no. 1)

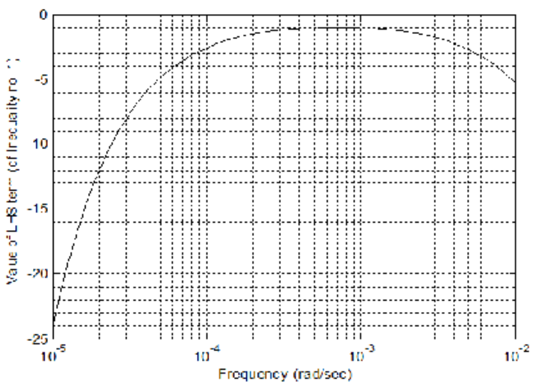

Fig. 3. Value of LHS term (of Inequality no. 1) over varying frequency.

Fig. 3 shows that the value of the LHS term (of Inequality no. 1) is less than minus one for all frequencies under consideration.

Thus the RBode Plot conditions were satisfied and hence no further tweaking of the controller was required.

The Bode plot (magnitude and phase) of the compensated system is shown in Fig. 4.

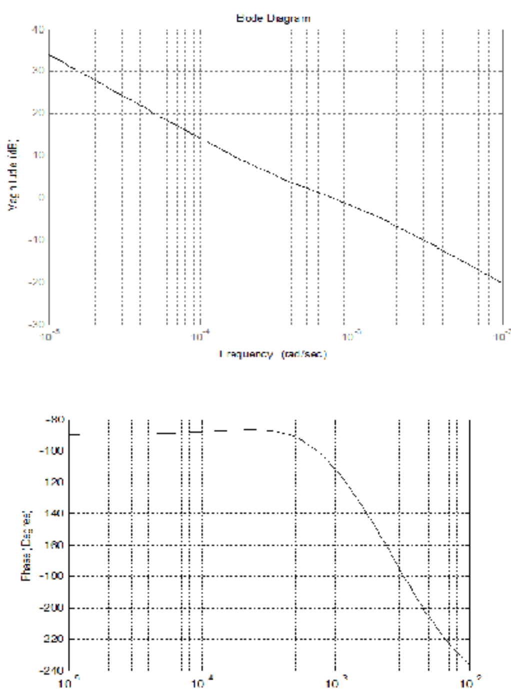

Fig. 4. Bode plot (magnitude and phase) of the compensated system.

VII. TIME DOMAIN ANALYSIS & COMPARISON WITH OTHER EXISTING METHOD

Time-domain analysis of the closed loop system was carried out to confirm closed-loop stability and robustness. The unit step responses of the systems (the nominal system and the extreme variations of structured uncertainties) are shown (in solid lines) in Fig. 5.

For comparative study, another controller was designed by traditional Cohen-Coon tuning. The transfer function of the Cohen-Coon controller:

$$C_{CC}(s) = \frac{436.860s + 0.406}{1076.011s}$$

The unit step responses of the systems (the nominal system and the extreme variations of structured uncertainties) with the Cohen-Coon controller are also shown (in dotted lines) in the same graph (Fig.5).

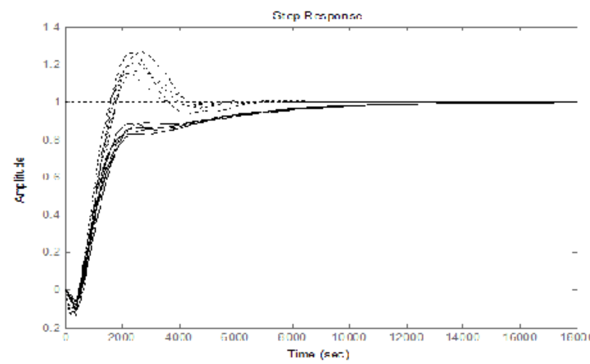

Fig. 5. Unit step response of the closed-loop system (with RBode designed controller) compared with that of closed loop system with Cohen-Coon controller.

It can be seen that closed-loop stability is achieved, and the time-responses show no overshoot which can be very important for industrial chemical processes. A small negative excursion at the beginning is also present.

Comparing with Cohen-Coon controller, it can be seen that the main advantage is the absence of overshoots.

VIII. CONCLUSION

We have considered a first-order dynamic lag with large time-delay as the nominal plant model of a boiler burning system, and a controller was designed according to the principles of Robust Bode (RBode) plot method. Simulations were done to ensure stability and robustness of the compensated system by considering structured uncertainties. A comparative study was also done between the RBode-designed controller and traditional Cohen-Coon controller.

Further work considering unstructured uncertainties is ongoing and hence not included in this paper. Through our work, applicability of RBode technique with time-delay systems – an application area previously unexplored – has been established, which, in turn, has widened the scope of application of this technique. As most industrial processes are time-delay systems, the success of this approach can have a considerable impact. It also indicates RBode method's potential in case of higher order systems (as many practical higher order systems may be approximated as a lower order system with time delay).

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