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LQG/LTR ROBUST CONTROL SYSTEM DESIGN FOR A LOW-PRESSURE FEEDWATER HEATER TRAIN

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Abstract

This paper uses the linear quadratic Gaussian with loop transfer recovery (LQG/LTR) control system design method to obtain a level control system for a low-pressure feedwater heater train. The control system performance and stability robustness are evaluated for a given set of system design specifications. The tools for analysis are the return ratio, return difference, and inverse return difference singular-value plots for a loop break at the plant output.

Introduction

The nuclear industry, with the support of the Department of Energy, is presently investigating modern control methods to replace the classical Proportional-Integral (PI) technique now widely in use. A subsystem of the nuclear power plant, the feedwater plant, has received considerable attention. The reason for this attention is that the feedwater plant has been responsible for three shutdowns per year for a BWR (boiling-water reactor).

To improve control the LQG/LTR[1] linear control design method is used to obtain a level control system for the low-pressure feedwater heater train of a nuclear plant. A control system design for robustness at the plant output is developed using the LQG/LTR procedure.

The singular-value plots of the return ratio, return difference, and inverse return difference for a loop break at the plant output are examined.

The Linearized Model

The nonlinear mathematical model of the low-pressure feedwater heater train shown in Fig. 1 is obtained using the Modular Modeling System (MMS).† The nonlinear plant is linearized about a nominal operating point resulting in a state differential equation of the form

$$\dot{x}(t) = Ax(t) + Bu(t) \ ,$$
$$y(t) = Cx(t) \ , \qquad (1)$$

where A, B, and C are the system matrices. The linearized model consists of 24 state variables, 4 inputs, and 4 outputs, which are defined in Table 1. The poles and zeros of the linearized plant are shown in Table 2.

The poles of this plant are all stable [no right half-plane (rhp) poles]. Also there should be no inherent problems in the control system design since there are no rhp zeros. The absence of rhp zeros is assurance that complete LTR is achievable provided the plant is at least stabilizable and detectable.[2]

LQG/LTR Controller Design

The poles and zeros of a plant are useful tools in assessing the general difficulty in obtaining a control system design. However, much more insight into how close a nominal plant comes to meeting certain frequency-domain design specifications is better evaluated using the singular-value plots.[2] The singular-value plot (SVP) of the return ratio for the nominal plant is shown in Fig. 2. This SVP shows that the plant exhibits an integral type of action deviating from the actual integral SVP by scaler magnitudes. Thus, it appears that by taking advantage of the inherent integral action of the plant caused by the poles' closeness to the origin of the s-plane, the effort required to obtain the desired loop shape can be minimized.

The unity feedback LQG/LTR control system design structure is shown in Fig. 3. The first step in designing an LQG/LTR controller for the feedwater plant requires the selection of the Kalman Bucy Filter (KBF) to obtain the appropriate performance and stability robustness criteria at the plant output. The loop transfer function at the output of the KBF (point 4 of Fig. 3) is described as

$$G_4(s) = C(sI - A)^{-1}F \tag{2}$$

where F is the filter gain necessary to obtain the frequency-domain loop shape to achieve the design specifications. Good command following and disturbance rejection[2] for this design requires that

$$\sigma_{\min}[G_4(s)] \geq 20\ dB \quad \forall \omega \leq 0.01\ rad/s \ . \tag{3}$$

Robustness for this system requires that

$$\sigma_{\min}[I + [G_4(s)]^{-1}] \geq \| \Delta G \| = 5\ dB \quad \forall \omega 1.0 \geq\ rad/s \ . \tag{4}$$

The second step of the LQG/LTR design procedure is to select the appropriate regulator gain (K) to recover the loop transfer function $G_4(s)$ of point 4 at the output node y (point 3 of Fig. 3). This is called the loop transfer recover (LTR) step.

The tools that assist in this control system design and analysis are CASCADE[3] (computer-aided system and control analysis and design environment) and Pro-Matlab.[4]

Control System Analysis

The LQG/LTR control system singular-value plots of the return ratio, return difference, and inverse return difference are shown in Figs. 4, 5, and 6 respectively. In examining the return ratio SVP of the LQG/LTR control system, the low-frequency system design specifications are seen to be met. Thus, good disturbance rejection and low sensitivity to parameter variations exist for this control system.

Good command following of zero steady-state error is typically associated with a robust system. This is true only if the original plant has poles at the s-plane origin or if the plant is augmented at the plant input (when robustness is desired at output) to add pure integrals. As previously mentioned, it was decided to make use of the plant's four existing poles that are close to the s-plane origin. Since these poles do not contribute true integral action, some steady-state error should be expected in the output transient response as shown in Fig. 7. The error occurs for plant output tank level two. The relative error amount for this transient response is 4%. The output response shown in Fig. 7 is obtained using the linearized plant.

The LQG/LTR control system meets the desired high-frequency requirements for stability robustness to model uncertainties.

Conclusion

It can be seen that the LQG/LTR control system design procedure allows the synthesis of a low-pressure feedwater heater train level control system that meets certain frequency-domain design specifications. In this case, by only using the inherent integral type of action that deviated slightly from ideal integral action, plant integral augmentation is avoided. Using these plant dynamics results in command following of one feedwater tank level with a slight steady-state error, which is expected since pure integrals did not exist in the plant.

The design of this robust control system shows that a desirable low-pressure feedwater heater train level control system is obtainable using the LQG/LTR procedure. Although the inherent plant dynamics can be used to avoid integral augmentation, the pitfall of expecting these exact plant characteristics to exist in the plant is unrealistic in an actual application. Thus to ensure an exact steady-state error of zero, the plant should be augmented with integrators.

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References

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3. J. D. Birdwell et al., *The CASCADE Final Report: Volume II—CASCADE Tools and Knowledge Base*, Electrical Engineering Department, The University of Tennessee, Knoxville, Feb. 19, 1988.

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†Modular Modeling System (MMS), © 1983 Electric Power Research Institute, Inc., Palo Alto, Calif.

‡Pro-Matlab™, Version 3.27a, © 1988 by The Mathworks Inc., Sherborn, Mass.

Table 1: Low-pressure feedwater heater state variables, control inputs, and outputs

State variables - x

1. Drain cooler exit enthalpy on shell side for FW heater 1 (BTU/lbm)
2. Drain cooler exit enthalpy on shell side for FW heater 2 (BTU/lbm)
3. Drain cooler exit enthalpy on shell side for FW heater 3 (BTU/lbm)
4. Drain cooler exit enthalpy on shell side for FW heater 4 (BTU/lbm)
5. Inlet pressure on tube side for FW heater 1 (PSIA)
6. Inlet pressure on tube side for FW heater 2 (PSIA)
7. Inlet pressure on tube side for FW heater 3 (PSIA)
8. Inlet pressure on tube side for FW heater 4 (PSIA)
9. Steam pressure on shell side for FW heater 1 (PSIA)
10. Steam pressure on shell side for FW heater 2 (PSIA)
11. Steam pressure on shell side for FW heater 3 (PSIA)
12. Steam pressure on shell side for FW heater 4 (PSIA)
13. Condensing region enthalpy on tube side for FW heater 1 (BTU/lbm)
14. Condensing region enthalpy on tube side for FW heater 2 (BTU/lbm)
15. Condensing region enthalpy on tube side for FW heater 3 (BTU/lbm)
16. Condensing region enthalpy on tube side for FW heater 4 (BTU/lbm)
17. Drain cooler exit enthalpy on tube side for FW heater 1 (BTU/lbm)
18. Drain cooler exit enthalpy on tube side for FW heater 2 (BTU/lbm)
19. Drain cooler exit enthalpy on tube side for FW heater 3 (BTU/lbm)
20. Drain cooler exit enthalpy on tube side for FW heater 4 (BTU/lbm)
21. Condensing region enthalpy on shell side for FW heater 1 (BTU/lbm)
22. Condensing region enthalpy on shell side for FW heater 2 (BTU/lbm)
23. Condensing region enthalpy on shell side for FW heater 3 (BTU/lbm)
24. Condensing region enthalpy on shell side for FW heater 4 (BTU/lbm)

Control inputs- u

1. Drain valve position demand for FW heater 1 (fraction open)
2. Drain valve position demand for FW heater 2 (fraction open)
3. Drain valve position demand for FW heater 3 (fraction open)
4. Drain valve position demand for FW heater 4 (fraction open)

Outputs- y

1. Level for FW heater 1 (inches)
2. Level for FW heater 2 (inches)
3. Level for FW heater 3 (inches)
4. Level for FW heater 4 (inches)

Table 2. Plant poles and zeros

Poles		Zeros	
(1)	−288.305	(1)	−176.505
(2)	−176.505	(2)	−288.305
(3)	−63.226	(3)	−63.226
(4)	−5.829	(4)	−4.896
(5)	−4.963	(5)	−5.829
(6)	−3.969	(6)	−3.945
(7)	−2.231	(7)	−2.269
(8)	−1.219	(8)	−1.218
(9)	−0.912	(9)	−0.906
(10)	−0.609	(10)	−0.596
(11)	−0.589	(11)	−0.610
(12)	−0.243	(12)	−0.243
(13)	−0.198	(13)	−0.200
(14)	−0.148	(14)	−2.933e−02 + j1.582e−03
(15)	−0.128	(15)	−2.933e−02 − j1.582e−03
(16)	−0.112	(16)	−4.612e−02
(17)	−7.293e−02	(17)	−7.039e−02
(18)	−4.983e−02	(18)	−0.101
(19)	−3.065e−02	(19)	−0.130
(20)	−2.438e−02	(20)	−0.148
(21)	−2.017e−03		
(22)	−2.558e−04		
(23)	−5.657e−05		
(24)	−2.726e−0		

- Tank levels 1, 3, and 4
- Tank level 2
-
-

Figure Captions

Fig. 1. Flow diagram of low-pressure feedwater heater train.

Fig. 2. SVP of return ratio.

Fig. 3. Block diagram of unity feedback LQG/LTR control system.

Fig. 4. SVP of return ratio of compensated system.

Fig. 5. SVP of return difference.

Fig. 6. SVP of inverse return difference.

Fig. 7. Closed-loop transient response of feedwater tank levels to a level demand of 2 inches.