Modeling, Simulation, and Control of an Oil Heater

Hongmian Zhuang, Fangzhou Bai, and Jianping Xue

ABSTRACT: This paper discusses the problems of modeling, simulation, and control of an oil heater. The decoupling control system is designed with the help of simulation and is evaluated using the inverse Nyquist array method. Much emphasis is placed on digital and analog computer simulation. The decoupling control system has been implemented with a single-board microcomputer and has worked well for over a year.

Introduction

Accompanied by the rapid development of modern industries, energy consumption and energy costs increase yearly. The drastic increase in energy costs has caused a change in the philosophy of process control system design. How to improve energy savings is a serious problem we now face. The oil heater discussed herein is an example of a petrochemical process that consumes a great deal of energy. The purpose of the design procedure is to obtain a practical energy saving control system for the heater. In the first phase of the design procedure, the mathematical model of the heater is developed. After the mathematical model has been validated, the control system is designed. However, before the control system is installed in the field, it is necessary to simulate the whole system to ensure that the desired criteria have been achieved.

This paper shows how the mathematical model of the oil heater is obtained and how the heater decoupling control system is designed with evaluation using the inverse Nyquist array method put forward by H. H. Rosenbrock [1], [2]. Much emphasis is on digital and analog simulation.

Mathematical Model of the Oil Heater

A diagram of the oil heater is shown in Fig. 1. The fluid to be heated is oil with the brand name DOWTHERM A, and it is to be used as the heat-exchange fluid for a succeeding process. The outlet temperature of the fluid DOWTHERM A is about 320°C. After the heat exchange has taken place, the inlet temperature is about 285°C.

The two control variables are the pressure of the fuel oil and the orientation of the duct damper. They are used to control the outlet temperature of the fluid DOWTHERM A and the oxygen percentage in the duct. Thus, the heater may be considered as a two-input/two-output controlled plant.

There are two basic tasks for the control system. The first task is to maintain the outlet temperature with as little fluctuation as possible and with an acceptable fast response. At the normal operating point, the fluctuation of outlet temperature must not exceed ±1°C. The second task is to reduce the oxygen percentage in the duct as much as possible, since the calorific efficiency of the heater depends on the oxygen. Under suitable conditions, the lower the oxygen percentage, the higher the calorific efficiency.

Experimental operation has shown that fluctuations in the pressure of the fuel oil not only influence the outlet temperature but also affect the oxygen percentage in the duct. The oxygen percentage increases when the fuel oil pressure is lowered, and the calorific efficiency of the heater is lowered, also. On the other hand, experimental operation shows that the oxygen percentage is reduced when the damper is closed, but there is an increase in the outlet temperature. Thus, there are strong interactions between the controlled variables and each of the controls.

The measurement of step responses was chosen as the simplest way to obtain the plant data necessary for modeling. An approximate linear time-invariant model of the plant was obtained by averaging the measured responses. The transfer functions for the components of the matrix model for the plant were obtained by curve fitting.

The two input variables are the pressure of the fuel oil P and the orientation of the duct damper X, and the two output variables are the fluid outlet temperature T and the oxygen percentage in the duct O. The transform of the two-dimensional vector Y representing the output variables is equal to the product of the matrix transfer function $G(s)$ times the transform of the two-dimensional vector U representing the input variables.

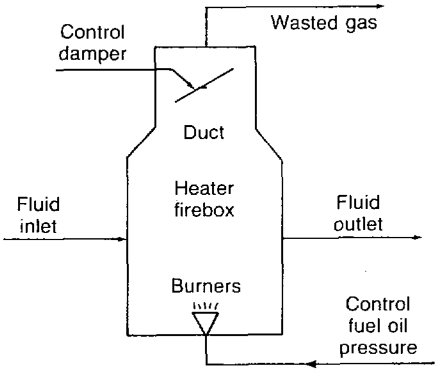

Fig. 1. Diagram of oil heater.

$$Y(s) = G(s)\, U(s)$$

The two-by-two matrix transfer function $G(s)$ obtained for the plant is presented here, where the dimensions of the variables have all been changed to volts and the time scale is in seconds.

$$\begin{bmatrix} T(s) \\ O(s) \end{bmatrix} = \begin{bmatrix} \dfrac{0.6}{2400s^2 + 85s + 1} & \dfrac{-0.04}{3000s^2 + 90s + 1} \\ \dfrac{-1.1}{70s + 1} & \dfrac{0.3}{70s + 1} \end{bmatrix} \begin{bmatrix} P(s) \\ X(s) \end{bmatrix} \quad (1)$$

Simulation of the Model

The correctness of the model is the key to designing a good controller. To examine the correctness of the model, simulation is necessary, and, for this problem, the simulation was implemented in conventional analog computers. One obvious advantage of analog computers is that they can be operated in the real-time mode. Since the behavior of the simulated model implemented in analog computers is very similar to that of the actual plant, the analog simulation is an efficacious

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technique for analysis, observation, and examination of the accuracy of the mathematical model and for checking the results of the design.

The plant transfer function $G(s)$ is made up of first- and second-order elements. In order to ensure simulation accuracy in the case of large time constants, the following analog blocks for first- and second-order elements were employed:

$$G_1(s) = K/(Ts + 1)$$

$$G_2(s) = K/(T^2s^2 + 2\zeta Ts + 1)$$

To observe the effects of interactions between two loops, the analog block diagram of the whole controlled plant was organized as shown in Fig. 2. As one would suspect from examining the plant transfer function $G(s)$, the open-loop step response of the system shows that there are interactions between the two output variables and each of the two controls.

Decoupling Control System Design

In a multivariable control system, the change of any input will usually affect all outputs, giving rise to system "coupling" or "interaction"; this may be undesirable in many control systems. The approach used here for the multivariable system is to remove the interacting effect so that one input affects only one output, and each output is affected by only one input.

An analog hybrid computer was utilized to design the decoupling precompensator matrix. Compared with a digital computer, the analog computer has the following features:

(1) Proper scale selection and simulation can be carried out in real time with the advantage of direct visualization.

(2) Criteria for minimization of interactions may be altered flexibly according to practical requirements.

(3) The constant precompensator matrix and the whole control system can be simulated and debugged, and the design results evaluated immediately.

The degree of interaction between the jth input and the ith output (a_{ji}) is defined as the ratio between the steady-state outputs due to a step input. The degree of interaction between the input and output of the original plant is

$$a_{21} = 183.3\%, \quad a_{12} = 13.3\% \quad (2)$$

There were only two inputs and two outputs; so the trial-and-error method was used to choose the precompensator matrix, because it could be conveniently implemented with the interactive analog computer. The resulting precompensator matrix K was used mainly to diagonalize the steady-state transfer function of the open-loop plant.

$$K = \begin{bmatrix} 1.326 & -0.089 \\ -3.67 & 1 \end{bmatrix} \quad (3)$$

The degree of interaction for the compensated plant is

$$a_{21}^0 = 0.22\%, \quad a_{12}^0 = 0.94\%$$

A general procedure can be used to diagonalize the steady-state open-loop plant when there are more than two inputs and outputs. The steady-state response of a transfer function $G(s)$ in response to a step input is obtained by taking the limit of the transfer function as the variable s goes to zero. Let the matrix B represent the steady-state output of the open-loop plant in response to step inputs for all the controls.

$$B = \lim_{s \to 0} G(s)$$

If the matrix B is square and has an inverse, then the precompensator matrix K, which diagonalizes the steady-state open-loop plant, is the inverse of the matrix B.

$$K = B^{-1}$$

To continue with the two-input/two-output controlled plant, let the matrix transfer function $Q(s)$ represent the transfer function of the plant after it has been compensated by the decoupling matrix K.

$$Q(s) = G(s)K$$

There are a number of methods for evaluating the decoupling of a control system. One approach is the INA (inverse Nyquist array) method put forward by Rosenbrock [1], [2]. This method is a multivariable frequency-domain technique. The method gives visual insight and is largely insensitive to small errors in the description of a system.

The main concept involved with the INA method is diagonal dominance. The row Gershgorin bands of $Q(s)$ are shown in Fig. 3, in which (a) and (b) correspond to the first and second rows, respectively, for ω varying from 0 to 0.1 rad/sec. Since these bands do not include the origins, the compensated plant $Q(s)$ is (row) diagonal dominant. The step response of $Q(s)$ verifies that the open-loop plant has been diagonalized.

A China-made HAP2-DJS131 hybrid computer was used to design the precompensator matrix as shown in the block diagram in Fig. 4.

In general, computation of the interaction criteria function is included in the dynamic process solution. The design program that decouples the precompensator matrix and the analog computer management program are run under the operational software loaded in the HAP2-DJS131 hybrid computer. The digital and analog computers are worked alternatively until the digital computer output gives the desired results. There are two points to be considered:

(1) Since the analog computer has limits on standard voltage (≤ 10 V) and coefficients setting (≤ 1), the elements of the precompensator matrix must be normalized through scale transformation.

(2) It is possible that the digital-to-analog

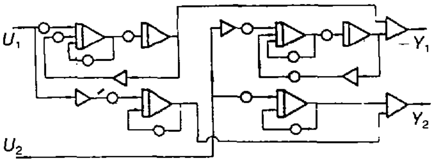

Fig. 2. Analog block diagram of plant.

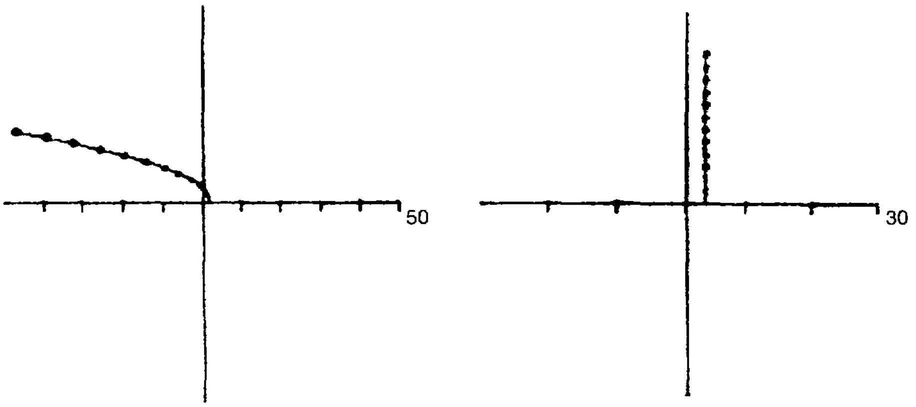

Fig. 3. Gershgorin bands of $Q(s)$.

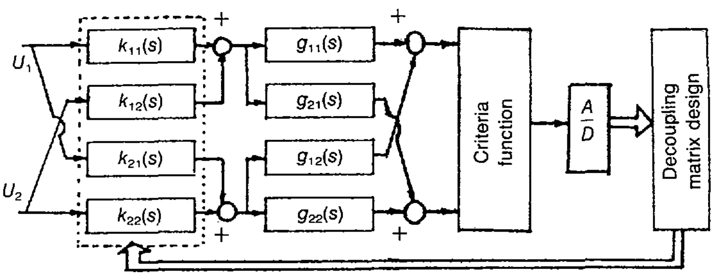

Fig. 4. Block diagram of hybrid computer design.

conversion may be out of range such that D/A would overflow; therefore, it is best to include value overflow processing digital subroutines.

The hybrid computing program package installed in the HAP2-DJS131 hybrid computer includes multivariable coordinate transformation, stochastic search, accelerated simplex, and complex methods. These methods can all be used to design the precompensator matrix. There are numerous papers and books that describe these methods. The multivariable accelerated simplex method was utilized to design the matrix.

The problem of designing the precompensator matrix using a hybrid computer has been studied. There are a few points that should be considered.

(1) The criteria function of interaction may be implemented either on the analog or the digital computer.

(2) The accuracy of the analog computer is lower than that of the digital computer. It may reach only 0.5–1.0 percent on average. To speed up the design, the output of the analog computer may be taken as the initial value of the digital computer.

(3) When the multivariable system has higher order, it is necessary to assign the tasks of the analog and digital computers equitably.

The design results employ both digital and hybrid methods. The addition of the decoupling precompensator matrix has greatly reduced the interactions between loops; therefore, the fuel oil pressure dominates the outlet temperature, and the orientation of the damper dominates the oxygen percentage at the duct. Now, it is time to use single-loop theory to design the controllers.

Design of Controllers

The design techniques of a single-loop control system are well known [3], [4]. To improve dynamic response and steady-state performance of the closed-loop system, we introduce two PI (proportional integral) controllers, with the parameters determined by the Nyquist plot technique:

$$k_{11}(s) = 4\left(1 + \frac{1}{100s}\right)$$

$$k_{22}(s) = 8\left(1 + \frac{1}{50s}\right)$$

The block diagram of the resulting closed-loop system is shown in Fig. 5, and the step response of the closed-loop system is shown in Fig. 6. The curves show that the resulting design is satisfactory, and the entire design process is finished [5], [6].

Sensitivity to Perturbations

Because the heater's operating point is not fixed due to variations in the load or fuel oil characteristics and environmental effects, the model of the plant is not invariant. Experiment shows that the diagonal elements of the transfer function matrix of the plant may vary significantly when the loads and fuel oil are changed. Under the assumption that the gain and poles of $g_{11}(s)$ vary +5 percent, and the gain and pole of $g_{22}(s)$ vary −5 percent, the perturbated system is still row diagonal dominant. The unit step response of the perturbed system shows there is very little degradation in performance due to perturbation in the parameters.

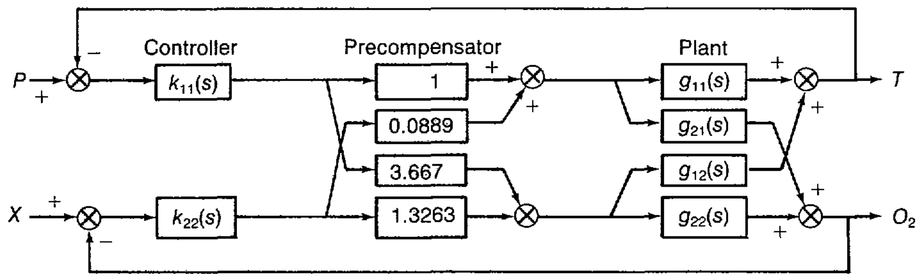

Fig. 5. Block diagram of resulting closed-loop system.

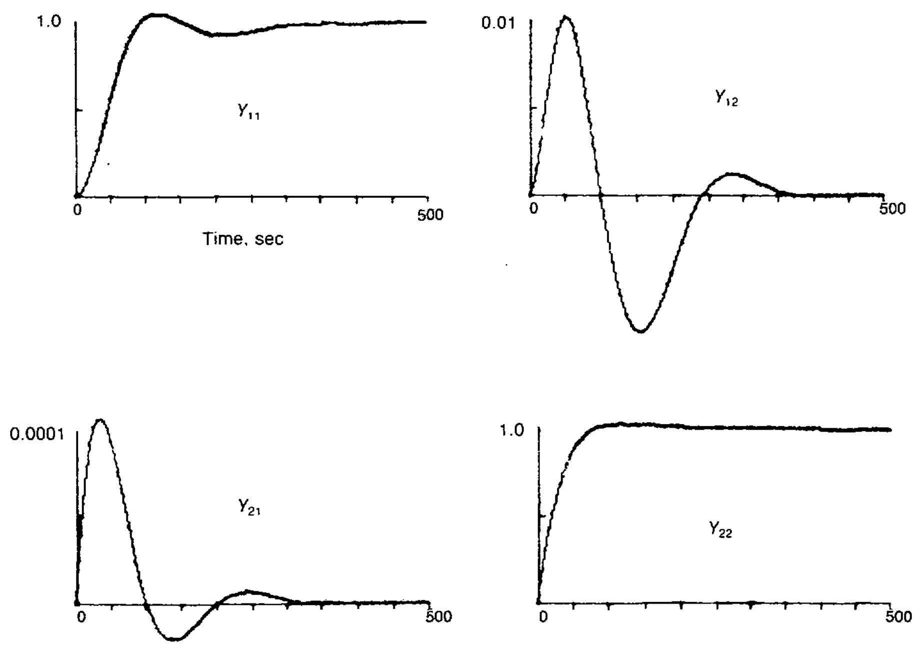

Fig. 6. Unit step response of closed-loop system for 500 sec.

Conclusions

At present, computer control systems are widely used in many fields. It is convenient with microcomputers to realize many complex control algorithms that are difficult for analog elements to implement. The use of a hybrid computer to design a decoupling control system is a novel method. It can carry out real-time simulation and, thus, speed up the control system design. The resultant control algorithms are often simple, which aids practical application.

The multivariable decoupling control system of the oil heater has been implemented with a Z-80-based single-board microcomputer and has operated successfully for over a year. The measurement indicates that the oxygen percentage lowers from the original 5.2 percent to 2.5 percent, and the calorific efficiency of the heater rises from the original 82.5 percent to 85 percent at present. Through this implementation, significant energy savings are achieved over previous operation.

References

[1] H. H. Rosenbrock, "Design of Multivariable Control Systems Using the Inverse Nyquist Array," *Proc. IEE*, vol. 116, pp. 1929–1936, 1969.

[2] H. H. Rosenbrock, *Computer-Aided Control System Design*, New York: Academic Press, 1974.

[3] N. Munro, *Modern Approaches to Control System Design*, Peter Peregrinus, Ltd., on behalf of the Institution of Electrical Engineers, England, 1979.

[4] D. H. Owens, *Feedback and Multivariable Systems*, Peter Peregrinus, Ltd., on behalf of the Institution of Electrical Engineers, England, 1978.

[5] H. Zhaung, F. Bai, J. Xue, and L. Ningsu, "Study of Diagonal Dominance in a Multivariable Control System with Hybrid Computer," *Inform. Contr.*, no. 3, pp. 1-5, 1986.

[6] J. Xue and F. Bai, "Decoupling Control of the Reboiler Oil Heater," *Proc. Industrial Process Modeling and Control Conf.*, Vol. II, pp. 328–333, 1985.

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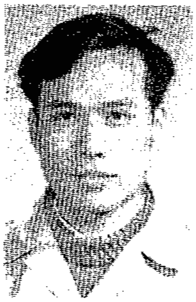

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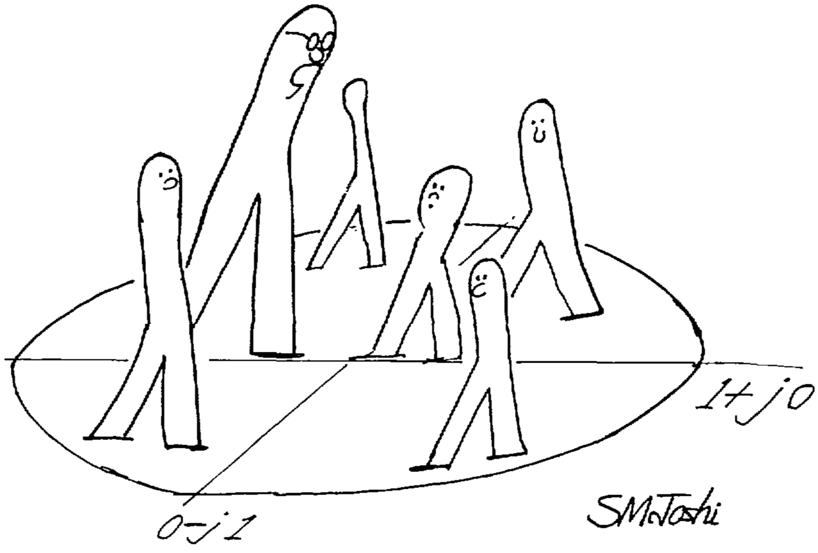
Out of Control



"And then, in the seventies came the computer revolution, and they confined us to this silly circle!"