

STRUCTURAL ANALYSIS FOR MULTIVARIABLE PROCESS CONTROL

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A method is introduced which retains internal structural information available from process models in feedforward and feedback control analysis of linear constant coefficient systems with the control objective of holding one or more outputs constant. Comparative examples illustrate some of the advantages of this approach over the corresponding terminal or external analysis.

TRANSFER matrix models of process systems have been used successfully in linear multivariable feedforward control analysis (Bollinger and Lamb, 1962; Haskins and Shigrovich, 1963; Vermeil, 1965). However, such models are inadequate for analytic linear multivariable composite feedforward-feedback control analysis. This paper introduces a structured matrix model for linear process systems that contains more information about the process than the corresponding transfer matrix model. With this additional information, unique optimal solutions of a class of composite feedforward-feedback control problems can be obtained. First, the general concept of "structure" in problem formulations is considered. It is then shown that this concept can be applied advantageously to some simple control problems, and finally a general structural matrix method for control analysis is presented.

Both feedforward and feedback control have characteristic advantages and disadvantages. Feedforward control has the advantage of rapid response and the disadvantage of sensitivity to model error causing permanent compensation error. Feedback control is characterized by relatively slow response, but also relatively little sensitivity to model error and no steady-state compensation error. Loeckie and McGilver (1967) have shown in single-variable control problems that composite feedforward-feedback control preserves the advantages of both types of control while tending to cancel the disadvantages.

Structural Information in Problem Formulation

To establish the meaning and significance of internal structure in problem formulation, it is helpful to consider the use of available information in problem formulation. Generally, the amount of available information which is contained in a problem formulation is one of the most critical factors in acquiring a problem solution. When the amount of information used is insufficient and provides a nonunique problem statement, problem solutions may be incomplete, nonunique, or impossible. The proper use of the available information is not always a simple proposition. Critical information is sometimes of a subtle nature and easily overlooked.

Dynamic programming is an example of the effective use of internal structural information. The information used is the serial or stagewise nature of certain decision and optimization problems. Consider a 10-stage system requiring a one-dimensional optimization of each stage. Analysis by dynamic programming uses a stage-by-stage approach such that 10 one-dimensional optimization problems must be solved. The corresponding solution by conventional calculus lumps the 10-stage problem into a single 10-dimensional problem which is usually inappreciated to solve.

The conventional calculus formulation can be considered an external or terminal formulation and the dynamic programming formulation an internal or structural formulation. The 10-dimensional problem of the calculus formulation could just as well be five, serial, one-dimensional problems, or any combination giving 10 dimensions overall. Such nonuniqueness is a general characteristic of terminal formulations.

Structural Formulation of Multivariable Processes

Internal structural information can also be used in multivariable process control analysis with significant advantages. An important characteristic of classical processes is that theoretical or mathematical models are usually available (Calvert and Coatsworth, 1961). This important information is lost if a terminal formulation is used (Kalman, 1963).

Although structural considerations are not limited to such problems, this paper considers only linear, lumped-parameter, single-stage multivariable systems. Such systems are described by the set of n linear differential equations:

$$\frac{dy_i}{dt} = \sum_{j=1}^n a_{ij}y_j + \sum_{k=1}^m b_{ik}x_k \quad i = 1, 2, \dots, n \quad (1)$$

Equation 1 represents a system with n inputs or disturbance sources, x_k , and n state variables, y_i . They are usually obtained from the nonlinear system model equations by retaining the first-order terms of their Taylor series expansion around the desired steady-state operating point.

The Laplace transform of Equation 1 can be expressed as

$$Y_i = \left[\sum_{j=1}^n a_{ij}Y_j + \sum_{k=1}^m b_{ik}X_k \right] \left(\frac{1}{s - a_{ii}} \right) \quad i = 1, 2, \dots, n \quad (2)$$

Before proceeding further, it will be worthwhile to consider a simple problem by the structural and the terminal approaches in order to distinguish between the two.

Example 1. Let the system be the specific case of Equation 2 with two state variables, Y_1 and Y_2 , and two manipulable inputs, X_1 and X_2 . For simplicity let $a_{11} = a_{22} = 0$. The control objective will be the dynamic uncoupling of Y_1 and Y_2 , so that variations in Y_1 do not affect Y_2 and vice versa.

The process can be represented by a signal flow graph as shown in Figure 1, *a*. (Signal flow graphs or node-directed branch diagrams along with Mason's rule for their direct analysis are discussed in most recent introductory texts on control analysis. Briefly, each node represents a summing junction whose value is equal to the sum of the contribution of all in-

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