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Digital control of a turbine-driven pumping system

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San Jose State University, 1991

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DIGITAL CONTROL OF A TURBINE-DRIVEN PUMPING SYSTEM

A Thesis

Presented to

The Faculty of the

Department of Electrical Engineering

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

John Zerwekh

December 1991

APPROVED FOR THE DEPARTMENT OF ELECTRICAL
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APPROVED FOR THE UNIVERSITY

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ABSTRACT

DIGITAL CONTROL OF A TURBINE-DRIVEN PUMPING SYSTEM

by John Zerwekh

A discrete control algorithm is developed to be used in a digital controller. The controller replaces the currently-installed analog controls in a turbine-driven pumping system of a boiling water reactor (BWR) known as the Reactor Core Isolation Cooling System (RCIC). The design steps are as follows: First, the non-linear equations which model the plant dynamics are developed, and these equations are linearized to provide a model for control design. Second, system identification of the currently-installed analog control system is accomplished via examination of data from laboratory tests of the actual hardware. Discrete transfer functions for turbine speed and system flow control are developed and simulated using the Matrix-X engineering analysis and control design software package. Finally, a discrete control algorithm is put forth which provides good system response and addresses some improvements to the original control system.

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Nomenclature

A	Cross sectional area (ft^2)
a, b, c, d, e, f, g	Pump curve fit constants
E	Pump efficiency (dimensionless)
F	Force (lbf)
f	Friction factor (dimensionless)
g	Acceleration due to gravity (ft/sec^2)
g_0	Gravitation constant ($\text{lbm}\cdot\text{ft}/\text{lbf sec}^2$)
H	Head (ft)
HP	Horsepower
I	Inertance (lbm/ft^4)
J	Rotational Inertia ($\text{lbm}\cdot\text{ft}^2$)
k	Ratio of specific heats for steam (1.3)
k_A	Area Conversion Constant ($144 \text{ in}^2/\text{ft}^2$)
k_f	Flow Conversion Constant [$448.9 \text{ gpm}/(\text{ft}^3/\text{sec})$]
k_Q	Flow Conversion Constant [$3600 (\text{lbm}/\text{sec})/(\text{lbm}/\text{hr})$]
k_P	Power Conversion Constant [$550 (\text{lbf}\cdot\text{ft}/\text{sec}^2)/\text{hp}$]
k_R	Flow Resistance Coefficient (ft/gpm^2)
k_v	Valve Resistance Coefficient (dimensionless)
K0-K10	Linearized model constants (See Table 2-1)
L	Length (ft)
M	Mass (lbm)
$\mathbf{M}$	Mach number (dimensionless)
m	Steam mass flow rate (lb_m/sec)
N	Pump speed (rpm)

ω Pump Speed (rad/sec)
P Pressure (lb_f/in^2)
Q Flow (gpm)
 ρ Weight Density (lb_f/ft^3)
s Slope for linear fit to steam turbine curve
v Velocity (ft/sec)
X Valve Actuator position (in)
Z Elevation Head (ft)

CHAPTER 1

Introduction

Aging analog control systems at several U.S. nuclear power plants have been replaced with commercially-available digital control equipment. Two recently-documented cases (EPRI NP-5502, EPRI NP-6143) show that the digital equipment can perform better and with higher reliability than the original analog controls.

While the two references above deal with digital feedwater control, other systems within a plant can benefit from similar retrofits. This paper specifically addresses the design of a digital algorithm for the control of the Reactor Core Isolation Cooling (RCIC) system of a General Electric Boiling Water Reactor (BWR).

The balance of this chapter provides a brief functional description of the RCIC system and controls. Development of equations describing the "plant" portion of RCIC is undertaken in chapter 2, and identification of the original analog controls is addressed in chapter 3. Development and implementation of the digital control algorithm are the subjects of chapters 4 and 5.

Functional Overview

The purpose of the RCIC system is to provide sufficient cooling water to the Nuclear Boiler if the normal feedwater flow is interrupted. When an interruption occurs, the

control rods of the reactor are quickly pushed into the core to shut down the nuclear reaction. Heat continues to be produced at a reduced level, however, due to decay of fission products in the core. As a result, steam is generated, and water inventory in the vessel is lost. The water is replaced by the RCIC system which utilizes the energy in the decay heat steam.

Modes of Operation

The system consists of a steam turbine, pump, piping and controls/instrumentation as shown in figure 1-1. In the normal mode of RCIC operation, steam from the pressure vessel drives the turbine which in turn drives the pump. Water is drawn from the condensate storage tank (CST) and pumped into the pressure vessel. The RCIC system must operate reliably at all vessel pressures between 165 and 1156 psia.

To demonstrate operability of the RCIC system, it is periodically tested. In order to reduce impact of such test activities on the operation of the power plant, a test line is incorporated in the piping design. In the test operation mode, water is drawn from the CST, pumped through an orifice in the test line, and returned to the CST. The orifice is sized such that the pump head required for test mode at rated

3

RCIC flow (600 gpm) is the same as that required for normal mode operation at the rated reactor pressure of 1040 psia.

Control Strategy

Control of the RCIC system is currently accomplished using two nested control loops, and a start up ramp generator (See figure 1-1). The inside loop measures the turbine speed (RPM), compares it to the speed setpoint, and adjusts the amount of steam admitted to the turbine in a manner which zeroes the speed error. The outside loop measures the pump flow and compares it to the flow setpoint. A signal proportional to the error (actually proportional + integral) is presented to the inside (speed) control loop as the speed setpoint. Thus the turbine speed is adjusted in a manner which zeroes the error between the flow setpoint and the actual flow. System flow is the output variable to be controlled.

System Start Up

During start up of RCIC, the control strategy is modified. The ramp generator (see figure 1-1) produces a speed setpoint which ramps from an idle value to a full speed demand value over a period of approximately 15 seconds. The speed controller follows this ramp until its value equals the speed setpoint signal from the flow controller. At this time, the ramp signal is disregarded, and the speed controller

begins to take its input from the flow controller. Control continues in this manner for the duration of the run.

CHAPTER 2

Plant Modeling

The first objective of this chapter is to develop the non-linear equations which model the dynamic behavior of the RCIC turbine, pump, and piping systems. Cumulatively these systems represent the "plant" portion of RCIC. Modeling of the "control" portion (sensor, control, and actuator hardware) is deferred until chapter 3.

The second objective of this chapter is to linearize the dynamic equations to form a linear model which represents the small signal dynamic behavior of the plant at a specific operating point of system water flow and vessel pressure. A block diagram of the linear model is shown in figure 2-1. The input to the plant model is ΔX , a small change in the position of the turbine governor valve linkage, while output ΔQ is the resulting change in RCIC system flow. The linearized equations developed throughout the chapter allow calculation of the value of each of the constants K_0 through K_{10} for a given steady state operating point.

Steady State Water Flow

Bernoulli's equation is used as a starting point to determine the equations for water flow in the RCIC system. Bernoulli's Equation relates the total head at a given point in a piping system to the total head at any other point. One

Figure 2-1: Linear Plant Model

This model represents the RCIC system dynamic behavior at a given operating point of reactor pressure and system flow. ΔX is a small change in the position of the turbine governor valve. ΔQ is the resulting change in system flow.

form of the equation is

$$Z_1 + k_A P_1 / \rho_1 + v_1^2 / 2g = Z_2 + k_A P_2 / \rho_2 + v_2^2 / 2g \quad (\text{ft}) \quad (2-1)$$

where Z is elevation head, P is pressure, ρ is the weight density, v is the velocity, and g is the acceleration due to gravity (Crane 1-5). Additional head loss and gain terms must be added to equation (2-1), however, since pumps are present in the system and friction losses are significant. The head loss due to friction in a uniform straight pipe is given by Darcey's Formula as

$$H_L = \gamma L v^2 / 2Dg \quad (\text{ft}) \quad (2-2)$$

where γ is the friction factor, L is the pipe length, and D is the hydraulic diameter (Crane 3-2). Likewise, head losses due to valves and fittings can be expressed as

$$H_L = k_v v^2 / 2g \quad (\text{ft}) \quad (2-3)$$

where k_v is constant (Crane 3-4). If the velocity head and friction head loss terms are lumped together, the total resistance head loss is a function of velocity:

$$H_R \propto v^2/2g. \quad (\text{ft}) \quad (2-4)$$

The flow is proportional to velocity,

$$Q \propto v \quad (2-5)$$

so that the head loss can be put in terms of the flow as

$$H_R = k_R Q^2 \quad (\text{ft}) \quad (2-6)$$

where k_R is the flow resistance coefficient.

The head introduced by a pump in a system is related to the pump suction and discharge pressures by

$$H_P = k_A(P_{\text{dis}} - P_{\text{suc}})/\rho. \quad (\text{ft}) \quad (2-7)$$

Utilizing equations (2-1), (2-6), and (2-7) the pump head required to drive water from the CST into the vessel at a constant flow rate is calculated as

$$H_P = Z + k_A P_{\text{diff}}/\rho + k_R Q^2 \quad (\text{ft}) \quad (2-8)$$

where Z is the difference in elevation between the CST and vessel, P_{diff} is the differential pressure between the CST and

vessel, and density is assumed to be constant throughout the system. The resistance constant k_R can be determined from design data representing a steady state operating point by rearranging (2-8) to

$$k_R = (HP - Z - k_A P_O / \rho) / Q_O^2. \quad (\text{ft/gpm}^2) \quad (2-9)$$

In the test mode of RCIC operation, water is drawn from the CST, pumped through a test line containing a restricting orifice, and returned to the CST. In this case, the elevation and pressure head terms in (2-8) become zero, and the pump head required to drive water through the test line is calculated from

$$H_{PT} = k_{RT} Q_T^2 \quad (\text{ft}) \quad (2-10)$$

where the test mode resistance coefficient can be calculated from power plant design data as

$$k_{RT} = H_{PT} / Q_O^2. \quad (\text{ft/gpm}^2) \quad (2-11)$$

The change in resistance head due to a small change in system flow from a given operating point (P_O, Q_O) is determined by differentiating equation (2-8) with respect to flow:

$$\frac{\partial H_P}{\partial Q} = 2k_R Q_0 \quad (\text{ft/gpm}) \quad (2-12)$$

From equation (2-12) the constant K_9 for the linearized plant model of figure (2-1) is defined as

$$K_9 = 2k_R Q_0 \quad (\text{ft/gpm}) \quad (2-13)$$

or, for the test mode,

$$K_9 = 2k_{RT} Q_0 \quad (\text{ft/gpm}) \quad (2-14)$$

System Inertance

Equations have been developed above which specify the pump head required to produce steady state flow in the RCIC system. Under changing flow conditions, however, fluid within the system is accelerated so that its inertance must be considered. Newton's law is applied to determine the flow acceleration due to a given pump driving head.

A representative cross section of the fluid in the system piping is shown in figure 2-2. The fluid slug is treated as a lumped mass of length L and cross-sectional area A (Doebelin 192-196). The force F on the slug is

$$\begin{aligned} F &= (P_1 - P_2)k_A A \quad (\text{lb}_f) \\ &= (P_{\text{diff}})k_A A \end{aligned} \quad (2-15)$$

Figure 2-2: Fluid Slug

The inertance is calculated by considering the water in the piping as a slug of length L and cross-sectional area A .

where P_1 and P_2 are the pressures identified in figure (2-2), and the mass M of the slug is

$$M = \rho L A g_o / g. \quad (\text{lb}_m) \quad (2-16)$$

Thus, Newton's law requires that the acceleration be

$$\frac{\partial v}{\partial t} = (F/M) g_o = (P_{diff}) k_A g / \rho L. \quad (\text{ft/sec}^2) \quad (2-17)$$

The flow acceleration can now be defined as

$$\frac{\partial Q}{\partial t} = k_f A \frac{\partial v}{\partial t} = k_f A (P_{diff}) k_A g / \rho L \quad (\text{gpm/sec}) \quad (2-18)$$

or

$$\frac{\partial Q}{\partial t} = k_f k_A (P_{diff}) g_o / I \quad (\text{gpm/sec}) \quad (2-19)$$

where the inertance I is defined as

$$I = \rho L g_o / A g. \quad (\text{lb}_m/\text{ft}^4) \quad (2-20)$$

The flow acceleration in terms of differential head is

$$\frac{\partial Q}{\partial t} = k_f \rho H_{diff} g_o / I \quad (\text{gpm/sec}) \quad (2-21)$$

where

$$H_{diff} = kA(P_{diff})/\rho. \quad (\text{ft}). \quad (2-22)$$

Thus, K_8 for the linear model becomes

$$K_8 = K_f \rho g_0 / I \quad ((\text{gpm/sec})/\text{ft}). \quad (2-22a)$$

The Pump Model

Water is driven through the piping of the RCIC system by a single stage centrifugal pump designed for steady state operation between 2000 and 4500 RPM. Performance data is supplied by the manufacturer in the form of pump curves similar to figures 2-3 and 2-4. Figure 2-3 relates pump head H and pump efficiency E to flow Q at a base rotational speed N_B . Figure 2-4 relates pump head H and pump efficiency E to pump speed N at a given flow rate. It is the subject of this section to generalize the performance information to pump modeling equations which allow calculation of head, efficiency, and pump drive horsepower at any operating point of pump speed N and system flow Q . In addition, the pump equations are linearized to provide constants for the linear model of figure (2-1).

The modeling process is started by determining an equation which closely fits the constant speed pump head curve supplied by the manufacturer. A type of fit which

Figure 2-3: Constant Speed Pump Characteristics ($N = 3560$ rpm)

The pump head and efficiency at constant speed are functions of flow. This plot compares the pump manufacturer's actual data (denoted by x markers) to the results of curve fit equations used for modeling (denoted by solid lines).

Figure 2-4: Constant Flow Pump Characteristics ($Q = 625$ gpm)

Pump head and efficiency are functions of pump speed and flow. This plot compares the general head and efficiency modeling equations to the manufacturers data for a given flow.

reflects the shape of the curve well is a monotonically changing power fit of the form

$$H_B = a + b(Q_B)^c \quad (\text{ft}) \quad (2-23)$$

where a , b , and c are constants. Table 2-1 and Figure 2-3 compare the manufacturer's data to data calculated from equation (2-23) where the constants a , b , and c have been chosen as follows:

$$a = 1793 \quad (2-24a)$$

$$b = -4.049 \times 10^{-7} \quad (2-24b)$$

$$c = 2.95. \quad (2-24c)$$

The solid head curve of figure 2-3 represents equation (2-23) whereas the X markers represent manufacturer data.

Table 2-1

PUMP PERFORMANCE vs. FLOW at $N_B = 3560$ RPM

FLOW (GPM)	ACTUAL HEAD(ft)	MODELED HEAD(ft)	ACTUAL EFF.	MODELED EFF.
0	1800	1793	0	0.04
400	1770	1774	0.57	0.56
600	1720	1730	0.70	0.71
800	1650	1645	0.76	0.79
1000	1510	1506	0.775	0.80
1200	1300	1302	0.76	0.73

The subscript B in (2-23) indicates that the head versus flow relationship holds only for a constant base speed N_B . To introduce varying pump speed into this equation, the pump affinity laws (Stepanoff 123-124) are used. The affinity laws express flow or head at a given speed to flow or head at a base speed as follows:

$$Q/Q_B = N/N_B \quad (2-25)$$

$$H/H_B = N^2/N_B^2 \quad (2-26)$$

Substituting (2-23) into (2-26) yields

$$H = (N/N_B)^2 [a + b(Q_B)^c] \quad (\text{ft}) \quad (2-27)$$

and substituting (2-25) into this result yields

$$H = (N/N_B)^2 [a + b(N_B Q/N)^c] \quad (\text{ft}) \quad (2-28)$$

as the general head equation for the pump. Equation (2-23) is actually a special case of equation (2-28) where pump speed N is equal to the base pump speed N_B .

The validity of equation (2-28) is confirmed for various pump speeds by holding pump flow Q constant and varying pump speed N over the recommended operational range. Comparison

to manufacturer data (figure 2-4) shows that equation (2-28) models the pump appropriately.

The pump efficiency is modeled in much the same manner as the pump head, except a polynomial curve fit is used instead of a power fit. Efficiency is modeled by

$$E = d + eQ_B + fQ_B^2 + gQ_B^3 \quad (2-29)$$

where

$$d = 8.786 \times 10^{-3} \quad (2-30a)$$

$$e = 2.083 \times 10^{-3} \quad (2-30b)$$

$$f = -1.872 \times 10^{-6} \quad (2-30c)$$

and

$$g = 5.496 \times 10^{-10}. \quad (2-30d)$$

Substituting equation (2-23) into (2-26) yields the general efficiency equation

$$E = d + e(N_B Q/N) + f(N_B Q/N)^2 + g(N_B Q/N)^3 \quad (2-31)$$

Figures 2-3 and 2-4 compare results of equation (2-31) to manufacturer efficiency data.

The output horsepower of the pump is proportional to the product of the flow and pressure (Stepanoff 124). It is given by

$$HP = \rho HQ / k_f k_p \quad (\text{hp}). \quad (2-32)$$

The horsepower required to drive the pump can be calculated by dividing the output horsepower by the efficiency of equation (2-31):

$$HP_D = \rho QH / k_f k_p E \quad (\text{hp}) \quad (2-33)$$

Linearized Pump Equations

Considering small changes in the pump speed ΔN as input, and small changes in pump head ΔH as output, the forward small signal transfer function for the pump is obtained by taking the partial derivative of equation (2-28) with respect to pump speed N :

$$K4 = \frac{\partial H}{\partial N} = \frac{-cbO_o}{N_B} (N_B Q / N_o)^{c-1} + 2H / N_o \quad (\text{ft/rpm}) \quad (2-34)$$

Additionally, head produced by the pump is a function of

flow. Changes in head due to changes in flow must be included in the linear pump model. In figure (2-1), the feedback path containing constant K5 accounts for this dependence. The value of K5 is obtained by taking the partial derivative of (2-28) with respect to flow. This yields

$$K5 = \frac{\partial H}{\partial Q} = (N/N_B)^{2-c} b c Q^{c-1}. \quad (\text{ft/gpm}) \quad (2-35)$$

The pump drive horsepower of equation (2-33) is a function of flow, head, and speed. A feedback path in the linear model is necessary for each of these dependencies. Taking partial derivatives with respect to each quantity yields

$$K7 = \frac{\partial HP}{\partial Q} = (\rho/k_f k_p) H_o [(1/E_o) - (Q_o/E_o^2) (\frac{\partial E}{\partial Q})], \quad (\text{hp/gpm}) \quad (2-36)$$

$$K6 = \frac{\partial HP}{\partial H} = (\rho/k_f k_p) Q_o/E_o, \quad (\text{hp/ft}) \quad (2-37)$$

and

$$K10 = \frac{\partial HP}{\partial N} = -((\rho/k_f k_p) Q_o H_o / E_o^2) (\frac{\partial E}{\partial N}). \quad (\text{hp/rpm}) \quad (2-38)$$

where

$$\frac{\partial E}{\partial Q} = e(N_B N_o) + 2f(N_B N_o)^2 Q_o + 3g(N_B N_o)^3 Q_o^2 \quad (1/\text{gpm}) \quad (2-39)$$

and

$$\begin{aligned} \frac{\partial E}{\partial N} = & - [e(N_B Q_0)/N_0^2] & (1/\text{rpm}) & (2-40) \\ & - [2f(N_B Q_0)^2/N_0^3] \\ & - [3g(N_B Q_0)^3/N_0^4]. \end{aligned}$$

From (2-36), (2-37), and (2-38), the constants for the upper three feedback paths of figure 2-1 can be evaluated.

Turbine Dynamics

The turbine and pump inertia is modeled as a single rotating lumped mass. The kinetic energy of the rotating mass is

$$KE = (1/2)J\omega^2 \quad (\text{Joule}) \quad (2-41)$$

where ω is the rotational speed in rad/sec, and J is the rotational inertia in kg-m^2 (Beer 759). The net power into the turbine is equal to the rate of change of the kinetic energy,

$$P_{\text{net}} = J\omega \frac{\partial \omega}{\partial t} \quad (\text{Watt}) \quad (2-42)$$

or

$$\frac{\partial \omega}{\partial t} = P_{\text{net}}/J\omega. \quad (\text{rad/sec}^2) \quad (2-43)$$

Thus, the acceleration of the turbine is directly proportional to net power supplied and inversely proportional to the current turbine speed. In terms of the units used throughout this report,

$$\frac{\partial N}{\partial t} = k_T \text{HP}_{\text{net}} / JN \quad (\text{rpm/sec}) \quad (2-44)$$

where

$$k_T = 1.614 \times 10^6 \quad \frac{\text{lbm-ft}^2\text{-rev}^2}{\text{hp-sec-min}^2} \quad (2-45)$$

is a constant to match units, and J has units lbm-ft^2 . To linearize (2-44) around an operating point of flow Q_o and speed N_o requires only that N in the denominator be replaced by N_o :

$$K_3 = \frac{\partial N}{\partial t} = k_T \text{HP}_{\text{net}} / JN_o \quad (\text{rpm/sec}) \quad (2-46)$$

Turbine Power

Power is applied to the turbine in the form of high pressure steam which is admitted through a governor valve. The amount of power applied to the turbine is a function of the steam flow rate, the turbine RPM, and the energy of the steam. For modeling purposes, it is assumed that the steam entering the turbine is at saturated conditions. Steam curves are shown in figure 2-5 which relate turbine horsepower to steam flow rate at several speeds. It is the subject of this section to fit an equation to the steam curves. This allows direct calculation of the turbine horsepower produced for a given steam mass flow rate.

The curves of figure 2-5 are approximately linear, with the slope determined by turbine speed. Each curve can be approximated by

$$m = s(HP) + m_o \quad (\text{lb}_m/\text{hr}) \quad (2-47)$$

where m is the steam mass flow rate, s is the slope of the line, and m_o is the mass flow producing no turbine movement.

A polynomial fit is used to calculate the slope as

$$s = (2.738 \times 10^{-6})N^2 - (2.414 \times 10^{-2})N + 89.35. \quad (2-48)$$

with

$$m_o = 2500 \text{ (lb}_m/\text{hr)} \quad (2-49)$$

Equation (2-47) is used to generate the curves of figure 2-6 which provide a reasonable approximation of the curves of figure 2-5.

Solving equation (2-47), for horsepower yields

$$HP = (1/s)(m - m_o), \text{ (hp)} \quad (2-50)$$

and differentiating this result with respect to steam mass

Figure 2-5: Turbine Horsepower Curves

The horsepower produced by the turbine for a given steam mass flow rate is a function of the turbine speed N . These curves represent data provided by the manufacturer.

Figure 2-6: Turbine Horsepower Curve Fits

The curves in this plot represent the linear equation used to model the turbine horsepower. Reasonable agreement with the manufacturer's data (Figure 2-5) is achieved.

flow rate produces the constant K_1 for the linear model as

$$K_1 = \frac{\partial \dot{H}P}{\partial \dot{m}} = (1/s) \quad (\text{hp}/(\text{lb}_m/\text{hr})) \quad (2-51)$$

or

$$K_1 = \frac{\partial \dot{H}P}{\partial \dot{m}} = k_q (1/s) \quad (\text{hp}/(\text{lb}_m/\text{sec}))$$

Turbine Steam Flow

During operation of the RCIC system, steam originates at the reactor pressure vessel and flows through the steam supply piping and governor valve to the turbine. Some pressure drop occurs in the steam supply piping, but the principal drop occurs at the governor valve. The flow is primarily a function of two quantities: (1) the pressure directly upstream of the valve, and (2) the cross-sectional area of the valve. An equation for the flow as a function of these quantities is developed in this section.

For modeling purposes it is assumed that the piping pressure drop between the vessel and the governor valve is constant at the design maximum value of 15 psi. Thus,

$$P = P_{RX} - 15 \quad (\text{lb}_f/\text{in}^2) \quad (2-52)$$

where P is the pressure immediately upstream of the governor valve, and P_{RX} is the reactor pressure.

The one dimensional isentropic mass flow of a perfect gas (Shapiro 157-163) is given by

(2-53)

$$m = A(k/RT)^{(1/2)} P M / [1 + M^2(k-1)/2]^{(1/2)} [(k+1)/(k-1)] .$$

where M is the mach number, R is the universal gas constant, T is the upstream temperature and k is the ratio of specific heats for steam. If the flow is assumed to be choked, the mach number is unity, and equation (2-53) becomes

(2-54)

$$m = A(kP^2/RT)^{(1/2)} [(k+1)/2]^{-(1/2)} [(k+1)/(k-1)]$$

For a perfect gas,

$$R = P/\rho'T. \quad (2-55)$$

Using (2-55) allows (2-54) to be written

(2-56)

$$m = A(kP\rho'g_o)^{(1/2)} [(k+1)/2]^{-(1/2)} [(k+1)/(k-1)]$$

The constant K_2 for the linear model is obtained by dividing through by the area:

(2-57)

$$K_2 = (k_A k P \rho' g_o)^{(1/2)} [(k+1)/2]^{-(1/2)} [(k+1)/(k-1)] \quad ((lb_m/sec)/ft^2)$$

Governor Valve Area

The governor valve cross sectional flow area is a linear function of the valve position.

Summary of Linear Model Constants

The linear model of figure 2-1 represents the small signal RCIC system dynamics linearized around an operating point of reactor pressure P_0 and system flow Q_0 . A steady state operating speed N_0 corresponds to this point. Table 2-2 summarizes the equations used to calculate each of the constants in the linear model based on the steady state conditions.

TABLE 2-2

Linear Model Constants

$$K1 = \frac{\partial HP}{\partial m} = k_q (1/s) \quad (hp/(lb_m/sec)) \quad (2-51)$$

$$K2 = (k_A k_P p' g_o)^{(1/2)} [(k+1)/2]^{-(1/2)} [(k+1)/(k-1)] \quad (lb_m/sec)/ft^2 \quad (2-57)$$

$$K3 = \frac{\partial N}{\partial t} = k_{THP_{net}}/JN_o \quad (rpm/sec) \quad (2-46)$$

$$K4 = \frac{\partial H}{\partial N} = -\frac{c_b Q_o}{N_B} (N_B Q/N_o)^{c-1} + 2H/N_o \quad (ft/rpm) \quad (2-34)$$

$$K5 = \frac{\partial H}{\partial Q} = (N/N_B)^{2-c_b} c_b Q^{c-1}. \quad (ft/gpm) \quad (2-35)$$

$$K6 = \frac{\partial HP}{\partial H} = (\rho/k_f k_p) Q_o/E_o, \quad (hp/ft) \quad (2-37)$$

$$K7 = \frac{\partial HP}{\partial Q} = (\rho/k_f k_p) H_o [(1/E_o) - (Q_o/E_o^2) (\frac{\partial E}{\partial Q})], \quad (hp/gpm) \quad (2-36)$$

$$K8 = K_f \rho g_o / I \quad ((gpm/sec)/ft). \quad (2-22a)$$

$$K9 = 2k_R Q_o \quad (ft/gpm) \quad (2-13)$$

$$K10 = \frac{\partial HP}{\partial N} = -(\rho/k_f k_p) Q_o H_o / E_o^2 (\frac{\partial E}{\partial N}). \quad (hp/rpm) \quad (2-38)$$

$$\frac{\partial E}{\partial Q} = e(N_B N_o) + 2f(N_B N_o)^2 Q_o + 3g(N_B N_o)^3 Q_o^2 \quad (1/gpm) \quad (2-39)$$

$$\begin{aligned} \frac{\partial E}{\partial N} = & - [e(N_B Q_o)/N_o^2] \quad (1/rpm) \quad (2-40) \\ & - [2f(N_B Q_o)^2/N_o^3] \\ & - [3g(N_B Q_o)^3/N_o^4]. \end{aligned}$$

Reduction of the Linear Model

The model of figure 2-1 can be greatly simplified using block diagram algebra. This is the object of the calculations in this section.

First, flow as a function of pump head is determined by reducing the feedback loops on the right hand side of the linear model. These transfer functions result:

$$T1 = \Delta Q / \Delta H_{PNET} = \frac{K8}{s + K8K9} \quad (2-58)$$

$$T2 = \Delta Q / \Delta H_P = \frac{K8}{s + K8(K9 - K5)} \quad (2-59)$$

Using figure (2-1) and equation (2-59) the block diagrams of figures (2-7a) and (2-7b) can be constructed. It follows from figure (2-7a) that the transfer function for a change in flow due to a change in turbine speed is

$$\Delta Q / \Delta N = \frac{K4K8}{s + K8(K9 - K5)} \quad (2-59a)$$

It follows from figure (2-7b) that the transfer function for a change in turbine speed due to a change in horsepower is

$$\Delta N / \Delta HP = \frac{K3/s}{1 + (K3/s)(K10 + K4K7T2 + K4K6 + K4K5K6T2)} \quad (2-60)$$

or

Figure 2-7a

Figure 2-7b

Figure 2-7: Intermediate Block Diagrams
 These diagrams illustrate process of reducing the linear model to a set of transfer functions.

Figure 2-8: Reduced Linear Model

This block diagram represents the entire plant portion of RCIC. Turbine input horsepower is a constant function of turbine governor valve area. Pump speed is a second order function of input horsepower. Flow is a first order function of pump speed.

$$\Delta N / \Delta HP = \frac{K3[s + K8(K9 - K5)]}{s^2 + [K8(K9 - K5) + K3(K4K6 + K10)]s + K3K8[K4(K6K9 + K7) + K10(K9 - K5)]} \quad (2-61)$$

Finally, the horsepower produced for a given steam governor valve position is

$$\Delta HP / \Delta X = K0 \times K1 \times K2. \quad (2-62)$$

The results of this section are summed up in figure (2-8) which shows the reduced block diagram for the entire plant. The pump speed response to small changes in actuator position is second order, and the dynamic nature of the response is determined by the values of the constants K3 through K10 which are operating point dependent. The flow response to changes in pump speed is first order, with a time constant dependent on operating point. A BASIC program which calculates the constants K0 through K10 and the transfer functions as a function of operating point is given in appendix A. Transfer functions which apply for extreme and rated values of reactor pressure and flow are shown in tables 2-3 and 2-4.

Table 2-3a: Transfer function $\Delta N/\Delta X$
(Turbine speed response to a change in Actuator Position)

REACTOR PRESSURE	FLOW	
	200 GPM	600 GPM (RATED)
165 PSIA	$6900s + 6410$ ----- $s^2 + 1.54s + 2.84$	$6350s + 28600$ ----- $s^2 + 5.64s + 7.53$
1040 PSIA (RATED)		$29200s + 89600$ ----- $s^2 + 4.63s + 18.7$
1156 PSIA	$31700s + 22000$ ----- $s^2 + 1.98s + 13.3$	$30900s + 93000$ ----- $s^2 + 4.62s + 20.0$

Table 2-3b: Transfer Function $\Delta Q/\Delta N$
(Flow response to a change in pump speed)

REACTOR PRESSURE	FLOW	
	200 GPM	600 GPM (RATED)
165 PSIA	2.88 ----- $s + 0.929$	3.64 ----- $s + 4.51$
1040 PSIA (RATED)		6.94 ----- $s + 3.07$
1156 PSIA	7.06 ----- $s + 0.699$	7.28 ----- $s + 3.01$

Tables 2-3: REACTOR INJECTION MODE TRANSFER FUNCTIONS

The transfer functions shown in these tables describe the small signal dynamic behavior of the RCIC system at various steady state reactor injection mode operating points.

Table 2-4a: Transfer Function $\Delta N/\Delta X$
(Turbine Speed Response to a Change in Actuator Position)

REACTOR PRESSURE	FLOW	
	200 GPM	600 GPM (RATED)
165 PSIA	$7940s + 56100$ ----- $s^2 + 7.58s + 4.29$	$4450s + 94300$ ----- $s^2 + 22.8s + 38.7$
1040 PSIA (RATED)		$29700s + 630000$ ----- $s^2 + 22.8s + 38.7$
1156 PSIA	$58900s + 417000$ ----- $s^2 + 7.58s + 4.29$	$33000s + 700000$ ----- $s^2 + 22.8s + 38.7$

Table 2-4b: Transfer Function $\Delta Q/\Delta N$
(Flow response to a change in pump speed)

REACTOR PRESSURE	FLOW	
	200 GPM	600 GPM (RATED)
165 PSIA	1.01 ----- $s + 7.07$	3.03 ----- $s + 21.2$
1040 PSIA (RATED)		3.03 ----- $s + 21.2$
1156 PSIA	1.01 ----- $s + 7.07$	3.03 ----- $s + 21.2$

Tables 2-4: TEST MODE TRANSFER FUNCTIONS

The transfer functions shown in these tables describe the small signal dynamic behavior of the RCIC system at various steady state test mode operating points.

CHAPTER 3

Turbine Speed Control Identification

A detailed layout of the current RCIC turbine speed governor system is shown in figure 3-1. It is the purpose of this chapter to investigate each important component of the system, explain its function, and identify its dynamic behavior. Additionally, the dynamic behavior of the RCIC system flow controller is presented.

Ramp Generator/Signal Converter

Upon RCIC system initiation, the Ramp Generator/Signal Converter (RGSC) box internally generates a linearly changing voltage signal which ramps from a voltage representing turbine idle speed to a voltage representing turbine maximum operating speed of 4500 RPM. The low signal selector, (see figure 3-1) compares the magnitude of the ramp to the magnitude of the flow error signal from the flow controller, chooses the signal which has the smaller magnitude, and presents it to the governor amplifier box as the speed set point. The total ramp time is adjustable, and the recommended setting is approximately 15 seconds.

Governor Amplifier Box

The governor amplifier box (EGM) contains a summing point, a speed section, and an amplifier section with adjustable gain and "stability". The speed section receives

a pulse train from the speed sensor and converts it to a voltage representing the turbine rotational speed. At the summing point, the turbine speed signal is subtracted from the speed setpoint received from the RGSC box. The resulting error signal is presented to the amplifier section which provides the current necessary to drive the solenoid pilot valve of the turbine governor valve actuator (EGR).

Results from laboratory tests (see appendix B) of the EGM box show the gain of the speed section to be

$$G_{FB} = 0.0027 \text{ V/RPM.} \quad (3-1)$$

Tests of the main amplifier at recommended gain and stability settings show the transfer function from speed setpoint voltage to output voltage to be

$$H_{EGM} = \frac{300(s + 10)}{s^2 + 28s + 1936} \quad (3-2)$$

Figure 3-2 shows the Bode plot of this small signal transfer function. For large speed setpoint signals, the output of the amplifier saturates. This results in clipping of the output signal at a magnitude of approximately 8 volts.

Figure 3-2: Governor Amplifier Response

This Bode plot shows the frequency response of the transfer function used to represent the governor amplifier with the gain and stability adjustments set to the recommended values. Frequency response test data are given in appendix B.

Turbine Governor Valve Actuator

The turbine governor valve actuator (EGR) positions the turbine governor valve via a mechanical linkage. The actuator contains a piston whose position is controlled by the increase/decrease of hydraulic fluid volume above/below the piston. An electrically positioned (solenoid) pilot valve controls the flow of hydraulic fluid to the cylinder. Thus the velocity of the actuator is controlled by the position of the pilot valve. Additionally, a "buffering" mechanism is incorporated which modifies the dynamic behavior of the system dependent upon a needle valve adjustment. Results from laboratory tests of the frequency response of the actuator at the recommended needle valve setting show the transfer function from voltage input to actuator position to be

$$H_{EGR} = \frac{52.2(s + 1.6)}{s(s + 7)(s + 160)} \quad (3-2)$$

Figure 3-3 shows the Bode plot of this transfer function. Laboratory data are given in appendix B.

Speed Sensor

The rotational speed of the turbine is measured by the magnetic pickup speed sensor. A toothed wheel which rotates with the turbine shaft is placed in close proximity to the

Figure 3-3: Governor Valve Actuator Response
 This Bode plot shows the frequency response of the transfer function used to represent the governor valve actuator. Test data are given in appendix B.

pickup which produces a voltage pulse as each tooth passes. This pulse train is presented to the speed section of the governor amplifier box.

Flow Controller

RCIC system flow is currently controlled by an analog proportional-integral process controller. The recommended settings for proportional and integral gain are:

$$K_P = 0.2 \quad (3-3)$$

$$K_I/K_P = 20.0 \text{ resets/min.} \quad (3-4)$$

The resulting continuous flow control transfer function is given by

$$H_{FC} = \frac{0.2s + 0.0667}{s} \quad (3-5)$$

Flow Sensor

Flow is sensed by measuring the differential pressure across an elbow in the water piping. The square root of the differential pressure is taken, and a milliamper signal representing flow is produced. The time constant of this sensor is assumed to be small with respect to the system flow dynamics.

CHAPTER 4

Discrete Control Formulation

In the preceding chapters, the transfer function of each plant and control hardware component of the RCIC system is presented. In this chapter, the transfer functions are combined to form continuous linear models of the turbine speed control loop and the overall flow control loop. Suitable discrete transfer functions for the compensators of each control loop are formulated, and the step responses of the discretely-controlled speed and flow loops are simulated.

Turbine Speed Control

Figure 4-1 shows the block diagram of the continuous linear model that represents the turbine and turbine speed control system. This model is directly based on the control hardware transfer functions identified in chapter 3 and the system transfer functions developed in chapter 2. The input to and output from the model are given in RPM for convenience only. When the design is put into hardware, RPM is represented by a voltage or milliamperere signal the magnitude of which is dependent upon the hardware chosen.

The original speed control system produces satisfactory responses. Since this is true, the design of a discrete algorithm for a digital controller to replace the governor amplifier box can be accomplished by emulating the transfer function of equation 3-2 in a discrete manner. However, the

Figure 4-1: Speed Control Loop Block Diagram

This diagram represents the entire speed control loop. The control hardware transfer functions HEGM and HEGR are identified in this chapter. The plant transfer function $\Delta N/\Delta X$ is developed in chapter 2.

Figure 4-2: Flow Control Loop Block Diagram

This diagram illustrates the connection of the flow control loop. The block labeled "Speed Loop" represents the entire model of figure 4-1. Transfer function $\Delta Q/\Delta N$ is developed in chapter 2.

transfer function of the EGM amplifier is unnecessarily complex. A lead compensator with transfer function

$$H = \frac{15(s+5)}{s + 50} \quad (4-1)$$

produces similar responses and is easier to convert to a discrete equivalent.

Equation (4-1) can be converted to an equivalent discrete (z) transfer function by the forward or backward rule, a zero-pole mapping procedure, or a zero order hold equivalent. (Franklin, Powell, and Workman, 1990, pp. 133 - 156). The Matrix-X control design package automates the conversion process (See file "DMODPREP" in appendix C.), and produces a zero order hold equivalent. The discrete equivalent of transfer function (4-1) is

$$H_z = \frac{15z - 13.8}{z - 0.223} \quad (4-2)$$

for a sample period of 30 mS. This period was chosen to provide a sample frequency approximately ten times the open loop bandwidth of the speed loop system. Franklin, Powell, and Workman discuss choice of sample rates on page 180 and in chapter 10.

It is noted that the pole in equation (4-2) is close to zero on the real axis of the Z plane. If the pole were moved

to zero, the form of the transfer function would exactly fit that of the discrete proportional-derivative controller. This is desirable because many commercially available controllers use this type of algorithm. Moving the pole in this manner and moving the zero slightly yields the transfer function

$$H_z = \frac{15z - 13.5}{z} \quad (4-3)$$

which produces good speed loop responses.

System Flow Control

The linear RCIC system model including flow control loop is shown in figure 4-2. In this case the input and output are given in terms of flow in gallons per minute. The block labeled "Speed Loop" represents the entire model of figure 4-1.

The dynamics of the controller given by equation (3-5) are converted to a discrete equivalent using the zero order hold technique as above. The resulting Z transfer function is:

$$G_z = \frac{0.2 z - 0.18}{z - 1} \quad (4-4)$$

Flow Response Results

Test mode system flow responses to steps in flow setpoint are shown in figures 4-3 and 4-4. Results are presented for rated conditions and for each of the extreme flow and reactor pressure conditions identified in table 2-3. The responses in each case are satisfactory.

Figure 4-3: Test Mode Flow Step Response at Low Flow

These plots show the RCIC system small signal flow step response. The upper plot is based on 200 gpm initial steady state flow and 165 psia reactor pressure. For the lower plot, the reactor pressure is 1156 psia. These conditions correspond to entries in table 2-4.

Figure 4-4: Test Mode Flow Step Response at High Flow

These plots show the RCIC system small signal flow step response at 600 gpm initial steady state flow. Reactor pressure differs for each plot, and is as follows: Upper plot, 165 psia; Center plot, 1040 psia; Lower plot, 1156 psia. These conditions correspond to entries in table 2-4.

For the reactor injection mode, the discretely controlled system produces excessive overshoot, particularly at low system flow. This problem is minimized by reducing the flow loop gain by a factor of 10. The resulting flow control transfer function is:

$$G_z = \frac{0.02 z - 0.018}{z - 1} \quad (4-4)$$

The reactor injection mode flow responses which result are shown in figures 4-5 and 4-6.

Figure 4-5: Reactor Injection Flow Step Response at Low Flow

These plots show the RCIC system small signal flow step response. The upper plot is based on 200 gpm initial steady state flow and 165 psia reactor pressure. For the lower plot, the reactor pressure is 1156 psia. These conditions correspond to entries in table 2-5.

Figure 4-6: Reactor Injection Flow Step Response at High Flow

These plots show the RCIC system small signal flow step response at 600 gpm initial steady state flow. Reactor pressure for each plot differs and is as follows: Upper plot, 165 psia; Center plot, 1040 psia; Lower plot, 1156 PSIA. These conditions correspond to entries in table 2-5.

CHAPTER 5

Discrete Control Implementation

This chapter addresses some of the practical aspects of implementing the discrete control system developed in chapter 4. Additionally, data taken from startup of an actual RCIC system is examined and explained. Suggestions are presented which will improve the response when implemented in the new digital control system.

Difference Equations

The Z transfer functions developed above can be implemented in a microprocessor-based controller through use of difference equations. For an explanation of this process, see Franklin, Powell, and Workman, 1990, pp. 46-56. The equations which represent the speed control loop transfer function is:

$$u(k) = 15 e(k) - 13.5 e(k-1) \quad (5-1)$$

Likewise, the difference equation which represents the flow control transfer function (equation 4-3) is:

$$u(k) = u(k-1) + 0.2 e(k) - 0.018 e(k-1). \quad (5-2)$$

The symbols $e(k)$ and $u(k)$ represent the input and output of each compensator at the current sample period. The quantities $e(k-1)$ and $u(k-1)$ represent the same quantities at the previous sample period.

It should be clearly stated at this point that the discrete transfer functions and resulting difference equations are developed for a given sample period. The hardware selected and the software program based on these difference equations must sample the required signals (speed and flow feedback and setpoint signals) at the specified rate. Failure to do so will result in a control response which may not be appropriate. Additionally, the speed control signal calculated using the difference equation must be converted to a continuous analog signal to drive the governor valve actuator. The easiest conversion to realize in hardware is a zero order hold.

Examination of the Startup Data

A brief examination of the RCIC startup data from an actual power plant illustrates some areas in which the system response could be improved.

Figures 5-1 through 5-3 show plots of governor amplifier output, governor valve position, turbine speed, speed ramp generator output, and flow controller output during startup of the RCIC system. When the system starts, the governor valve is wide open. The turbine trip and throttle valve (upstream from the governor valve, see figure 3-1) opens and allows a very high steam flow rate through the governor valve. This results in extremely high turbine acceleration that may cause the turbine to over speed. At this time the

Figure 5-1: RICI Startup Speed Plot

This plot shows data taken during start of an actual RICI system with the original speed and flow controls. The turbine speed peaks dramatically because the governor valve is fully open at startup initiation.

Figure 5-2: RIC I Startup Plot: EGM and EGR Output

This plot shows data taken during start of an actual RCIC system with the original speed and flow controls. The governor valve actuator (EGR) starts out fully open, then slams closed as feedback control becomes effective.

Figure 5-3: RICI Startup Plot: Flow Controller Output

This plot shows data taken during start of an actual RCIC system with the original speed and flow controls. The flow controller starts at the high saturation level due to integrator wind up.

turbine speed is much higher than the setpoint from the ramp generator. The resulting speed error causes the governor amplifier output to swing to the low saturated level; in turn, the governor valve quickly closes, and the turbine speed is reduced. At this point, reasonable control action commences, and the system proceeds to full flow operation. It is noted, however, that the flow controller is wound up to its high saturation limit during the latter portion of the speed setpoint ramp. This causes flow to overshoot the setpoint level, and can again cause turbine over speed.

One additional complication can occur in the startup sequence. Since the governor valve actuator is a hydraulic device which depends on hydraulic pressure that is not produced until the turbine rotates, operation of the actuator can be delayed upon turbine startup. If this delay occurs, the over-speeding problem is aggravated.

The turbine over-speeding problem can be addressed in several ways. One which has been implemented by GE in the past is to install a small bypass line around the turbine governor valve, and start the system with the valve in a fully closed position. This results in slower acceleration and good feedback control being established before the turbine over speeding.

Another possible solution is to replace the turbine governor valve actuator with motor-driven device. This

approach would allow proper control of the system to commence immediately upon system startup from a closed governor valve position. To implement this solution, a new speed control (and perhaps flow control) difference equation would be required; the dynamics of the motor-driven actuator would have to be taken into account.

The integrator wind up problem can be easily solved if flow control, speed control, and ramp generation are all handled by the same software in the same controller. To eliminate wind up, the integration action is inhibited until the speed setpoint ramp reaches the flow control algorithm output produced by proportional action only. At this point, normal proportional-integral flow control action commences.

Controller Pseudocode

The algorithm for the proposed digital controller is shown in figure 5-4 in pseudocode form. The purpose of this code is to clarify the interaction of the speed ramp generation, closed loop speed control, and closed loop flow control. The variables used are defined at the top of the program. The functions Get_QSP, Get_QFB, and Get_NFB acquire the specified analog signal, convert it to engineering units, and restart the analog to digital conversion process. The function Set_VOUT sets the turbine control actuator voltage which is held at this level for the entire sample period.

```

NSP = 0           ! Speed Setpoint
NFB = 0           ! Speed Feedback
NFB_old = 0       ! Speed Feedback from previous sample time
NERR = 0          ! Speed Error
NERR_old = 0      ! Speed Error from previous sample time
VOUT = 0          ! Actuator voltage control signal
QSP = 0           ! Flow Setpoint
QFB = 0           ! Flow Feedback
QERR = 0          ! Flow Error
QERR_old = 0      ! Flow Error from previous sample period
QCOU = 0          ! Flow Controller Output
INC = 9           ! RPM Increment for Ramp
Max_RPM = 4500    ! Maximum Ramp RPM

While (NSP < Max_RPM) Loop
    Start_time = Get_time
    SET_VOUT(VOUT)
    NERR = NSP - Get_NFB
    QSP = Get_QSP
    VOUT = 15*NERR - 13.5*NERR_old
    NERR_old = NERR
    NSP = NSP + INC
    Wait until Get_time - Start_time >= 30 mS
    IF (NSP > FSP*KP) EXIT LOOP
End Loop

Loop
    Start_time = Get_time
    Set_VOUT(VOUT)
    NFB = Get_NFB
    QERR = Get_QSP - Get_QFB
    QCOU = QCOU + 1.5*QERR - 1.35*QERR_old
    NERR = 4500*QCOU - NFB
    VOUT = 15*NERR - 13.5*NERR_old
    QERR_old = QERR
    Wait until Get_time - Start_time >= 30 mS
End Loop

```

Figure 5-4: Controller Pseudocode

This figure presents the basic structure of the control code used to implement the discrete control function in a high level programming language.

Alternative Control Hardware

It is likely that the speed and flow control functions of the RCIC system could be performed by general purpose "off-the-shelf" controllers. The speed loop control is proportional-derivative, and the flow loop control is proportional-integral. These functions, as well as the ramp generation capability used during the turbine startup sequence, are readily available.

One particularly convenient hardware option may be to use analog process control I/O modules which are part of a larger programmable logic controller system. This larger system could handle various relay logic type signals associated with the RCIC system as well as coordinating the speed and flow loop controllers.

Summary

The goal of this report has been to develop the control algorithm presented in this chapter. The process involved two basic steps.

First, equations for each portion of the plant were developed, verified, and linearized in chapter 2. A program was written so this modeling of the plant portion of the RCIC system can be easily repeated for different power plants with different RCIC flow capacities or physical configurations.

The second basic step was to develop a workable discrete algorithm for a new digital speed/flow controller. This

process was accomplished primarily by emulating the dynamics of the existing control hardware in a discrete manner. It was discovered, however, that the flow response in the reactor injection mode is improved by reducing the flow loop gain by a factor of 10.

The final step was to examine the response produced by the existing control system and make some suggestions for improvement. Careful choices concerning implementation of the new control algorithm and selection of the new control hardware should produce a significantly improved system response.

Works Cited

Beer, Ferdinand P., and E. Russell Johnston Jr. Vector Mechanics for Engineers: Statics and Dynamics. New York: McGraw, 1984.

The Crane Company. Flow of Fluids through Valves, Fittings, and Pipe. New York, 1980.

Doebelin, Ernest O. System Dynamics: Modeling and Response. Columbus: Merrill, 1972.

Franklin, Gene F., J. David Powell, and Michael Workman. Digital Control of Dynamic Systems. Reading: Addison, 1990.

Implementation of a Digital Feedwater Control System at Dresden Nuclear Power Plant Units 2 and 3. EPRI NP-6143, Contractors Commonwealth Edison Co. and Atomic Energy of Canada Ltd. Palo Alto: 1988.

Requirement and Design Specifications of a BWR Digital Feedwater Control System. EPRI NP-5502, Contractor, Science Applications International Corp. Palo Alto: 1987.

Shapiro, Ascher. The Dynamics and Thermodynamics of Compressible Fluid Flow. New York: Ronald P, 1953.

Stepanoff, Alexey J. Centrifugal and Axial Flow pumps. New York: Wiley, 1957.

APPENDIX A

Transfer Function Calculation Program/Results

This appendix contains the source code listing of the BASIC program RCIC which calculates the constants K0 through K10 of the linear model and the resulting linear model transfer functions at specific operating points of reactor pressure and RCIC system flow. The program requires an input file containing the information for each operating point, and produces output to the screen on an IBM PC or compatible computer. Input files and results which provide a basis for figures 2-3 and 2-4 are included following the source code listing.

A:\RCIC2.TXT

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```

'Program RCIC
'This program reads an input file which contains information about
'the RCIC system for a particular operating point of water flow and
'reactor pressure. Steady state values of pump head, turbine
'speed, steam mass flow rate, and control valve area are calculated.
'The transfer functions are generated which represent the plant (turbine,
'pump, and piping) linearized about the given steady state operating point.
'This information is printed to an output file which is suitable for
'execution by the Matrix-x control simulation software package.
'
'The input file should contain the following information, one item per line:
'
'1) Comment
'2) Comment continued
'3) Reactor pressure in psia.
'4) Required RCIC flow in GPM.
'5) Difference in elev. CST to RX. + for RX higher. 0 for test mode. (ft.)
'6) Piping Resistance Coeff. ( values differ for test and RX inject modes)
'7) Inertance of water in piping ( ft*sec/gpm )
'8) Density of saturated steam at reactor pressure minus 15 psia.

DIM SHARED PRX AS SINGLE      'Reactor Pressure in PSIA
DIM SHARED Q AS SINGLE        'System Flow in GPM
DIM SHARED PHEAD AS SINGLE    'Total pump head
DIM SHARED PHEADMID AS SINGLE 'Temp var. used in pump speed calc.
DIM SHARED EHEAD              'Elevation head (ft).
DIM SHARED KR                 'Piping resistance coeff. (ft*min^2/gal^2)
DIM SHARED I                  'Inertance of water in piping ( ft*sec/gpm)
DIM SHARED NLO AS SINGLE      'Pump speed Lo limit used in pump speed calc.
DIM SHARED NHI AS SINGLE      'Pump Speed Hi limit used in pump speed calc.
DIM SHARED NMID AS SINGLE     'Temp. pump speed used in pump speed calc.
DIM SHARED N AS SINGLE        'Pump speed in RPM
DIM SHARED HPDR AS SINGLE     'Pump drive horsepower
DIM SHARED ROIN AS SINGLE     'Steam density at turbine inlet in lbm/ft^3
DIM SHARED PIN AS SINGLE      'Pressure at turbine inlet in PSIA
DIM SHARED PEF AS SINGLE      'Pump Efficiency
DIM SHARED TEMP AS SINGLE     'Temp. var used in pump efficiency calc.
DIM SHARED MDOT AS SINGLE     'Steam mass flow rate lbm/sec
DIM SHARED GS AS SINGLE       'Steam flux at turbine control valve
DIM SHARED AV AS SINGLE       'Turbine control valve area
DIM SHARED infile AS STRING   'Name of file containing input data
DIM SHARED COMMENT1 AS STRING
DIM SHARED COMMENT2 AS STRING
DIM SHARED C1 AS SINGLE       'Delta steam flow / delta hp. ((lbm/hr)/hp)
DIM SHARED K1 AS SINGLE       'Delta hpover / delta stm flw (hp/(lbm/sec))
DIM SHARED K2 AS SINGLE       'Delta steam flow / delta gov. valve area
DIM SHARED K3 AS SINGLE       'Delta turbine speed / delta horsepower
DIM SHARED K4 AS SINGLE       'Delta pump head / delta pump speed
DIM SHARED K5 AS SINGLE       'Delta pump head / delta flow
DIM SHARED K6 AS SINGLE       'Delta drive horsepower / delta pump head

```

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```

DIM SHARED K7 AS SINGLE      'Delta drive horsepower / delta flow
DIM SHARED K71 AS SINGLE
DIM SHARED K8 AS SINGLE      'Delta flow velocity / delta pump head
DIM SHARED K9 AS SINGLE      'Delta resistance head / delta flow
DIM SHARED K10 AS SINGLE     'Delta drive horsepower / delta pump speed
DIM SHARED K101 AS SINGLE
DIM SHARED PBO AS SINGLE     'Transfer function coefficients
DIM SHARED PA1 AS SINGLE
DIM SHARED PAO AS SINGLE
DIM SHARED TB1 AS SINGLE
DIM SHARED TBO AS SINGLE
DIM SHARED TA2 AS SINGLE
DIM SHARED TA1 AS SINGLE
DIM SHARED TAO AS SINGLE
'
CONST K = 1.3                'Ratio of specific heats for steam
CONST GC = 32.174            'Prop constant (lbm*ft/lbm*sec^2)
CONST ROWAT = 62.4          'Density of water at oper. temp. (lb/ft^3)

'The following constants are plant specific.

CONST KT = .1.4148          'Turbine constant to match units (HP/Btu/sec)
CONST NB = 3560             'Base speed for pump curves (RPM)
CONST KD = .0002528         'Pump constant to match units
CONST A = 1793              'Pump curve fit constants
CONST B = -4.049E-07
CONST C = 2.95
CONST D = .008786
CONST E = .002083
CONST F = -1.872E-06
CONST G = 5.499E-10
CONST J = 85                'Combined Turbine and Pump inertia
CONST K0 = 4.28             'Delta Gov. vlv area / Delta actuator pos. (in^2 / in)

'Get input file name from user and read data.

CLS
LOCATE 22
INPUT "Enter Name of input data file:", infile
OPEN infile + ".IN" FOR INPUT AS #1
LINE INPUT #1, COMMENT1
LINE INPUT #1, COMMENT2
INPUT #1, PRX
INPUT #1, Q
INPUT #1, EHEAD
INPUT #1, KR
INPUT #1, I
INPUT #1, ROIN
CLOSE #1
CLS

```

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```

'Calculate Required Pump Head ( zero ehead means test mode )
IF EHEAD > 0 THEN
  PHEAD = KR * Q * Q + EHEAD + 144 * (PRX - 14.7) / ROWAT
ELSE
  PHEAD = KR * Q * Q
END IF
'Calculate Pump Speed with crude bisection method

NLO = 10
NHI = 5000
PHEADMID = 0
WHILE ABS(PHEAD - PHEADMID) > .001 * PHEAD
  NMID = NLO + (NHI - NLO) / 2
  PHEADMID = (NMID / NB) ^ 2 * (A + B * (NB * Q / NMID) ^ C)
  IF PHEADMID < PHEAD THEN
    NLO = NMID
  ELSE
    NHI = NMID
  END IF
WEND
N = NMID

'Calculate Pump Efficiency

TEMP = NB * Q / N
PEFF = (D + E * TEMP + F * TEMP * TEMP + G * TEMP ^ 3)

'Calculate Pump Drive Horsepower

HPDR = KD * Q * PHEAD / PEFF

'Calculate required steam mass flow rate

C1 = (2.738E-06 * N * N - .02414 * N + 89.35)
MDOT = (C1 * HPDR + 2500) / 3600

'Calculate steam flux through control valve

GS = .08333 * (K * GC * ROIN * (PRX - 15)) ^ .5 * ((K + 1) / 2) ^ (-.5 * (K + 1) / (K - 1))

'Calculate Valve Area

AV = MDOT / GS

'Print results to screen.

LOCATE 3, 5
PRINT "Input Data File: " + infile

```

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```

LOCATE 6, 5
PRINT COMMENT1
LOCATE 7, 5
PRINT COMMENT2
LOCATE 9, 5
PRINT USING "Reactor Pressure: #### PSIA"; PRX
LOCATE 11, 5
PRINT USING "System Flow: #### GPM"; Q
LOCATE 13, 5
PRINT USING "Pump Head: #### FT"; PHEAD
LOCATE 14, 5
PRINT USING "Pump Speed: #### RPM"; N
LOCATE 15, 5
PRINT USING "Pump Drive HP: #### HP"; HPDR
LOCATE 16, 5
PRINT USING "Pump Efficiency: #### %"; PEFF * 100
LOCATE 18, 5
PRINT USING "Steam Flow: #### lbm/sec"; MDOT
LOCATE 20, 5
PRINT USING "Valve Area: #### in^2"; AV
LOCATE 21, 5
PRINT USING "Actuator Pos.: #### in"; AV / K0
LOCATE 23, 5
INPUT "Press RETURN to continue", junk$
CLS
'
'/////////////////////////////////////////////////////////////////
'Transfer function calculation
K1 = 3600 * (1 / C1)
K2 = GS
K3 = 1614000# / (J * N)
K4 = 2 * PHEAD / N - (C * B * Q / NB) * (NB * Q / N) ^ (C - 1)
K5 = (N / NB) ^ (2 - C) * B * C * Q ^ (C - 1)
K6 = KD * Q / PEFF
TEMP = NB / N
K71 = E * TEMP + 2 * F * TEMP * TEMP * Q + 3 * G * TEMP ^ 3 * Q ^ 2
K7 = KD * PHEAD * (1 / PEFF - Q * K71 / (PEFF * PEFF))
K8 = 1 / I
K9 = 2 * KR * Q
K101 = -E * NB * Q / (N * N) - (2 * F * (NB * Q) ^ 2) / (N ^ 3) - (3 * G * (NB
* Q) ^ 3) / (N ^ 4)
K10 = -KD * Q * PHEAD * K101 / (PEFF * PEFF)
'Transfer function. Pump speed / Actuator position
TB1 = K0 * K1 * K2 * K3
TB0 = TB1 * K8 * (K9 - K5)
TA2 = 1
TA1 = K8 * (K9 - K5) + K3 * (K4 * K6 + K10)
TA0 = K3 * K8 * (K4 * (K6 * K9 + K7) + K10 * (K9 - K5))
'Transfer function. System flow / Pump speed.
PB0 = K4 * K8

```

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```

PA1 = 1
PA0 = K8 * (K9 - K5)
LOCATE 5, 1
PRINT "K1 = "; K1
PRINT "K2 = "; K2
PRINT "K3 = "; K3
PRINT "K4 = "; K4
PRINT "K5 = "; K5
PRINT "K6 = "; K6
PRINT "K7 = "; K7
PRINT "K8 = "; K8
PRINT "K9 = "; K9
PRINT "K10 = "; K10
LOCATE 23, 5
INPUT "Press RETURN to continue", junk$
CLS
LOCATE 5, 5
PRINT "Pump speed / Actuator Position"
LOCATE 7, 5
PRINT TB1, TBO
LOCATE 8, 5
PRINT TA2, TA1, TAO
LOCATE 10, 5
PRINT "System flow / Pump speed"
LOCATE 12, 5
PRINT PBO
LOCATE 13, 5
PRINT PA1, PA0

'Print transfer function to file

OPEN infile + ".tf" FOR OUTPUT AS #1
PRINT #1, "//Plant transfer functions for file " + infile
PRINT #1, "//Trans. Function. Actuator position to pump speed"
PRINT #1, "TNUM = [", TB1, TBO, "]"
PRINT #1, "TDEN = [", TA2, TA1, TAO, "]"
PRINT #1, "//Trans. Function. Pump speed to system flow"
PRINT #1, "PNUM = [", PBO, "]"
PRINT #1, "PDEN = [", PA1, PA0, "]"
LOCATE 23, 5
INPUT "Press RETURN to end", junk$
END

```

05/07/90 File C11
Low RX pressure, Test mode, low flow.
165
200
0.0
6.79E-3
0.3968
0.35923

```
//Plant transfer functions for file C11
//Trans. Function. Actuator position to pump speed
TNUM = [      7937.438      56108.01      ]
TDEN = [      1      7.581991      4.292789      ]
//Trans. Function. Pump speed to system flow
PNUM = [      1.008922      ]
PDEN = [      1      7.068781      ]
```


5/02/90 File C13
Low RX pressure, Test Mode, Rated flow.
165
600
0
6.79E-3
0.3968
0.35923

```
//Plant transfer functions for file C13
//Trans. Function. Actuator position to pump speed
TNUM = [      4446.916      94304.8      ]
TDEN = [      1      22.74786      38.67736      ]
//Trans. Function. Pump speed to system flow
PNUM = [      3.02895      ]
PDEN = [      1      21.20679      ]
```

5/02/90 File C33
Rated RX pressure, Test mode, rated flow.
1040
600
0.0
6.79E-3
0.3968
2.3430

```
//Plant transfer functions for file C33
//Trans. Function. Actuator position to pump speed
TNUM = [      29687.59      629578.5      ]
TDEN = [      1      22.74786      38.67736      ]
//Trans. Function. Pump speed to system flow
PNUM = [      3.02895      ]
PDEN = [      1      21.20679      ]
```

05/07/90 File C41
High RX pressure, Test mode, low flow.
1156
200
0.0
6.79E-3
0.3968
2.6029

```
//Plant transfer functions for file C41
//Trans. Function. Actuator position to pump speed
TNUM = [      58927.76      416547.4      ]
TDEN = [      1      7.581991      4.292789      ]
//Trans. Function. Pump speed to system flow
PNUM = [      1.008922      ]
PDEN = [      1      7.068781      ]
```

05/07/90 File C43
High RX pressure, Test mode, rated flow.
1156
600
0.0
6.79E-3
0.3968
2.6029

```
//Plant transfer functions for file C43
//Trans. Function. Actuator position to pump speed
TNUM = [      33014.03      700121.6      ]
TDEN = [      1      22.74786      38.67736      ]
//Trans. Function. Pump speed to system flow
PNUM = [      3.02895      ]
PDEN = [      1      21.20679      ]
```


05/07/90 File R11
Low RX pressure, RX injection mode, low flow.
165
200
90.8
2.33E-4
0.1763
0.35923

```
//Plant transfer functions for file r11
//Trans. Function. Actuator position to pump speed
TNUM = [      6898.901      6409.195      ]
TDEN = [      1      1.540546      2.843934      ]
//Trans. Function. Pump speed to system flow
PNUM = [      2.883506      ]
PDEN = [      1      .9290167      ]
```

05/07/90 File R13
Low RX pressure, RX injection mode, rated flow.
165
600
90.8
2.33E-4
0.1763
0.35923

```
//Plant transfer functions for file R13
//Trans. Function. Actuator position to pump speed
TNUM = [      6352.017      28616.47      ]
TDEN = [      1          5.63766      7.531801      ]
//Trans. Function. Pump speed to system flow
PNUM = [      3.644083      ]
PDEN = [      1          4.5051      ]
```

5/02/90 File R33
Rated RX pressure, RX injection mode, rated flow.
1040
600
90.8
2.33E-4
0.1763
2.3430

```
//Plant transfer functions for file R33
//Trans. Function. Actuator position to pump speed
TNUM = [      29174.08      89615.52      ]
TDEN = [      1      4.631022      18.69679      ]
//Trans. Function. Pump speed to system flow
PNUM = [      6.936727      ]
PDEN = [      1      3.071751      ]
```

05/07/90 File R43
High RX pressure, RX injection mode, rated flow.
1156
600
90.8
2.33E-4
0.1763
2.6029

```
//Plant transfer functions for file R43
//Trans. Function. Actuator position to pump speed
TNUM = [      30931.76      92953.51      ]
TDEN = [      1      4.618801      19.97952      ]
//Trans. Function. Pump speed to system flow
PNUM = [      7.276249      ]
PDEN = [      1      3.005115      ]
```


APPENDIX B

Laboratory Test Data

This appendix provides the laboratory data which support the Bode plots and transfer functions put forth in chapter 3.

Governor Amplifier Box

Table B-1 shows results acquired during laboratory tests of the governor amplifier box under the following conditions:

- 1) Speed setpoint input voltage is 0.40 volts peak to peak.
- 2) Speed sensor input at zero frequency (shorted).
- 3) Gain setting: 7.5 (GE recommended)
- 4) Stability setting: 7.0 (GE recommended)

Table B-1
Amplifier Frequency Response Data

Freq. (Hz)	Output (V)	Ph. (deg)	Gain (dB)
0.10	0.62	0.0	3.8
0.20	0.62	3.7	3.8
0.40	0.64	6.1	4.1
1.0	0.71	18.4	5.0
2.0	1.00	35.6	7.9
3.0	1.36	39.6	10.6
4.0	1.87	40.6	13.4
5.0	2.58	36.3	16.2
6.0	4.64	26.6	21.3
8.0	4.98	-21.6	21.9
10	3.85	-60.2	19.7
20	1.13	-97.1	9.0
40	0.46	-112	1.2

Table B-2 shows results acquired during laboratory tests of the governor amplifier box under these conditions:

- 1) Speed setpoint input shorted.
- 2) Sine wave with 6 volt p-p amplitude applied to speed sensor input.
- 3) Gain setting 7.5 (GE Recommended)
- 4) Stability setting 7.0 (GE Recommended)

Table B-2
Governor Amplifier Speed Section Gain Data

Input Freq.(Hz)	Equivalent RPM	Output Voltage
000	000	2.19
200	250	1.17
400	500	0.14
600	750	-0.88
800	1000	-1.93
1000	1200	-2.97
1200	1500	-5.06
1400	1750	-6.09
1600	2000	-7.14
2000	2500	-8.10 (Saturated)

A DC bias is present in the output voltage measurements shown. In an operating RCIC system, the amplifier output is offset under steady state conditions because a non-zero voltage is required to maintain the turbine governor valve actuator at zero velocity. The magnitude of the offset in these test data, however, does not necessarily represent the real case. For the models of this paper, the amplifier output is assumed to be zero at steady state. Additionally, it should be noted that the output voltage shown includes the effect of the DC gain of the main amplifier section. To obtain the gain of the speed section only, the main amplifier

gain must be divided out. From the test data, the overall gain is

$$G = 0.0042 \quad \text{V/rpm} \quad (\text{B-1})$$

and the speed section gain is

$$G_{\text{spd}} = 0.0042/1.55 = 0.0027 \quad \text{V/rpm.} \quad (\text{B-2})$$

Governor Valve Actuator

Tables B-3 and B-4 show results acquired during laboratory tests of the governor valve electric/hydraulic actuator (servo). The output voltage values are taken from the slider of a linear potentiometer excited by a constant voltage source. Output position ranges from 0 to 2 inches corresponding linearly to output voltages between 0 and 38.3 Volts. AC input to the solenoid is kept at a constant 4.0 volts peak to peak. Table B-3 results are for a needle valve setting of 0.25 turn. Table B-4 results are for the GE-recommended needle valve setting of 0.5 turn.

Table B-3
Governor Valve Actuator Frequency Response
Needle Valve Setting = 0.25 Turn

Frequency (Hz)	Phase (deg)	Gain (db)
0.01	-86.0	12.1
0.02	-67.6	6.8
0.04	-50.4	2.2
0.06	-35.4	0.82
0.08	-29.5	0.11
0.10	-30.7	-0.22
0.20	-27.0	-0.66
0.40	-27.0	-1.5
0.60	-33.9	-2.3
0.80	-38.3	-3.2
1.0	-43.0	-3.6
2.0	-67.6	-6.8
4.0	-78.6	-11.7
6.0	-88.5	-15.0
8.0	-90.4	-17.2
10	-105	-18.9
20	-129	-25.2
30	-166	-31.4
40	-172	-34.3

Table B-4
Governor Valve Actuator Frequency Response
Needle Valve Setting = 0.5 Turn

Frequency (Hz)	Phase (deg)	Gain (db)
0.1	-7.4	0.26
0.2	-12.3	-0.113
0.4	-25.8	-0.873
0.6	-31.0	-1.50
0.8	-35.4	-2.24
1.0	-41.8	-3.05
2.0	-65.1	-6.32
4.0	-81.1	-11.2
6.0	-89.2	-14.8
10.0	-93.4	-19.1
20.0	-127	-26.9
30.0	-137	-29.2

APPENDIX C

Matrix-X Diary Files

This appendix contains the Matrix-X diary files used to create the simulation models used throughout this paper. The models were created with Matrix-X version 5.22 on an IBM PC compatible computer.

```
//File EGM.TF
//Transfer function for EGM/RGSC
//Settings: EGM: Gain = 7.5, Stability = 7.0
//Transfer function for unity DC gain:
cnum = 194*[1 10]
cden = [1 28 1936]
//EGM gain volts/volt
gegm = 1.5
//EGM speed section gain v/rpm
gfb = 0.0027
//Signal converter gain volts/rpm
gsc = 0.0027
//Convert to cascade compensator with unity feedback
cnum = cnum*gfb*gegm
//Alter set point gain accordingly
gsp = gsc/gfb
```

```
//File EGR2.TF
//Transfer function for EGR Actuator at
// one half turn needle valve setting.
ANUM = 52.2*[ 1 1.6]
ADEN = poly([-7 -160])'
return
```

```
//File Flow.TF
// Transfer function for continuous flow controller
// Includes gains required for unity feedback system
fnum = [ 1.5 0.5]
fden = [ 1 0 ]
```



```
//File NEWCOMP1.TF
//Transfer function for proposed egm replacement
//Transfer function for unity DC gain:
cnum = 10*[1 5]
cden = [1 50]
//EGM gain volts/volt
gegm = 1.5
//EGM speed section gain v/rpm
gfb = 0.0027
//Signal converter gain volts/rpm
gsc = 0.0027
//Convert to cascade compensator with unity feedback
cnum = cnum*gfb*gegm
//Alter set point gain accordingly
gsp = gsc/gfb
```

```

//
// File PLOTFLOW.D
// This file forms the closed
// turbine speed control loop,
// forms the closed flow control loop,
// and plots the step response
exec('flow.tf')
exec('newcompl.tf')
exec('egr2.tf')
exec('r33.tf')
//
// Inputs:  CNUM,CDEN: Compensator transfer function
//          ANUM,ADEN: Actuator Dynamics transfer
//                function ( does not include pole at zero )
//          TNUM,TDEN: Turbine ( actuator pos to speed)
//                transfer function
//          GSP      : Setpoint Gain
//          PNUM,PDEN: Pump/Piping Transfer Function
//
// Outputs: CLNUM,CLDEN : Closed flow loop transfer
//                function, step response
//
aden = convolve([1 0],aden);
//
//Combine Actuator and turbine transfer function
//
num = convolve(anum,tnum);
den = convolve(aden,tden);
//
//Add compensator
//
num = convolve(cnum,num);
den = convolve(cden,den);
//
//Form closed speed loop
//
[s,ns] = sform(num,den);
[s,ns] = feedback(s,ns);
[clnum,clden]=tform(s,ns);
clnum = gsp*clnum;
//
//Add Speed to Flow T function
//
clnum = convolve(clnum,pnum)
clden = convolve(clden,pden)
//
//Add Flow Controller
//

```

```
num = convolve(fnum,cnum)
den = convolve(fden,cden)
//
//Form closed flow loop
//
[s,ns] = sform(num,den);
[s,ns] = feedback(s,ns);
[cnum,cden] = tform(s,ns)
//
//Plot step response
//
plot('xmin /0/ xmax /50/ ymin /0/ ymax /1.5/ hold'
plot('xlabel /TIME/ hold')
plot(['title/Closed Loop Step Response / hold')
plot('ylabel/System Flow/ hold'])
[t,y]=step(cnum,cden,50);
plot(t,y)
pause
erase
return
```

```

//File dmodprep.d
//This file sets up the transfer functions
// required by the linear
//discrete controller flow simulation model
//John Zerwekh
//10-6-91
deltat = 0.03
//
//Form lead compensator discrete equivalent
//For reference only, digital PD eqn substituted below
//
num = [15 75]
den = [1 50]
[s,ns] = sform(num,den);
sd = discretize(s,ns,deltat);
[dlcnum,dlcden] = tform(sd,ns)
//
//Substitute digital PD equivalent here
//
dlcnum = [15 -13.5]
dlcden = [1 0]
dlcnum = dlcnum * 0.0027
//
//Form flow (PI) compensator discrete equivalent
//
num = [0.2 0.0667]
den = [1 0]
[s,ns] = sform(num,den);
sd = discretize(s,ns,deltat);
[dpinum,dpiden] = tform(sd,ns)
dpinum = dpinum * 4500 / 600

```

```
//  
//File dlc.b  
//File to build superblock to represent  
// discrete lead compensator  
//for RCIC speed loop  
//John Zerwekh  
//10-2-91  
//  
build
```

```
Edit Super-Block  
dlc  
0.03  
0  
Define Block  
2  
Dynamic Systems  
Num - Den Coeffs.  
Number of Inputs  
1  
Number of Outputs  
1  
Parameter Entry  
1  
dlcnum  
dlcden  
Y  
Connect Blocks  
External Input  
1  
2  
External Output  
1  
2  
Describe Blocks  
top  
mat
```

```
//  
//File DPI.B  
//File to build discrete flow control compensator  
//John Zerwekh  
//10-2-91  
build  
  
Edit Super-Block  
dpi  
0.03  
0  
Define Block  
2  
  
Dynamic Systems  
Num - Den Coeffs.  
Number of Inputs  
1  
Number of Outputs  
1  
Parameter Entry  
1  
dpinum  
dpiden  
Y  
Connect Blocks  
External Input  
1  
2  
External Output  
1  
2  
Describe Blocks  
top  
mat
```

```
//File spsys.b
//File to build RCIC speed loop model
// with discrete compensator
//John Zerwekh
//10-2-91
//
build
```

```
Edit Super-Block
spsys
0
Define Block
1
Algebraic Equations
Sum of Vectors
Number of Inputs
2
Number of Outputs
1
Parameter Entry
2
+1,-1
Define Block
2
Super-Block
Block Name
dlc
```

```
Number of Inputs
1
Number of Outputs
1
Parameter Entry
Define Block
3
Dynamic Systems
Num - Den Coeffs.
Block Name
sys
Number of Inputs
1
Number of Outputs
1
Number of States
5
Parameter Entry
2
snum
```

sden

Y

Connect Blocks

Internal Path

1

2

Internal Path

2

3

Internal Path

3

1

1,2

0,0

External Input

1

1

1,1

0,0

External Output

1

3

Describe Blocks

top

mat


```
//File flsys.b
//File to build RCIC flow loop
//with discrete compensators
//John Zerwekh
//10-2-91
build
```

```
Edit Super-Block
flsys
0
Define Block
1
Algebraic Equations
Sum of Vectors
Number of Inputs
2
Parameter Entry
2
+1,-1
Define Block
2
Super-Block
Block Name
dpi
```

```
Parameter Entry
Define Block
3
Super-Block
Block Name
spsys
```

```
Parameter Entry
Define Block
4
Dynamic Systems
Num - Den Coeffs.
Block Name
pupi
```

```
Parameter Entry
0
pnum
pden
Y
Connect Blocks
Internal Path
1
```

```
2
Internal Path
2
3
Internal Path
3
4
Internal Path
4
1
1,2

0,0

External Input
1
1
1,1

0,0

External Output
1
4
top
mat
```

```
//File dflow.d
//File to build discrete flow model
//and show step response
//John Zerwekh
//10-5-91
t = [0:0.1:15]';
u = ones(t);
//
//Combine actuator and turbine transfer functions
//and build model.
//
exec('egr2.tf')
aden = convolve([1 0],aden)
snum = convolve(anum,tnum)
sden = convolve(aden,tden)
exec('dlc.b')
exec('dpi.b')
exec('spsys.b')
exec('flsys.b')
build
6
flsys
y = sim(t,u);
plot(t,y)
pause
erase
```