Teaching with the

KRi Coupled-Tank Control Apparatus

Model PP-100

Application Note Ref: CT-104
Date: December 18, 1995

Prepared by: KW Lim, UNSW &
KK Sin, *KRi*
for KentRidge Instruments Pte Ltd

Teaching with the
KRi Coupled-Tank Control Apparatus PP-100

IMPORTANT NOTICES

Acknowledgements

The *KRi* Coupled-Tank Control Apparatus PP-100 is designed and manufactured by KentRidge Instruments Pte. Ltd. in collaboration with Hyatech, Australia.

Document File: CT104C.DOC

Printed in Singapore

TABLE OF CONTENTS

TABLE OF FIGURES

TEACHING WITH THE *KRi* COUPLED-TANK CONTROL APPARATUS PP-100

KW Lim and KK Sin

OVERVIEW

The *KRi* Coupled-Tank Control Apparatus PP-100 is a low-cost pilot plant designed for laboratory teaching of both introductory and advanced control systems theory. This application note outlines a set of experiments which uses the apparatus. Figure 1 shows a photograph of the apparatus. It consists of two small tower-type tanks mounted above a reservoir which functions as storage for the water. Water is pumped into the top of each tank by two *independent* pumps. The level of water in each tank is clearly visible on the attached scale at the front of the tanks. Each level is monitored by a capacitive-type probe. Each tank is fitted with an outlet near its base. The amount of water which returns to the reservoir is approximately proportional to the head of water in the tank since the return tube at the base of the tank functions as a pseudo-linear hydraulic resistance. An internal baffle controls leakage between the two tanks to simulate complex tank arrangements: it can be raised or lowered to change the inter-tank resistance. A detailed description of the apparatus can be found in the operator and service manual.

The *KRi* Coupled-Tank Control Apparatus PP-100 can be used for teaching system modeling using static and transient measurements; steady state error analysis; transient response studies; and for evaluating the design, operation and application of common controllers as well as controller tuning methods. This apparatus also demonstrates fluid transportation and level controls, dynamic problems typical in the process control industry. Application note CT-101 describes how the apparatus can be configured as two SISO plants, one second order plant, one cascaded control plant or one MIMO plant.

The experiments suggested in this note complement an introductory level subject in control systems engineering. Each of the experiments can be completed in a 2 to 3 hour laboratory period. With the longer duration, students can be expected to carry out a detailed analysis and to relate the experimental observations to mathematical models if desired.

REFERENCES

1. Astrom, K.J. and Wittenmark, B. Computer controlled systems: Theory and design. Prentice-Hall 1990 ISBN 0-13-172784-2
2. Banks, Stephen P Control Systems Engineering Prentice Hall ISBN 0-13-171794-4
3. Franklin G F, Powell J D and Abbas Emami-Naeini Feedback Control of Dynamic Systems Addison-Wesley ISBN 0-201-11540-9
4. Hunter R P Automated Process Control Systems - Concepts and Hardware (2nd Ed) Prentice Hall ISBN 0-13-054479-5
5. Kuo B C Automatic Control Systems 5th Ed Prentice Hall International ISBN 0-13-055070-1
6. Luyben W.L. Process Modeling, Simulation and Control for Chemical Engineers 2nd Edition McGraw Hill Internationa Edition 1990 ISBN 0-07-100793-8

7. Murrill PW Fundamentals of Process Control Theory Instrument Society of America ISBN 0- 87664-507-4
8. Seborg, DE, Edgar TF and Mellichamp DA Process Dynamics and Control John Wiley and Sons, 1989 ISBN 0-471-86389-0
9. Shinskey F G Process Control Systems - Application/ Design/ Adjustment Mc-Graw Hill Book Co ISBN 0-07-056891-X

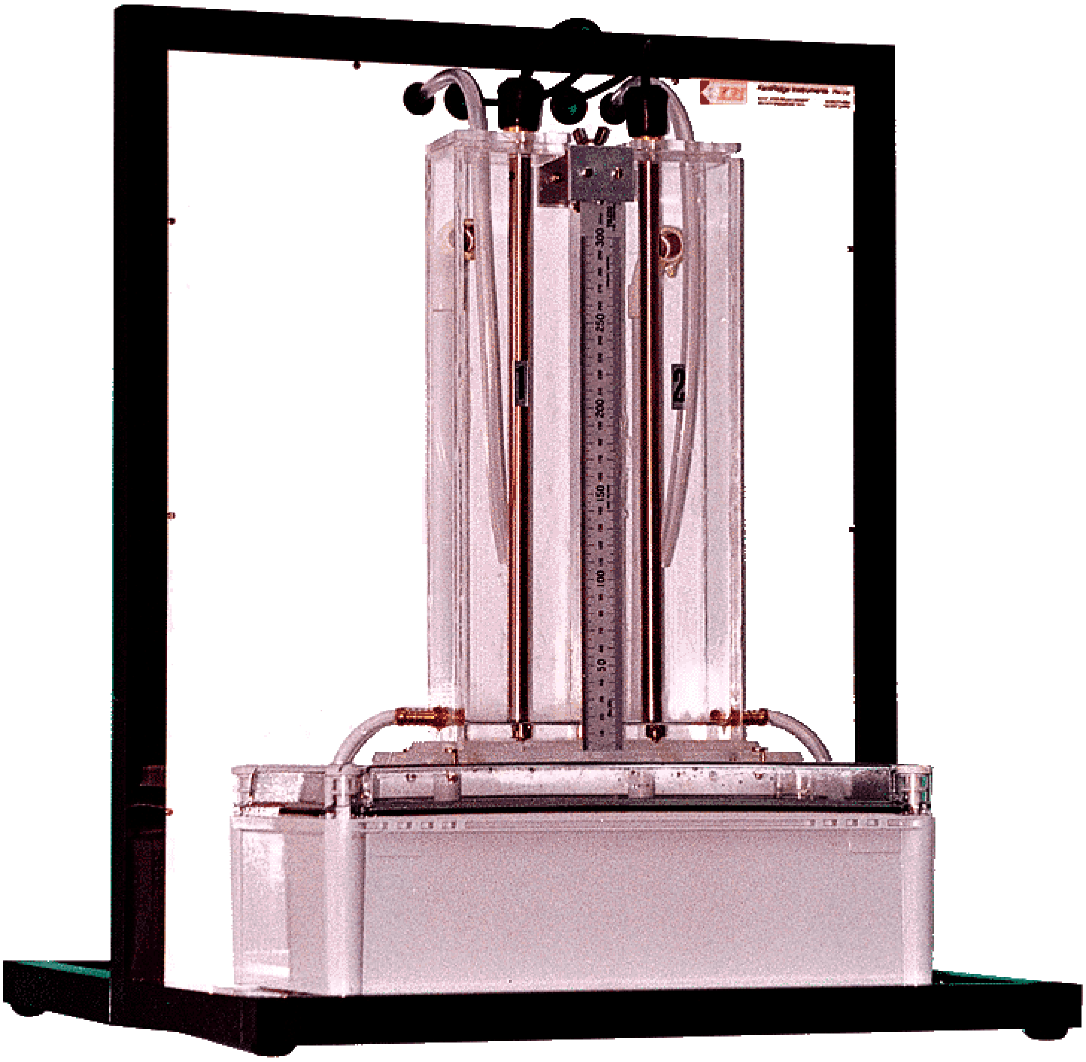

Figure 1 *KRi* Coupled-tank control apparatus Model PP-100

RELATED REFERENCES

1. *Coupled-Tank Control Apparatus: Operator and Service Manual*, KentRidge Instruments.

2. *A Template for Implementing Computer Control on the KRi Coupled-Tank Control Apparatus PP-100*, Application Note: CT-100, KentRidge Instruments, 1995.

3. *Application Examples of the KRi Coupled-Tank Control Apparatus PP-100*, Application Note: CT-101, KentRidge Instruments, 1995.

4. *Dynamic Models for the KRi Coupled-Tank Control Apparatus Model PP-100*, Application Note: CT-102, KentRidge Instruments, 1995.

5. *Experiments Using the KRi Coupled-Tank Control Apparatus Model PP-100*, Application Note: CT-103, KentRidge Instruments, 1995.

OTHER *KRi* PRODUCTS

KentRidge Instruments Pte Ltd offers a family of control apparatus or equipment for teaching and research in control engineering:

- Fan & Plate Control Apparatus **PP-200**
- Inverted Pendulum **PP-300**
- FlexiDrive **PP-400**
- Dual Process Simulator **KI-101**
- Mixed Signal Test Unit **TU-100**
- Controller Boards **UC96**

For more information, please contact:

KentRidge Instruments **Pte Ltd**
Block 51, Ayer Rajah Crescent, #05-14/15, Singapore 139948
Tel: +(65) 774 4685 Fax: +(65) 774 4695 Email: kriskk@kri.com.sg

EXPERIMENT 1: CHARACTERIZING SYSTEM COMPONENTS

Objectives

- To become familiar with the main components of the coupled-tank control apparatus.
- To estimate important system parameters.

Synopsis

This is a three-part experiment which introduces the main components and important parameters of the PP-100.

Figure 2 shows a schematic of the coupled tank apparatus. The first part of the experiment involves calibration of the level sensors. This exercise will allow the students to relate water level measured in volts to the actual head of water H_1 and H_2 in the tanks. The second part estimates the proportionality constant for discharge of water through the outlet spigot. The third part involves calibration of the volumetric flow rate of each pump, Q_{i1} and Q_{i2} and its steady state relationship to applied voltage.

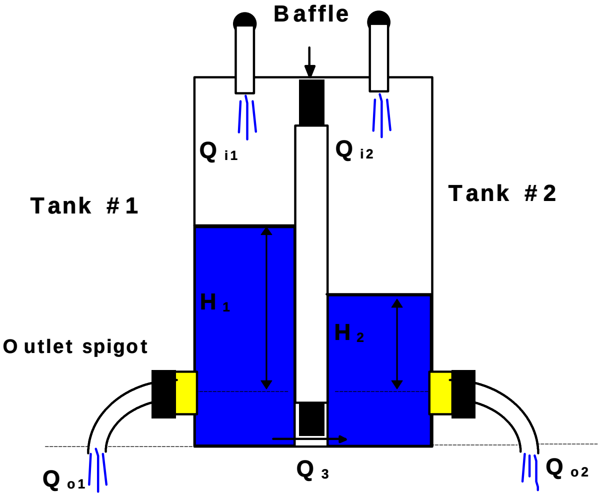

Figure 2 Diagram of coupled-tank control apparatus

Lessons Learned and Data Obtained

1. Modeling from physical principles
2. How to characterize the level sensors and the actuator (pumps)
3. Estimating the rate of discharge of water through an orifice
4. Calibration graphs for the coupled-tank control apparatus.

EXPERIMENT 2: STEADY STATE SYSTEM RESPONSE

Objective

- To measure the steady state response of the coupled-tank apparatus configured as a two tank system.

Synopsis

The system dynamics of the coupled-tank control apparatus can be modeled by a set of nonlinear state equations:

$$\begin{aligned} A_1 \frac{dH_1}{dt} &= Q_{i1} - \alpha_1 \sqrt{H_1} - \alpha_3 \sqrt{H_1 - H_2} \\ A_2 \frac{dH_2}{dt} &= Q_{i2} - \alpha_2 \sqrt{H_2} + \alpha_3 \sqrt{H_1 - H_2} \end{aligned} \quad \text{.............}(1)$$

An analysis of Equation (1) at steady state shows that the steady state characteristics of the apparatus are dependent on operating levels.

In this experiment, the water level in tank #2 is the process variable (plant output) and the inflow to tank #1 is the manipulated variable (plant input). The steady state gain of the plant is defined as the

$$\frac{\text{change in output}}{\text{change in input}} \quad \text{..}(2)$$

From equation (1), the steady state gain is a function of the operating level and the proportionality constants. This experiment explores the steady state gain characteristics of the plant and its dependence of operating point.

Lessons Learned and Data Obtained

1. How to configure the PP-100 as a second-order plant.
2. How to measure steady-state response of coupled-tank control apparatus.
3. To illustrate the nonlinear nature of the coupled-tank control apparatus.

EXPERIMENT 3: DYNAMIC STEP RESPONSE

Objective

- To measure the step response of the coupled-tank control apparatus.

Synopsis

In this experiment, the water level in tank #1 (or #2) is the process variable (plant output) and the inflow to tank #1 is the manipulated variable (plant input). This experiment will explores the step response of the plant and its dependence on operating point. The coupled-tank control apparatus is first configured as a first order plant and then as a second order plant.

A mathematical model of the coupled-tank control apparatus is described in application note CT-102. For small perturbations in inflow and level, the nominal transfer function for the first order plant (or configuration) is

$$\frac{h_1(s)}{q_1(s)} = \frac{K}{(Ts+1)} \quad \text{...}(3)$$

while for the second order plant (or configuration), it is of the form

$$\frac{h_2(s)}{q_1(s)} = \frac{K(s+\beta)}{s^2 + 2\xi\omega_n s + \omega_n^2} \quad \text{...}(4)$$

In this experiment, the step responses of the plant are used to estimate the gain K, time constant T, natural frequency ω_n and damping factor ξ in the above equations. The dependence of the step response, and therefore process parameters in equations (3) and (4), on operating point (level) is also investigated.

Lessons Learned and Data Obtained

1. How to measure step response.
2. How to configure the coupled-tank control apparatus as a first order and a second order plant.
3. How to use the step response to estimate the nominal transfer function
4. Relationship between the nominal model, the configuration and operating point.

EXPERIMENT 4: OPEN LOOP (MANUAL) CONTROL

Objectives

- To observe the performance and limitations of open loop control (manual control) for setpoint change and for disturbance rejection.

Synopsis

In industrial control, we wish to set the process variable (PV) to some desired set point profile. We do this by adjusting the manipulated variable (MV). On the coupled tank apparatus, the MV is the input flow rate (through the pumps). The process may be subject to disturbances *e.g.* a change in water outflow or a change in the second pump inflow.

The process variable should track the setpoint both dynamically and at steady state. If the set point is constant, this is called the regulation problem. If the set point varies, this is called the servo problem. Furthermore, we would like to achieve this tracking of the set point even if there are plant load changes or disturbances. We can emulate a disturbance by changing the flow of water into the second tank. Naturally, we also need a stable response.

In this experiment, we examine the performance of open loop control or manual control. Figure 3 shows a block diagram of the control scheme. Here the MV is set to a value which the human operator estimates will yield a PV at the desired setpoint.

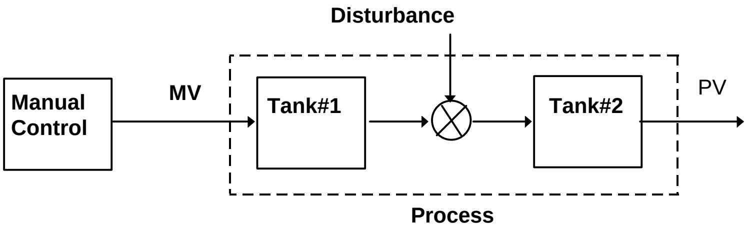

Figure 3 Block diagram of open loop control

Lessons Learned and Data Obtained

1. The effect of disturbances on the process variable
2. The performance and limitations of open loop control (manual control) for setpoint change and for disturbance rejection.
3. The setpoint and disturbance response of the process under open-loop or manual control.

EXPERIMENT 5: INTRODUCTION TO FEEDBACK CONTROL

Objectives

- To study the transient and steady state performance of the coupled-tank control apparatus under proportional feedback control

Synopsis

In this experiment, we introduce feedback control. We begin by examining the performance of a simple proportional feedback controller. Figure 4 shows a block diagram of the control scheme. Here we compare the measured PV with a desired setpoint (SP). The MV is proportional to the resulting error signal. This moves the process variable towards the desired setpoint. Through feedback, the controller can also detect and reject disturbances on the process variable. A further advantage of feedback is that the transient response to change in setpoint or rejection of disturbance can be adjusted with a properly tuned controller.

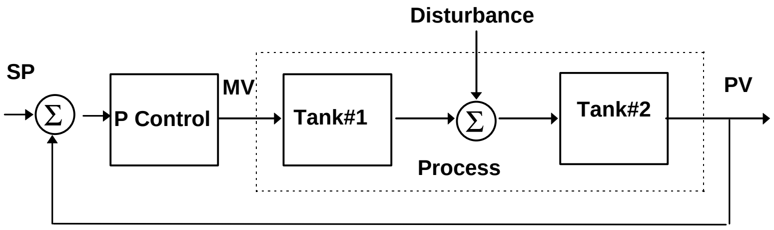

Figure 4 Block diagram for proportional feedback control

Lessons Learned and Data Obtained

1. Application of feedback control for setpoint tracking and load rejection.
2. The difference between disturbance response and setpoint response.
3. Presence of steady-state errors under feedback control.
4. How to tune a P controller (by trial and error).
5. The closed-loop setpoint and disturbance response of the process under P control.

EXPERIMENT 6: INTRODUCTION TO INTEGRAL AND DERIVATIVE CONTROL

Objectives

- To study the transient and steady state performance of the coupled-tank control apparatus under proportional, integral and derivative feedback control

Synopsis

With proportional control, it is not possible to remove steady state error. This experiment introduces integral and derivative feedback to improve control.

In integral control, the MV is proportional to the integral of the error signal. Unfortunately a purely integral controller tends to give an oscillatory response. In practice it is usually used in combination with proportional control. The resulting controller is called proportional plus integral control (PI).

In many processes, the transient response with PI response may be too slow. Rate or derivative action is necessary. With rate action, a component of the MV is proportional to the rate of change of the error signal. The resulting controller is called a proportional plus integral plus derivative controller (PID).

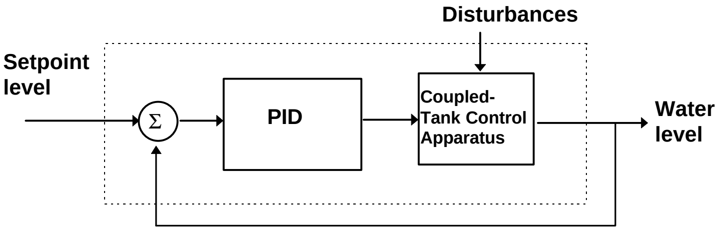

Figure 5 Feedback with a PID Controller

Figure 5 shows the block diagram of a feedback arrangement with a PID controller. To use the PID controller effectively, it is necessary to understand the function of each term of the controller. and its effect, on the closed loop system response. It is also necessary to tune the PID controller.

Lessons Learned and Data Obtained

1. Use of integral control to remove steady-state error.
2. Use of derivative control to improve transient response.
3. Application of PID control in process control.
4. How to tune a PID controller (by trial and error).
5. The closed loop setpoint and disturbance response of the process under PID control.

EXPERIMENT 7: TUNING A PROPORTIONAL, INTEGRAL AND DERIVATIVE (PID) CONTROLLER

Objectives

- To tune a PID controller using Ziegler-Nichols tuning rules.

Synopsis

The three term or PID controller is the most common feedback controller used in industrial control. To use the PID controller effectively, it is necessary to tune the PID controller for optimal performance. Tuning is selection of the proportional gain K, the reset time T_i and the derivative gain T_d. The three parameters should be selected to meet a set of defined goals. These goals typically require a plant response (PV) with minimal steady state error (offset), insensitivity to load disturbances and an acceptable transient response to setpoint changes and to disturbances.

In practice, the choice of proportional gain, reset time and rate gain is a compromise between setpoint tracking and disturbance rejection. If a mathematical model of the plant is known or can be determined, then selecting the controller's parameters becomes relatively simple. Unfortunately, in many industrial applications, a reliable mathematical model is not available or is difficult to determine. Fortunately empirical rules have been developed for tuning PID controllers which do not require an explicit model. A widely known set of rules is that proposed by Ziegler and Nichols in 1942.

In this experiment, we will study two methods of tuning a PID controller which are based of Ziegler and Nichols' empirical rules:

(1) The Open Loop Method

In the open loop method, the plant is modeled as a first order process with steady state gain K, time constant T and dead time τ . With the feedback loop open, a step input (MV) signal is applied and the step response (process reaction curve) of the process is recorded. From the step response, we can obtain approximate values for K, T and τ. The P or PI or PID parameters are then calculated from Ziegler and Nichols' empirical rules which relates them to K, T and τ.

(2) The closed-loop tuning method

The process is placed in closed loop control with a proportional controller. The proportional gain is increased until the PV goes into continuous constant amplitude oscillation. The corresponding value of proportional gain is called the ultimate gain, K_{cu} and the period of oscillation is called the ultimate period, P_u. The P or PI or PID parameters are then calculated from Ziegler and Nichols' empirical rules K_{cu} and P_u

Lessons Learned and Data Obtained

1. How to tune a PID controller in open-loop and closed-loop configuration using empirical rules.
2. The difference between open-loop and closed-loop tuning.

3. The difference between tuning for setpoint and disturbance response.
4. The setpoint and disturbance response of the process under PID control.