Teaching with the

KRi Fan and Plate Control Apparatus

Model PP-200

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KRi Fan and Plate Control Apparatus PP-200

IMPORTANT NOTICES

Acknowledgements

The Fan and Plate Apparatus PP-200 is designed and manufactured by KentRidge Instruments Pte. Ltd. in collaboration with the National University of Singapore.

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TEACHING WITH THE *KRi* FAN AND PLATE CONTROL APPARATUS PP-200

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OVERVIEW

This application note outlines a set of experiments which uses the *KRi* Fan & Plate Control Apparatus PP-200. The PP-200 apparatus consists of a hinged rectangular plate and a variable speed fan. The angular orientation of the plate is controlled by blowing an air stream at it with the fan. The fan is driven by a dc motor and the plate rotation angle is measured with a low friction potentiometer. Figure 1 shows a photo of the apparatus. A detailed description of the apparatus can be found in its operator and service manual[1].

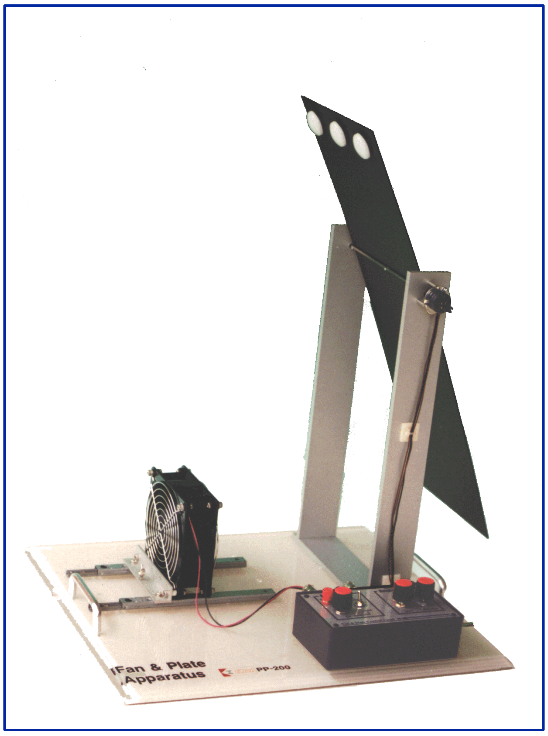

Figure 1 *KRi* Fan & Plate Control Apparatus PP-200

The apparatus contains rich dynamics, suitable for evaluating modern advanced digital controllers. Important dynamic elements include the fan motor time constant, air transport lag, resonant poles, disturbances from air turbulence and a non-minimum phase response. Loading the plate allows a change in the dominant time constant while moving the position of the fan allows a change in dead time. Therefore the PP-200 is also a versatile plant for evaluating controller robustness.

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[1] See "*KRi* Fan & Plate Control Apparatus Model PP-200: Operator and Service Manual"

There is a total of six (6) experiments suggested for the Fan & Plate Control Apparatus. The first three experiments are suitable for an undergraduate course in control systems engineering while the last three are appropriate for an advanced undergraduate course or a postgraduate course. 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.

RELATED PUBLICATIONS

1. *Dynamic Models for the KRi Fan & Plate Control Apparatus PP-200*, Applications Note: FP-201, KentRidge Instruments Pte Ltd, 1996.
2. *Experiments using the KRi Fan & Plate Control Apparatus PP-200*, Applications Note: FP-202, KentRidge Instruments Pte Ltd, 1996.
3. *KRi Fan & Plate Control Apparatus Operator and Service Manual*, KentRidge Instruments Pte Ltd, 1995-1997.

OTHER *KRi* PRODUCTS

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

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

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EXPERIMENT 1: CHARACTERIZING SYSTEM COMPONENTS

Objectives

- To introduce the major dynamical elements of the Fan & Plate Control apparatus.
- To measure the steady state response of the plate angle to fan voltage.

Synopsis

This is an experiment to introduce the major dynamical elements of the PP-200 and to obtain an estimate of its steady state response. Figure 2 below is a block diagram of the main subsystems in the apparatus. The first block on the left represents the fan motor and power amplifier dynamics. The input to the block is a single ended dc voltage in the range 0-5 Volts. The second block represents air stream dynamics. This is principally a transport lag, the magnitude of which is varied by moving the physical location of the fan. The disturbance input shown represents air turbulence or an external torque applied to the plate. The third block represents the plate dynamics. The output of this block is the plate angle.

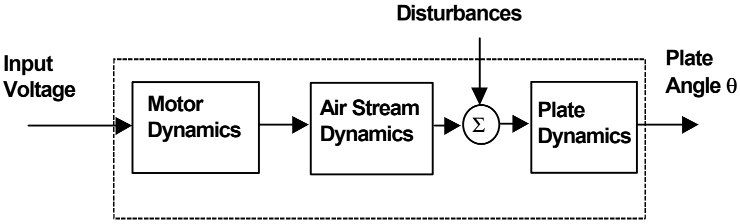

Figure 2 Block diagram of fan and plate control apparatus

The plate angle is measured with a rotary potentiometer. The first part of this experiment is a calibration of the angle sensor. This will allow users to relate angle measured in volts to the actual angular orientation of the plate. The second part establishes the operational range of the apparatus under different configurations. Configurations are altered by moving the fan and/or adding weights to the plate. The third part of this experiment measures the steady state relationship between the voltage signal and the plate angular orientation.

Lessons Learned and Data Obtained

1. How to use the Fan & Plate Control Apparatus as a single input single output plant.
2. Maximum range of plate angle for each configuration.
3. How to measure and estimate steady state gain of the process.

EXPERIMENT 2: DYNAMIC STEP RESPONSE

Objective

- To measure the step response of the Fan & Plate Control Apparatus.
- To estimate the parameters of a simple first order model with dead time.
- To examine the relationship between a nominal model and the operating point

Synopsis

On the Fan & Plate Control Apparatus, the angular orientation of the plate is the *process variable* (or plant output) and the voltage applied to the fan motor is the *manipulated variable* (or plant input). This experiment examines the step response characteristics of the plant and its dependence on operating point.

In the block diagram of Figure 2, the fan motor dynamic response is faster than the plate dynamic response. The air stream dynamics may be represented by a transport lag. Ignoring the resonant dynamics, due for instance to the flexing of the plate, a nominal model of the whole plant consists of a first order transfer function with dead time. This nominal linear model is applicable for small perturbations in the input voltage within its operating range. The coefficients of the nominal model depend on the operating point (mean plate angle). A mathematical model of the Fan & Plate Control Apparatus is described in application note FP-201.

For changes in applied voltage against changes in angle, the nominal transfer function is

$$\begin{bmatrix} \frac{dh_1}{dt} \\ \frac{dh_2}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_1} & \frac{k_{12}}{T_1} \\ \frac{k_{21}}{T_2} & -\frac{1}{T_2} \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} + \begin{bmatrix} \frac{k_1}{T_1} & 0 \\ 0 & \frac{k_2}{T_2} \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \end{bmatrix} \quad \text{..(1)}$$

In this experiment, the step response of the plant is used to estimate the gain, time constant and transport lag in Equation (1). Students will be encouraged to attempt manual control of the plate angle and to assess the difficulty of maintaining a desired plate angle in the face of disturbances.

Lessons Learned and Data Obtained

1. How to obtain the step response of the Fan & Plate Control Apparatus.
2. How to use the step response to estimate the nominal transfer function
3. Relationship between the nominal model and the configuration and operating point.
4. The difference between disturbance response and setpoint response.
5. The performance and limitations of open loop control (manual control) for setpoint change and for disturbance rejection.

EXPERIMENT 3: FEEDBACK USING A PID CONTROLLER

Objective

- To study the transient and steady state performance of the Fan & Plate Control Apparatus under proportional, integral and derivative feedback control

Synopsis

The Fan & Plate Control Apparatus PP-200 is a laboratory bench top emulation of a process with rich dynamics. In this apparatus, the process variable (PV) is the plate angle. We wish to set the PV to some desired set point profile. We do this by adjusting the manipulated variable (MV). On the fan and plate control apparatus, the MV is the fan motor voltage. The process may be subject to disturbances *e.g.* a torque perturbation to the plate.

We would like the process variable to 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. Naturally, we also need a stable response.

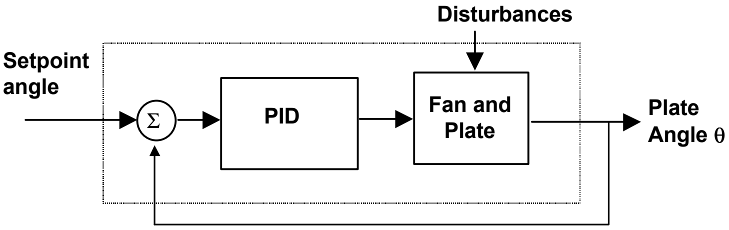

Figure 3 Feedback with a PID Controller

Figure 3 shows the block diagram of a feedback arrangement with a PID controller. The three terms or PID controller is the most common feedback controller used in industrial control. To use the PID controller effectively, it is necessary to understand the function of each term of the controller. In this experiment, each term of the PID controller, and its effect, on the closed loop system response is examined. It is also necessary to tune the PID controller. Tuning is the 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. 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. This experiment will demonstrate the use of these rules as the starting point for tuning PID controllers.

Lessons Learned and Data Obtained

1. The function of each term in a PID controller.
2. How to tune a PID controller.
3. The closed loop setpoint and disturbance response of the process under PID control.

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EXPERIMENT 4: SYSTEM IDENTIFICATION

Objectives

- To introduce a least squares parameter estimation technique for identifying a dynamic model of the process

Synopsis

For good control of a dynamic process, we may need a dynamic model of the process. There are a large number of techniques for obtaining a dynamic model [1,2]. In application note FP-201, a model structure is established for the fan & plate control apparatus from physical principles. To complement physical modeling, a black box approach first assumes a model structure and then attempts to determine the model parameters.

The aim of this experiment is to demonstrate the use of correlation and parameter estimation methods for *System Identification* on the fan & plate control apparatus PP-200. With an appropriate choice of input signal, a set of input-output data is collected from the apparatus and conditioned with appropriate signal processing. The parameter estimation process begins with a hypothesis on the model order and delay. The physical model given in application note FP-201 provides a good starting point.

A variety of least squares techniques [3] can be applied to obtain the model coefficients. With the many software packages now available on hardware platforms varying from personal computers to mainframes, computing a least squares estimate is simple. The initial hypothesis is then tested in a series of model validation steps. If the test results are unsatisfactory, the model order and/or delay is modified for another attempt.

Lessons Learned and Data Obtained

1. Signal conditioning for system identification
2. Applying linear least squares and model validation
3. Choosing an appropriate input sequence for system identification
4. A nominal first order model and a nominal 3rd order model for the apparatus

References

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Comment

This experiment is appropriate for a second course in control at the advanced undergraduate level or at a postgraduate level.

EXPERIMENT 5: POLE PLACEMENT CONTROL

Objectives

- To obtain a controller transfer function given the desired closed-loop response and a nominal plant model.
- To evaluate the performance of a pole placement digital controller

Synopsis

Figure 4 below shows a block diagram of the apparatus with a discrete time transfer function represented by G(z). The controller block is represented by the transfer function D(z). N(z), Y(z), $Y_{sp}(z)$ represent disturbances, plate angle and desired plate angle respectively.

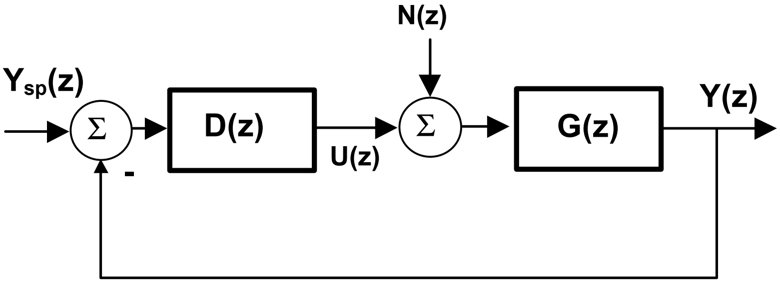

Figure 4 Block diagram of closed-loop system

The problem is to find the controller transfer function D(z) so that the closed loop system has the desired system properties. Equation (2) below shows the closed loop transfer functions.

$$\begin{aligned} Y(z) &= \frac{G(z)D(z)}{1+G(z)D(z)} Y_{sp}(z) + \frac{G(z)}{1+G(z)D(z)} N(z) \\ U(z) &= \frac{D(z)}{1+G(z)D(z)} Y_{sp}(z) - \frac{G(z)D(z)}{1+G(z)D(z)} N(z) \end{aligned} \qquad \text{................ (2)}$$

We design D(z) so each of the transfer functions meets appropriate performance criteria. For stability, we also expect each transfer function to be stable. If there are no common factors in D(z) and G(z) this is equivalent to requiring that 1+D(z)G(z) have stable roots. With a common factor, we must ensure, in addition, that the controller does not attempt to cancel an unstable open loop pole with a controller zero. It is also important that we do not attempt to cancel non minimum phase open loop zeros with a controller pole.

This experiment will use the models obtained in Experiment 4 to design and realize a pole placement controller for the apparatus. The nature of the plant model will allow students to explore issues related to unstable pole-zero cancellations.

Lessons Learned and Data Obtained

- Specifying desired closed-loop transfer functions
- How to obtain the controller transfer function given the desired closed loop response and a plant model.
- Realizing a digital controller
- Evaluating the performance of a pole placement digital controller
- Effects of poles of system performance

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Comment

This experiment is appropriate for a second course in control at the advanced undergraduate level or at a postgraduate level.

EXPERIMENT 6: PREDICTIVE CONTROL ON THE FAN & PLATE CONTROL APPARATUS

Objectives

- To introduce predictive control for controlling a process with dead-time
- To compare the performance of a conventional PID controller with a predictive controller

Synopsis

Dead-time or transport lag is a common part of many industrial processes. A dead-time element adds phase lag to a feedback loop. If a standard PID controller is used, significant de-tuning is required to preserve stability. This leads to reduced system performance. In many cases, particularly quality loops with long dead time, it may not even be possible to use PID control at all.

One strategy for enhancing closed loop performance is to use predictive control. A well-known predictive controller is the Smith Predictor controller. This is now available as a standard block in many commercial digital controllers.

Over the last decade, significant improvements have also been reported with the use of long range predictive controllers. Algorithms in this category include dynamic matrix control (DMC) and generalized predictive control (GPC).

The air stream in the Fan & Plate Control Apparatus introduces a significant transport lag. This adjustable transport lag is used in this experiment to demonstrate the application of predictive control. Both the Smith Predictor controller and the GPC algorithm will be evaluated on this apparatus and the performance compared to a conventionally tuned PID controller.

Lessons Learned and Data Obtained

1. Realization of a simple Smith Predictor controller
2. How to commission a Smith Predictor controller
3. Design and realization of a generalized predictive controller (GPC)
4. How to commission a GPC
5. Performance of conventional PID control with predictive controls on a process with dead-time
6. Role of digital pre-filtering on predictive controls

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Comment

This experiment is appropriate for a second course in control at the advanced undergraduate level or at a postgraduate level.