

FEEDFORWARD TEMPERATURE CONTROL USING A HEAT FLUX MICROSENSOR

by

Douglas John Lartz

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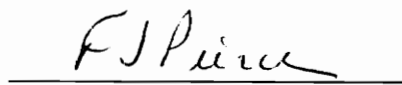
in

Mechanical Engineering

APPROVED:


T.E. Diller, Co-chair


H.H. Cudney, Co-chair


F.J. Pierce

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Committee Co-chairs: T. E. Diller and H. H. Cudney

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ABSTRACT

The concept of using heat flux measurements to provide the input for a feedforward temperature control loop is investigated. The feedforward loop is added to proportional and integral feedback control to increase the speed of the response to a disturbance. Comparison is made between the feedback and the feedback plus feedforward control laws. The control law with the feedforward control loop is also compared to the conventional approach of adding derivative control to speed up the system response to a disturbance.

The concept was tested using a simple flat plate heated on one side and exposed to a step change in the convective heat loss on the other side. A controller was constructed using an analog computer to compare the feedforward and feedback approaches. The conventional control approach was tested using a commercial temperature controller. The feedback and feedforward approaches were also simulated.

The results showed that the feedforward control approach produced significant

improvements in the response to the disturbance. The integral of the squared error between the setpoint and actual temperature was reduced by approximately 90 percent by the addition of feedforward control to the feedback control. The maximum temperature deviation from the setpoint was also reduced by 70 percent with the addition of feedforward control. Qualitative agreement was obtained between the experimental results and the computer simulations. The conventional approach of adding derivative control to the proportional and integral control showed an increase of 20 percent in the integral of the squared error, but offered no significant improvement in the maximum temperature deviation. The addition of derivative control also caused the stability of the system to decrease, while the addition of feedforward had no adverse effects on the system stability.

The concept of using heat flux measurements for feedforward control was successfully demonstrated by both simulations and experiments.

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"He only is my rock and my salvation: he is my defence; I shall not be moved." Psalm 62:6 (KJV)

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Nomenclature

A	plate surface area (cm^2)
C	plate specific heat [$\text{J}/(\text{kg K})$]
$D(t)$	plate heat transfer disturbance (W)
$e(t)$	error voltage (Volts)
$E(t)$	heat flux microsensor output (Volts)
E_o	reference voltage (Volts)
G	proportionality constant ($\text{V}/\text{V}^{1/2}$)
G_f	feedforward gain ($\text{V}/\text{V}^{1/2}$)
G_{PA}	power amplifier gain (V/V)
h	convection coefficient [$\text{W}/(\text{m}^2 \text{K})$]
k_i	integral gain [$\text{V}/(\text{V s})$]
k_p	proportional gain (V/V)
I_p	integral of power (W s)
I_{sc}	integral of squared error [$(^\circ\text{C})^2 \text{s}$]
m	plate mass (kg)
P_b	proportional band (%)
$q''(t)$	plate heat flux (W/cm^2)
q_c	plate heat transfer (W)

q_h	heater power (W)
R	heater resistance (Ohms)
S	heat flux microsensor sensitivity [$\mu\text{V}/(\text{W}/\text{cm}^2)$]
t_d	derivative time constant (sec)
t_i	integral time constant (sec)
$T(t)$	plate temperature ($^{\circ}\text{C}$)
$v(t)$	heater voltage (Volts)
$v_c(t)$	feedback control voltage (Volts)
$v_f(t)$	feedforward control voltage (Volts)
V	plate volume (m^3)
ρ	plate density (kg/m^3)
τ	first order system time constant (sec)
<u>subscript</u>	
o	steady-state condition

Chapter 1.0

Introduction

1.1 Objective and Approach

The objective of this research is to demonstrate the concept of feedforward temperature control. This new temperature control approach is accomplished through the use of a Heat Flux Microsensor (HFM) which directly measures heat transfer from a surface. Comparison is made between the experimental performance of the feedforward approach and the conventional feedback proportional-integral-derivative (PID) control approach. The comparison is made for the control systems applied to a simple flat plate which is heated on one side and exposed to a step change in the convective heat loss on the other side. Evaluation of the systems are made based on how well each responds to the disturbance. The criteria for comparison are the integral of the squared error between the setpoint and the actual temperature, maximum temperature variation from the steady state value, settling time, and the integral of the power over a set time interval including the transient response to the disturbance.

1.2 Feedback and Feedforward Control Background

Feedback control systems have been widely used to control many parameters of physical systems, including temperature. For many years PID controllers have been used in

industry to control temperature (Carr, 1989). The drawback to feedback control is that a disturbance must affect the control parameter before the controller takes corrective action. This drawback is a special concern for systems having relatively long time constants where the response and recovery of the control parameter from a disturbance is slow. Feedforward control gives corrective action before disturbances affect the output (Ogata, 1990). The feedforward approach anticipates a change in the control parameter before the change actually takes place and begins corrective action as soon as a disturbance is detected.

Figures 1.1 and 1.2 illustrate the concepts of feedback temperature control and feedback temperature control with an added feedforward control loop. These concepts are illustrated by Laplace-domain block diagrams of the control systems applied to a simple lumped capacity thermal system heated by a heater. Figure 1.1 shows the block diagram for the feedback control system and Fig. 1.2 shows the diagram for the system with the added feedforward control loop.

At the first summing point in Fig. 1.1 the measured voltage, $C(s)$, is subtracted from the setpoint voltage, $R(s)$, giving the error, $E(s)$. This error represents the difference between the desired and measured temperatures. The error then goes to the controller which can have proportional, integral, and derivative components. The controller transfer function, G_c , has units of volts/volt. After the controller block is a diode to prevent negative voltages from passing through to the heater. The heater supplies heat when it is given a positive or a negative voltage, the power output depends on the magnitude of the

applied voltage. The diode prevents a runaway temperature situation which could result when large negative errors (i.e. temperatures much greater than the setpoint) cause the controller to try to "cool" the system, but can only add heat. The control voltage then goes to an output device which amplifies the voltage so that the heater can supply the needed amount of power. The output gain, G_p , has units of volts/volt. After the control voltage is amplified it goes to the heater which has a transfer function, G_h , with units of watts/volt.

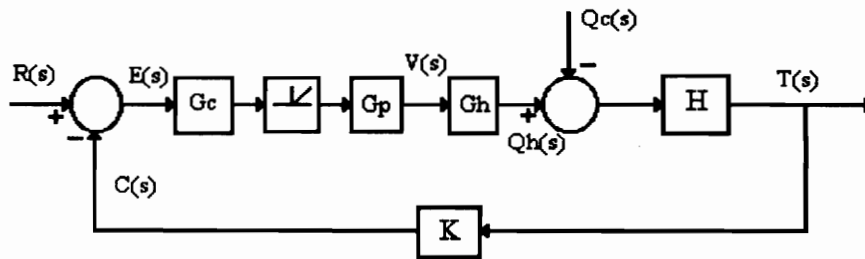


Fig. 1.1 Block Diagram of Feedback System

The second summing point in the diagram is where the disturbance due to changes in the heat transfer loss is taken into account. The result of this summing point is the net rate of heat addition to the system (in watts), which is the rate that heat is added by the heater minus the magnitude of the heat loss. Block H is the transfer function which gives the temperature of the system in $^{\circ}\text{C}$ from the net heat added to the system. The units of the transfer function H are $^{\circ}\text{C}/\text{watt}$. Block K in the feedback loop represents the temperature sensor gain which has units of volts/ $^{\circ}\text{C}$.

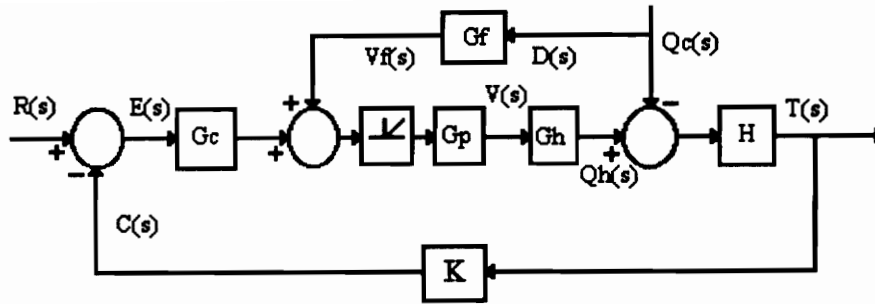


Fig. 1.2 Block Diagram with Feedforward Loop

If the time constant of the transfer function H is long and if the disturbance is of a long enough duration, the temperature of the system may vary unacceptably from the setpoint and it may be slow to return to the desired value. Figure 1.2 shows how this problem may be corrected. In this diagram $D(s)$ is a measured disturbance in watts, G_f is the feedforward transfer function which has units of volts/watt, and $V_{ff}(s)$ is the feedforward control voltage. When a disturbance is detected the feedforward control loop immediately adds a voltage to the control voltage supplied by the feedback control loop.

1.3 Overview of Thesis

Chapter 2 is a literature review beginning with the conventional methods of temperature control. This is followed by a review of previous applications of feedforward control and a presentation of the Heat Flux Microsensor which is used to create the feedforward temperature control loop. Computer simulation models of the feedback and feedforward control systems are presented in Chapter 3. Chapter 4 contains a description

of the experimental setup and procedure. Experimental and simulation results are presented and discussed in Chapter 5. Conclusions, including recommendations for future work, are found in Chapter 6.

Chapter 2.0

Literature Review

This chapter reviews the literature pertaining to temperature control in both the conventional feedback algorithm and the application of feedforward control. Section 2.1 reviews the conventional temperature control approach as employed in industrial processes. This conventional approach uses feedback control with either on/off or PID control. Also, temperature control used in experimental fluid mechanics and heat transfer is illustrated. In the second section, the concept of feedforward control as applied to temperature is explored. The Heat Flux Microsensor is also introduced as a tool for implementing feedforward control in the experimental study.

2.1 Temperature Control

Electronic temperature controllers which have been widely used in industrial processes typically use one of two types of feedback control algorithms, on/off control or proportional-integral-derivative (PID) control (Carr, 1989). These algorithms are employed by either analog or digital controllers. The feedback control signal for these algorithms is an electrical output from a thermocouple, thermistor, resistance temperature sensor, or other temperature sensor which is used to measure the temperature being controlled.

The first of these algorithms, on/off control, provides heat to the system when the temperature of the system is below the setpoint temperature and supplies no heat when the temperature is at or above the setpoint. This heat output is either full on or full off depending on whether the measured temperature is less than or greater than the setpoint. On/off controllers typically include a hysteresis band below the setpoint to prevent rapid cycling of the heat output. The heat output is not turned on until the temperature drops the width of the hysteresis band below the setpoint. The advantage of on/off controllers is that they are relatively inexpensive, but the disadvantage is that they cannot maintain a stable setpoint temperature, having oscillations at least as large as the hysteresis band.

Typically, the three terms of a PID controller are defined as proportional band, P_b , integral time constant, t_i , and derivative time constant, t_d (Carr, 1989). The proportional band is expressed as a percentage of the maximum controller setpoint range. The controller supplies maximum heating power when the temperature is below the setpoint by the width of the proportional band. For example, if a controller has a setpoint range of 200 °C and the proportional band setting is 10 percent, maximum heating power will be supplied when the temperature is 20 °C below the setpoint, 50 percent of the maximum power will be supplied when the temperature is 10 °C below the setpoint, etc. Because lower proportional band settings cause higher power output for small errors, a low proportional band setting corresponds to a high value of proportional gain, k_p . The integral time constant and the derivative time constant are time constants usually expressed in minutes or seconds.

The PID control algorithm is employed either in full PID control or as a subset such as proportional only, proportional plus derivative (PD), or proportional plus integral (PI). The proportional only control provides an output which is proportional to the error between the setpoint and the measured temperature. This type of control will have a steady-state error, also called droop, between the setpoint and actual temperature which will be less for smaller proportional band settings. PD control adds a derivative term to the proportional only control. The derivative term contributes to the output when the temperature changes, and this added output is directly related to the rate of change. The object of adding the derivative term is to speed up the control response to rapid changes in the measured temperature. The steady-state error will still be present with PD control, however, and some PD controllers feature a manual reset which can be adjusted to eliminate the steady-state error. This manual reset does not automatically compensate for disturbances which may arise in the system, so it may need to be readjusted periodically to maintain the setpoint.

PI control adds an integral term to the proportional only control to eliminate the steady-state error. The integral action adds output to the proportional output until the error is driven to zero, thus it automatically determines the proper steady-state power level for the system. Full PID control adds the derivative term to the PI control. As with the PD control, the derivative is added to improve the system response to rapid temperature changes.

Another example of a temperature control approach is implemented in the constant temperature anemometer used in experimental fluid mechanics (Lomas, 1986). The temperature of the hot wire anemometer is maintained by a Wheatstone bridge circuit having the sensor in one leg. When the bridge becomes unbalanced because of a change in the fluid flow velocity, the bridge output voltage provides input to a controller which changes the current supplied to the bridge. This change in the current supplied to the bridge returns the bridge to balance and maintains the temperature of the hot wire. Because the change in current is proportional to the bridge unbalance voltage, this is a proportional controller.

An on/off controller has been modified to control the temperature in an experiment for determining the critical heat flux on a simulated microelectronic chip (Auracher *et al.*, 1992). This modification consists of adding a high frequency periodic signal, called dither, to the output of the on/off controller before the control signal is amplified by a power supply. The addition of the high frequency signal causes the controller to behave much like a proportional controller in maintaining steady-state power output without on-off cycling.

2.2 Feedforward Control

A textbook example of feedforward temperature control is provided by Ogata (1990). In this example, a fluid is to be heated to a desired temperature by passing it through a heat exchanger to receive heat from steam. The temperature controller operates a valve which regulates the flow of steam through the heat exchanger, controlling the

outlet temperature of the fluid passing through the heat exchanger. Feedback input to the temperature controller is provided by measurement of the fluid temperature at the outlet of the heat exchanger. The temperature controller also has a feedforward input which comes from measurement of the fluid flow at the inlet of the heat exchanger. Thus, a change in the flow rate of the fluid into the heat exchanger will be immediately offset by a change in the flow rate of the steam. This will maintain a proper balance between the flow rates of the fluid and the steam, thereby reducing temperature variations at the outlet of the heat exchanger caused by fluctuations in the entering fluid flow rate.

In order to implement a feedforward control algorithm such as the one in the previous example, the disturbance must be measurable, and the effects of the disturbance on the control parameter must be known. The effects must be known so that an appropriate corrective action can be taken. This may require extensive modeling and simulation for very complex systems such as a crude oil preheating furnace (Fuchs *et al.*, 1993) or it may require only a simple energy balance as in the case of the heated plate featured in this study. Using modeling and simulation, Fuchs *et al.* (1993) studied the effects of disturbances on the furnace outlet crude oil temperature. The studied disturbances were changes in the crude oil flow rate and inlet temperature. Also, simulation results are shown for feedforward control used to compensate for these disturbances in flow rate and inlet temperature. These simulation results showed that feedforward control improved the response to disturbances in the inlet temperature but did not offer appreciable improvement in the response to flow disturbances.

The advantages of feedforward control are beginning to be recognized in the electric power generating industry. Control systems featuring feedforward inputs have been implemented at power plants (Hitz *et al.*, 1992; Zhu *et al.*, 1992). One of these articles describes a control system for controlling the temperature of steam from the superheater at an Australian power plant (Hitz *et al.*, 1992). One feature of this control system is using measurements of boiler air flow and steam flow to provide input to a feedforward algorithm. The measurement of boiler air flow provides a measure of the rate of heat addition in the superheater and the measurement of steam flow provides a measure of the heat required to achieve the desired superheated steam temperature. Zhu *et al.* (1992) describe the process of developing a model for the response of a power plant to measurable disturbances so that the model can be incorporated into a feedforward algorithm. The feedforward algorithm had been implemented at another power plant and each plant required a customized model of its response characteristics. Because of performance improvements at the first plant, the analysis was performed to determine if similar improvements could be achieved at the second plant.

2.3 The Heat Flux Microsensor

In order to compensate for a disturbance by using feedforward control, the disturbance must be measured. The method of measuring the disturbance for this experimental study is by the use of the Heat Flux Microsensor (HFM). The Heat Flux Microsensor allows the measurement of disturbances which were previously

unmeasurable. The contribution of this work is to demonstrate how these measurements can be used to achieve improved temperature control.

The heat flux microsensor is manufactured using microfabrication techniques. The sensor consists of a thin thermal resistance layer, approximately 1 μ m thick, across which thin-film thermocouples are deposited to measure the temperature difference between the two sides of the layer. Because the temperature difference between the two sides of the resistance layer is small, multiple thermocouple pairs are connected in series so that the voltages produced add together to give a measurable output. This voltage output is proportional to the heat flux passing through the thermal resistance layer and is mathematically represented by

$$q''(t) = \frac{E(t)}{S} , \quad (2.1)$$

where $q''(t)$ is the heat flux passing through the sensor, $E(t)$ is the voltage output, and S is the sensitivity of the sensor.

The sensor also features a Resistance Temperature Sensor (RTS) which can be used to measure the surface temperature at the HFM location. The entire sensor is less than 2 μ m thick and is mounted on a ceramic substrate. Because the sensor is so thin, the response time to changes in heat flux is less than 20 microseconds. Details of the sensor construction and performance have been reported in the literature (Hager *et al.*, 1991; Hager *et al.*, 1993).

Because the voltage output of the sensor is proportional to the heat flux passing through it, a change in the heat flux will produce a corresponding change in output voltage

$$E(t) - E_o = S[q''(t) - q_o''] \quad , \quad (2.2)$$

where E_o and q_o'' are the initial undisturbed output voltage and heat flux, respectively.

Thus, a heat flux disturbance can be measured directly as a voltage change which can serve as the input for feedforward control.

Chapter 3.0

Control System Computer Simulations

Computer simulations of the feedback and feedforward temperature control systems were performed using Personal Simulation Language (PSL). PSL is a product of Blacksburg PC-Dynamics. These simulations were developed initially to test the theory of using heat flux measurements as input for a feedforward control loop. The simulation results are included along with the experimental results (in Chapter 5) to show how the theory matches the experiments. The following sections briefly describe the model which was used to simulate the systems. Specifics about the use of PSL and descriptions of the blocks can be found in the PSL users manual.

3.1 Model of Thermal System

A solid body losing heat to its surroundings and having one source of heat addition is modeled using the lumped thermal capacity assumption. The temperature of the body is assumed to be uniform throughout and the time rate of change of the temperature is proportional to the net rate of heat added to the body. The lumped capacity assumption produces

$$\frac{dT}{dt} = \frac{1}{mC} [q_h(t) - q_c(t)] \quad , \quad (3.1)$$

where m is the mass of the solid body, C is the specific heat of the body, $q_h(t)$ is the rate of heat addition to the body by the source, and $q_c(t)$ is the total rate of heat loss from the surface of the body. The total heat loss from the body may be through both convection and radiation.

The solid body which was used in the experiments was a flat plate made of aluminum. The value of $1/mC$ used in the computer simulations was calculated to be 0.00556 (K/J). This calculation was made using the plate dimensions and density and specific heat values for pure aluminum from a textbook table (Incropera and DeWitt, 1990). These values from the table are density, ρ , equal to 2702 kg/m³ and specific heat, C , equal to 903 J/(kg K).

The disturbance in the experimental system is a change (an increase, in this case) in the air flow over the surface of the heated plate. This increase in air flow results in a corresponding increase in the convection coefficient which in turn results in an increase in the convective heat loss from the plate surface. Because the transient period for development of the flow is assumed to be small relative to the thermal time constant of the system, the flow disturbance can be modelled as a step disturbance. A step increase in the air flow will then result in a step increase in the convection coefficient. Because the maximum temperature variation of the plate surface due to the disturbance is small (approximately 3°C) compared to the difference (approximately 25°C) between the surface temperature and the flow temperature, the convective heat loss can be considered a step increase from an initial steady-state value to a final steady-state value. The radiation

component of the total heat loss is not affected by the flow disturbance, therefore the heat loss disturbance is caused only by the increase in convection. This treatment of the heat loss disturbance as a step increase simplifies the modeling of the system for the computer simulations.

3.2 Computer Simulation Model of Feedback Control System

The PSL block diagram of the feedback control system model is shown in Fig. 3.1. Referring to the feedback model in Fig 3.1, block number 1 is the setpoint in °C. Block 2 subtracts the temperature of the plate from the setpoint to give the error which is then converted to voltage by block 3 which is a gain representing the error sensitivity of the controller (specifically 0.01 V/°C). Blocks 4 and 5 are the proportional and integral components of the feedback controller whose outputs are combined by the summing block 6. The controller output is represented mathematically by

$$v_c(t) = k_p e(t) + k_i \int e(t) dt \quad , \quad (3.2)$$

where $v_c(t)$ is the control voltage, $e(t)$ is the error voltage, k_p is the proportional gain, and k_i is the integral gain. A unipolar power amplifier which amplifies only positive control voltages is represented by blocks 7, 8, and 9. Block 7 passes only positive values of the controller output, block 8 is a dead band to represent an offset in the amplifier input-output function, and block 9 is the voltage gain. The offset and voltage gain for the amplifier used in the experiments are presented in Appendix A. The heater which supplies

heat to the plate is represented by blocks 10, 11, and 12, which square the amplifier output voltage and divide by the heater resistance. This produces the heater power which is defined by

$$q_h(t) = \frac{[v(t)]^2}{R} \quad (3.3)$$

Blocks 13, 14, and 15 represent the total heat loss from the plate, $q_c(t)$, as a step function which increases from an initial value to a final value when the disturbance begins at time equal to t_0 . The total heat loss is subtracted from the heater power by block 16, resulting in the net rate of heat addition to the plate. From Eq. 3.1 this quantity is proportional to the derivative of the temperature with respect to time. Block 17 integrates this time derivative to give the temperature of the plate as a function of time. The parameters of the integrator block are the initial undisturbed temperature, T_o , and the proportionality constant, $1/mC$. Blocks 18 and 19 give the integral of the squared error of the temperature over time and block 20 gives the integral of the heater power. The integral of the squared error, I_{se} , is defined by

$$I_{se} = \int [T(t) - T_o]^2 dt \quad (3.4)$$

where $T(t)$ is the plate temperature as a function of time and T_o is the undisturbed steady-state temperature of the plate. The integral of the heater power, denoted I_p , is defined

$$I_p = \int q_h(t) dt \quad (3.5)$$

3.3 Computer Simulation Model of Feedforward Control System

In the block diagram of the feedforward simulation model (Fig. 3.2), blocks 18, 19, 20, and 21 represent the feedforward loop which is added to the feedback control system. Block 18 determines the disturbance by subtracting the initial heat loss from the value of the heat loss function. This disturbance is represented mathematically by

$$D(t) = q_c(t) - q_o \quad , \quad (3.6)$$

where $D(t)$ is the disturbance and q_o is the initial undisturbed heat loss. The disturbance (in Watts) is then multiplied by the heater resistance and the square root of this result is then determined (block 20) which gives the voltage that must be added to the heater to compensate for the disturbance. Block 21 multiplies this voltage by the reciprocal of the power amplifier gain to yield the voltage that must be added to the controller output at block 6. The feedforward control voltage to compensate for the disturbance is represented by

$$v_f(t) = \frac{\sqrt{D(t)R}}{G_{PA}} \quad , \quad (3.7)$$

where $v_f(t)$ is the feedforward control voltage and G_{PA} is the power amplifier gain. The integral of the squared error is calculated by blocks 22 and 23, and the integral of the heater power is calculated by block 24.



Fig. 3.1 PSL Block Diagram for Feedback Simulation

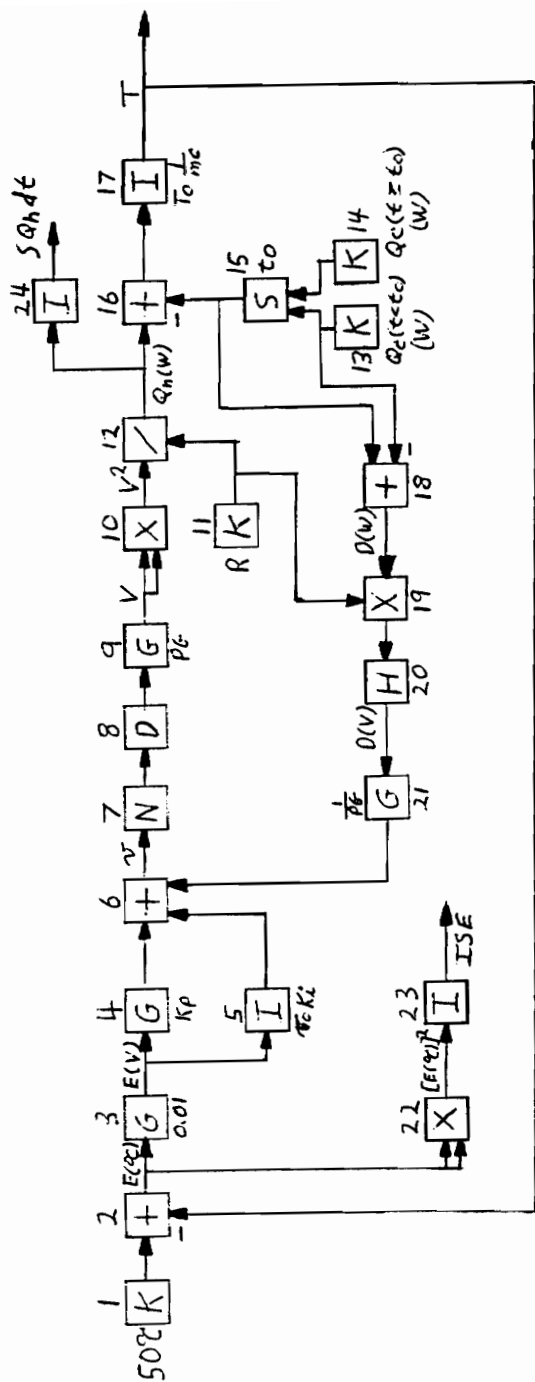


Fig. 3.2 PSL Block Diagram for Feedforward Simulation

Chapter 4.0

Experimental Setup and Procedure

This chapter describes the experimental setup and procedure which was used to demonstrate the concept of using heat flux measurements for the input to a feedforward temperature control loop. The first section describes the simple flat plate which was used in the experiments and the heaters which were used to heat the plate. Also described are the sensors located on the plate surface and the air jet which creates the heat flux disturbance. The second section describes the control system hardware used. Under this section are subsections describing the analog control system which was used to demonstrate the affects of adding feedforward control and the commercial temperature control equipment which was used to compare the feedforward approach to the conventional approach of adding derivative control to the feedback control loop. The third section describes the instrumentation which was used to acquire data from the experiments. The last section outlines the procedure used to obtain the experimental results and also the procedure for obtaining the computer simulation results.

4.1 Plate and Heater Arrangement

Figure 4.1 shows the plate and heater arrangement used in conducting the experiments. The plate used for this investigation is made of aluminum, and is 7.62 cm (3

in.) square by 1.27 cm (1/2 in.) thick. The plate is mounted in a wood frame which insulates the edges. Electric resistance heaters manufactured by Watlow provide heat to the back of the plate, four heaters 2.54 cm by 7.62 cm (1 in. by 3 in.) are used. Two of the heaters are of the silicon rubber type having resistance of 720 Ohms, and two are of the etched foil type with resistance of 52.3 Ohms. The four heaters are wired in parallel which results in an equivalent resistance of 26 Ohms. The heaters are sandwiched between the plate and the tempered hardboard back, with an etched foil and a silicon rubber heater located along each side of the plate back. A foil heater is located next to the plate and a rubber heater is located between it and the hardboard back. A coating of Omegatherm 201 thermal grease is applied between the foil heaters and the plate surface to ensure good conduction into the plate and a shim of thin basswood is located between the rubber heaters and the hardboard back to maintain tight physical contact. A slot along the bottom edge of the plate allows the heater lead wires to exit the assembly.

The plate is fitted with two type-T thermocouples located near its center, one of which is used as the sensor for the feedback control and to record the plate temperature. The other thermocouple is sometimes used as an additional means of checking the plate temperature. The thermocouples are mounted in the plate by soldering the two thermocouple wires together inside a short length of brass tubing which is then press fit into holes drilled through the plate. The thermocouples are sanded flush with the surface of the plate. At the center of the plate is the Heat Flux Microsensor which is used to provide the input for the feedforward control loop. The HFM is mounted on a circular

ceramic substrate which is 2.54 cm (1 in.) in diameter and 0.635 cm (1/4 in.) thick. The ceramic material is aluminum nitride which has a thermal conductivity of 165 W/(m K), this value is similar to that for aluminum.

The plate is mounted perpendicular to an unheated circular air jet which impinges on the center of the plate. The jet is created by an orifice which has a diameter of 3.81 cm (1.5 in.) at the end of a plenum. The plate is located 12.7 cm (5 in.) from the jet outlet.

The first order system time constant, τ , is estimated to be 77.5 seconds. This value is determined using a convection coefficient, h , of 400 W/(m² K).

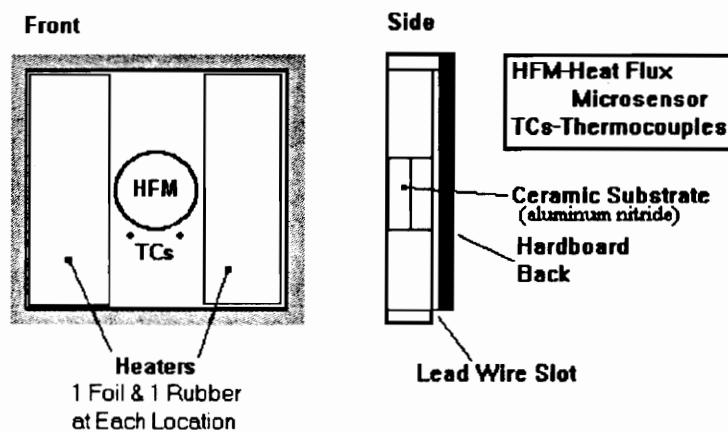


Fig. 4.1 Diagram of Plate and Heater Arrangement

4.2 Control System Hardware

The major part of the investigation uses an analog computer which is configured as a controller to demonstrate the affect of adding a feedforward loop to the proportional and integral feedback control. A second part of this investigation uses commercial

temperature control hardware to demonstrate the affect of adding derivative control to the feedback proportional and integral control. This is to compare the affects of adding derivative control with adding a feedforward control loop to the feedback control.

4.2.1 Commercial Temperature Controller

Conventional temperature control hardware manufactured by Eurotherm is used for part of the experimental investigation. A Model 810 controller unit and a Model 831 Silicon Controlled Rectifier (SCR) are the components of this system. The Model 810 is a microprocessor based 3-term (PID) controller (Eurotherm, 1987). The particular unit used features phase angle pulse (PAP) output, type-T thermocouple input, 0-200°C input range, and 120 V_{ac} supply voltage. The features of the Model 831 SCR unit used include a current rating of 20 A_{rms}, a 120/240 V_{ac} voltage rating, and PAP input with phase angle firing. The controller and SCR are mounted in a sheet metal box, fitted with plugs for the thermocouple input and the SCR output, forming a portable control system unit.

4.2.2 Analog Control System

The controller for this part of the investigation is built using a Comdyna GP-6 analog computer which provides the necessary components for reference voltages, summers, integrators, and amplifiers. The output of the controller then goes to a Kepco Model JQE 55-5 MVP power supply which is configured as an amplifier, providing a unipolar voltage gain of 114 V/V. The method of calibrating the power amplifier gain is

described in Appendix A. Because the amplifier is unipolar, negative control voltages which could result from measured temperatures much greater than the setpoint will not give an output to the heaters. This offers protection against creating runaway temperatures.

The sensor output for the feedback control comes from one of the type-T thermocouples in the plate. The thermocouple signal is amplified by an Omega OMNI-AMP IIA amplifier with a gain of 100. The amplifier output goes to one channel of a Frequency Devices Model 9002-LP02 low-pass filter with the cut-off frequency set at 20 Hz to remove noise (especially 60 Hz noise) from the temperature signal. The filter pre-gain is set at 2.5, thus the total amplification of the thermocouple signal before being sent to the analog computer is 250. Because the sensitivity of type T thermocouples at the operating temperature (about 50 °C) is approximately 40 $\mu\text{V}/^\circ\text{C}$ (Dally *et al.*, 1984), the error sensitivity of the controller is 10 $\text{mV}/^\circ\text{C}$. A schematic of the feedback control system is shown in Fig. 4.2.

The Heat Flux Microsensor is used as a sensor for the feedforward control loop. The sensitivity of the HFM used in this experiment is 50 $\mu\text{V}/(\text{W}/\text{cm}^2)$. The sensor output goes to a Vatell Corp. amplifier, which is designed for use with the sensor, having a gain of 1000 and then to another Omega OMNI-AMP IIA amplifier with a gain of 100. The signal is then fed to the analog computer.

The feedforward control is implemented in the analog computer using a linearized square root function. This linearized function was determined by using Taylor series

expansion as suggested by Dorf (1989). The Taylor series expansion of a function, $f(x)$, about a point, x_0 , is defined by

$$f(x) = \sum_{n=0}^{\infty} \frac{f^{(n)}(x_0)}{n!} (x - x_0)^n \quad . \quad (4.1)$$

The first two terms of this series expansion yields

$$f(x) = f(x_0) + f'(x_0)[x - x_0] \quad . \quad (4.2)$$

Combining Eqs. 2.2, 3.6, and 3.7 yields an expression for the feedforward control voltage

$$v_f(t) = \frac{\sqrt{[E(t) - E_o]AR}}{G_{PA}} \quad , \quad (4.3)$$

where A is the plate surface area exposed to the heat loss. This equation can be rewritten

$$v_f(t) = \frac{G}{G_{PA}} \sqrt{E(t) - E_o} \quad , \quad (4.4)$$

where G is a proportionality gain defined by

$$G = \sqrt{\frac{AR}{S}} \quad . \quad (4.5)$$

The feedforward control voltage can then finally be written as

$$v_f(t) = G_f \sqrt{E(t) - E_o} \quad . \quad (4.6)$$

For the particular setup used in the experiment the feedforward gain, G_f , was determined to be $48.2 \text{ V/V}^{1/2}$.

Applying the linearization shown in Eq. 4.2 to the square root function produces

$$[E(t) - E_o]^{1/2} = (E_o)^{1/2} + \frac{1}{2}(E_o)^{-1/2}[E(t) - E_o] \quad , \quad (4.7)$$

where E_o is the initial undisturbed voltage, which was chosen to be 1 μ V, and $E(t)$ is the input voltage. The final result of this linearization procedure is

$$[E(t) - E_o]^{1/2} = \frac{(E_o)^{1/2}}{2} + \frac{(E_o)^{-1/2}}{2}[E(t)] \quad . \quad (4.8)$$

Therefore, the feedforward control voltage has a constant part and a part that is proportional to the input voltage. Figure 4.3 shows the schematic with this feedforward control loop added.

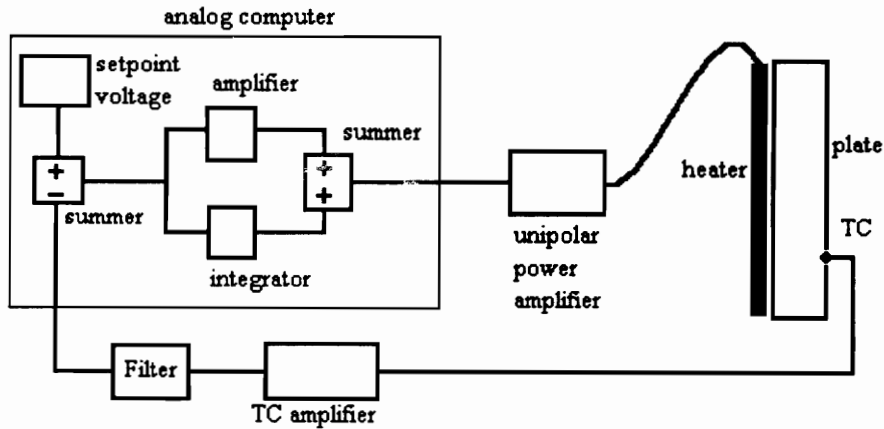


Fig. 4.2 Schematic of Feedback Control System

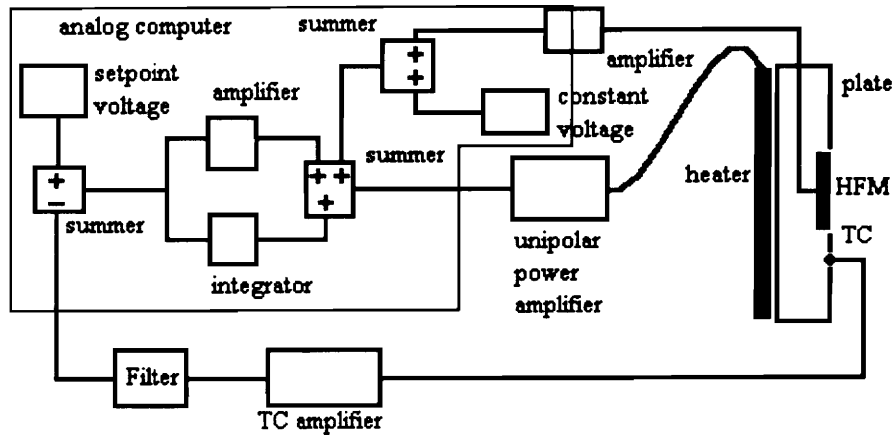


Fig. 4.3 Schematic of Control System with Feedforward Loop Added

4.3 Instrumentation

A schematic of the instrumentation arrangement is shown in Fig. 4.4. The instrumentation used to acquire data for this investigation consists of a Hewlett-Packard 3478A digital multimeter and a PC equipped with analog-to-digital and GPIB interface boards. The HP multimeter features a connection for a GPIB cable, which is used to read the voltage supplied to the heaters into the computer. The thermocouple voltage from the Omega amplifier is fed to the second channel of the Frequency Devices filter which, like the first channel for the feedback control input, has the cut-off frequency set to 20 Hz. This filtered signal goes to the A/D board to provide a temperature record. The pre-gain of this filter channel is set to 10 for a sensitivity of 40 mV/°C for this signal. Splitting the thermocouple signal through two channels of the filter isolates the controller from the data

acquisition. This isolation prevents electronic interference from the analog computer from feeding back to the temperature record. A BASIC computer program is used to acquire a simultaneous record of the heater voltage through the GPIB and the temperature data through the A/D. This BASIC program is listed and described in appendix B. The thermocouple signal is also split before the Omega amplifier, with this branch going to a Doric Trendicator 410A thermocouple readout. The plate temperature is monitored from the LED display which gives the temperature in °C.

For the Eurotherm experiments, the signal split off before the Omega amplifier goes to the controller input instead of the Doric. Only one filter channel is used, the one filtering the temperature signal going to the A/D.

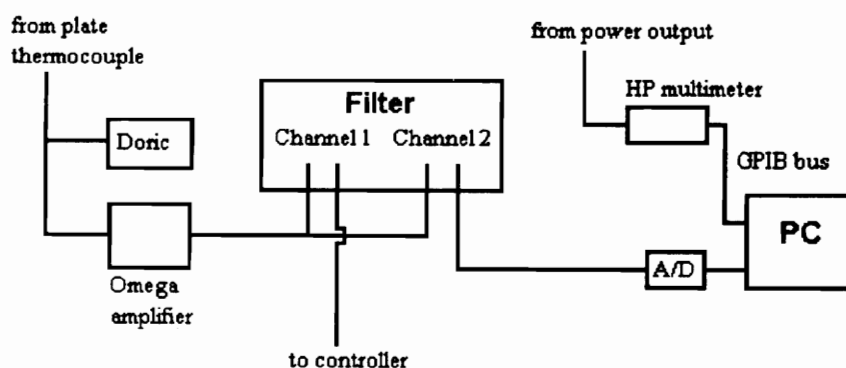


Fig. 4.4 Schematic of Instrumentation

4.4 Procedure

This section describes the procedure which was used to demonstrate the feedforward temperature control concept. The first subsection outlines the experimental procedure and the second subsection describes the procedure used to obtain the results for the computer simulations of the control systems.

4.4.1 Experimental Procedure

The response of the control systems to a step increase in the heat loss from the plate surface was tested. This step disturbance was created by the jet which impinges on the flat plate being started from zero flow to full flow. This was effected by turning on the blower which forces air through the orifice creating the jet flow. The blower starts from rest and reaches its full speed very quickly, therefore the jet can be assumed to start instantaneously.

The first step in the experimental procedure was tuning the controller to determine the "best" proportional and integral gain settings. These "best" settings are the ones which result in the minimum value for the integral of the squared error of the temperature response to the step disturbance. The tuning procedure for the Eurotherm system was a fairly simple process because there are only certain discrete settings. The Eurotherm tuning was accomplished by following the steps outlined in the operation manual for the controller unit. These steps closely match the closed-loop cycling method described by Carr (1989). After the "best" proportional and integral settings were determined using this

procedure, data was recorded for these settings as well as the adjacent settings. The integral of the squared error was calculated from the recorded data to verify whether or not these setting gave the minimum error value.

Tuning the analog controller was a more difficult procedure because of the gains are continuously variable using the analog computer potentiometers. Therefore, a trial and error approach was employed to find a response that exhibited the characteristics of being near critically damped (i.e. an initial temperature drop due to the disturbance followed by a slight overshoot before settling back to the setpoint value). The temperature responses of the system during the tuning process were observed by viewing the thermocouple output on the display screen of an HP 3562A Dynamic Signal Analyzer. After the critically damped response was determined, data was recorded for these gain values. Data was also recorded for proportional and integral gains incrementally changed from the determined values. The integral of the squared error was calculated from these data records to determine the minimum error gain settings.

Once the minimum error gain settings were determined, the added control feature was employed. For the Eurotherm controller the added feature was to use derivative control in addition to proportional and integral control. Derivative control was added to the determined proportional and integral control settings and data was recorded for the three lowest derivative settings. Because the addition of derivative control made the temperature response less stable, the system response was improved by increasing the

system damping by changing the proportional and integral settings. For the lowest derivative setting, tests were run with increased proportional and integral settings.

For the analog controller, feedforward control was added to improve the temperature response. The gain of the feedforward loop was tuned so that when the feedforward loop was used without the feedback loop, the final steady-state heater voltage was approximately the same as the final steady-state voltage supplied by the feedback control alone. This feedforward gain then gives an approximate compensation for the step disturbance in the heat loss. A temperature and heater voltage record was acquired for the tuned feedforward open loop (without feedback control). The tuned feedforward loop was then added to the already determined feedback proportional and integral gains, and the response measured. The feedback gains were adjusted to give overdamped and underdamped temperature response. The tuned feedforward control loop was also added to these feedback gain settings. Data was recorded for the critically damped, overdamped, and underdamped feedback response and also for the three corresponding cases with the added feedforward control loop. Also recorded was a record of the HFM output to show the heat flux disturbance experienced at the plate surface.

The thermocouple signal which was used for feedback control and temperature recording was scaled by adjusting the zero offset of the Omega amplifier so that the output of the amplifier was 50 mV when the plate temperature was 50 °C. Using this approach, the controller setpoint voltage is 125 mV and the recorded voltage is 500 mV when the temperature is at the setpoint. Using this reference setting and the sensitivity (40

mV/°C), the voltage record can be converted to temperature. Because the room temperature which provided the reference junction of the thermocouple varied slightly over time it was necessary to readjust the zero offset occasionally to maintain the setpoint. A Dana Digital Multimeter 5100 was used to monitor the temperature signal.

The Vatell amplifier was zeroed with the plate at room temperature. This produced an output of approximately 1 mV when the plate was heated with the jet turned off, giving the initial undisturbed voltage output, E_0 , of the HFM. Therefore, 1 μ V was chosen for the value of E_0 as previously stated. The Dana multimeter was used to check the output of the Vatell amplifier before each feedforward test. The zero offset was readjusted, if necessary, to maintain consistency of initial voltages between tests. The zero offset of the Omega amplifier used in the feedforward control loop was adjusted so that zero input produced zero output.

When starting up the analog controller to heat the plate from room temperature, the integrator was short circuited to prevent it from saturating. The plate temperature was brought up from room temperature to near the setpoint by proportional control only.

Data records were acquired by starting with the jet turned off and the plate temperature stabilized. The data acquisition program was then started and after a few seconds the blower was started to cause the air jet to hit the plate and increase the convective heat loss from the plate surface. After the data acquisition program had finished acquiring data the blower was turned off and the temperature was allowed to

stabilized for the next test. Data was recorded over a time span of approximately 140 seconds.

4.4.2 Computer Simulation Procedure

The simulation for the feedback system was developed and refined first, and then the feedforward loop was added to the feedback model. The simulations were performed to test the concept of using heat flux measurements for feedforward control before proceeding with the experimental tests. Once the computer models were refined and operating, the preliminary simulation results showed that the feedforward approach to temperature control was promising. The experimental work using the analog control systems was then carried out.

The parameters of the computer models were set to match the corresponding parameters of the actual control system used in the experiments. These parameters include power amplifier gain and offset, heater resistance, initial and final steady state heat losses (i.e. values for step disturbance), and proportional and integral control gains. The simulations were run over a time interval of 140 seconds, to match the experimental time records, using a time step of 0.5 seconds. A comparison between the experimental results and the simulation results showed a higher damped temperature response for the simulation results even though the proportional and integral gains were the same as the experimental values. This difference in the response is due to modeling inaccuracies, most likely the lumped capacity assumption is not completely valid. The proportional and

integral gains used for the simulations were reduced to match the response to the experimental response. A trial and error approach was used to match the simulation response to the experimental response for the critically damped, overdamped, and underdamped feedback cases. These same feedback gains were then used in the feedforward simulations.

The simulation data for each case was tabulated to a file which was then loaded into a Quattro Pro spreadsheet to produce plots. The data which was tabulated was the output for the temperature, heater power, integral of the squared error, and the integral of the power.

Chapter 5.0

Experimental and Computer Simulation

Results and Discussion

This chapter presents the experimental results of the investigation and discusses those results. Also presented and discussed are the results of the computer simulations of the feedback and feedforward control systems. The experimental results which are presented here were prepared using Quattro Pro spreadsheets. After the data was written to a file by the acquisition program, the file was copied to a data disk and given a name to identify the specific test. The data files are imported into Quattro Pro as comma and " " delimited files. A template spreadsheet was created to speed up the processing of multiple data files. Each data file was loaded into the template spreadsheet, processed, and saved as a separate spreadsheet file. The final spreadsheet files were saved with only the pertinent data included and with all formulas converted to their numeric values to reduce the disk space required to save them.

The time interval between data points was determined by dividing the total length of the time record, the difference between the start and end times, by the number of data points recorded. It is assumed that the data acquisition loop executes with a uniform time period for each data point. The time axis for the plots is then constructed by starting with

time equal to zero for the first data point and increasing the time by the calculated increment for each successive point.

The integral values were calculated from the data by using the trapezoid rule. The quantity to be integrated was averaged for two adjacent data points and multiplied by the time interval. Integrals were then determined by summing the incremental areas over the desired time length. For the integral of the squared error, the temperature at each data point was subtracted from the steady-state value and squared. This squared error was then integrated over the entire time record as described above. The steady-state temperature was determined by averaging the values of the first 40 data points (or all the data points before the beginning of the disturbance if less than 40). The heater power was calculated by squaring the heater voltage and dividing by the heater resistance value of 26 Ohms. The integral of the power was calculated over the first 100 seconds after the beginning of the disturbance.

The following sections discuss the experimental results obtained using the Eurotherm controller, the experimental results from the analog control systems, and the results of the computer simulations of the control systems.

5.1 Results for Commercial Controller

Plots of the temperature response and heater power versus time for the Eurotherm control system are shown in Figs. 5.1 and 5.2. Figure 5.1 is the results for the controller using only proportional and integral control. The results with derivative control added are

shown in Fig. 5.2. Table 5.2 contains the integral of the squared error (I_{se}) and the integral of the heater power (I_p) over the first 100 seconds of the disturbance.

The controller settings used for the results with proportional and integral control only are the proportional band, P_b , equal to 6% and the integral time, t_i , equal to 30 seconds. These are the values that were determined using the tuning procedure recommended in the Eurotherm operation manual. Because the addition of derivative control decreased the stability of the system response, the damping was increased when the derivative term was used. The controller parameters used for the results with derivative added are proportional band equal to 8%, integral time equal to 30 seconds, and derivative time, t_d , equal to 5 seconds. These controller settings are shown in Table 5.1.

The purpose of adding derivative control to proportional and integral control is to improve the transient response of the system by speeding up the response to sudden changes in the temperature of the system (Carr, 1989). Comparing the power curves in Figs. 5.1 and 5.2 it can be seen that the addition of derivative control to the proportional and integral control does slightly increase the slope of the power curve at the beginning of the disturbance and also reduces the time lag between the power peak and the temperature minimum point. The addition of derivative control causes the response to the step disturbance to become less stable, therefore the damping is increased by changing the proportional and integral settings. The increased damping causes the integral of the squared error to increase because the recovery from the disturbance is slowed down. Thus, in order to implement derivative control, the damping of the system must be

increased which cancels out the benefit of the derivative control in giving a quicker initial response to the disturbance.

These results show that the addition of derivative control to proportional and integral control does not have a significant affect on improving the temperature response to a step disturbance.

Table 5.1 Eurotherm Controller Settings

TERMS	P_b (%)	t_i (s)	t_d (s)
PI	6	30	-----
PID	8	30	5

Table 5.2 Integrals of Eurotherm Results

TERMS	I_{sc} [(°C) ² s]	I_p (W s)
PI	44.89	5769.49
PID	54.21	6779.43

5.2 Results for Analog Feedback and Feedforward Control

The results for the critically damped feedback control are plotted in Fig. 5.3. Using the same feedback gains with the added feedforward control loop produced the results shown in Fig. 5.4. The results of the overdamped case are shown in Figs. 5.5 and 5.6 for the feedback control and the feedback plus feedforward control, respectively. The underdamped feedback results are plotted in Fig. 5.7 and the feedforward results for the

same gains are shown in Fig. 5.8. Table 5.4 gives the results of the squared error and heater power integrations. Again, the power is integrated over the first 100 seconds of the disturbance to include the transient response of the power curve as it goes from the initial steady-state value to the final steady-state value.

Table 5.3 shows the gain values which were used to obtain the experimental results with the analog controller. The critically damped response was achieved using a proportional gain, k_p , of 30 and an integral gain, k_i , of 3.0. For the overdamped response the proportional and integral gains are 30 and 2.0 respectively. A proportional gain of 12.5 and an integral gain of 1.75 gives the underdamped response.

A comparison of the analog control system results shown in Figs. 5.3 and 5.4 shows the effect of adding a feedforward control loop to the feedback control using the tuned proportional and integral gains. Corresponding results are shown in Figs. 5.5 and 5.6 for the overdamped feedback gains. Figures 5.7 and 5.8 show the affect of adding a feedforward control loop to an underdamped feedback control loop. All three of these comparisons show that the power response at the beginning of the disturbance is speeded up by the addition of the feedforward control loop. The feedforward control loop causes the power curve to have a vertical slope at the beginning of the disturbance which reduces the lag time between the power and temperature responses. This improvement in the power response is most easily seen in the plots for the underdamped feedback control loop, as seen in Figs. 5.7 and 5.8. It is quite evident in the other plots also. The added

feedforward control loop has the advantages of derivative control in that it speeds up the initial response to the disturbance but it does not cause the system to become less stable.

The results in Table 5.4 show that the integral of the squared error is reduced by nearly a factor of ten by the addition of the feedforward control loop for all three feedback gain settings tested. The plots show that the addition of the feedforward control loop reduces the initial temperature drop at the beginning of the disturbance to approximately 0.3 °C. The initial temperature drop for the feedback control in Figs. 5.3 and 5.5 is approximately 1 °C and in Fig 5.7 (underdamped) the drop is about 1.7 °C. The only affect of the feedforward control loop on the temperature overshoot after the initial temperature drop is to increase it slightly. The feedback control can correct the overshoot while the feedforward control loop reduces the initial temperature drop due to the disturbance.

The lowest integral of squared error value is found for the case where the feedforward control loop is added to the overdamped feedback control. Figures 5.7 and 5.8 show that the settling time for the underdamped feedback gains is reduced by the addition of the feedforward control loop. This reduction in the settling time is approximately 20 seconds and is due to the near elimination of the initial temperature drop. For the other two feedback settings, the settling time is approximately the same with the added feedforward control loop as it is without. This is because the added feedforward control loop increases the overshoot as well as reducing the initial temperature drop. The power curves integrated over the first 100 seconds of the disturbance shown in Table 5.4 vary by less than 10 percent for all the tests. The total energy required to return the

system to steady-state, therefore, is not affected by the addition of the feedforward control loop. These experimental results reflect the results obtained by the computer simulations of the feedback and feedforward control systems (see Sec. 5.3) within expected modeling inaccuracies.

Table 5.3 Analog Controller Gains

	k_p (V/V)	k_i [V/(V.s)]
DAMPING		
CRITICAL	30.0	3.0
OVER	30.0	2.0
UNDER	12.5	1.75

Table 5.4 Integrals of Analog Controller Results

	I_{se} [(°C) ² s]		I_p (W s)	
	Feedback	Feedforward	Feedback	Feedforward
DAMPING				
CRITICAL	7.06	0.93	6452.89	6678.81
OVER	8.87	0.82	6287.21	6251.52
UNDER	28.31	3.30	6192.88	6240.72

The first order system time constant for the experimental system is calculated to be approximately 77.5 seconds. The convection coefficient used to determined this time constant was 400 W/(m² K). This convection coefficient was determined by using the final steady-state heater power from the experimental results (58 W), the plate surface area, and the approximate temperature difference between the plate surface and the air flow (25 °C). The time constant gives a measure of the speed at which the system recovers from a temperature change. This value (77.5 seconds) will produce a relatively slow response.

Therefore, the addition of a feedforward control loop to the feedback control shows significant improvement in the temperature response of the system.

Figure 5.9 shows the output of the Heat Flux Microsensor as a function of time. This plot is a direct measure of the disturbance in the heat loss experienced by the plate. The sensitivity of the Heat Flux Microsensor, S , is equal to $50 \mu\text{V}/(\text{W}/\text{cm}^2)$. This sensitivity was supplied by the Vatel Corp. The heat flux disturbance plot in Fig. 5.9 shows that although the heat flux exhibits turbulent fluctuations, the disturbance can be very easily represented by a step function where the heat flux increases from an initial value to a final value instantaneously at some time equal to t_0 . The increase in the heat flux due to the disturbance is seen in the plot as being roughly a factor of 25-30. This signal is the input to the feedforward control loop which is added to the control system.

Figure 5.10 is a plot of the heater power and temperature for the feedforward control loop operating as an open loop with the feedback loop disconnected. This plot illustrates the performance of the feedforward loop alone. These feedforward open loop results were produced using a feedforward gain of $40.2 \text{ V}/\text{V}^{1/2}$. This gain is approximately 5/6 of the value determined from the theory. The input to the feedforward loop as represented by Fig. 5.9 results in an output to the heaters as seen in the power curve in Fig. 5.10. The power curve is an almost perfectly flat step function because the Kepco Model JQE 55-5 MVP power supply operating as an amplifier has poor frequency response characteristics, as stated in the operation manual. This poor frequency response causes the power supply to act as a filter which removes the turbulent fluctuations from

the control output. The temperature response for the feedforward open loop is also shown in Fig. 5.10. After disconnecting the feedback loop the temperature of the plate begins to decrease slowly (before the disturbance is begun). This decrease is because the square root function in the feedforward loop is approximated by a linear function and the feedforward gain is tuned to supply (approximately) the steady-state power after the disturbance. Therefore, the feedforward loop does not supply enough power to maintain the setpoint temperature before the disturbance. The temperature begins to decrease rapidly after the disturbance is started and then it bottoms out and begins to increase again. The increase is steeper at first and then begins to level off as the temperature approaches a steady-state value where the heat loss from the plate is equal the power supplied by the heaters. This temperature curve shows that the feedforward loop cannot provide precise temperature control by itself, it must be used in concert with the feedback loop to maintain a desired setpoint. This is because feedforward control is open loop control, having inherent inaccuracies. Therefore, feedback control is needed to compensate for the imperfections in the functioning of the feedforward control (Ogata, 1990). Also, the feedback control will compensate for any unmeasurable disturbances which are not detected by the feedforward control.

5.3 Results of Computer Simulations

A plot of the temperature and heater power versus time for the critically damped feedback simulation is shown in Fig. 5.11. The feedforward simulation results using the

same gains is shown in Fig. 5.12. The results of the feedback and feedforward simulations for the overdamped case are shown in Figs. 5.13 and 5.14 respectively. Figures 5.15 and 5.16 show the response plots for the underdamped feedback and feedforward simulations.

The controller gains used to obtain the simulation results are shown in Table 5.5. The feedback gains used in the simulation for the critically damped case were proportional gain, k_p , equal to 18.0 and integral gain, k_i , equal to 2.4. For the overdamped case the proportional gain was 18.0 and the integral gain was 1.8. The proportional gain was 6.5 and the integral gain was 1.5 for the underdamped case.

Table 5.6 gives the results of the integral of the squared error and the integral of the power. The integral of the squared error is taken as the value of the integral at the end of the time record. Because the initial and final steady state errors are zero they do not add to the integral, therefore the integral over the entire simulation time is equal to the integral over the length of the transient response time. The power integral was calculated over the first 100 seconds of the disturbance by subtracting the value of the integral at 10 seconds (the beginning of the disturbance) from the value at 110 seconds.

The simulation results presented here closely match the responses of the experimental data. Comparison between the experimental results and the simulations are easily made from the plots shown in Figs. 5.17 and 5.18. These two plots combine the experimental results with simulation results for the feedback and feedforward control systems. Only the critically damped feedback control case is illustrated, however the other two damping levels would produce similar comparisons. For all three damping cases the

improvement of the temperature response due to the addition of feedforward to the feedback control in the simulations mirrors the improvement in the experimental data. As also seen in the experimental results, the integral of the squared error is reduced to approximately one tenth of the feedback control values by the addition of the feedforward control loop. The power curves are slightly different because of inaccuracies in the modelling of the plate. The peak power in the experimental results are approximately 60-80 Watts higher than the peak values seen in the simulation results. There is likely a temperature gradient across the plate cross section and a time lag from when the heat is applied at the back of the plate by the heaters to the time it reaches the front surface. Also the conduction within the plate is probably not completely one dimensional. These factors contribute to the difference in the power curves.

Because the simulation results show qualitative agreement with the experimental results, the simulation provides a good model of the system behavior.

Table 5.5 Simulation Gains

	k_p (V/V)	k_i [V/(V s)]
DAMPING		
CRITICAL	18.0	2.4
OVER	18.0	1.8
UNDER	6.5	1.5

Table 5.6 Simulation Integrals

	$I_{sc} [(\text{°C})^2 \text{ s}]$		$I_p (\text{W s})$	
	Feedback	Feedforward	Feedback	Feedforward
DAMPING				
CRITICAL	6.82	0.74	5796.18	5796.08
OVER	9.18	0.98	5796.11	5796.21
UNDER	27.94	3.35	5796.21	5796.31

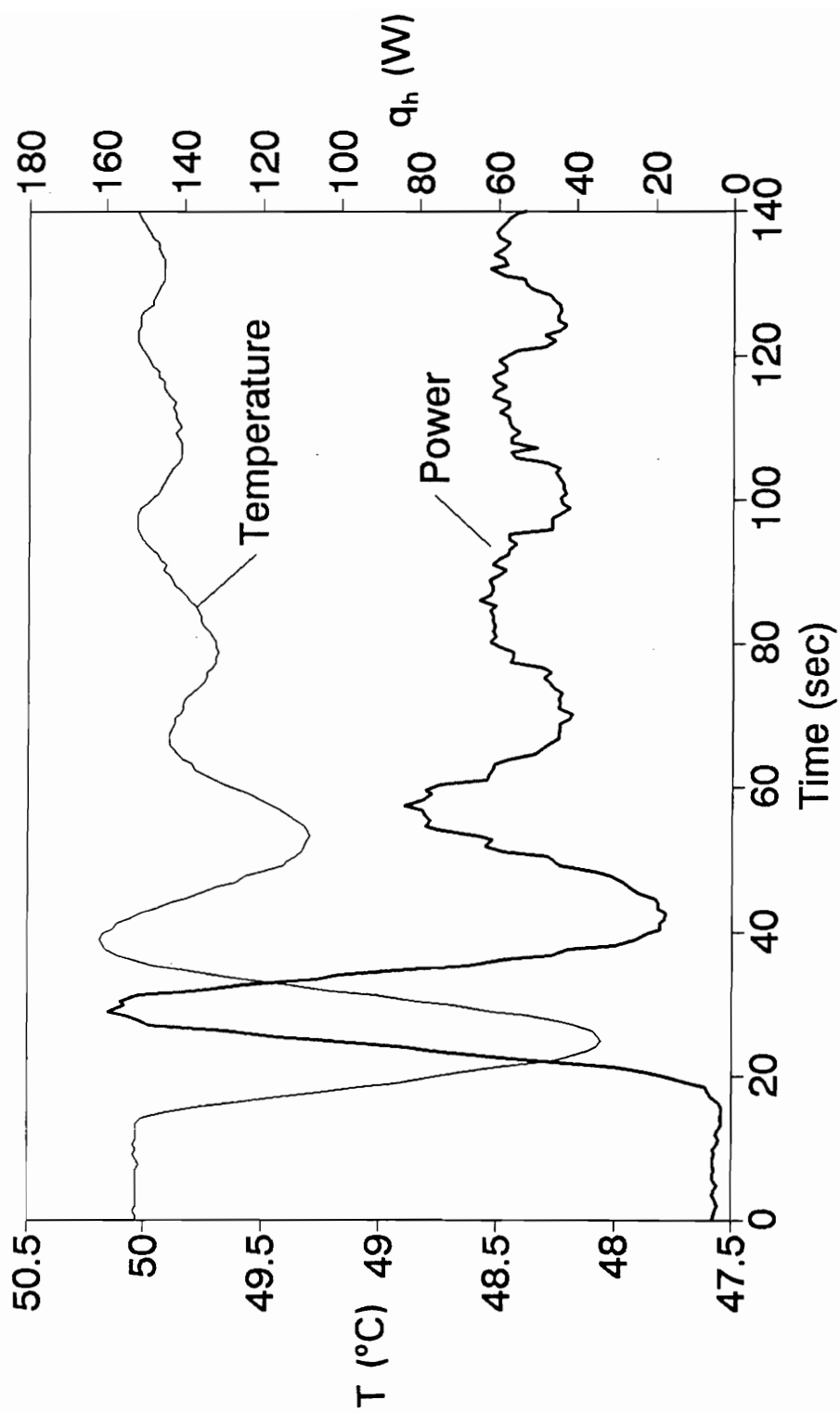


Fig. 5.1 Eurotherm Controller Results With PI Control

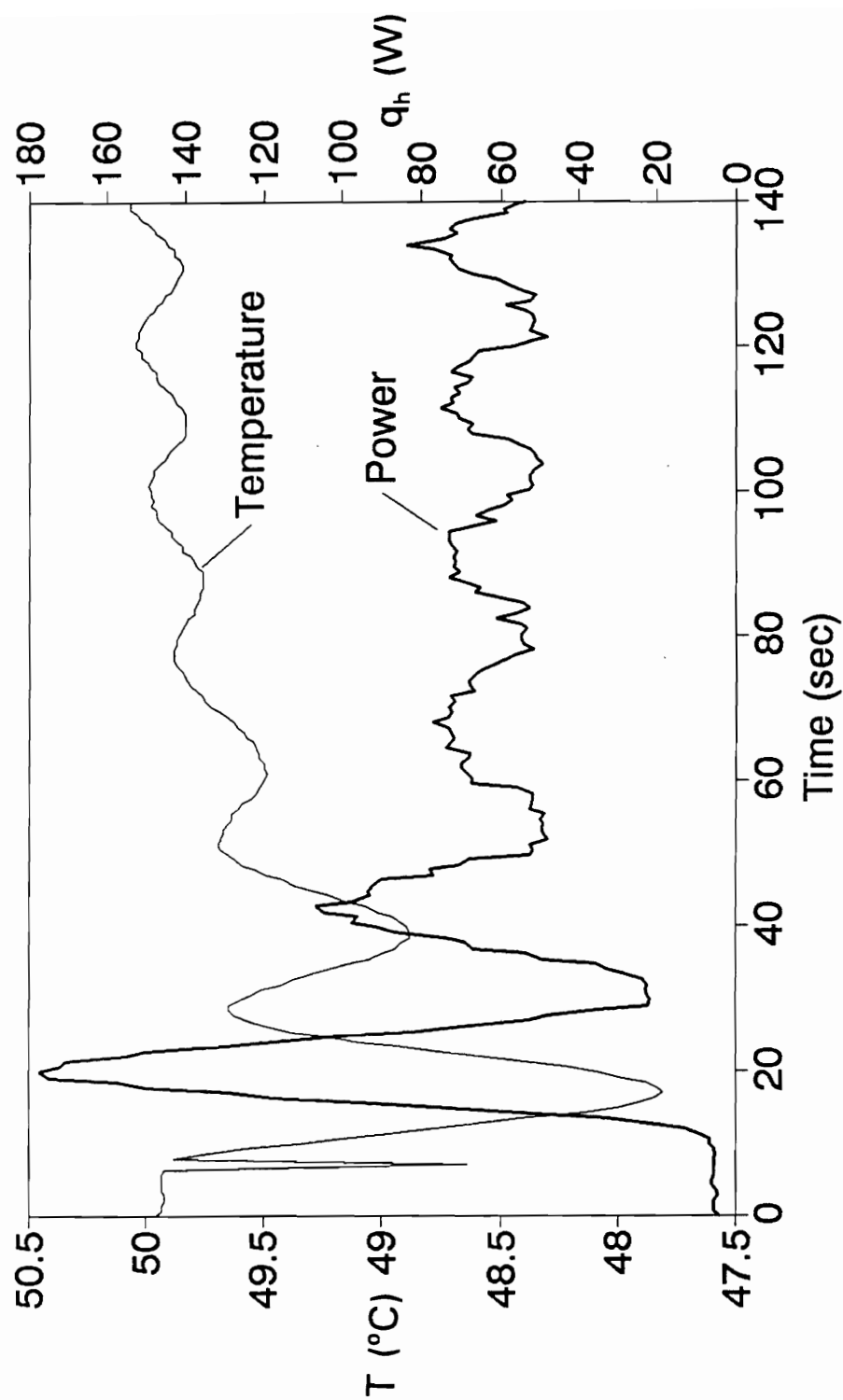


Fig. 5.2 Eurotherm Controller Results With PID Control

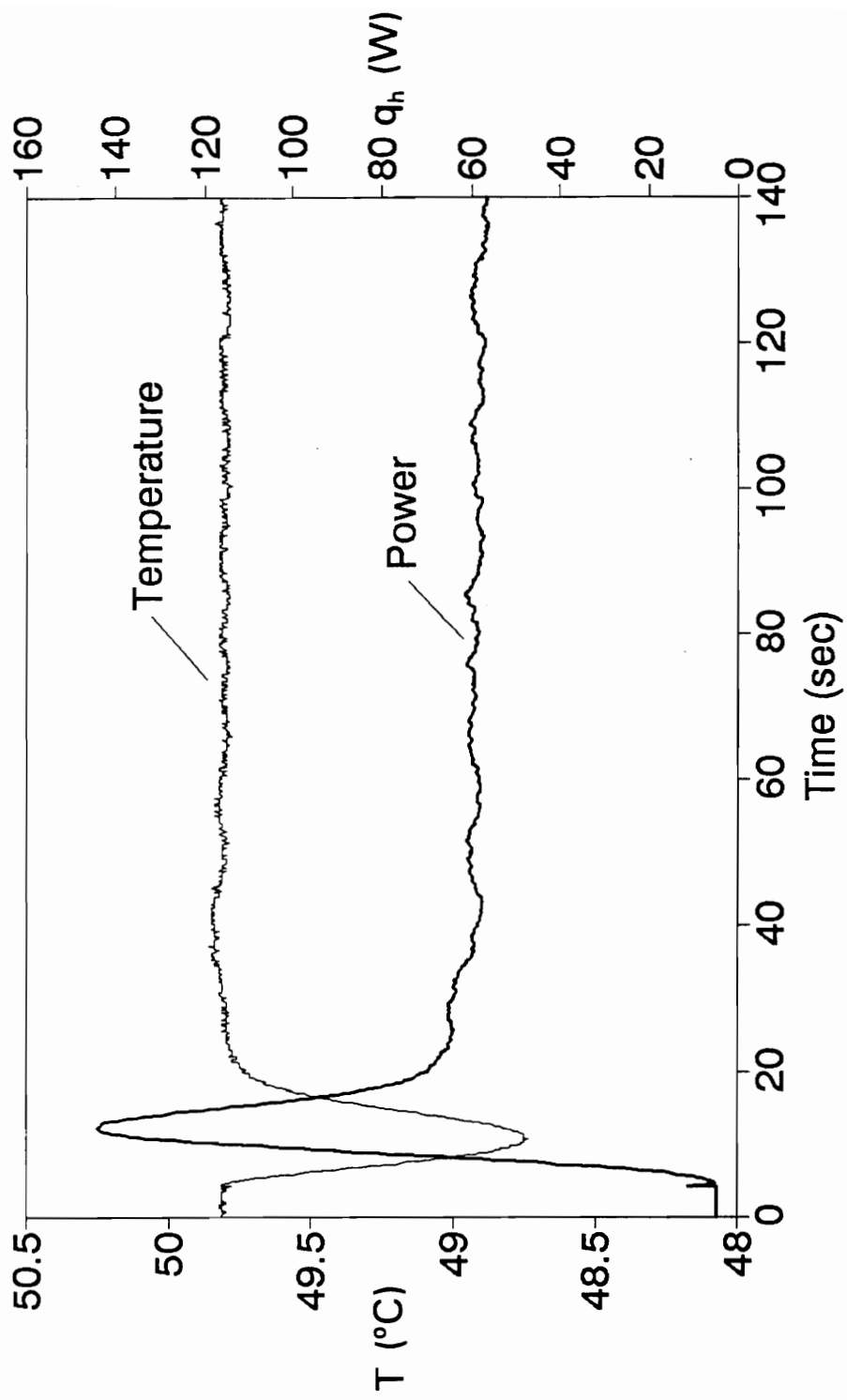


Fig. 5.3 Analog Feedback Controller Results-Critical Damping

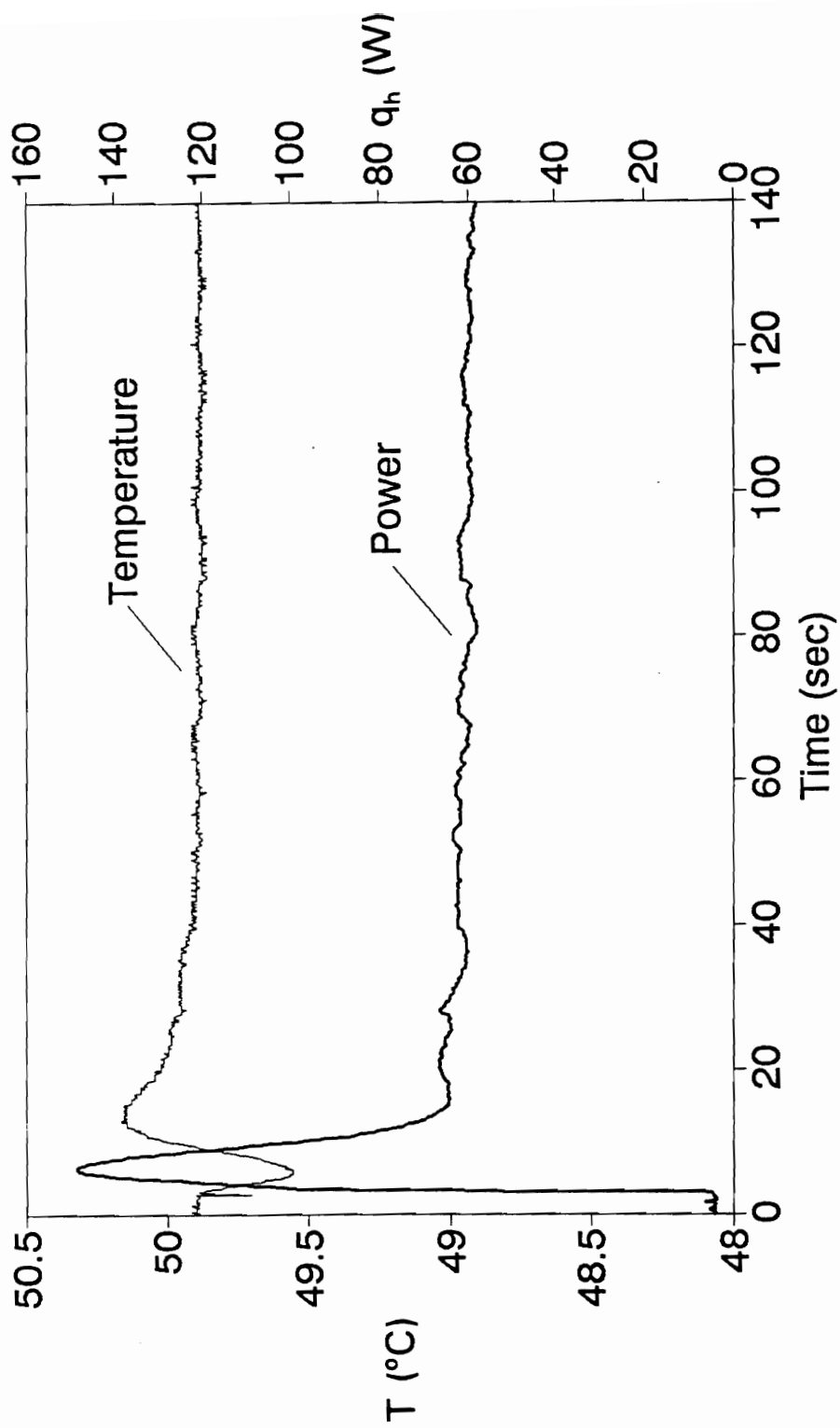


Fig. 5.4 Feedforward Results With Critical Damped Feedback

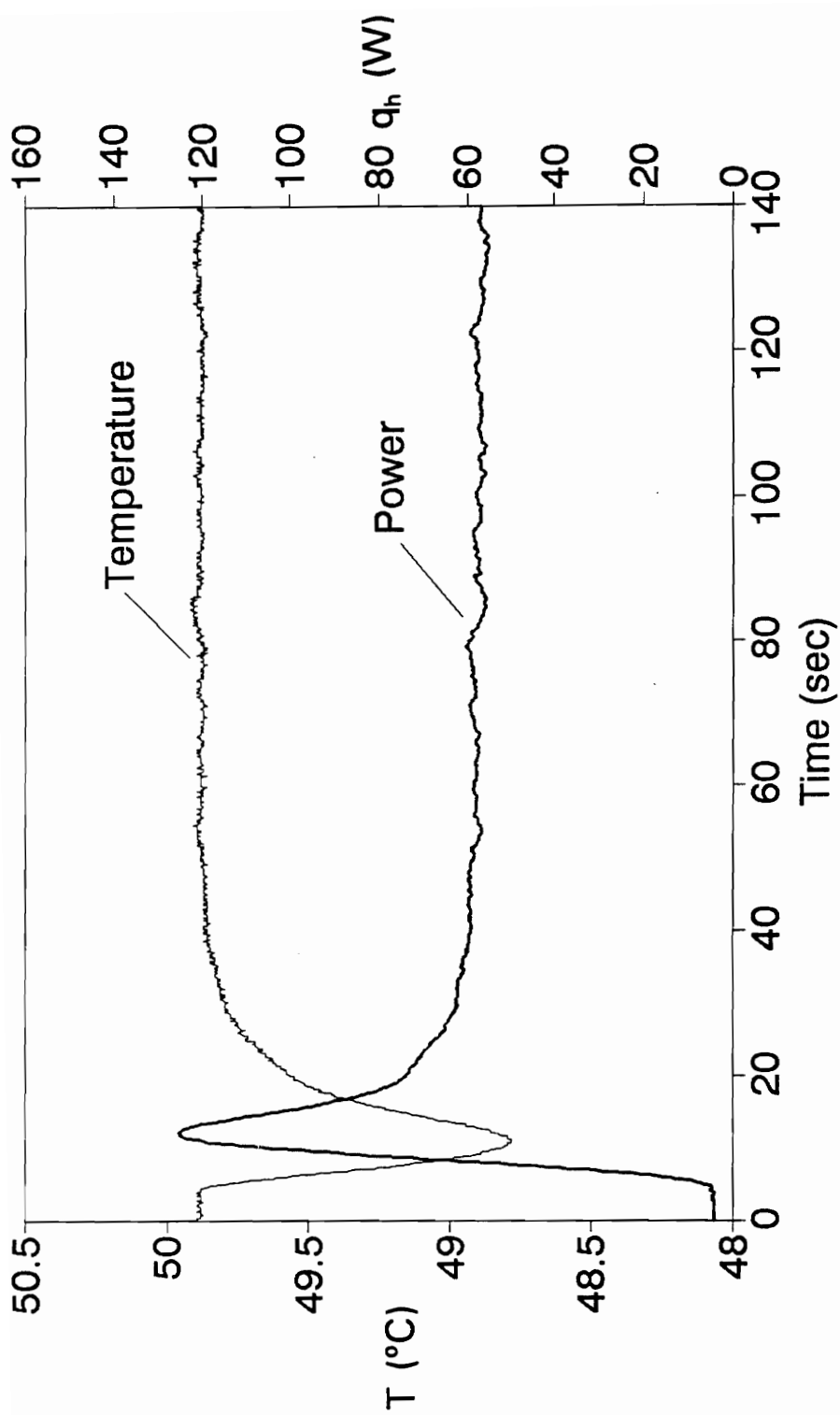


Fig. 5.5 Analog Feedback Controller Results-Overdamped

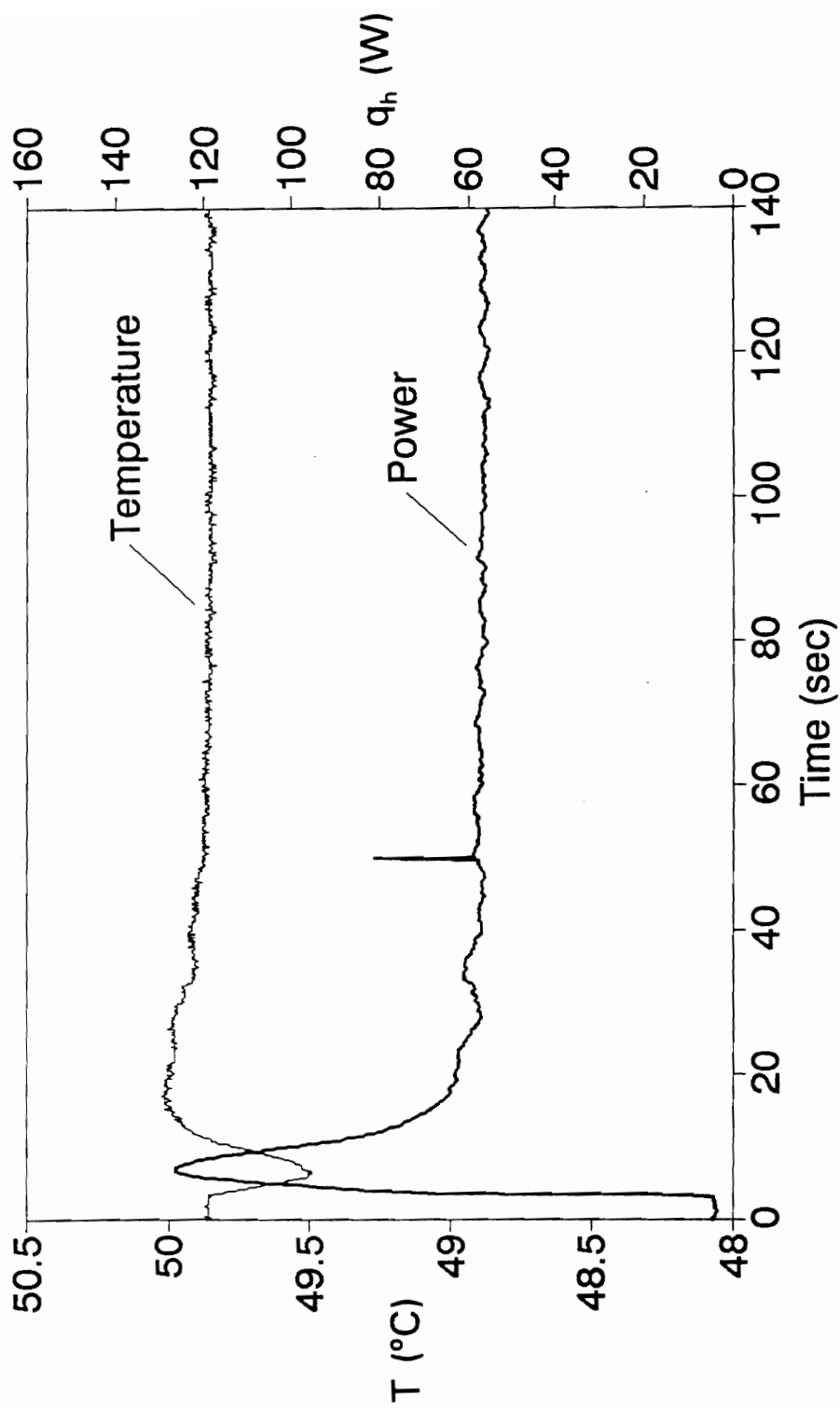


Fig. 5.6 Feedforward Results for Overdamped Feedback

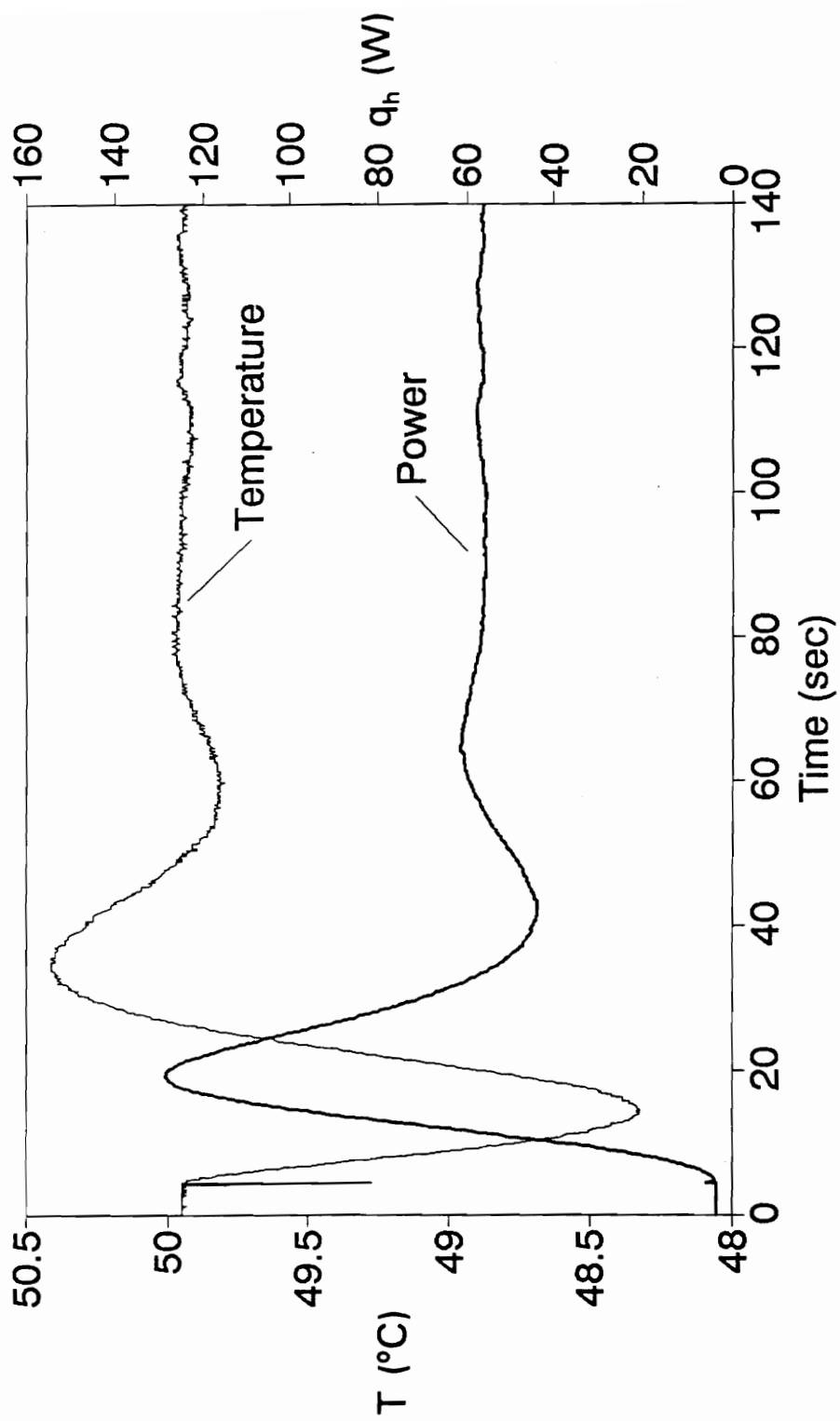


Fig. 5.7 Analog Feedback Controller Results-Underdamped

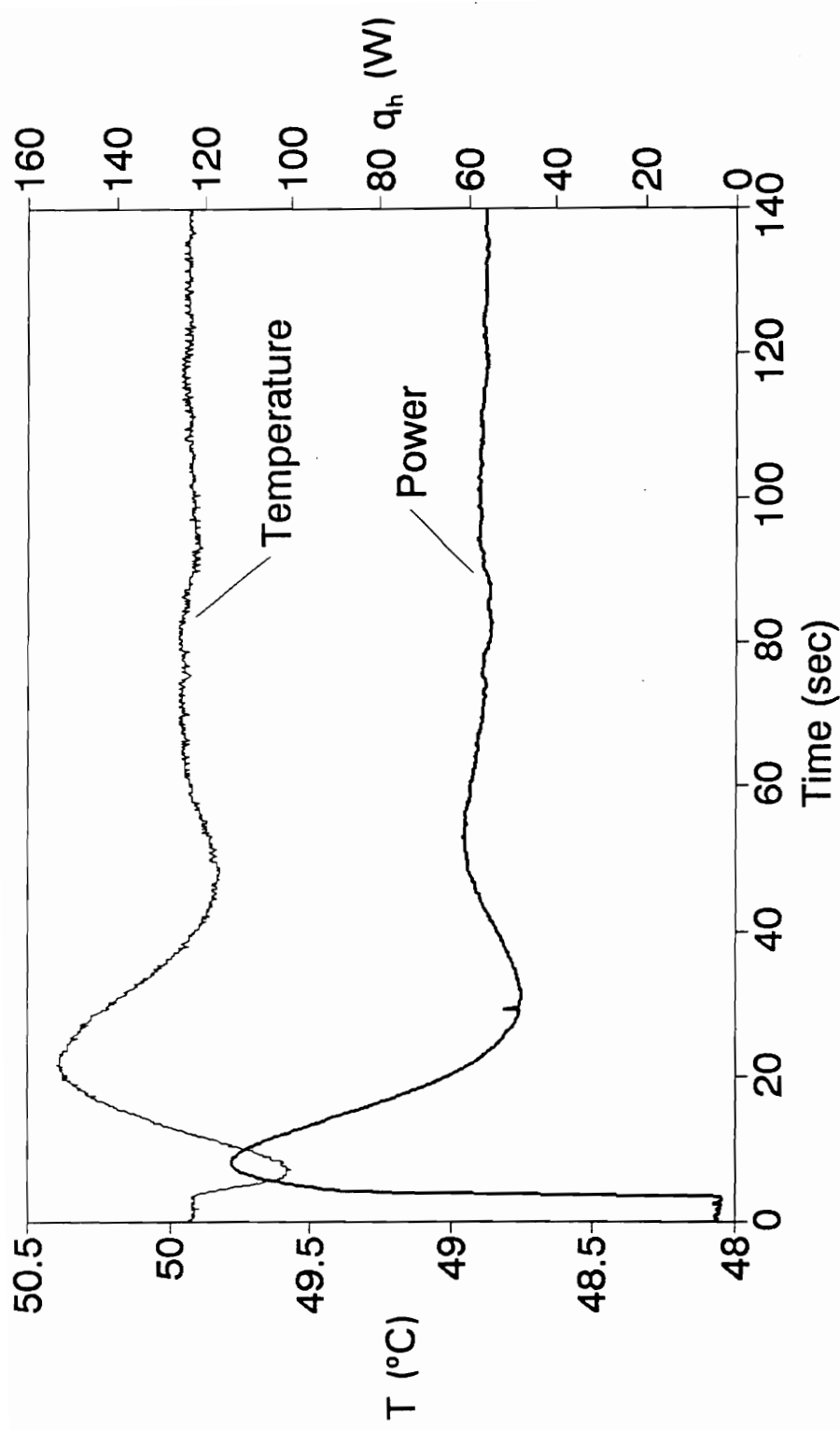


Fig. 5.8 Feedforward Results for Underdamped Feedback

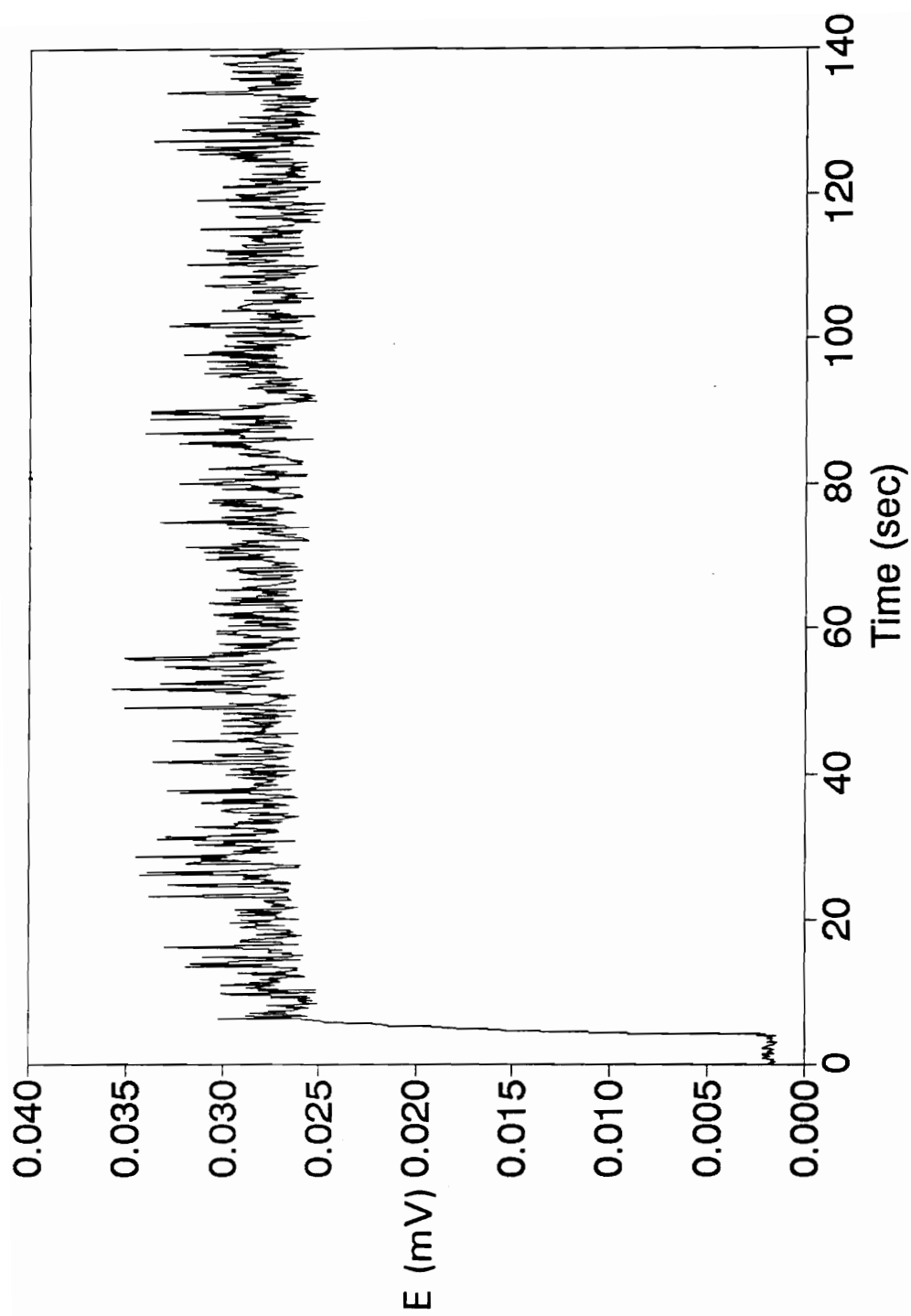


Fig. 5.9 Heat Flux Disturbance

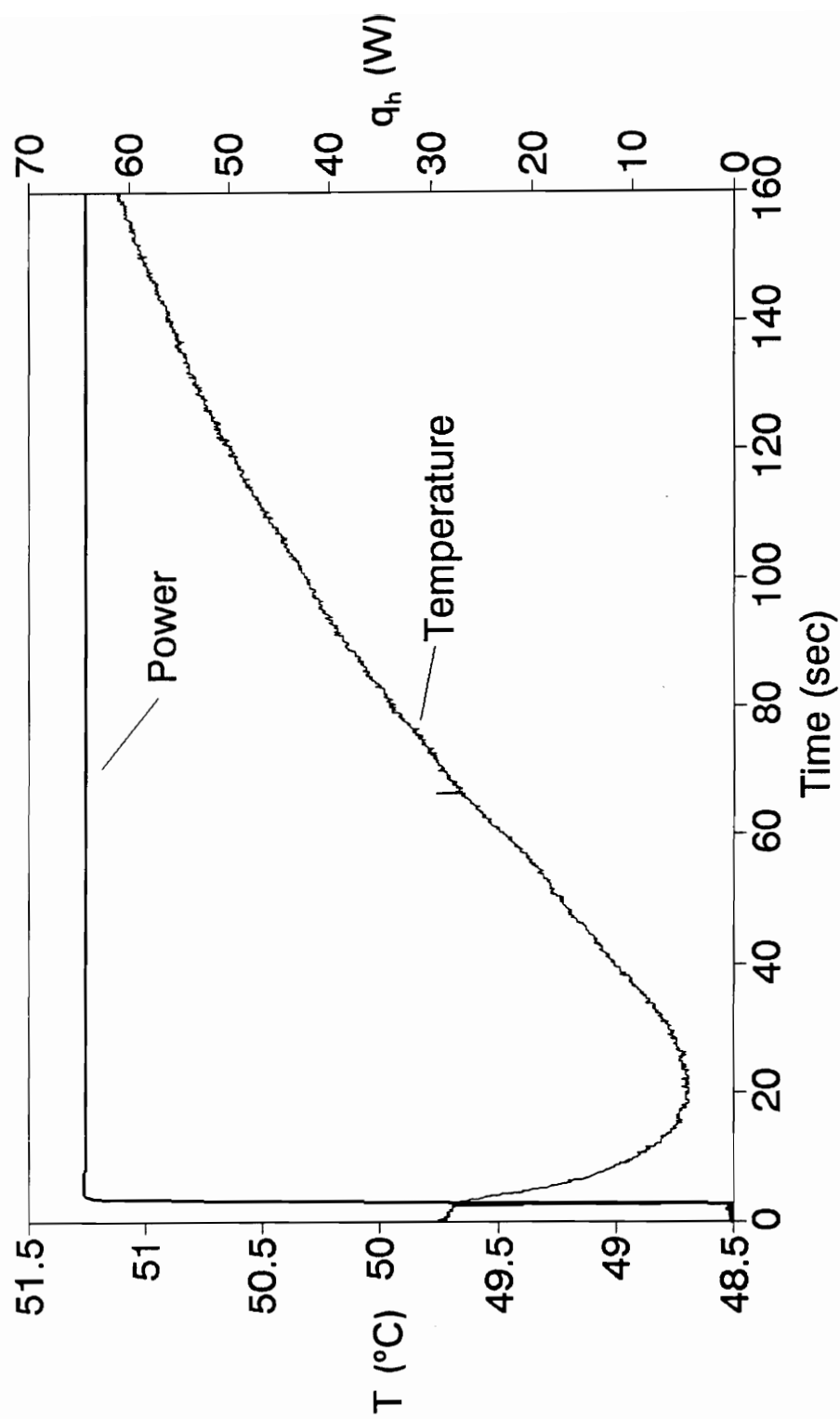


Fig. 5.10 Feedforward Open Loop Results

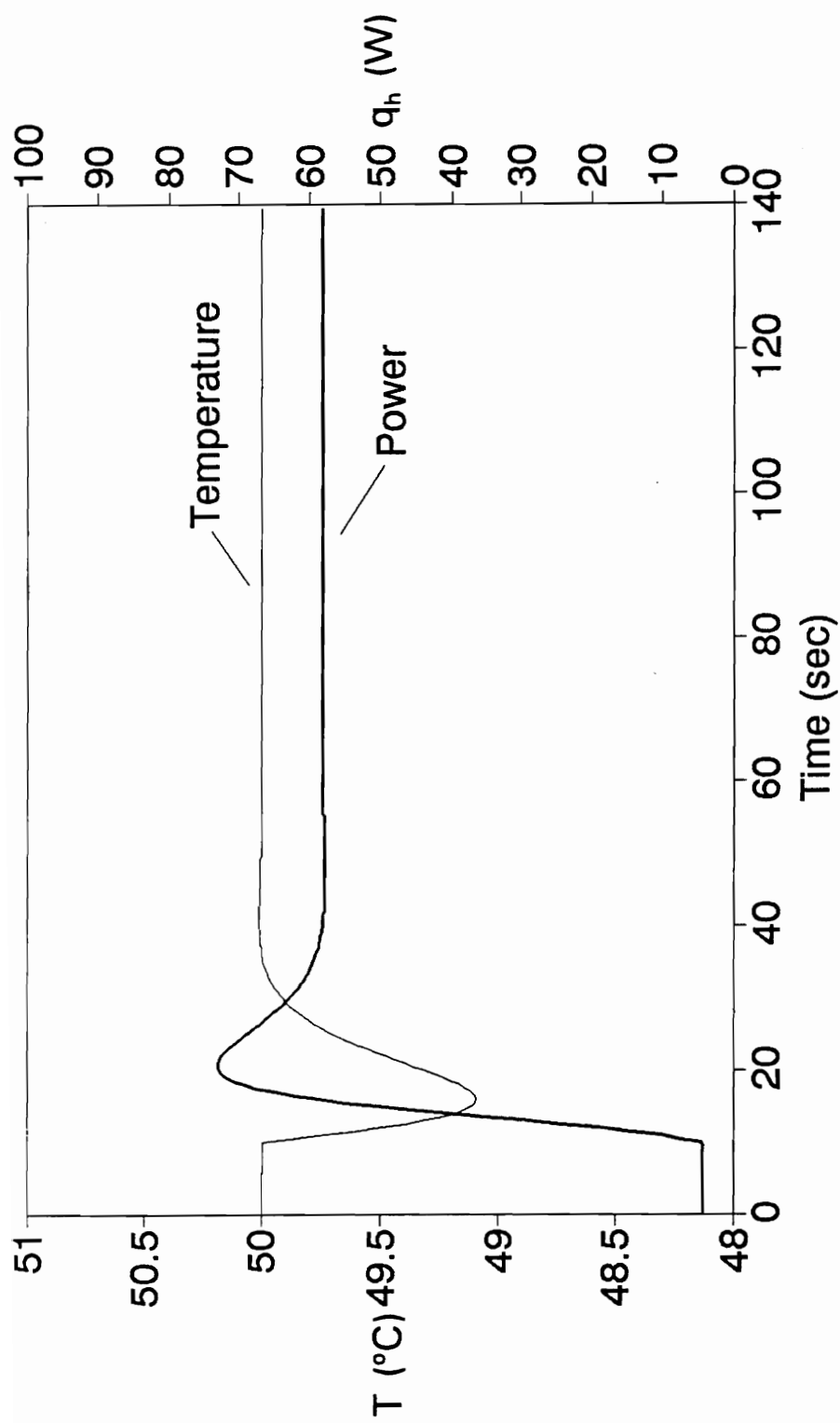


Fig. 5.11 Feedback Simulation Results-Critical Damping

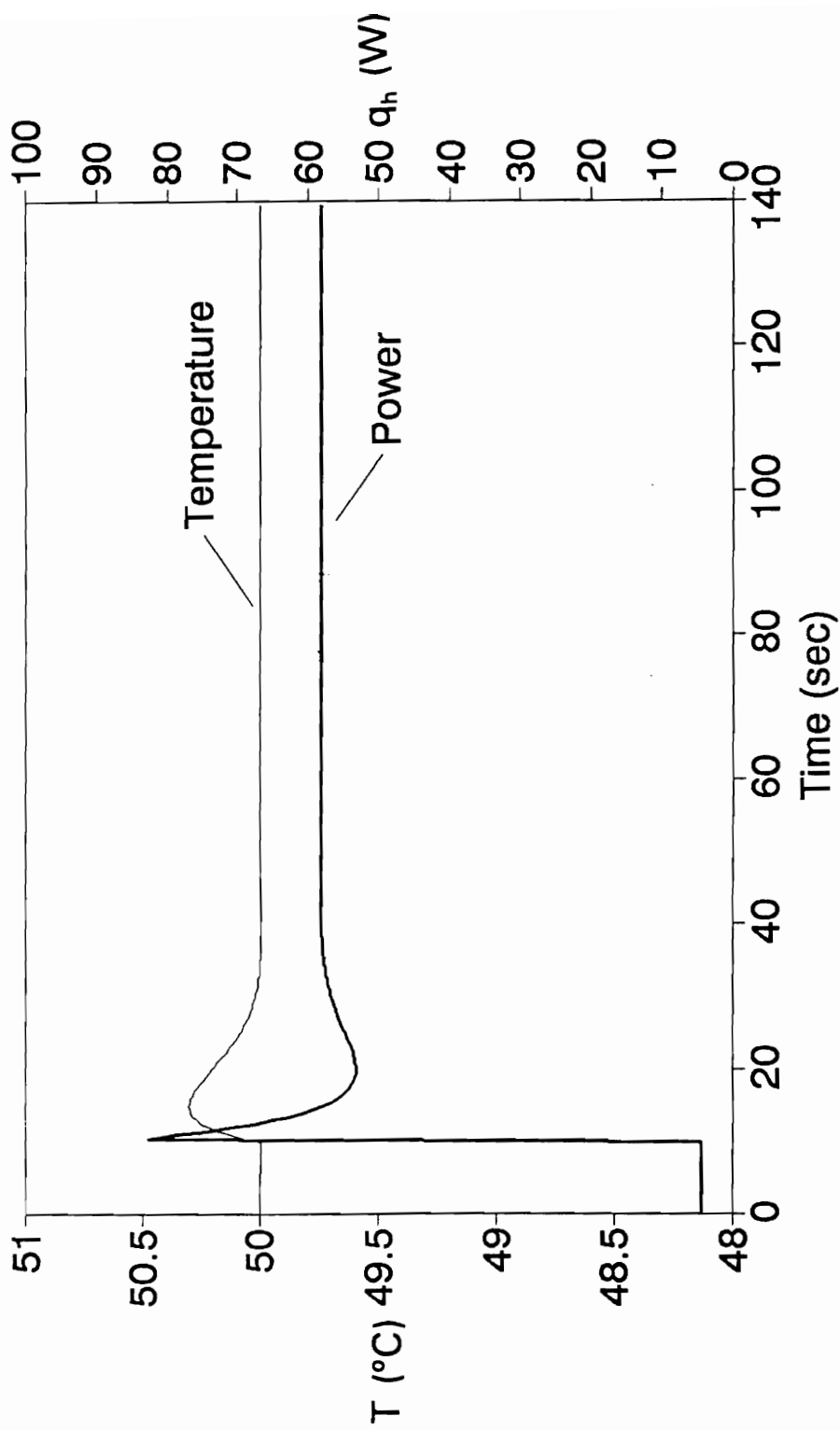


Fig. 5.12 Feedforward Simulation Results With Critical Damped Feedback

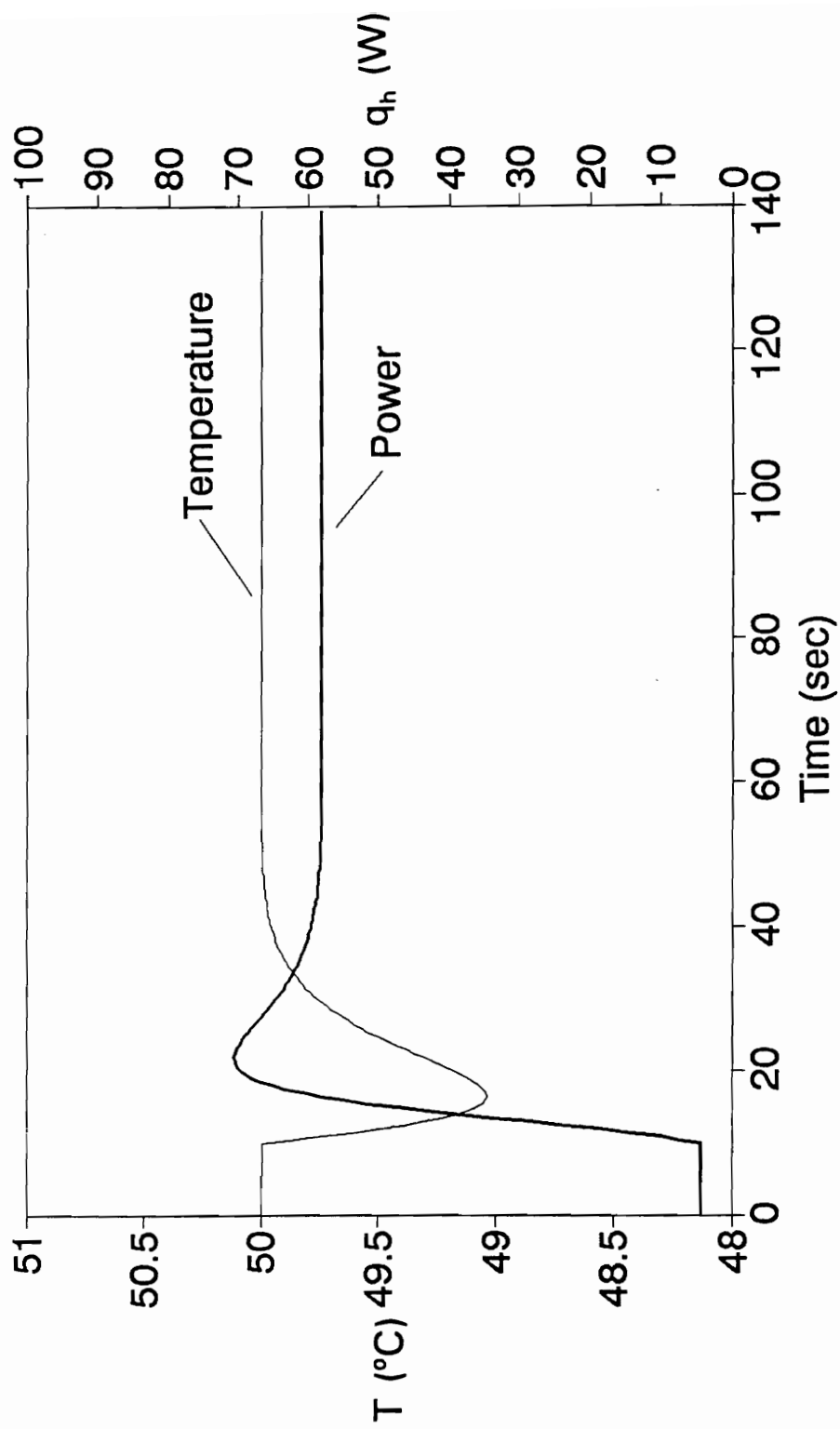


Fig. 5.13 Feedback Simulation Results-Overdamped

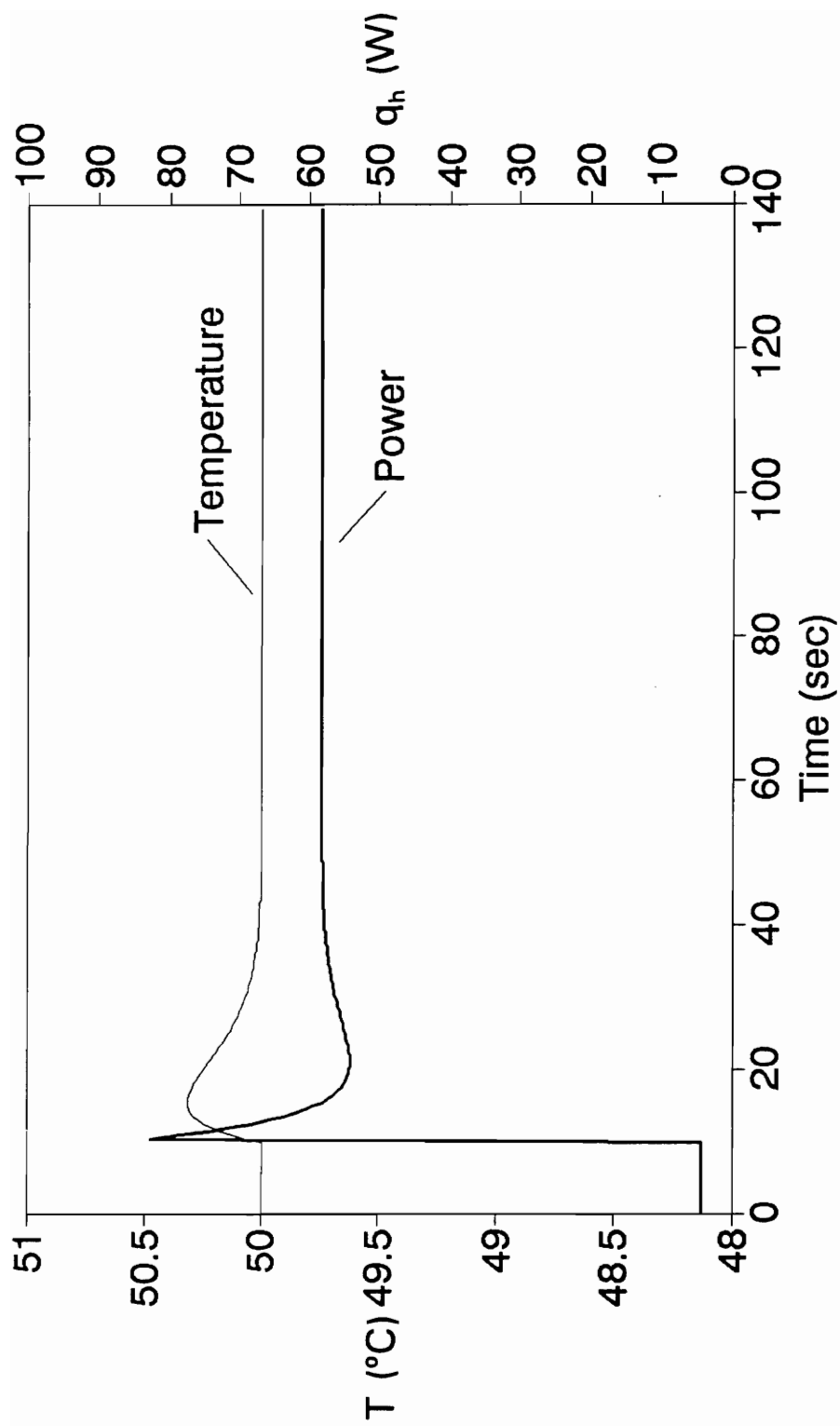


Fig. 5.14 Feedforward Simulation Results for Overdamped Feedback

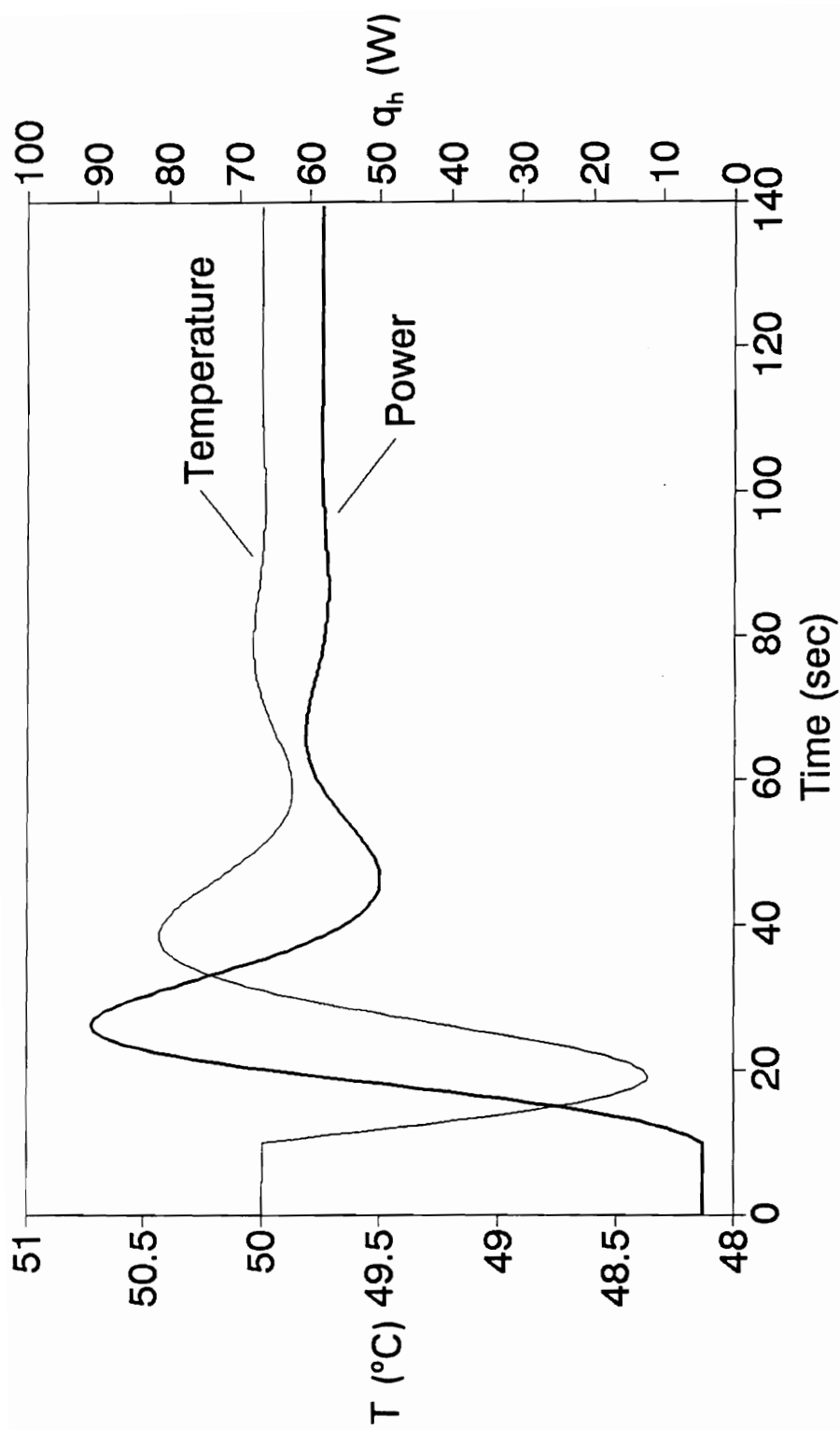


Fig. 5.15 Feedback Simulation Results-Underdamped

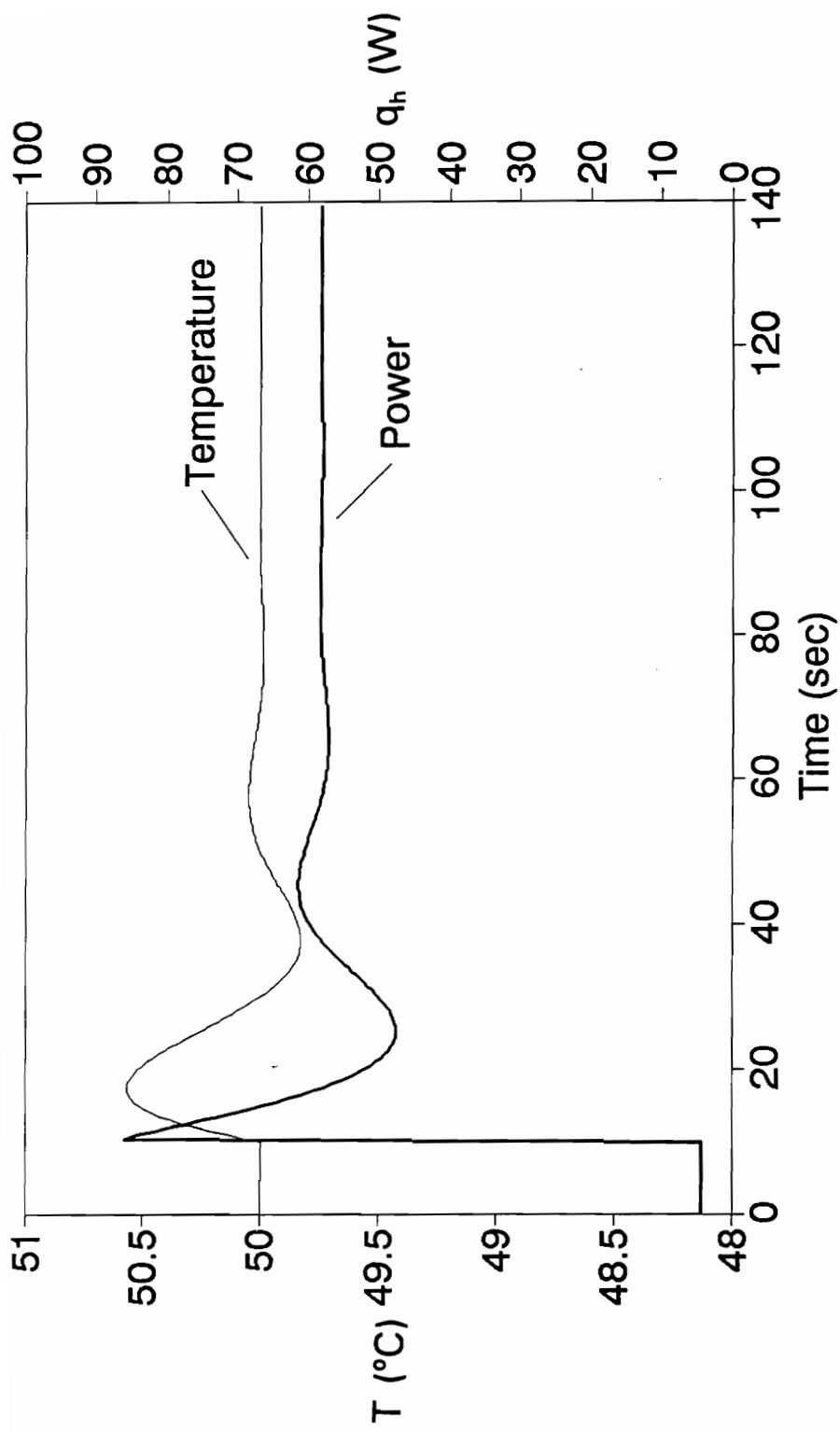


Fig. 5.16 Feedforward Simulation Results for Underdamped Feedback

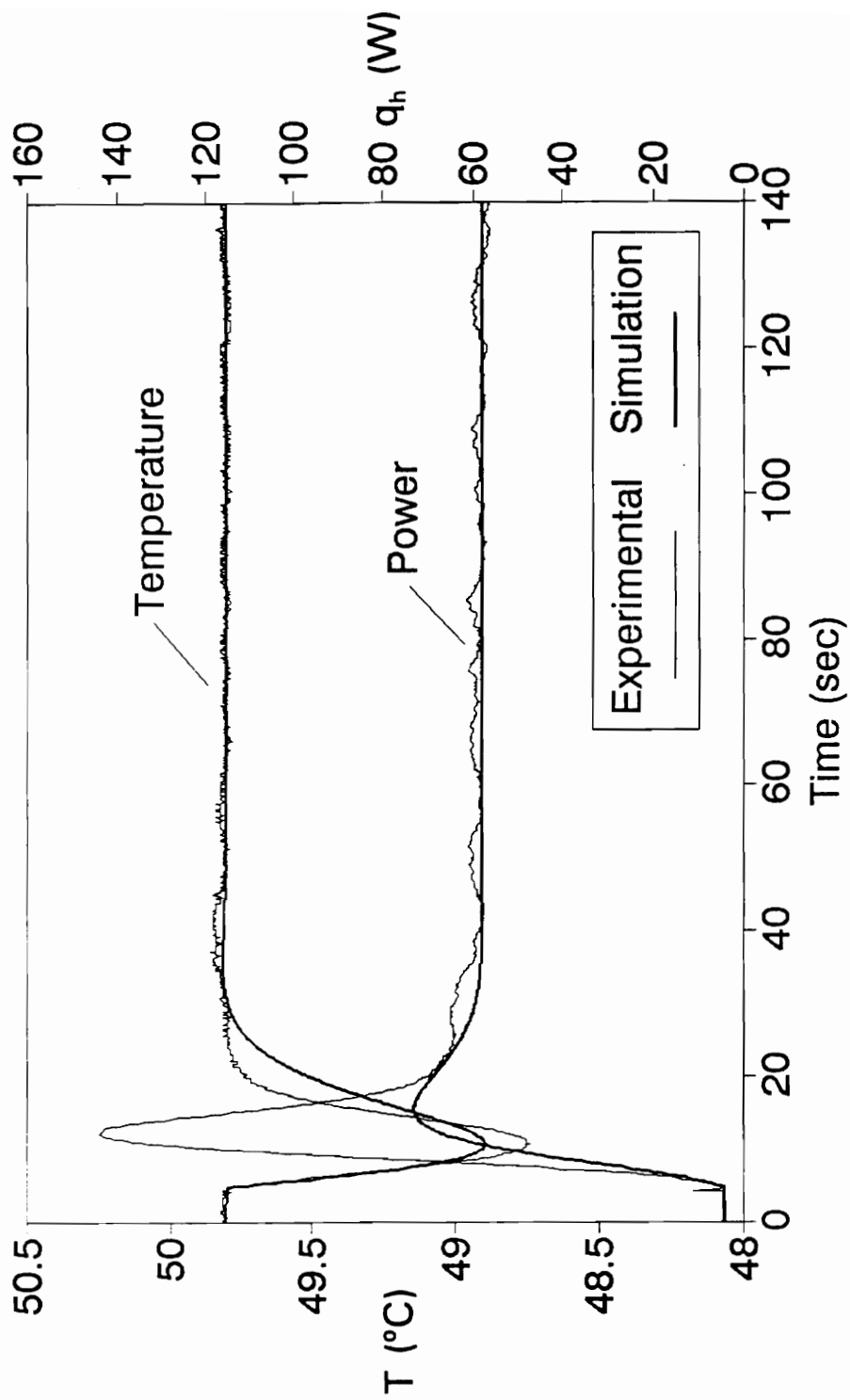


Fig. 5.17 Comparison of Feedback Experimental and Simulation Results-Critical Damping

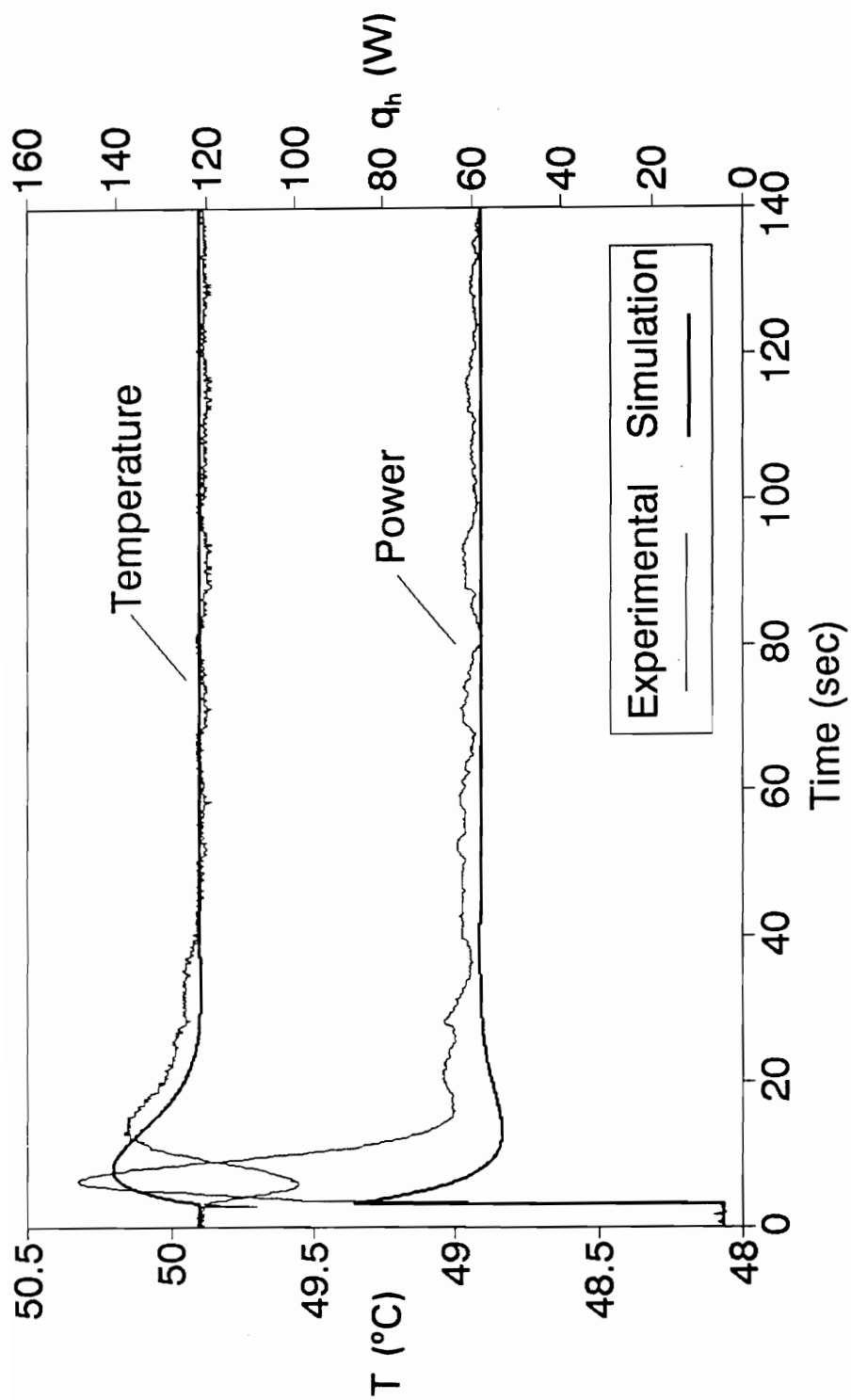


Fig. 5.18 Comparison of Feedforward Experimental and Simulation Results With Critical Damped Feedback

Chapter 6.0

Conclusions

6.1 Summary of Major Results

The concept of using heat flux measurement to provide the input for a feedforward temperature control loop was successfully demonstrated. This demonstration was carried out for a simple flat plate which was heated on one side and exposed to a step increase in the convective heat loss on the opposite side. The magnitude of the disturbance was quite large, the heat loss increased by a factor of 25-30. The temperature and the power response was compared between feedback control and feedback control with an added feedforward loop. Also, this new control approach was compared to the conventional control approach using a standard PID controller.

The results showed that the addition of the feedforward control loop to the feedback proportional and integral control improved the response of both the temperature and the power. The improvement in the temperature response was shown by the integral of the squared error being reduced by almost 90 percent when the feedforward control loop was added to the feedback control loop. The initial temperature drop due to the disturbance was reduced by at least 70 percent, this is the primary cause of the reduced error. The addition of the feedforward control caused the power to respond immediately

when the heat flux disturbance was detected. This immediate response reduced the lag time between the peak heater power and the minimum plate temperature.

The experimental results closely matched the results obtained from the computer simulations of the feedback and feedforward control systems. The major differences between the simulations and the experiments were that lower feedback gains were required to match the simulation and experimental results and the experimental heater power peaks were much greater than the simulation power peaks. These differences are due to inaccuracies in the modelling of the plate.

The addition of derivative control to the proportional and integral control caused the response of the system to become less stable. The addition of derivative control did speed up the initial response to the disturbance, but the decreased stability had to be corrected by increasing the system damping through the proportional and integral control. The increased damping slowed down the recovery of the temperature from the disturbance.

The demonstration showed that the feedforward approach is better than the derivative approach because the addition of the feedforward loop does not change the stability of the system, while the addition of derivative control decreases the system stability. Because the feedforward approach anticipates a temperature change in the plate before the change occurs, the deviation from the setpoint is greatly reduced.

6.2 Future Work

Future work in this area should include further refinements to the control system which may improve its performance and testing the response to other types of disturbances. The refinements to the control system could feature the use of a digital algorithm which employs a true square root function for the feedforward control voltage, instead of the linearized function used in this study. The Heat Flux Microsensor could also be used as the only control sensor in a feedback plus feedforward control system because it features a resistance temperature sensor. As a complete control sensor, the RTS output could be used to provide input for the feedback control and the HFM output would serve as input for the feedforward control loop. Because the temperature and heat flux measurements would be taken at nearly the same location, this approach could offer more precise temperature control at the sensor location. The feedforward control approach may also be investigated for more complicated thermal systems, such as those involving heating and cooling. The measurement of heat flux for use as input for feedforward temperature control may someday become common practice in applications where rapid but stable response to a disturbance is of critical importance.

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APPENDIX

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Appendix A

Characterization of Power Amplifier

Output/Input Relationship

A Kepco Model JQE 55-5 MVP power supply was used as a power amplifier for the output of the analog controller. This section outlines the procedure for determining the voltage gain for this unit.

The gain for this amplifier is dependent upon the resistance value of a resistor which is connected in series with the positive input voltage and the positive input terminal. A gain of approximately 100 V/V was desired for this experiment, therefore different resistors were tried on the input terminal until the output voltage was observed to be about 100 times the input voltage. This resistor was then selected for the input resistor. The relationship between the input and output of the amplifier was then determined by recording random input data points and the corresponding output value. The input voltages were generated by using one of the analog computer reference voltages and potentiometers. The input was varied so that the output was within the expected operating range (approximately 0-65 Volts) and the output versus the input was recorded. A total of 18 data points were recorded. The voltages were read from the Dana Digital Multimeter 5100 and the HP 3478A Digital Multimeter. The data was then processed using a linear least-squares curve fit.

A plot of the measured data and the linear curve fit for the data points is shown in Fig. A.1. This plot shows a very good linear relationship for the amplifier, with a correlation coefficient very nearly equal to one (calculated value of 0.9999995). The slope of the curve was determined to be 114.1 V/V and the x-intercept was found to be 0.034 Volts. The slope represents the amplifier gain and the x-intercept represents the offset. Input voltages less than the offset will not produce an output from the amplifier. These gain and offset values were used in the computer simulations described in Chapter 3. The amplifier gain value was also used to determine the feedforward gain.

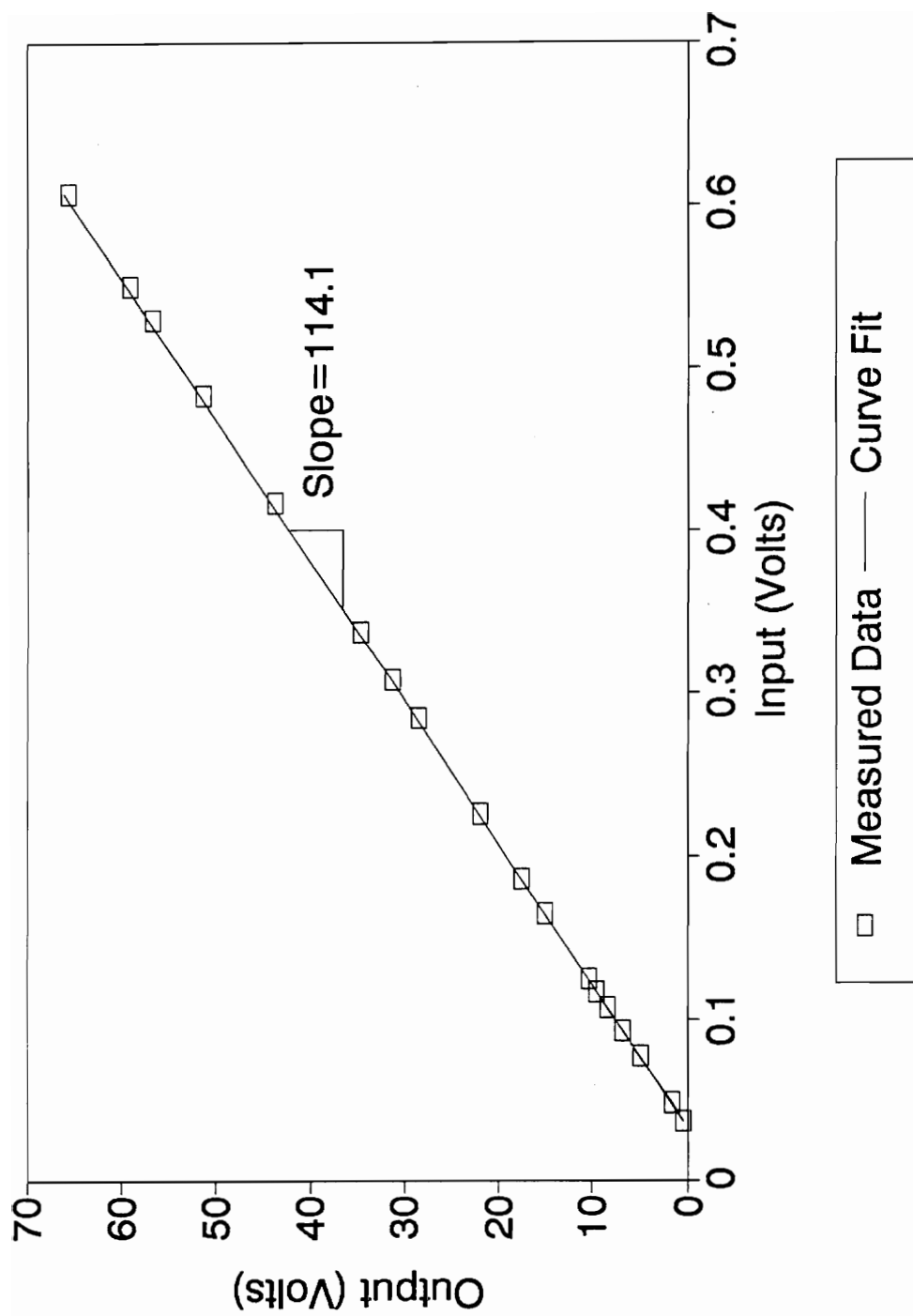


Fig. A.1 Power Amplifier Input-Output Plot

Appendix B

Data Acquisition Program

The data acquisition program listed in this section was adapted from GPIB examples. The program runs on an IBM PC and uses the BASICA programming language. The computer is fitted with GPIB and A/D interface boards for acquiring data. The program acquires heater voltage data by taking readings from the HP 3478A digital multimeter through the GPIB and temperature data by reading the signal through the A/D. The data is acquired in a loop which takes a reading from the HP multimeter and then reads the A/D, the acquired data are stored as array variables. It is assumed that the acquisition of all the data for a single point is completed nearly simultaneously (i.e. lines 220-320 are assumed to execute in rapid succession), thus the data can be treated as a simultaneous record of heater voltage and temperature data. The program also reads the time from the system clock before entering and after finishing the data acquisition loop. The acquired data is then written to a data file on disk. The start and finish times for the acquisition loop and the number of data points acquired are written at the beginning of the file, this data is used to determine the time interval between data points. Another loop then writes the multimeter reading and the A/D voltage reading to the data file.

The program listed here is the version that records the DC heater voltage supplied by the analog control system. The version which acquires the true RMS value for the

Eurotherm SCR output voltage is slightly different. For this true RMS reading from the multimeter, the command string in line 180 is changed to "F2RAZ0N3T5" (the multimeter operation manual explains the remote programming commands). Because the multimeter takes longer to get a reading in the true RMS AC volts mode than in the DC volts mode, the number of data point that can be acquired over the same time span is less. Therefore, the number of data points is reduced to 200 by changing the upper bound of the loops at lines 200 and 380. The time interval between data points for the DC voltage is approximately 0.11 seconds while the interval for the AC readings is approximately 0.72 seconds. The speed of this data acquisition program is limited mostly by the speed of the multimeter in getting readings.

The program listing contains comment statements to outline the operation of the program. The first part of the program (lines 10-50) contains commands that are standard for GPIB programs.

Data Acquisition BASICA Program
Adapted from GPIB by Frank Caldwell and Doug Lartz
July 1993

```

10  CLEAR ,60000! : IBINIT1 = 60000! : IBINIT2 = IBINIT1 + 3 : IBINIT3 = IBINIT1 + 6 :
    IBINIT4 = IBINIT1 + 9: BLOAD "bib.m",IBINIT1
20  CALL IBINIT1 (IBFIND,IBTRG,IBCLR,IBPCT,IBSIC,IBLOC,IBPPC,IBBNA,IBONL,
    IBRSC,IBSRE,IBRSV,IBPAD,IBSAD,IBIST,IBDMA,IBEOS,IBTMO,IBEOT,
    IBRDF,IBWRTF,IBTRAP,IBDEV,IBLN,IBLINES,IBCONFIG)
30  CALL IBINIT2 (IBGTS,IBCAC,IBWAIT,IBPOKE,IBWRT,IBWRTA,IBCMD,IBCMDA,
    IBRD,IBRDA,IBSTOP,IBRPP,IBRSP,IBDIAG,IBXTRC,IBRDI,IBWRTI,IBRDIA,
    IBWRTIA,IBSTA%,IBERR%,IBCNT%)
40  CALL IBINIT3 (SENDCMDS,SENDSETUP,SENDDATABYTES,SEND,SENDLIST,
    RECEIVSETUP,RCVRESPMSG,RECEIVE,SENDIFC,DEVCLEAR,
    DEVCLEARLIST,ENABLELOCAL,ENABLEREMOTE,SETRWLS,SENDLLO)
50  CALL IBINIT4 (PASSCONTROL,READSTATUSBYTE,TRIGGER,TRIGGERLIST,
    PPOLLCONFIG,PPOLLUNCONFIG,PPOLL,RESETSYS,FINDRQS,ALLSPOLL,

```

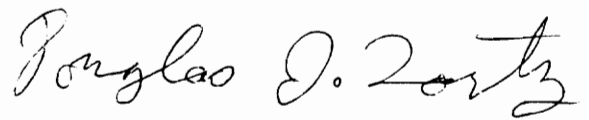
```

        FINDLSTN,TESTSYS,IBRDKEY,IBWRTKEY,WAITSRQ,TESTSRQ)
60 REG1%=&H2EC:REG2%=&H2ED:GAIN%=1:CHAN%=1:SG%=3333:SG1=33.33
70 LOW%=3:HIGH%=3
80 DIM RD$(1000):DIM VALUE%(1000):DIM TME%(1000):DIM LOW%(1000):
    DIM HIGH%(1000)
90 OUT REG2%,&HF      'initialize
100 TEMP=INP(REG1%)    'the
110 WAIT REG2%,&H2,&H2  'data translation
120 WAIT REG2,&H4
130 OUT REG2%,&H1      'board
140 CLS:KEY OFF
150 DVM%=4:DSA%=20:PLT%=3:DSK%=1:T%=200:RD$=SPACE$(11)    'gpib
    system addresses
160 BDNAME$="DEV4"      'string name for voltmeter
170 CALL IBFIND(BDNAME$,DVM%)    'select device for future use
180 WRT$="F1RAZON4T3"    'command string to voltmeter to prepare for reading
190 TIME1$=TIME$        'read start time from system clock
200 FOR SAMPLES%=1 TO 1250    'beginning of acquisition loop
210 CALL IBWRT(DVM%,WRT$)    'send command string to voltmeter
220 CALL IBRD(DVM%,RD$)    'read value from voltmeter
230 RD$(SAMPLES%)=RD$      'put value into array element
240 OUT REG2%,&HC        'begin data translation read
250 WAIT REG2%,&H2,&H2
260 OUT REG1%,GAIN%        'set gain
270 WAIT REG2%,&H2,&H2
280 OUT REG1%,CHAN%        'set channel
290 WAIT REG2%,&H5
300 LOW%(SAMPLES%) = INP(REG1%)    ' get low byte
310 WAIT REG2%,&H5
320 HIGH%(SAMPLES%) = INP(REG1%):    ' get high byte
330 NEXT SAMPLES%        'get next sample
340 TIME2$=TIME$        'read finish time from system clock
350 N%=SAMPLES%-1        'number of data points collected
360 OPEN "RECORD.DAT" FOR APPEND AS #1    'open data file
370 PRINT #1,TIME1$,TIME2$,N%    'write start/end times and number of points
380 FOR SAMPLES% = 1 TO 1250    'begin loop to write data to file
390 VALUE%(SAMPLES%)=LOW%(SAMPLES%)+HIGH%(SAMPLES%)*256    'generate 12 bit
    number
400 SG1$=STR$((VALUE%(SAMPLES%)-2048)/2047)    'convert to real number
410 PRINT #1,RD$(SAMPLES%),SG1$    'write data to file
420 NEXT    'increment loop counter
430 END

```

Vita

Douglas John Lartz was born on June 4, 1964 in Freeport, Illinois to Mr. & Mrs. William Lartz. He was raised on a farm in rural Carroll County, Illinois and attended Chadwick Community Schools. His college career began at Sauk Valley Community College in Dixon, Illinois where the Pre-engineering curriculum led to an Associate of Science degree in May, 1988. His college education continued at Memphis State University in Memphis, Tennessee where he earned a Bachelor of Science in Mechanical Engineering degree cum laude in December, 1991. After completion of the undergraduate degree Mr. Lartz came to Virginia Polytechnic Institute & State University in Blacksburg, Virginia to begin graduate studies in January, 1992. These graduate studies have led to the completion of a Master of Science in Mechanical Engineering in 1993.

A handwritten signature in cursive script that reads "Douglas J. Lartz". The signature is written in dark ink and is positioned to the right of the main text block.