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Ekström, L.; Jensen, Lars; Ljung, Lennart; Hänsel, Richard

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EXPERIMENTS WITH COMPUTER CONTROL OF AN AIR CONDITIONING PLANT

L. Ekström

R. Hänsel

L.H. Jensen

L. Ljung

This work has been a cooperation between the Department of Building Science and the Division of Automatic Control, Lund Institute of Technology, Lund and the Swedish Steam Users' Association, Malmö. The work is also a part of a research project supported by Grant D698 from the Swedish Council for Building Research.

Abstract

Digital control of an air conditioning plant using a process computer is considered. Several different control laws have been tested. It is shown that control laws based on models of the plant have better performance than conventional ones. It is also shown that the models, which are based on identification experiment, are capable of predicting the closed loop behaviour of the control system very well.

Implementations using a conventional proportional valve with a positioner, as well as using an on-off magnetic valve are tested and compared.

Table of contents

1 Introduction

This work is a cooperation between the Department of Building Science, the Division of Automatic Control and the Swedish Steam Users'Association, Malmö.

It can be seen as a continuation of Ekström-Hänsel-Jensen-Ljung (1974), in which dynamic models of an air conditioning plant have been determined from experimental data.

This second part of the work deals with the determination of regulators based on the earlier obtained models in a similar manner as reported in Jensen-Ljung (1973a).

One purpose with this work is to show how models can be used to determine good regulators.

Another purpose is to show that direct digital control can be used in air conditioning plants.

A short description of the plant is given in section 2. The model used to determine regulators is given in section 3. The different regulators are determined in section 4. Some fullscale experiments are reported in section 5. Comparisons are made between experiments using statistical data and simulated and full scale experiments. This is done in section 6. An implementation using a magnetic onoff valve instead of the normal valve is documented in section 7. Finally, in section 8, some conclusions are drawn from the experiments.

2 Plant and equipment

The airconditioning plant is situated in an office building at the Swedish Steam Users' Association, Malmö. It supplies a lecture room (260 m^3) with heated outdoor air. The capacity is 10 to 11 air changes per hour. The lecture room is also heated by convectors along the windows. The outlet air temperature is measured and is regarded as the variable to be controlled. The inlet air is heated by a water to air crossflow heatexchanger. The hot water flow is controlled by a valve, connected to a regulator. The inlet air temperature is not allowed to decrease below 10 ^{0}C. Otherwise condensation may take place in the inlet airduct. Further details are given in Ekström-Hänsel-Jensen-Ljung (1974).

The measurement and control equipment is a coupler/controller system (Hewlett Packard) connected as a teletype to a PDP-15 process computer (Digital). The coupler/controller can measure ten analog inputs and control four analog and logical outputs. The analog inputs were connected to thermistor bridges. Further details are given in Jensen (1973b).

The PDP-15 process computer has 32 k core memory, a 256 k disc, three dectape units and a x-y display. All programs were run in the realtime executive RSX-plus. Details about the used programs are given in Jensen (1974).

The normal telephone net and lowspeed modems were used as communication line between the coupler/controller in the lecture room at Malmö and the process computer at the Division of Automatic Control at Lund.

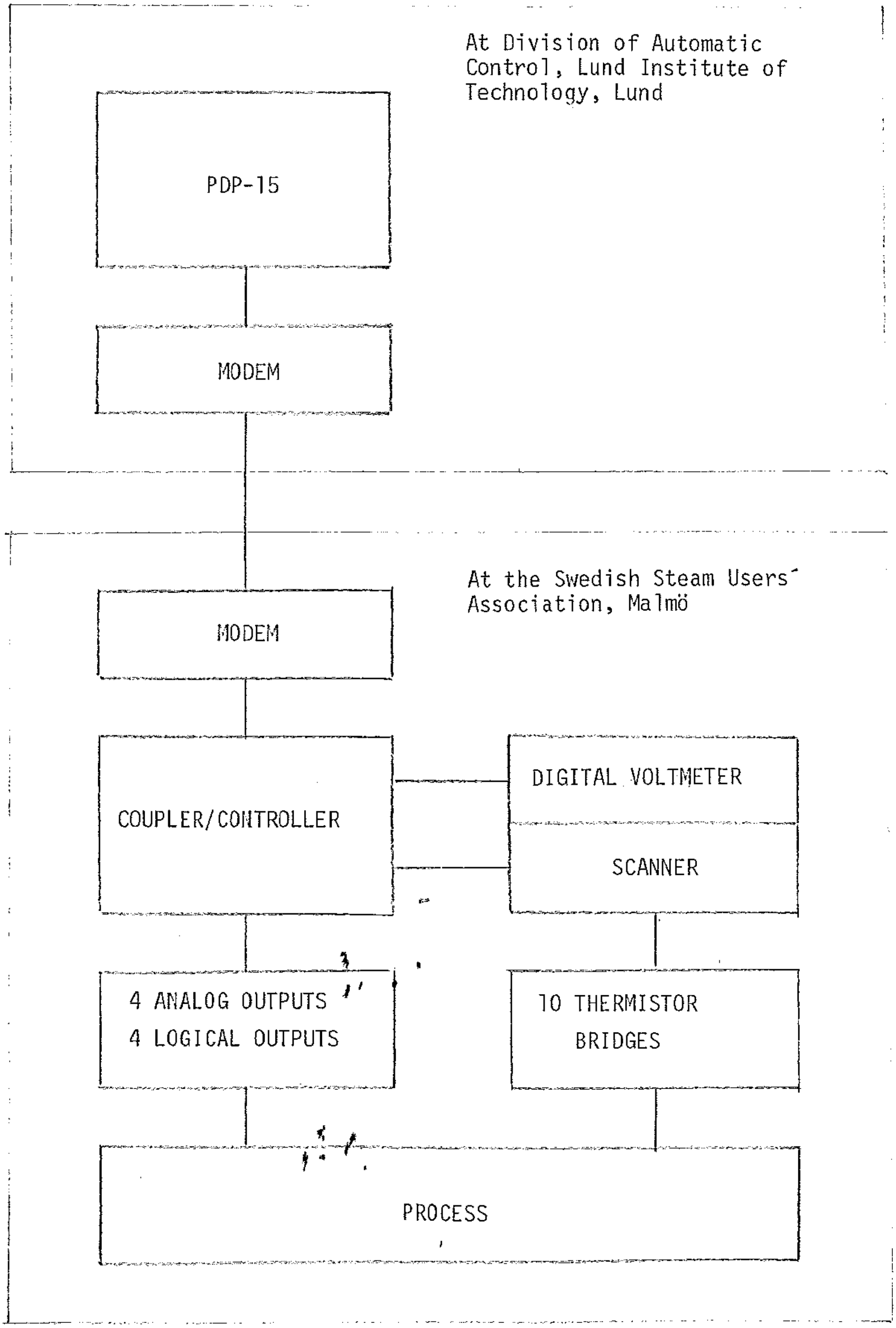

Figure 2.1 Plant and equipment

3 A mathematical model of the process

The variable to be controlled i.e. the output of the process is the temperature of the outlet air from the room. This variable will be denoted by y. The input to the process is the command signal to the control valve in the heatexchanger, as described in section 2. This variable will be denoted by u.
To be able to determine good regulators to the process a mathematical model of it is very useful. In Ekström-Hänsel-Jensen-Ljung (1974) it is described how such a model is determined, using identification experiments. A suitable model turns out to be

$$y(t) - 0.9455\, y(t-1) + 0.0375\, y(t-2) = -0.0318\, u(t-3) - 0.0309\, u(t-4) \qquad (3.1)$$

where the time unit is one minute. Here y is in ^{o}C and u in volts.

4 Determination of regulators

In this section we will determine regulators that control the outlet air temperature using the command signal to the valve servo as input.

The purpose of the control is to maintain a constant room air temperature under various disturbances. Som of the most important disturbances may be the following:

Outdoor air temperature
Sun radiation
Wind
Persons
Illumination
Machines
Change of room air
Random air circulations

Some of the disturbances appear more or less like step disturbances, while the heating process has a slow response. Since feedforward terms are not feasible, the control cannot be able to eliminate the disturbances without some overshoot.

If a window is opened for a short while the temperature usually changes quickly. But the heat capacity in walls, ceiling and floor together is in many cases 100 times larger the heat capacity of the room air. Therefore the air temperature resumes its old value even without control, due to heat exchange with the walls, ceiling and floor. Consequently the control law should react differently on this kind of disturbance than on a more long term disturbance like change of outdoor temperature. The temperature noise due to random aircirculations must also be regarded when a control is designed.

The process under consideration is quite slow. It takes several hours to evaluate the performance of a regulator. Thus even the tuning of a straightforward PID regulator will be very time consuming. Consequently, simulation of different control laws on a good mathematical model of the process saves a lot of time. Also, more complex regulators may have to be used. This is often the case when there are time delays in the system. To determine such regulators a model is very valuable. Optimal control laws can be synthesized from the model, applying e.g. Linear Quadratic control theory.

The regulators have been developed and tested using the interactive computer program package SYNPAC and the model given in section 3. The program package is described in Wieslander (1973).

First a PI and a PID regulator are tuned by a trial and error method (section 4.1). A comparison is made with regulators obtained by the Ziegler Nichols rule. The critical gain and frequence were found by simulation (section 4.2).

Linear quadratic control theory has also been used to obtain regulators (section 4.3). The procedure is the same as in Jensen-Ljung (1973a).

All regulators have been tested with a pulse disturbance added to the output signal. The response of the open loop system to this disturbance is shown in figure 4.1.

The sampling interval is one minute.

4.1 PID regulators tuned by simulation

The coefficients of a standard PID controller were chosen on the basis of simulation. Suitable PI and PID regulators turned out to be

$$u(t) = 2.\ y(t) + 0.25 \int_0^t y(t)\,dt \qquad (1)$$

and

$$u(t) = 8.\ y(t) - 4.\ y(t-1) + 0.5 \int_0^t y(t)\,dt \qquad (2)$$

The responses of the closed loop systems obtained with these regulators are given in figure 4.1.

4.2 PID regulators based on Ziegler Nichols rule

The critical gain and frequence were found by simulation. The gain was found to be 6.75 $V/^{o}C$ and the frequence 0.42 rad/min. See figure 4.2. The regulators turned out to be

P regulator

$$u(t) = 3.375\ y(t) \qquad (3)$$

PI regulator

$$u(t) = 3.04\ y(t) + 0.246 \int_0^t y(t)\,dt \qquad (4)$$

PID regulator

$$u(t) = 11.65\ y(t) - 7.6\ y(t-1) + 0.54 \int_0^t y(t)\,dt \qquad (5)$$

These regulators are somewhat similar to the former PI and PID regulators tuned by simulation. Only the gain of the derivative term differs appreciably from the gain in the PID regulator (2). The closed loop responses are given in figure 4.2.

4.3 Regulators obtained from linear quadratic control theory

Linear quadratic control theory was applied to the model (3.1) in the same way as described in Jensen-Ljung (1973a). The loss-function was chosen as follows

$$V = \sum_{t=0}^{\infty} q_1 \tilde{y}^2(t) + q_2 y^2(t) + q_3 u^2(t)$$

where

$$\tilde{y}(t) = \sum_{t=0}^{t} y(t)$$

and

q_1, q_2 and q_3 are suitable constants.

Choosing different values on q_1, q_2 and q_3 shows that the maximum deviation of the output could not be made as small as wanted. This is mainly due to the delay of two minutes in the system.

A suitable response of the closed loop system was achieved with $q_1 = 4$, $q_2 = 4$ and $q_3 = 1$. The corresponding regulator is

$$\begin{aligned} u(t) = {} & 10.99\, y(t) - 1.33\, y(t-1) + 1.61\, \tilde{y}(t) + \\ & + 0.42\, u(t-1) + 0.48\, u(t-2) + 0.53\, u(t-3) \\ & + 0.30\, u(t-4) \end{aligned} \qquad (6)$$

The closed loop pulse response is shown in figure 4.3. In this figure also the responses corresponding to the loss function constants $q_1 = 1$, $q_2 = 1$ and $q_3 = 1$ and $q_1 = 10$, $q_2 = 10$ and $q_3 = 1$ are also shown.

4.4 Noise sensitivity

All regulators have been tested with noise disturbance. White noise was added to the output of the model. It was found that the regulators discussed above are not very sensitive to noise.

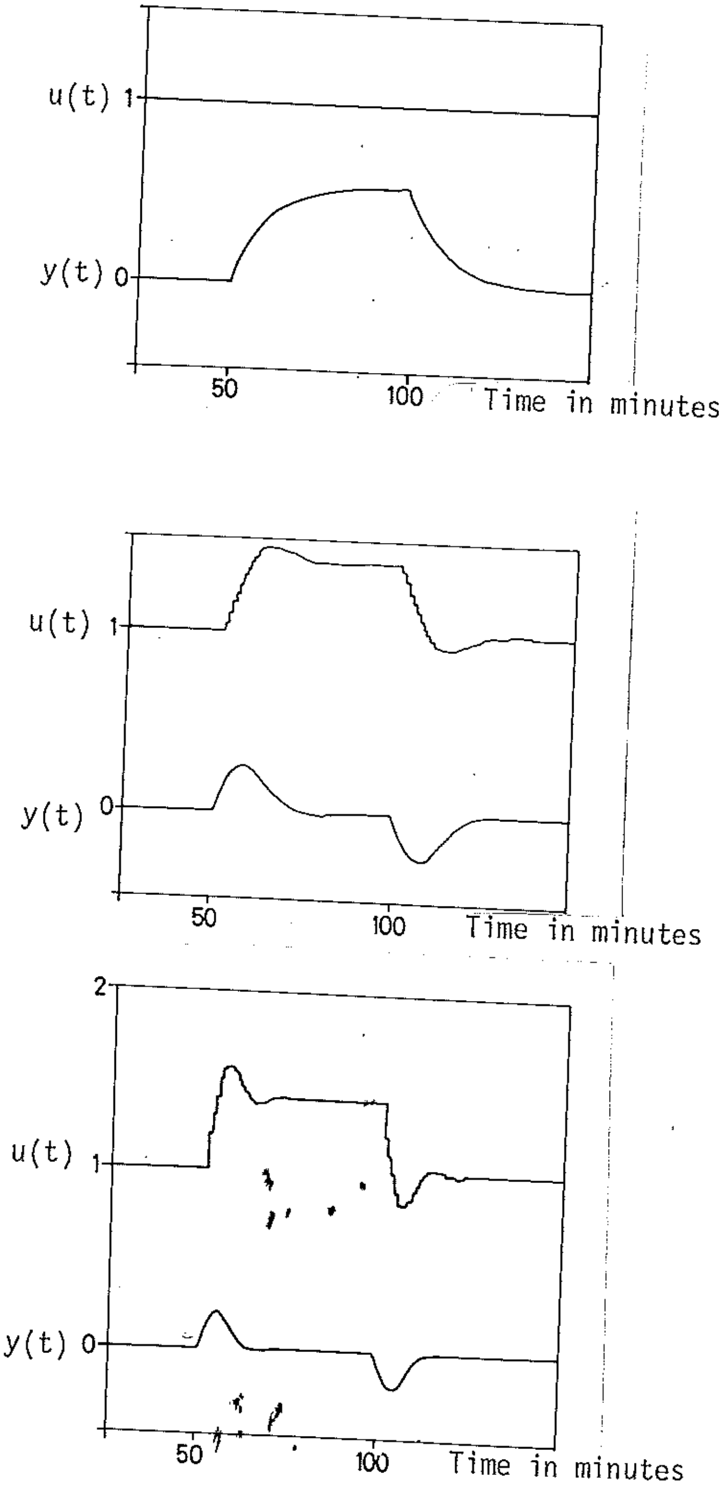

Figure 4.1 From top to bottom simulations of open loop, a tuned PI regulator (1), tuned PID regulator (2). The input u(t) has been transformed to u(t) = 0.5 u(t) + 1. The y axis is given in ^{0}C and 2 V.

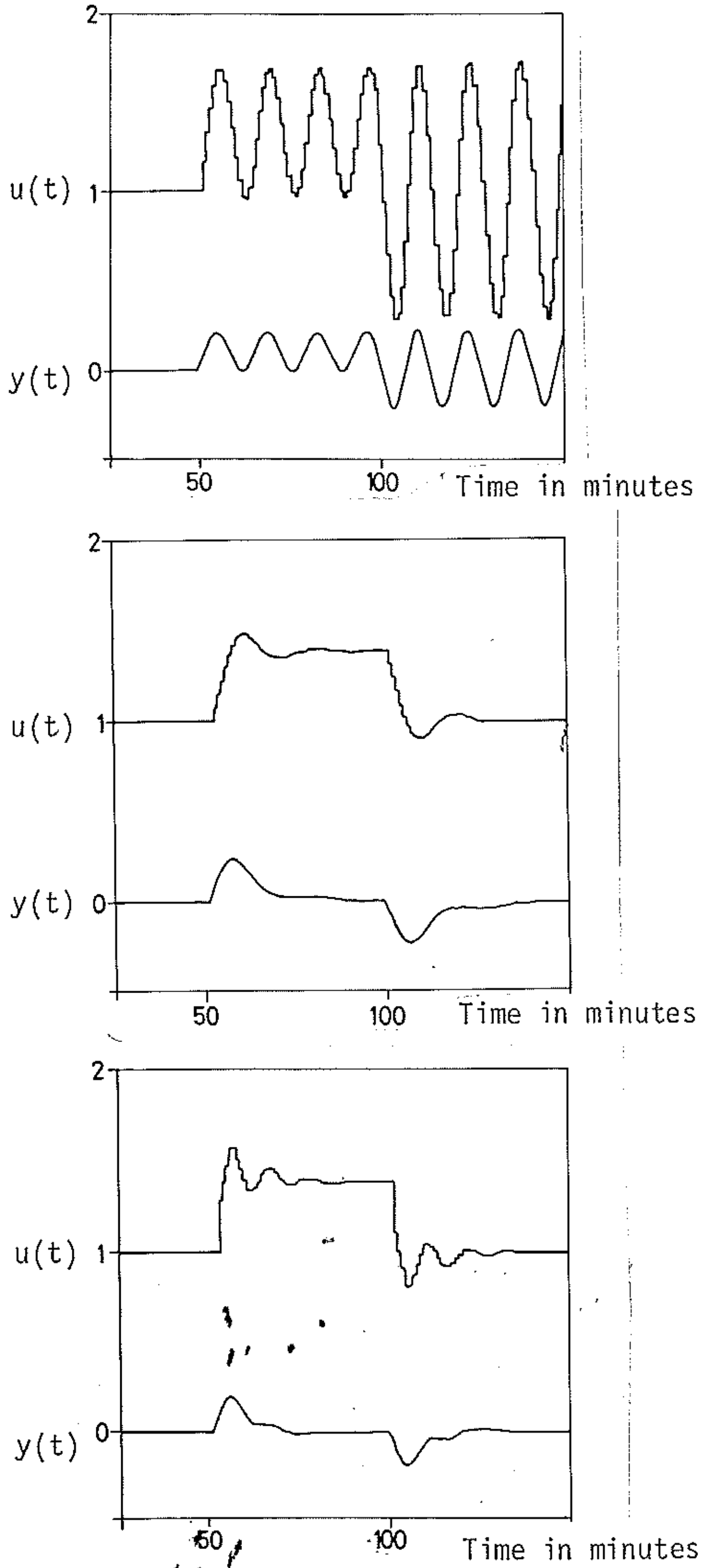

Figure 4.2 From top to bottom simulations of a P regulator with critical gain, a PI régulator (4) and a PID regulator (5), both computed according to the Ziegler Nichols rule. The input has been transformed to u(t) = 0.5 u(t) + 1. The y-axis is given in ^{0}C and 2 V.

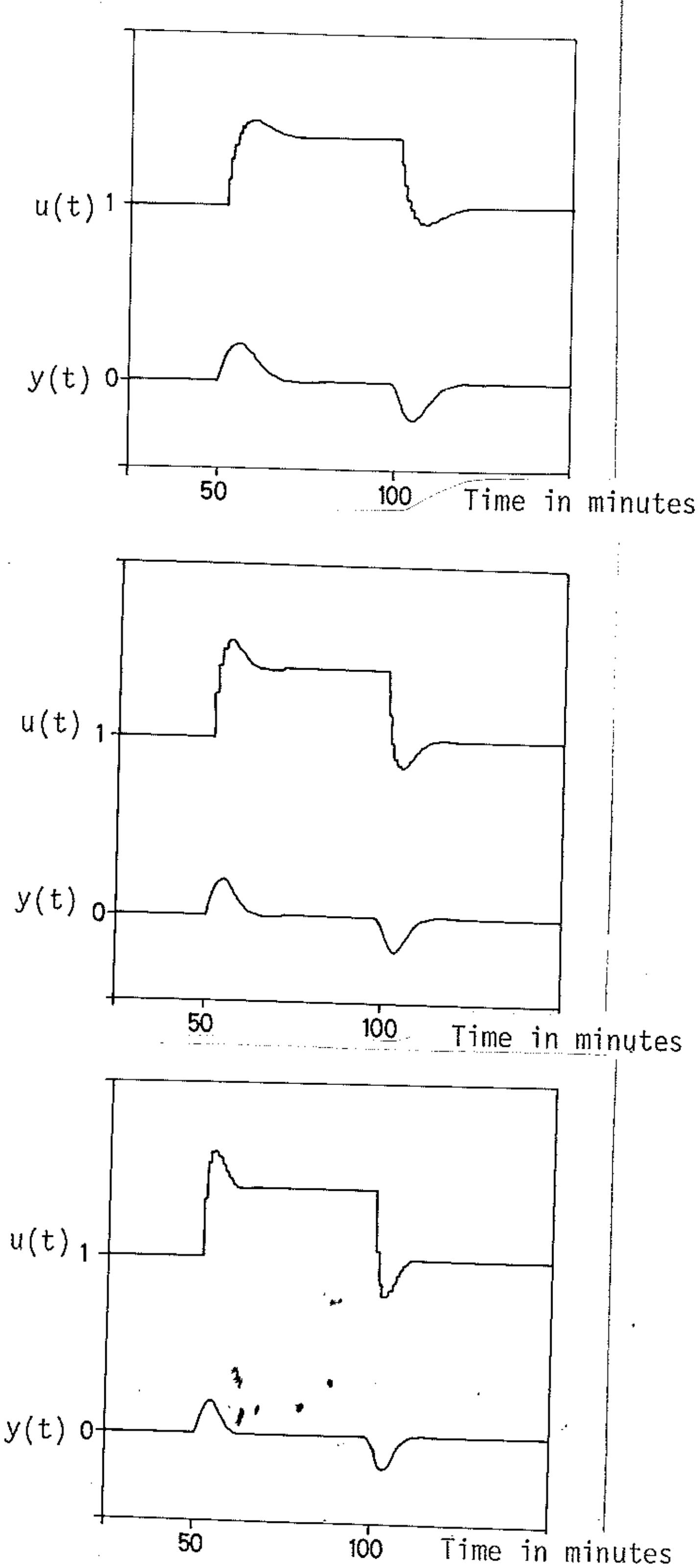

Figure 4.3 From top to bottom simulations of three linear quadratic regulators. The loss function constants are (1,1,1), (4,4,1) and (10,10,1). The input u(t) has been transformed to u(t) = 0.5 u(t) + 1. The y-axis is given in ^{o}C and 2 V.

5 Fullscale control experiments

To test a control law it would be convenient to artificially generate some of the earlier discussed disturbances in a full scale experiment. This has been done with a test run of 150 minutes duration. Movable air heaters in the lecture room were turned on between the 20th and 25th and between the 70th and 110th minute. The situation of the movable air heaters is shown in figure 5.1.

The heating effect of the movable air heater has been varied from 1 kW, 2 kW to 4 kW. The air conditioning plant is dimensioned to compensate for a heat load of about 6 kW.

The air temperature after the room is measured in a reference airduct situated at one end of the room (see figure 5.1). Since the position of the air heaters are not symmetric with respect to this airduct the different heat loads will not act as disturbances proportional to the electric effect.

Another feature that makes the different heat loads imcomparable is the temperature dependant heat transfer coefficient between room air and room surfaces. Consequently if the heat load is doubled then the temperature rise would not be doubled.

All regulators implemented on the computer were subject to the following conditions.

The control signal was always limited to the interval (-1.,7.) volts. The upper limit ensures that the valve cannot close completely and the security limits will then not be vialated. The reason for the other limit is to make the operating region symmetric. These limits have to be updated according to the outdoor air temperature.

The previous control signal was used, if the difference between the new control and the previous one was in the interval (-0.25,0.25) volts. This was done because of a dead zone and hysteresis in the positioner servo.

The output, i.e. the air temperature after the room, may oscillate due to the dead zone. If the desired input value is, say, 0.0 volt and the last input was 0.125 volt, then the input may oscillate around 0.0 volt.

If it possible to avoid a dead zone in the plant then this should be done. The valve could instead be controlled directly by the computer without any servo. The valve is moved up or down during a certain amount of time. This can be made rather accurate, since the full stroke time is about 60 seconds. The computer can easily start and stop the valve with a accuracy less than 0.1 second.

The integral term in the controllers was not updated when the computer control signal was outside the interval (-1.,7.) volts. The integral can be interpreted as a control signal setpoint value. It is then natural not to update the integral when the control signal is on either limit.

The sampling interval has been 1 minute throughout all experiments.

The setpoint value for the air temperature after the room has been 22.5 ^{o}C throughout all experiments. The normal control setpoint value was close to this value.

No data filtering has been made in any of the regulators. The temperature measurement accuracy is better then $\pm$0.05 ^{o}C

The derivative of the output y(t) has been implemented as the difference y(t) - y(t-1).

The different types of control experiments will be presented in the subsections.

5.1 The open loop system.

The open loop system has been tested with three different heat loads of 1, 2 and 4 kW. The results are given in figure 5.2 - 5.4.

The open loop system has been run after the analog PI regulator. The valve position will then be the last one used by the analog PI regulator.

5.2 An analog PI regulator

This analog PI regulator has also been run as the open loop system. The results are given in figure 5.2 - 5.4. The P band was set to 4 ^{o}C which corresponds to a P-gain of 4.5 V/^{o}C. The integral time was set to 15 minutes which corresponds to a I-gain of 0.3 V min/^{o}C.

The regulator is a Mikronik 75 regulator (Honeywell) with the modules T 04 and M 01.

5.3 Digital PID regulators

The earlier given PI regulator (1) has been run through the same test runs as the open loop system. The results are given in figure 5.2 - 5.4.

The also earlier given P, PI and PID regulators computed using Ziegler Nichols rule and a PID regulator (2) tuned by simulation have been tested with a heat load of 2 kW. The results are given in figure 5.5.

5.4 Regulators based on linear quadratic control theory

The earlier given regulator (6) has been tested in the same manner as the open loop system for three different heat loads. The results are given in figure 5.2 - 5.4.

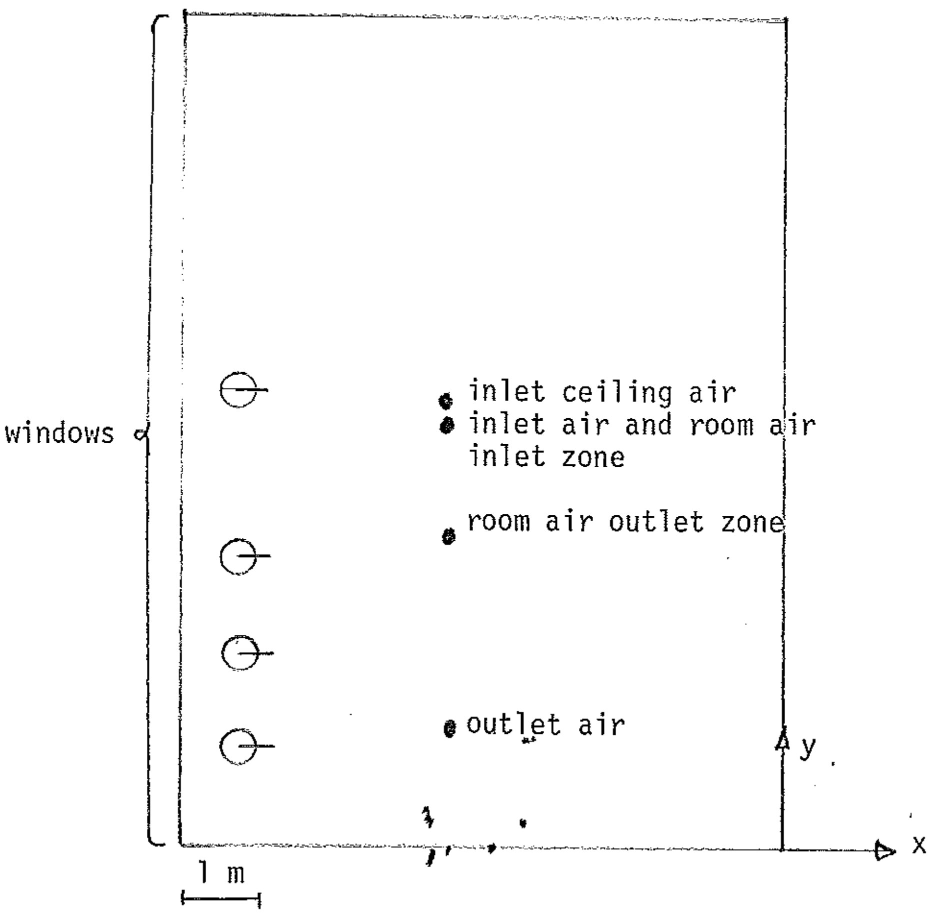

Figure 5.1 Placement of air heaters ⊖ and temperature sensors •.

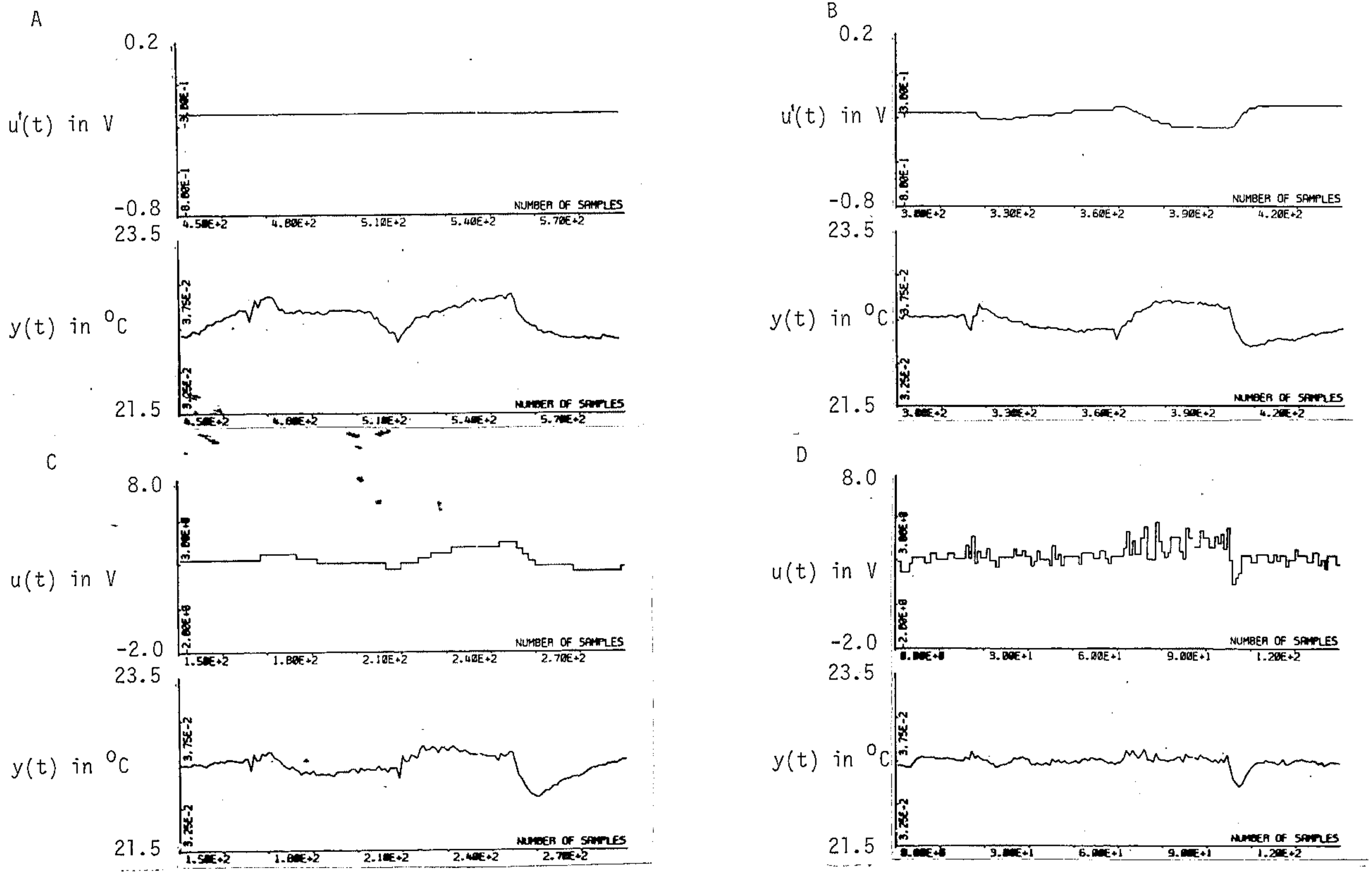

Figure 5.2 Full scale experiments with a heat load of 1 kW. u(t) is the control signal in volts and u'(t) is the position of the valve in volts ($u'(t) \approx -0.1\, u(t)$). y(t) is the air temperature after the room in °C.

A Open loop
B An analog PI regulator
C A computer PI regulator (1)
D A linear quadratic regulator (6)

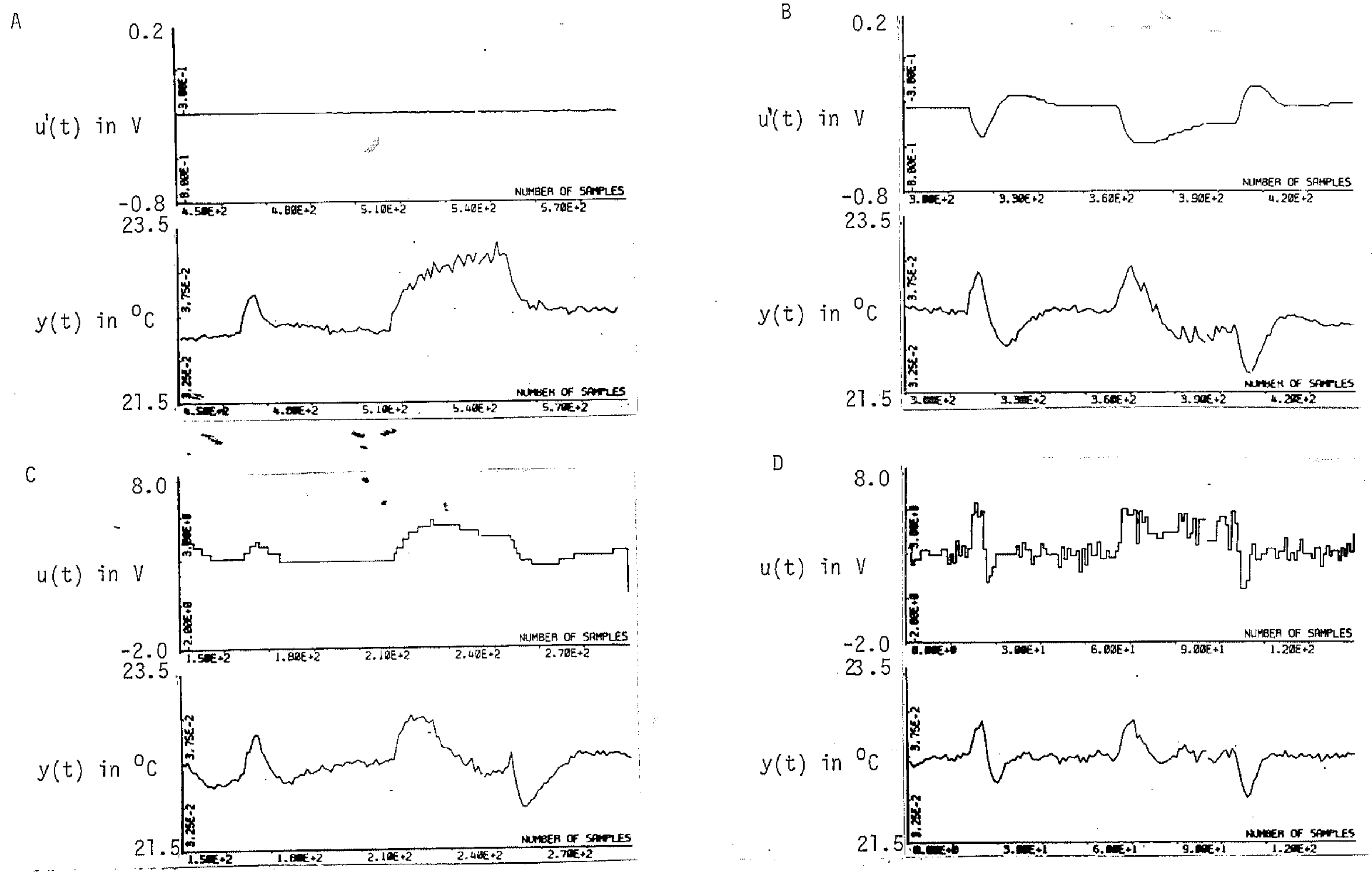

Fig 3. Climate control.
Full scale experiments with a heat load of 2 kW. u(t) is the control signal in volts and u'(t) is the position of the valve in volts ($u'(t) \approx -0.1\, u(t)$). y(t) is the air temperature after the room in °C.

A Open loop
B An analog PI regulator
C A computer PI regulator (1)
D A linear quadratic regulator (6)

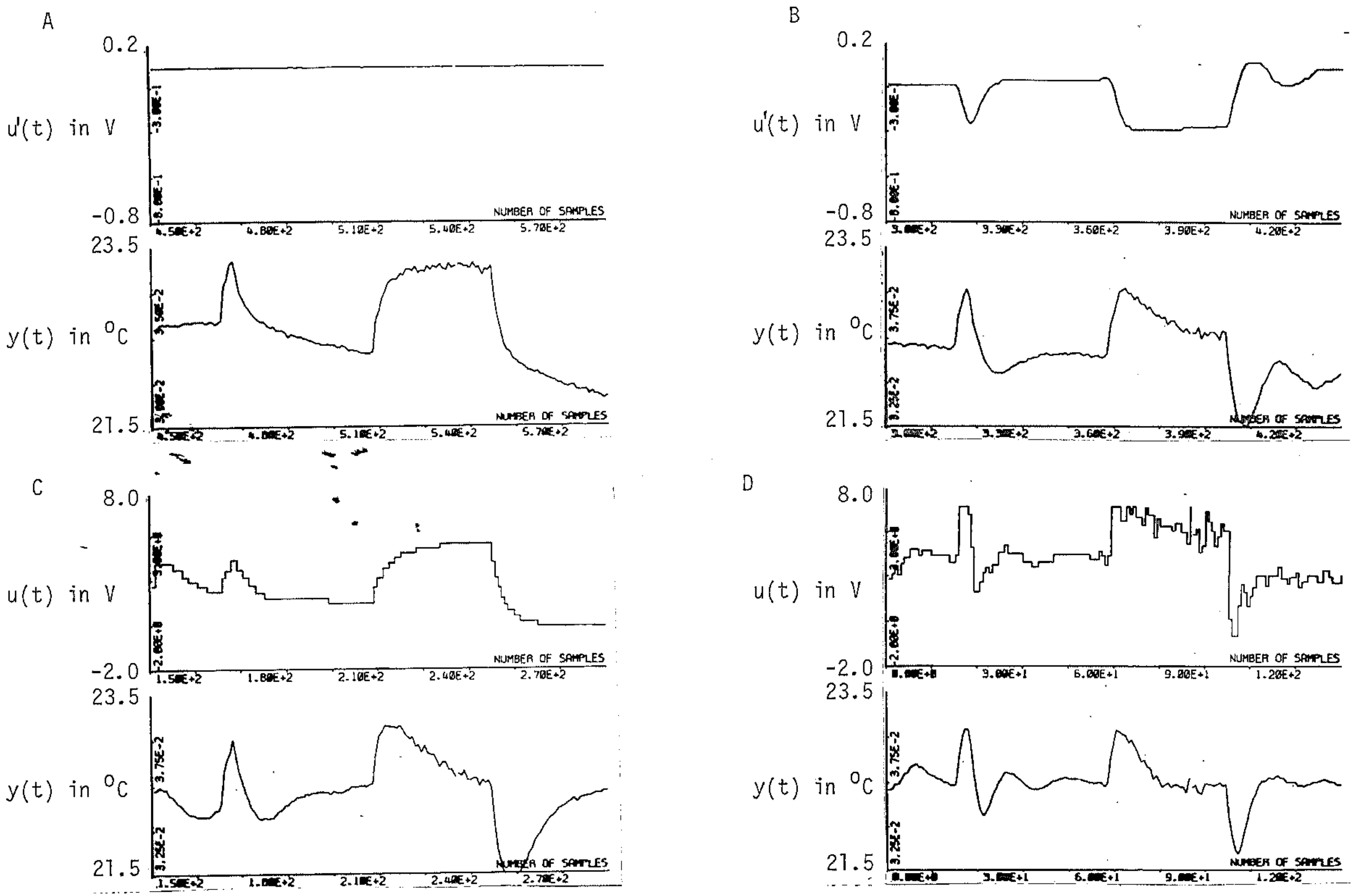

Figure 5.4 Full scale experiments with a heat load of 4 kW. u(t) is the control signal in volts and u'(t) is the position of the valve in volts ($u'(t) \approx -0.1\, u(t)$). y(t) is the air temperature after the room in ^oC.

A Open loop
B An analog PI regulator
C A computer PI regulator (1)
D A linear quadratic regulator (6)

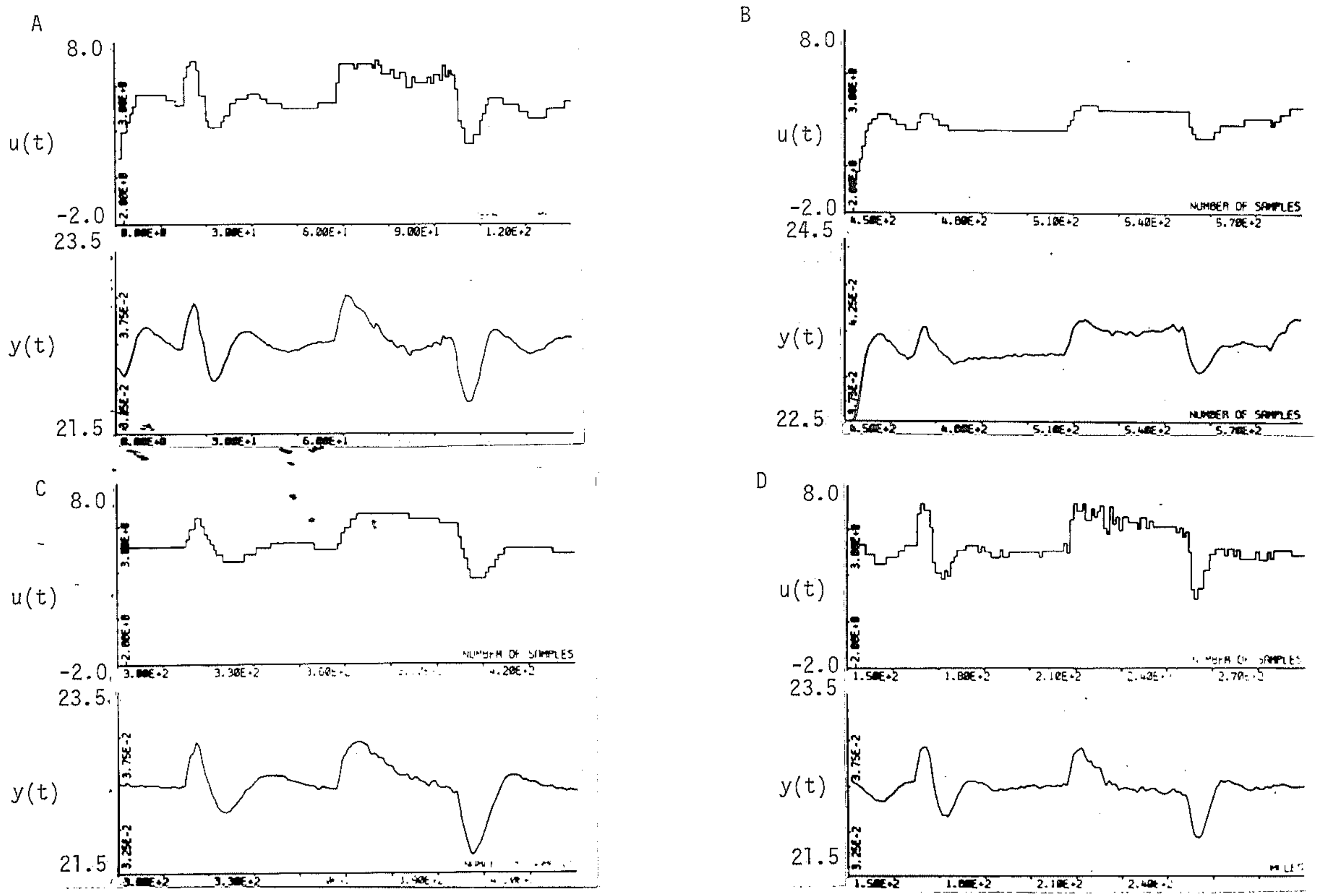

Figure 5.5 Full scale experiments with a heat load of 2 kW. u(t) is the control signal in volts and y(t) is the air temperature after the room in °C. All regulators are implemented on the computer.

A A PID regulator (2) B A P regulator (3)
C A PI regulator (4) D A PID regulator (5)

6 Comparison

The regulators tested will be evaluated using some different methods.

The first method is to use statistics such as mean, rootmean-square, minimum and maximum deviation from the setpoint value. This is done in section 6.1 for the experiments given in figure 5.2 - 5.4.

In section 6.2 the simulated closed loop system are compared with the full scale runs. This reveals how good the used model is.

6.1 Statistical data for the experiments

Statistics have been computed from test runs with the heat loads 1 kW, 2 kW and 4 kW. Four experiments have been considered on each heat load level. These were as follows

- open loop system
- analog PI regulator
- digital PI regulator
- digital regulator based on linear quadratic control theory

These are all shown in figure 5.2 - 5.4.

The output the air temperature after the room has been the analyzed variable. Mean, rootmeansquare, maximum and minimum deviation have been computed for two time periods namely samples 21 - 70 and samples 71 - 150. During the first period the short five minute heat load occurs. The 40 minute long heat load is contained in the second part.

The setpoint 22.5 °C has been subtracted except for the analog PI regulator. The mean value for 150 samples was substracted in this case. This meanvalue has been computed to 22.48 °C, 22.35 °C and 22.38 °C for the heat loads 1 kW, 2 kW and 4 kW.

The result is given in the tables 6.1 - 6.3 for the different heat loads of 1 kW, 2 kW and 4 kW.

Table 6.1

Statistics of the air temperature after the room from different experiments with a heat load of 1 kW.

A Direct digital control LQ
B Direct digital control PI
C Analog PI controller
D Open loop
1 Part one samples 21-70
2 Part two samples 71-150

Control type	Period	Statistics in °C mean	rms	min.	max.
A	1	0.00	0.03	-0.07	0.12
A	2	0.00	0.08	-0.30	0.14
B	1	0.02	0.08	-0.12	0.15
B	2	0.00	0.17	-0.38	0.02
C	1	0.02	0.08	-0.12	0.20
C	2	0.00	0.20	-0.28	0.25
D	1	0.20	0.22	0.00	0.37
D	2	0.08	0.19	-0.16	0.38

Table 6.2

Statistics of the air temperature after the room from different experiments with a heat load of 2 kW.

A Direct digital control LQ
B Direct digital control PI
C Analog PI controller
D Open loop
1 Part one samples 21-70
2 Part two samples 71-150

Control type	Period	Statistics in °C			
		mean	rms	min.	max.
A	1	0.04	0.13	-0.30	0.40
A	2	0.00	0.15	-0.48	0.41
B	1	0.03	0.12	-0.23	0.33
B	2	0.02	0.25	-0.53	0.53
C	1	0.06	0.19	-0.30	0.52
C	2	-0.06	0.25	-0.63	0.59
D	1	-0.09	0.14	-0.21	0.25
D	2	0.29	0.39	-0.18	0.82

Table 6.3

Statistics of the air temperature after the room from different experiments with a heat load of 4 kW.

A Direct digital control LQ
B Direct digital control PI
C Analog PI controller
D Open loop
1 Part one samples 21-70
2 Part two samples 71-150

Control type	Period	Statistics in ^{o}C mean	rms	min.	max.
A	1	0.03	0.19	-0.37	0.59
A	2	0.04	0.26	-0.81	0.58
B	1	-0.10	0.21	-0.37	0.50
B	2	-0.07	0.49	-1.13	0.66
C	1	-0.01	0.21	-0.26	0.67
C	2	-0.01	0.41	-0.86	0.68
D	1	-0.38	0.45	-0.66	0.35
D	2	-0.35	0.68	-1.19	0.33

6.2 Comparison of simulated and fullscale closed loop systems

This is done for two different regulators: a PI regulator (1) and the regulator (6). The simulated and full scale closed loop system are given in figure 6.1 and 6.2 for two different heat loads of 2 kW and 4 kW. The open loop system is also given in figure 6.1 for 2 kW heat load and in figure 6.2 for 4 kW heat load.

The heat load has not been modelled. The heat load v(t) in kW has been added directly to the output as follows

$$y(t) + a_1\ y(t-1) + a_2\ y(t-2) = b_1\ u(t-3) + b_2\ u(t-4) + cv(t)$$

The constant c has been tuned by simulation to 0.05 ^{o}C/kW using the 2 kW open loop experiment.

This constant c has been used in the five other simulations.

It is seen that the model quite well predicts the behaviour of the controlled system. Consequently the model (3.1), which was obtained from identification experiments as described in E-H-J-L (1974), is quite appropriate for designing control laws.

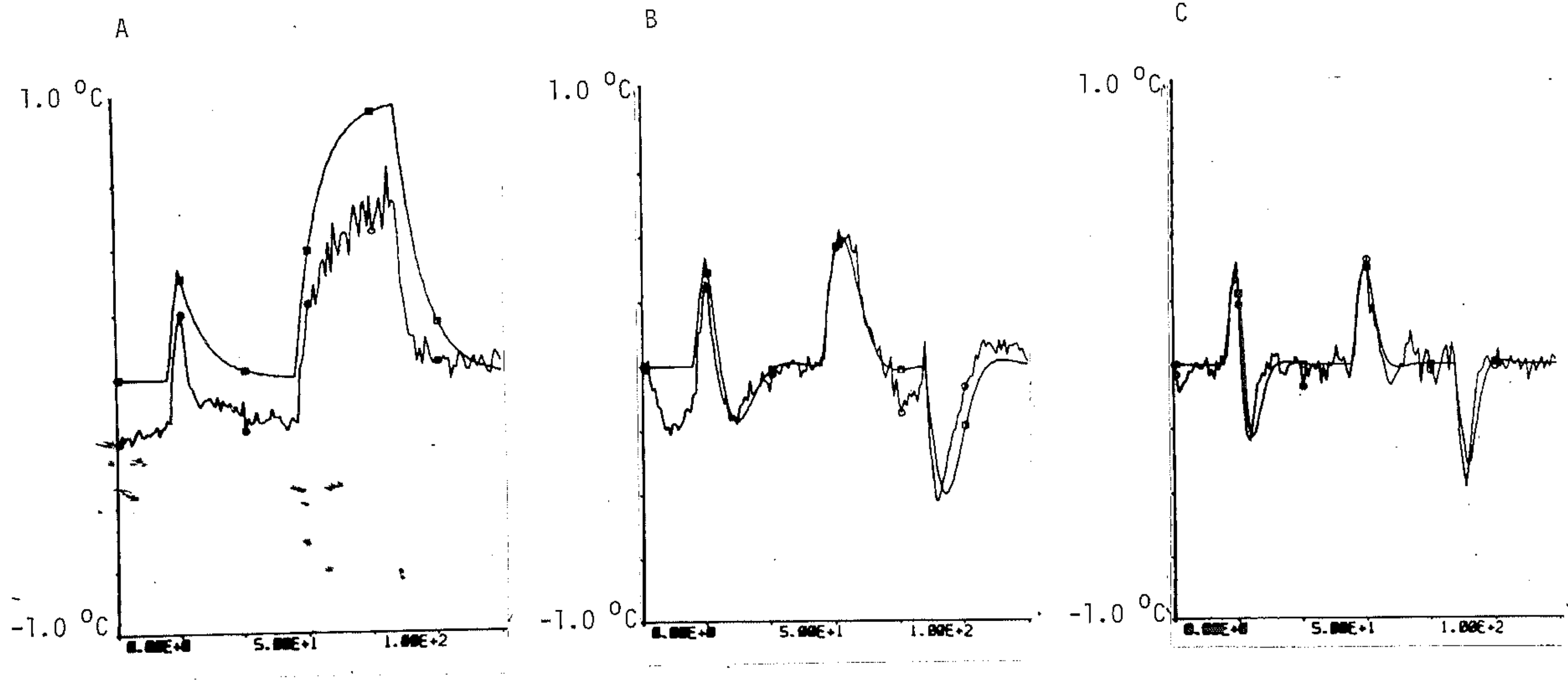

Figure 6.1 A comparison between the simulated output (smooth line) and the full scale output (rough line). Heat load 2 kW.

A Open loop

B A PI regulator tuned by simulation (1)

C A linear quadratic regulator (6).

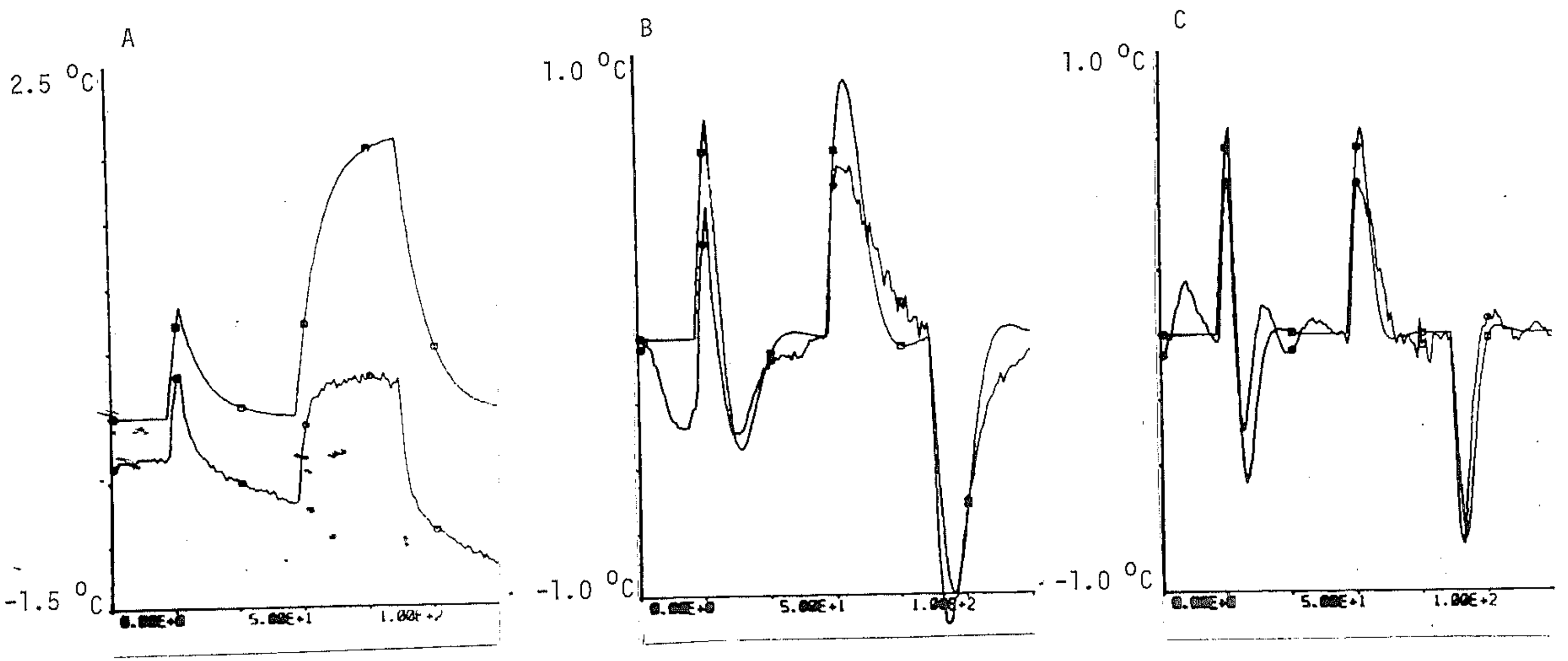

Figure 6.2 A comparison between the simulated output (smooth line) and the full scale output (rough line).
Heat load 4 kW.
A Open loop
B A PI regulator-tuned by simulation (1)
C A linear quadratic regulator (6)

7 Implementation using a magnetic onoff valve

The main purpose with this section is to investigate if it is possible to use onoff control in an air conditioning plant. The purpose is not to achieve the optimal onoff control. Only control laws that controls the air temperature after the room with the valve are studied.

7.1 Background

Most air conditioning plants with water to air crossflow heat-exchangers have usually got a valve to control the waterflow to the heatexchanger. A positioner is needed to position the valve. Both the valve and the positioner may be expensive (about 700 S.kr)

If the heat capacity in the recirculation loop in which the heatexchanger is situated, is large in comparison with the heat capacity of the air flow then it might be possible to use onoff control of the water flow to the recirculation loop and the heatexchanger. Only an onoff valve is needed. Another advantage except from the cost (about 300 S.kr) is that full control power can be used without any extra wear of the valve. The onoff valve is assumed to switch on and off during every sampling interval.

Onoff control can also easily be implemented on a computer.

One disadvantage is that the back-up is lost if no bypass valve is placed parallel with the onoff control. The need for back-up is small if the onoff valve is used in a postheater unit.

7.2 Determination of onoff period time

Straightforward simulations have been made with pure onoff control. The period time and the amplitude of the oscillations turned out to be 10 minutes and 1.2 ^{o}C at 50% load. This gives then an onperiod of five minutes and an offperiod of also five minutes. From other models of the process it turns out that the air temperature after the heatexchanger will drop below the security limit (10 ^{o}C) in same cases. Thus pure onoff control can not be used.

Pulse length modulated control seems to be one solution. Then the control laws that were derived in section 4 and tested with the normal valve as reported in section 5, can alternatively be implemented using the magnet valve.

For how long time can the onoff valve be closed before the air temperature after the heatexchanger drops below 10 ^{o}C? Condensation can take place in the airduct below 10 ^{o}C. This will determine the longest possible time that the onoff valve can be closed.

A simple lumped parameter model can be used for these calculations. Consider that the outdoor air temperature is u(t) and it is heated to 20 ^{o}C. The mass in the heatexchanger has usually an average temperature $x_1(t)$ about 60 ^{o}C when u(t) = -20 ^{o}C. The average air temperature in the heatexchanger is assumed to be an average value of the inlet temperature u(t) and the outlet temperature $x_2(t)$.

Two simple heat balance equations can be set up for the average heatexchanger temperature $x_1(t)$ and the outlet air temperature $x_2(t)$. The onoff valve is closed at t = 0.

$$C\frac{dx(t)}{dt} = K\left[(u(t) + x_2(t))/2 - x_1(t)\right] \qquad (7.1)$$

$$Q\ (x_2(t) - u(t)) = K\left[x_1(t) - (u(t) + x_2(t))/2\right] \qquad (7.2)$$

The constants C, K and Q can be estimated roughly. The amount of water in the recirculation loop is about 0.008 m^3. The heat capacity of the tubes and the heatexchanger are roughly about one fourth of the heat capacity of the water amount. This gives

$$C = 41900\ J/{}^{o}C$$

The heat capacity of the air flow Q is easily computed as follows:

$$Q = \frac{2800\ m^3/h\ \ 1.2\ kg/m^3\ \ 1000\ J/kg\ {}^{o}C}{3600\ sec/h}$$

$$Q = 930\ W/{}^{o}C$$

The heat transfer coefficient between the air and the heatexchanger is computed from steady state values of $x_1(t) = 60\ {}^{o}C$, $x_2(t) = 20\ {}^{o}C$ and $u(t) = -20\ {}^{o}C$ and equation (3.2). This gives

$$K = 620\ W/{}^{o}C$$

Now equations (7.1) and (7.2) can be simplified to:

$$T\frac{dx_1(t)}{dt} = -\ x_1(t) + u(t) \qquad (7.3)$$

$$x_2(t) = (x_1(t) + u(t))/2 \qquad (7.4)$$

$$T = 4C/3K = 90\ sec$$

The maximum turn off time is given in table 3.1 for different outdoor temperatures.

Table 7.1

Maximum turn-off time as a function of outdoor air temperature

	Temperatures in ^{o}C				Turn-off time t_o in seconds
$u(t)$	$x_1(0)$	$x_1(t_o)$	$x_2(0)$	$x_2(t_o)$	
-20	60	40	20	10	25
-10	45	30	20	10	29
0	30	20	20	10	37
10	15	10	20	10	∞

This crude model indicates that the period time for the onoff control must be less than 1 minute.

7.3 Fullscale control experiments

The same regulators given in section 4 will be tested with a pulse length modulated control signal. The test run will be the same. The sampling interval is also 1 minute and the onoff period time was 30 seconds. The dead zone in the control signal was removed in this case.

The total dynamic and static properities of the plant may not change too much, when a magnetic onoff valve is used, if the normal regulators should be used. The dynamic can only be speeded up by a small amount. The static properities can be checked by plotting the air temperature after the airduct as a function of the normal control signal and the pulse length modulated control signal. The result is shown in figure 7.1. Both curves are rather linear and the slopes are 2.34 $^{o}C/V$ for the normal valve and 2.90 $^{o}C/V$ for the onoff valve. This means that the models obtained for the normal valve, will be adequate also for the magnetic valve.

The difference about 4 ^{o}C between the two curves is due to different outdoor air temperature, which is 2 ^{o}C for the normal valve and 6 ^{o}C for the onoff valve.

The onoff valve curve is about 14 ^{o}C for a control signal of 9 volts, which is rather strange. The temperature should be closer to the outdoor temperature. One explanation is that the normal valve is not completely closed. Another explanation is that the air is heated in the airduct. The air fan will also rise the air temperature with 0.5 to 1.0 ^{o}C.

Three regulators from section 4 have been run in fullscale. They have also been run in fullscale with the normal valve. The regulators were a PI regulator (1) and a PID regulator (2) both tuned by simulation and a regulator (6) based on linear quadratic control theory.

The result of the fullscale experiments are shown in figure 7.2, 7.3 and 7.4 together with the corresponding experiments with the normal valve.

The normal valve control signal u(t) has been converted as follows into time valve open (tvo) and time valve closed (tvc):

$$tvo = 30 \frac{9 - u(t)}{18.} \quad \text{seconds}$$

$$tvc = 30 \frac{u(t) + 9}{18.} \quad \text{seconds}$$

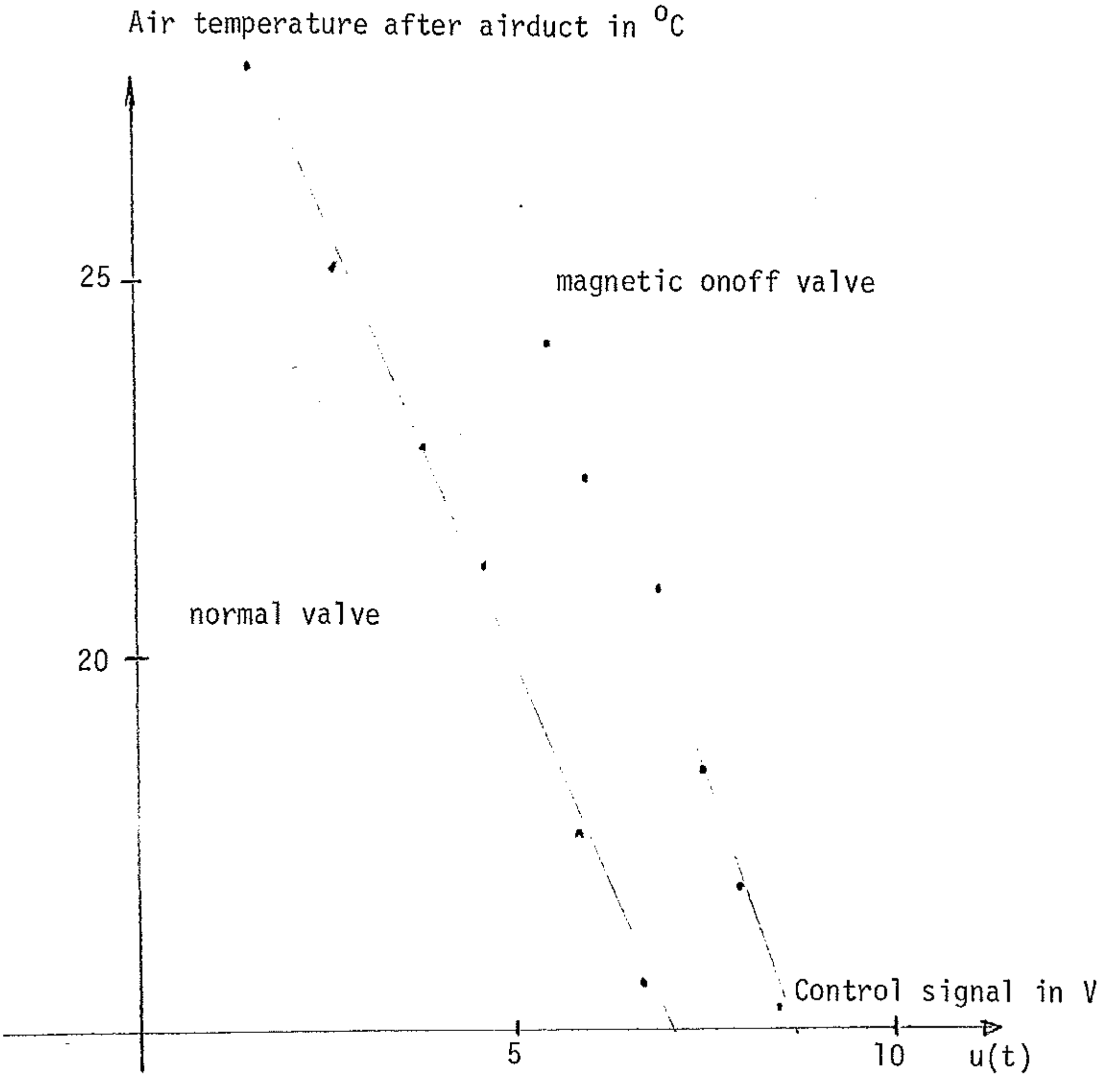

Figure 7.1 Air temperature after airduct as a function of control signal for both normal and onoff valve control.

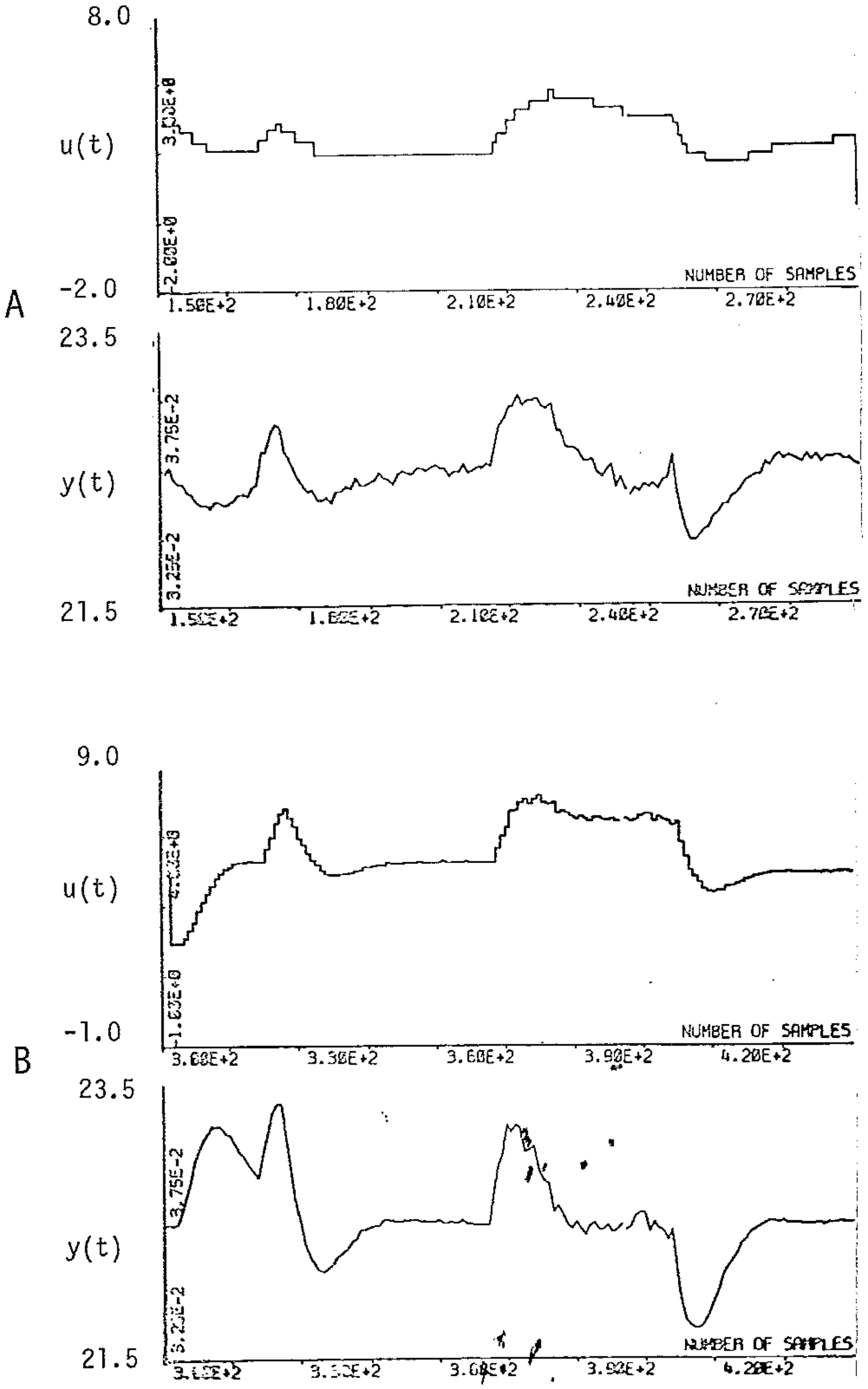

Figure 7.2 Experiments with a tuned PI regulator (1)

A Normal valve control

B Onoff valve control

y(t) air temperature after room in ^{o}C

u(t) control signal in V

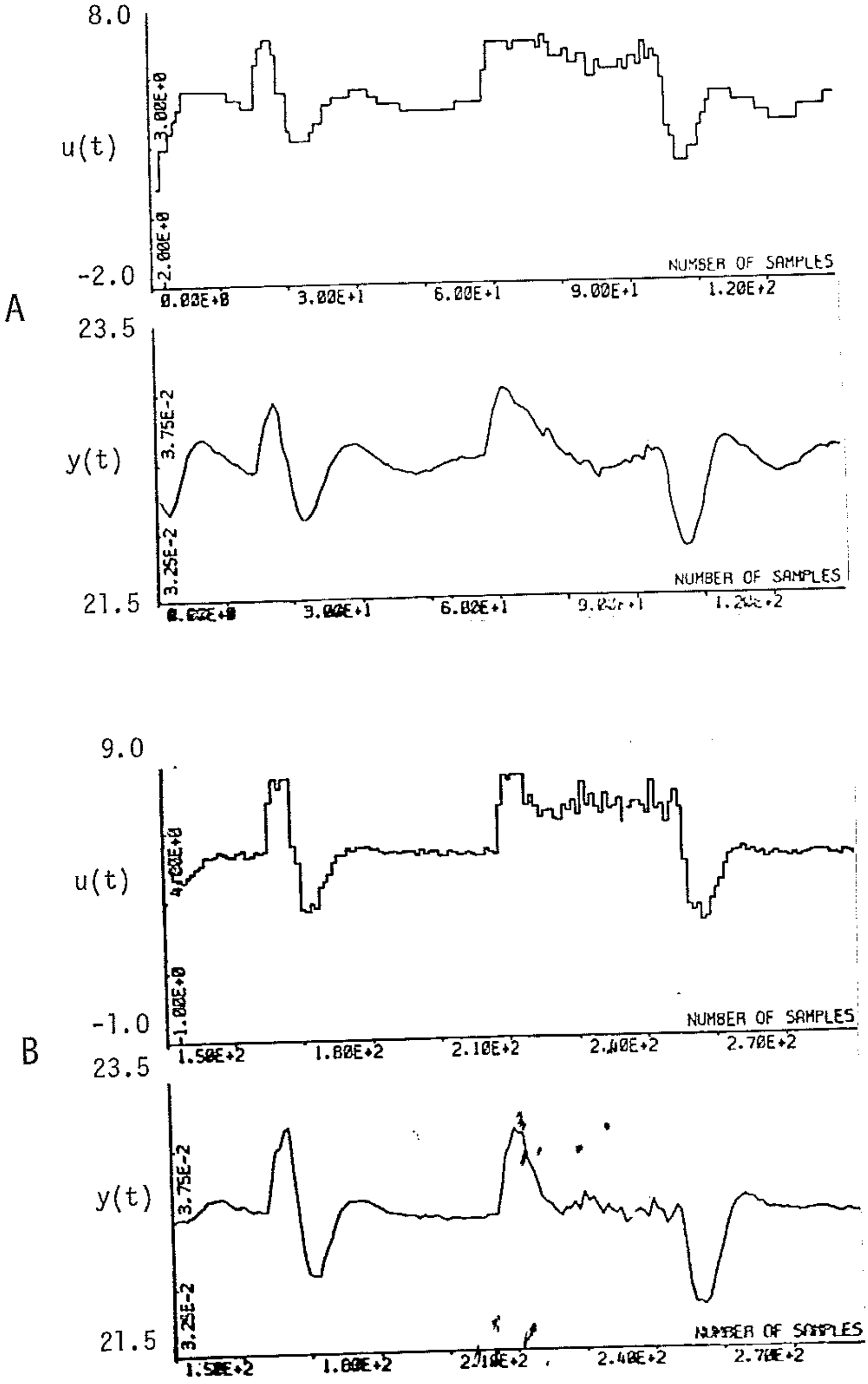

Figure 7.3 Experiments with a tuned PID regulator (2)

A Normal valve control

B Onoff valve control

y(t) air temperature after room in ^{o}C

u(t) control signal in V

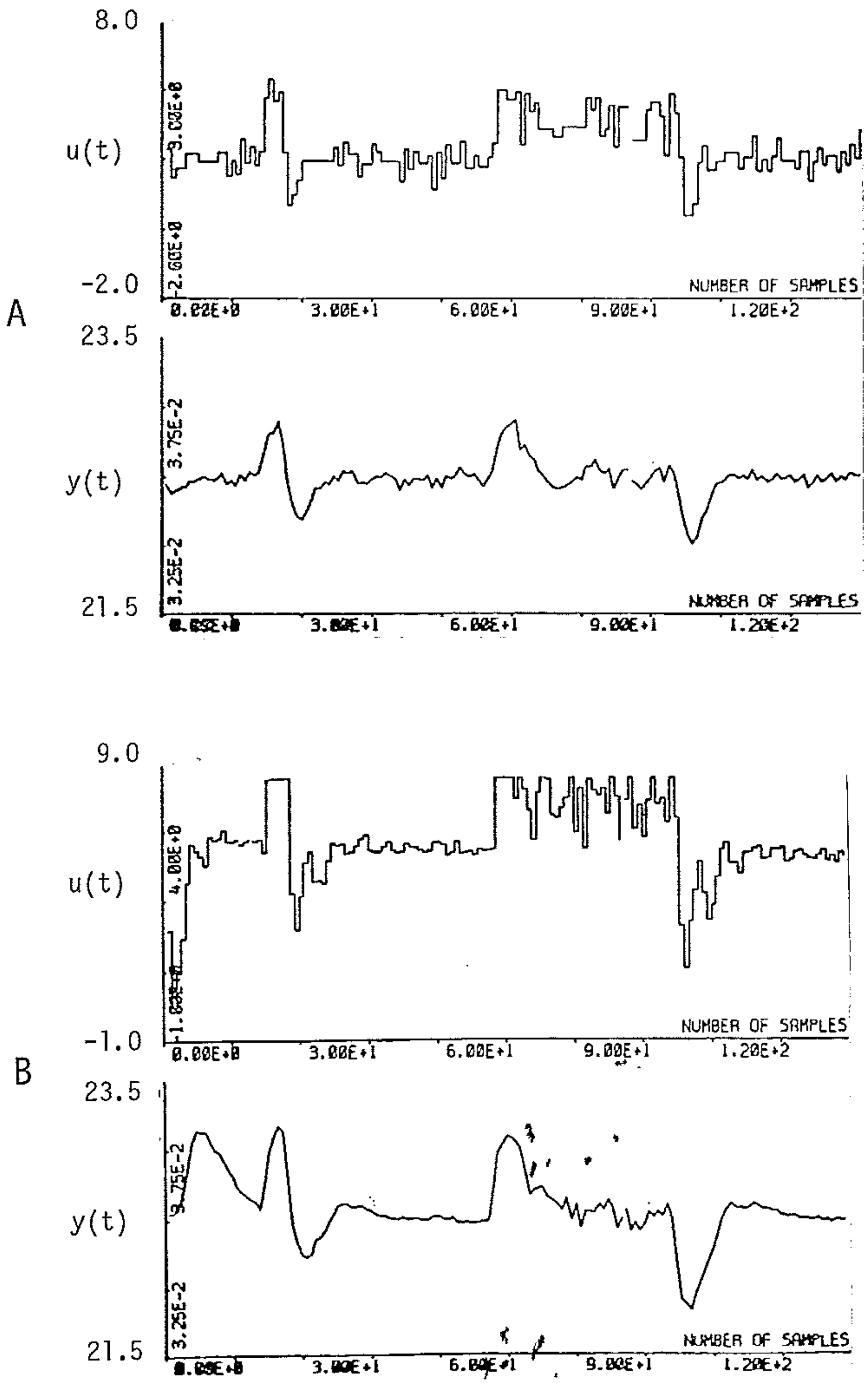

Figure 7.4 Experiments with a linear quadratic regulator (6)

A Normal valve control

B Onoff valve control

y(t) air temperature after room in ^{o}C

u(t) control signal in V

7.4 Comparison and remarks

It is not possible to compare the experiments with normal valve and with onoff valve completely. The experiments were not made at the same time. The outdoor and the hot water temperatures were not the same. The air heater could also have been moved. The used effect might also have been 3 kW instead of 2 kW.

The onoff valve experiments have not had a nice start. The integral has not had the right value in the start.

The amplitude of the air temperature after the lecture room are somewhat larger in the onoff valve experiments. The air temperature curves seems to be more smooth in the onoff valve experiments. This is due to that there is a dead zone in the positioner to the normal valve.

A sumup of advantages and disadvantages of normal valve and onoff valve control is given below.

factor	normal valve	onoff valve
cost	~700 S.kr	~300 S.kr
backup	good	none
control wires	3	2
position wires	3	-
position accuracy	<1%	<1‰
leakage	none?	none?
control power	modest	high
audiable noise	small	some
electrical noise	small	some

The two major factors that will determine a choice is the cost and the need of backup. A manually operated bypass valve can be placed parallel with the onoff valve. This might be a solution of the need of backup. The need of backup in post-heaters is not so great. The preheating might be sufficient.

A third factor is the leakage in the normal valve due to obstacles in the valve seat. An onoff valve is supposed to close completely. Even a small leakage will be rather costsome when the air has to be cooled during the summer.

The air conditioning plant has not been designed to be controlled with an onoff valve. Some remarks are given below about how a design can be made.

- A longer onoff period can be used if the amount of water in the recirculation loop is increased. The flow should also be increased.
- Too large amount of water will make the process slow and more difficult to control.
- The onoff period time should not be the same as the recirculation time. If they are equal the recirculation water can be both very hot and cold. The freezing protection might go into action.

8 Conclusions

The experiences of the experiments can be summarized as follows:

It is very valuable to have a model of the system. It can be used for tuning control parameters by simulation as well as for control law synthesis. The experiments show that a second order model of the process is able to predict the closed loop system very well.

Regulators that use old input values when computing the new one have better performance than conventional regulators. Because of the time delay in the system the effect of the input is not seen until after two minutes. It is therefore valuable to know the inputs during this period.

The experiments also showed that digital control could be made better than the used analog control. The temperature deviation from the setpoint could be kept less than 0.1 °C in one point in steady state. However it should be pointed out that the temperature differences between different points in a room can be one or two degrees.

The experiments have also demonstrated the possibility of using minicomputers to control air conditioning plants.

In particular, onoff control of a magnetic valve, using pulse length modulated signals may be an attractive way of implementing the control laws on a computer.

9 References

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