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DIFFERENT DYNAMIC MODELS IN AN AIRCONDITIONED BUILDING

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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

Some identification experiments have been carried out with an airconditioning plant and a connected lecture room using a process computer. The purpose of the work was to get models of the process suitable when designing a regulator. Different discrete time single input and single output models have been identified from data. The sampling interval was one minute. The models turn out to be of first and second order. Continuous time transfer functions are also given.

1 Introduction

This report is a documentation of some identification experiments with an airconditioning plant connected to a lecture room and of the result of the identifications. The work has been made in cooperation with the Swedish Steam Users´ Association, Malmö. The purpose of the work was to get models suitable to use, when designing a regulator. A process computer was used to control the experiments and to log data. The sampling interval was one minute. Ten inputs were measured and one output was controlled.

A short description of the plant and the experiment equipment is given in section 2.

In section 3 some simple models are derived based on construction data and on simplifying assumptions. This is done to see if it is possible to determine suitable models in this way without making any experiments.

In section 4 two identification methods are used to determine models, namely the least squares method and the maximum likelihood method. It seems to be sufficient to use second order models. Discrete time models and the corresponding continuous time transfer functions are given for the best models.

In section 5 a comparison is made between the models based on construction data and models derived from measurements. Some remarks are also made about some unexpected properities of the plant, which have been revealed by the experiments and the models.

2 Plant and equipment

2.1 The plant

The plant is best described in figure 2.1. The plant consists mainly of the following parts:

valve servo
valve
water recirculation loop with pump
water to air crossflow heatexchanger
fan
inlet airduct
room
outlet airduct

The room volume is about 260 m^3 and its area about 87 m^2. The number of air changes is 11 per hour. Further details about the plant is given in appendix 1.

The valve servo consists of an electronic circuit, a position potentiometer and a positioner. The electronic circuit compares the position potentiometer signal p_a with the desired position signal p_d. The valve is positioned up or down according to the difference between the two earlier mentioned signals as in figure 2.2. The electronic circuit can also be characterized as a relay with deadzone and hysteresis.

The valve controls the flow into the recirculation loop. The water to air crossflow heatexchanger is situated in this loop. The outdoor air passes through the heatexchanger, the fan, the inlet airduct, the room and the outlet airduct. The air inlets are situated in the ceiling in every second crossection. The outlets are situated in the ones between.

The air temperature in the room is not controlled directly.

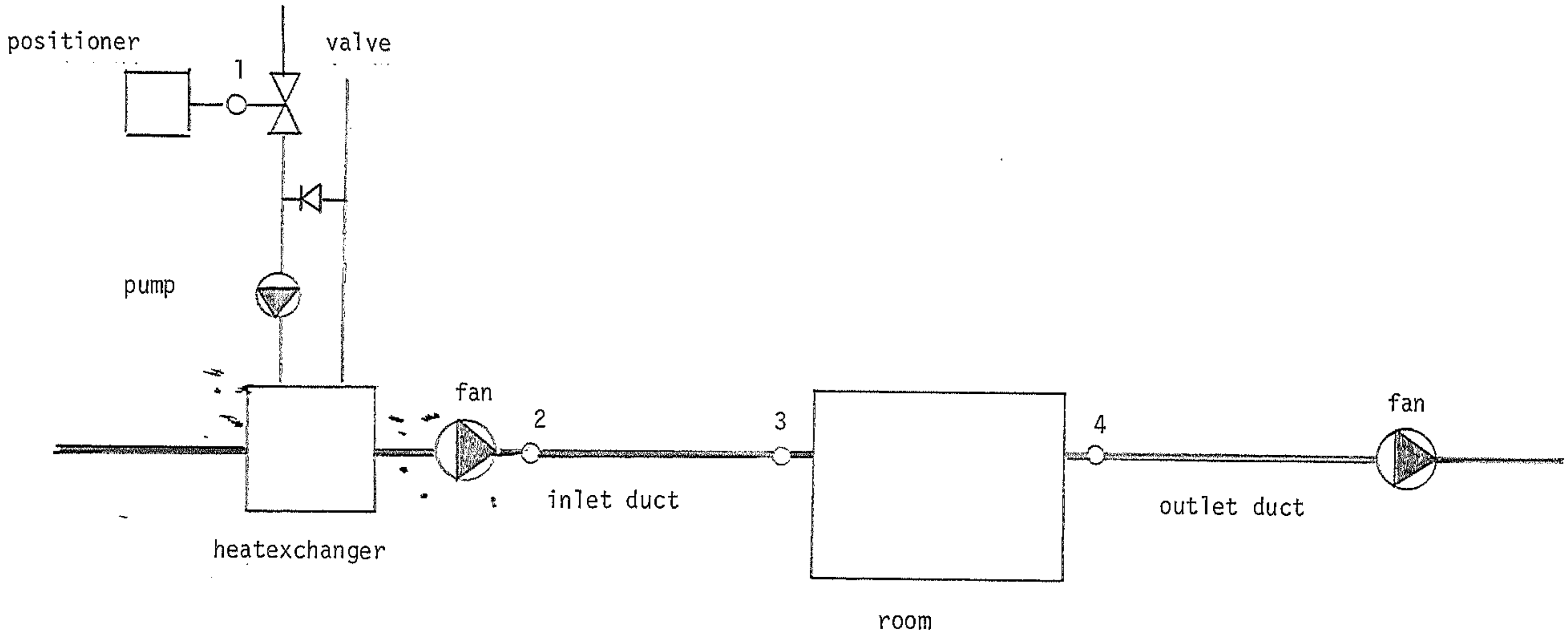

Figure 2.1 The air conditioning plant, room and measurement points.

1. valve position
2. airtemperature after heatexchanger
3. airtemperature after inlet duct
4. airtemperature after room

2.3 Process computer and programs.

The process computer PDP-15 (Digital) has 32 k core memory, one 256 k disc, three dectape units, three teletypes and a display. All experiments were carried out with the realtime executive RSX-plus.

Computer programs controlled the measurements, generated the input sequence and set out the control signal.

All inputs and outputs were logged. These could also be displayed on-line.

The identification program package IDPAC was run in the batch system DOS. The program package IDPAC is described in Gustavsson, Selander and Wieslander (1973).

2.4 Communication link.

The process computer is situated at the Division of Automatic Control, Lund Institute of Technology, Lund and the lecture room at the Swedish Steam Users' Association, Malmö. Low-speed modems (max 200 baud) were used as communication line. Both the computer and c/c used teletypespeed (110 baud), which is equivalent to ten ASCII characters per second. Measuring all inputs and controlling all outputs will take about 30 seconds.

Instead the outlet airtemperature is controlled.

The air temperature after the heatexchanger is not allowed to go below 12 °C. Otherwise condensation can take place in the airduct. To avoid this a second control loop is required. The air temperature after the heatexchanger is then controlled.

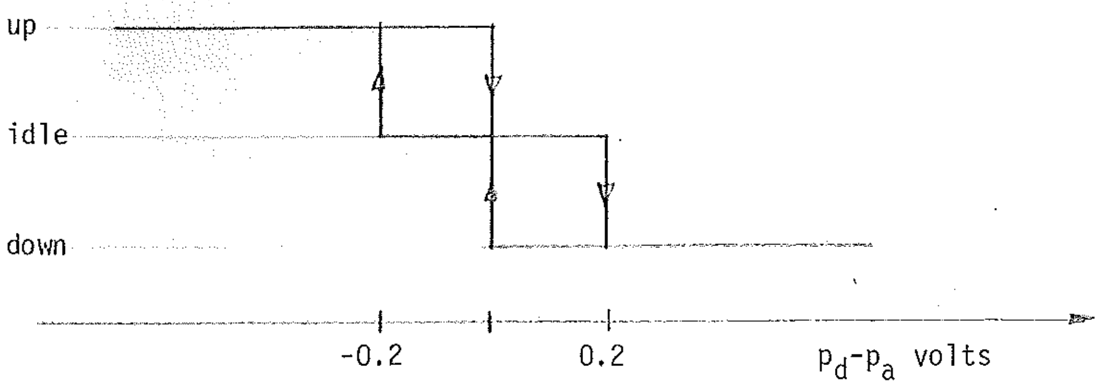

Figure 2.2 Function of the electronic circuit.

2.2 Measurement and control equipment

The measurement and the control were carried out by a coupler/controller unit (Hewlett Packard) connected to a process computer. The c/c can measure 10 analog inputs and control 4 analog and 4 logical outputs. 5 analog inputs were connected to thermistor bridges for 15-35 °C and 5 for 0-100 °C. Further details are given in Jensen (1973).

The exact location of different temperature sensors is given in appendix 2. How the outputs were used is given in appendix 3.

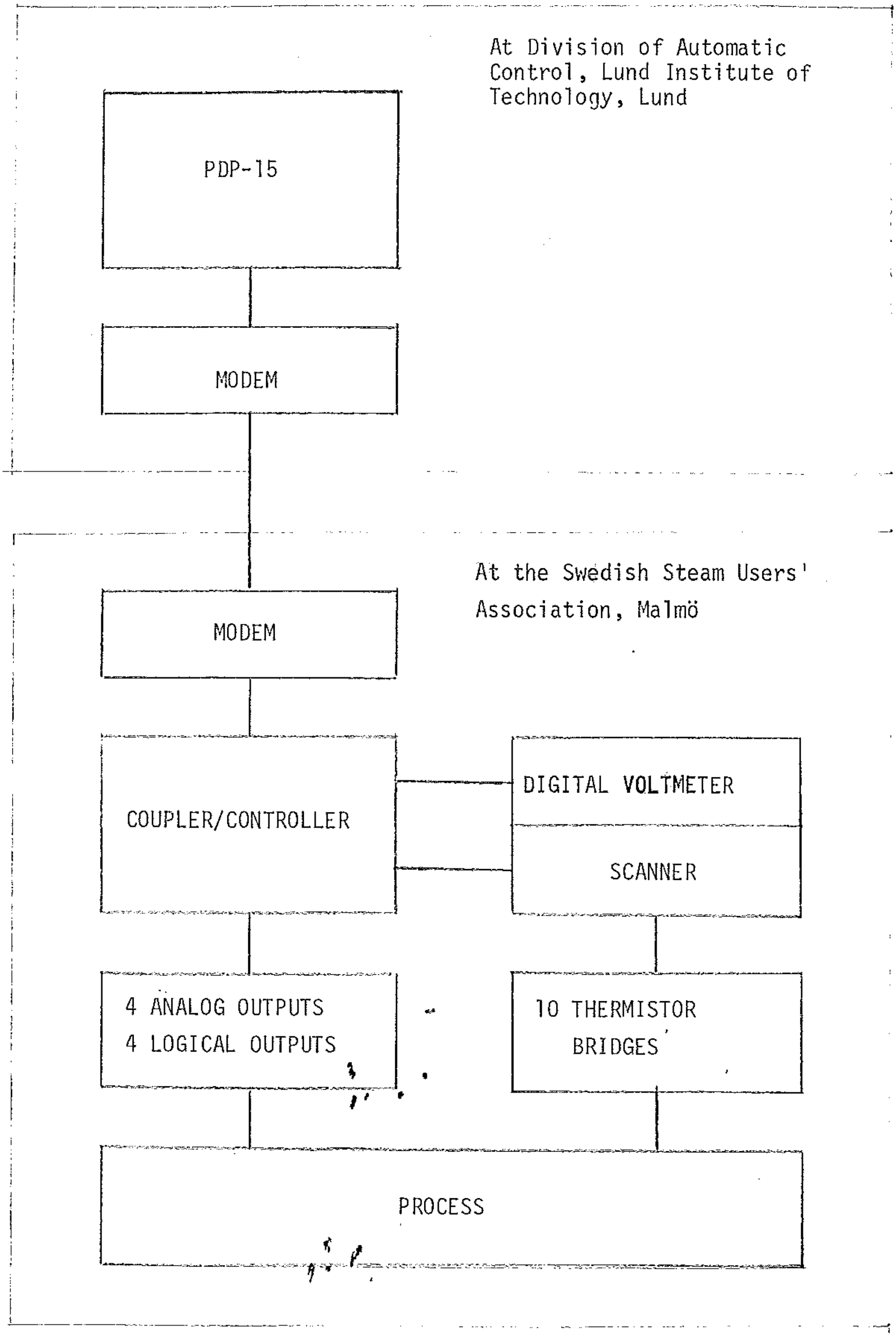

Figure 2.3 Plant and equipment

3. Simple models based on construction data

The purpose with this section is just to get some very crude estimates of static gains and main time constants of difficult parts of the process. Transportation delays will be omitted.

3.1 Control signal to airtemperature after heatexchanger.

This process part can be rather well described by a first order system, if the recirculation time is about the same as the main time constant of the heatexchanger. The time constant of the simplified model becomes

$$T = -1/\ln (K \cdot q)$$

where K is the static gain of the heatexchanger (water in to water out) and q is the percentage of recirculation. The time unit is supposed to be the recirculation time t. Details about how the formula is achieved are given in Jensen (1974). This formula shows that the time constants depend on the valve and valve position. Crude estimates are:

$K \approx 0.8$

$q_{open} = 0.5$

$q_{closed} = 1.0$

$t \approx 20$ sec.

This gives:

$T_{open} = 22$ sec.

$T_{closed} = 90$ sec.

The heat exchanger should be able to increase the air temperature 39°C. The control signal can vary between -7.5 to 7.5 volts. This gives a crude estimate of the static gain:

$K = 39^\circ C/-15\ V \approx -2.6^\circ C/V$

3.2 Air temperature before airduct to air temperature after airduct.

The air in the airduct can exchange heat or cold with the walls of the airduct. The heat capacity in the airduct walls is about 20 times the heat capacity in the air in the airduct. If the heat capacity in the air is neglected then it is possible to get two simple heatbalance equations.

$$0 = K(x_2 - x_1) + Q(u - x_1)$$

$$C\dot{x}_2 = K(x_1 - x_2)$$

x_1 = air temperature
x_2 = airduct wall temperature
u = inlet air temperature
C = heat capacity airduct walls
K = heat transfer constant between air and air duct walls
Q = heat transfer constant for airsteam through air duct

The continuous transferfunction between inlet and outlet air temperature can easily be found as:

$$G(s) = \frac{Q}{Q+K} + \frac{K}{Q+K\ (sC(Q+K)/QK+1)}$$

The transferfunction consists of one direct term Q/(Q+K) and a first order system with static gain K/(Q+K) and time constant C(Q+K)/QK. Using plant data the model parameters becomes:

$$Q = 1.200 \cdot 1000 \cdot 2800/3600 = 930 \text{ W}/^{0}\text{C}$$

$$K = \pi \cdot 0.4 \cdot 20 \cdot 50 = 1260 \text{ W}/^{0}\text{C}$$

$$D = Q/(Q+K) = 0.42$$

$$K = K/(Q+K) = 0.58$$

$$T = 7800 \cdot 460 \cdot 0.0007/50/0.42 = 120 \text{ sec}$$

3.3 Air temperature before room to air temperature after room.

A very simple first order model for the input-output system inlet air temperature to outlet air temperature can easily be obtained if the room air is assumed to be totally mixed and the heated air, the walls (the ceiling, the floor and the furniture is supposed to be included in "walls") and the outdoor air temperature are assumed to be inputs and not affected by the room air temperature.

The assumption that the temperature of the walls is not affected by the room air temperature may be a good approximation if the heat capacity of the walls is far larger than the heat capacity of the room air. Then the wall temperature will only change very slowly and with small amounts.

The heat balance equation becomes:

$$C\dot{x} = -(nC + Ah)x + nCu_1 + Ahu_2$$

Here is x = room air temperature
u_1 = heated air temperature
u_2 = other temperature inputs
A = surface between room air and walls
C = room air heat capacity
h = heattransfercoefficient for surface A
n = the number of room air changes per time unit

If the heat balance equation is Laplace transformed one will get the transferfunction between the input and the output as:

$$G_1(s) = \frac{K_1}{sT + 1}$$

The relations between parameters in the heat balance equation the ones in the transferfunctions are:

$$T = C/(nC + Ah)$$

$$K_1 = nC/(nC + Ah)$$

Crude calculations gives:

$$nC = 1000 \text{ W/}^{\circ}\text{C}$$

$$C = 330000 \text{ Joule/}^{\circ}\text{C}$$

$$Ah = 500 \text{ W/}^{\circ}\text{C}$$

which gives

$$T = 220 \text{ sec}$$

$$K = 0.67$$

A temperature sensor can be regarded as fast first order system with a transferfunction $G(s) = 1./(sT + 1.)$ where T is less than 20 seconds. This is the case if the sensor is placed in the airstream. This fast first order system has been neglected.

3.4 Control signal to airtemperature after room

To design temperature control regulators, the interesting dynamics is from the control signal to valve positioner to the outlet air temperature. A model of this process can be obtained by combining the three parts described above into a third order transfer function. The static gain is then easily computed as

$$K = -2.6\ 1.\ 0.67 = -1.8^{\circ}C/V$$

The main time constant T is estimated from a step response shown in figure 3.1. The used transfer funtion was

$$G(s) = \frac{-2.6}{(s + 1)} \left[0.58 + \frac{0.42}{(s\ 2. + 1)}\right] \frac{0.67}{(s\ 3.6 + 1)} \qquad (3.1)$$

$T \approx 7.5$ min

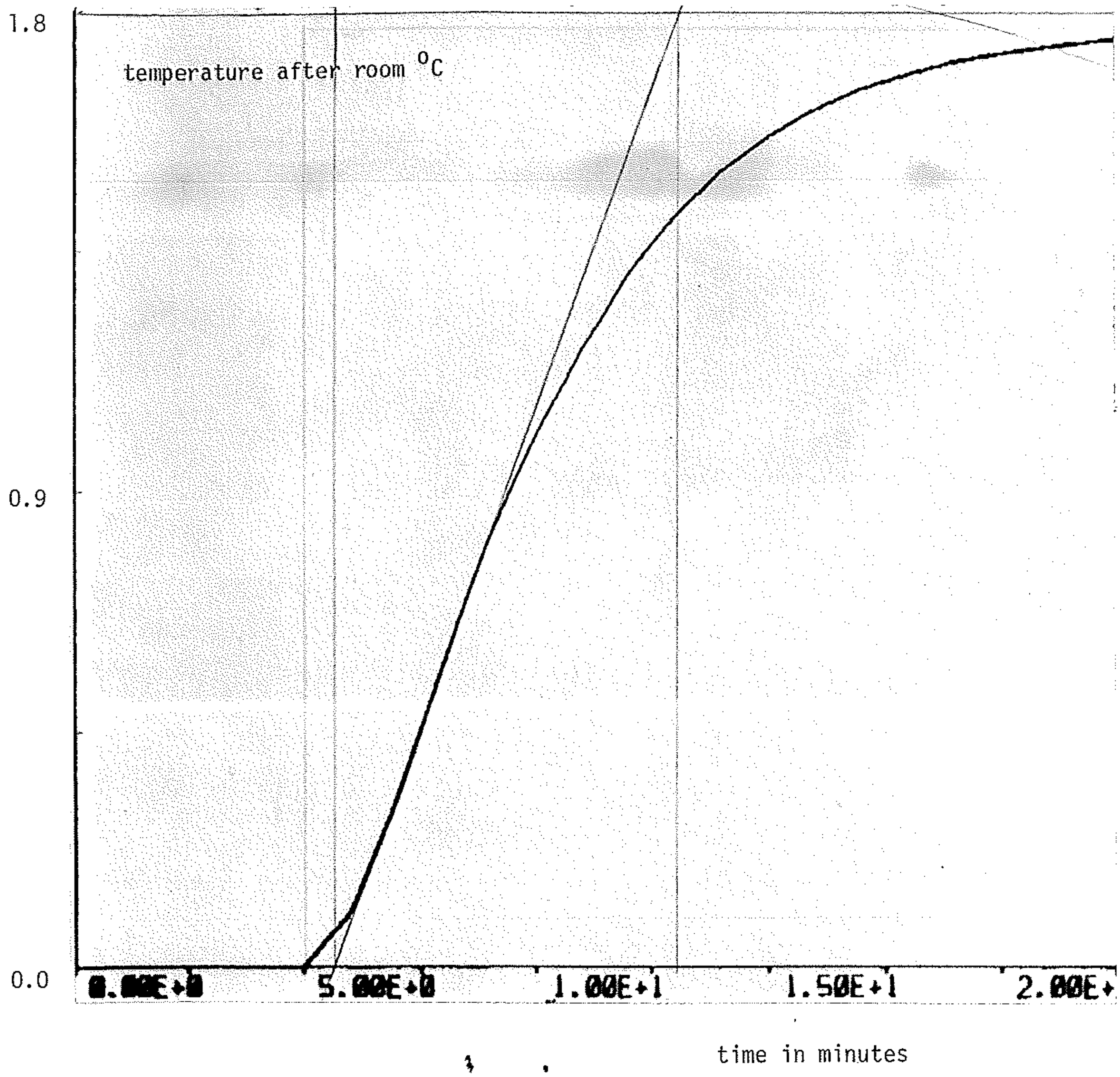

Figure 3.1 Stepresponse from the transferfunction (3.1). The step amplitudes is -1 volt and it starts at sample 5. The simulation is done with a computer. The sampling interval is 1 minute.

4. Identification

4.1 Identification experiments

To be able to identify the dynamics of a process, a suitable input signal has to be chosen. This was done by using a PRBS (Pseudo Random Binary Sequence) signal. Details about the PRBS signal can be found in Davis (1970). The signal sequence assumes only two values. The signal was used as a control signal to the valve servo. Three experiments were made as follows:

Experiment 1

PRBS order n = 7
Basic period T = 4 min
Total period NT = 508 min (N = $2^n - 1$)
Experiment length 518 min
Control signal max. level 5. V
Control signal min. level 1. V
Convectors switched off.

Experiment 2

PRBS order n = 6
Basic period T = 10 min
Total period NT = 630 min (N = $2^n - 1$)
Experiment length 617 min
Control signal max. level 7. V
Control signal min. level -1. V
Convectors switched off.

Experiment 3

As experiment 2 except that the convectors situated under the windows were switched on, and that experiment length was 517 minutes.

Experiment 2 is shown in diagrams 1 - 3. The four signals are from above control signal to the valve positioner, air temperature after the heat exchanger after air duct and after the room.

4.2 Models, identification methods and results

Using the experimental data described above, the dynamics from the control signal to valve positioner (denoted by u(t)) to the outlet air temperature (denoted by y(t)) was modelled as follows. First the coefficients of a difference equation

$$y(t) + a_1 y(t-1) + \ldots + a_n y(t-n) =$$
$$= b_1 u(t-k-1) + \ldots + b_n u(t-k-n) + v(t) \qquad (4.1)$$

were determined using a <u>least squares criterion</u>. The model parameters a_i and b_i are thus found by minimizing the loss function

$$V = \sum_{t=1}^{N} v(t)^2$$

Further details about the method are given in Åström (1968).

The achieved discrete time models can easily be transformed to continuous time models. The transfer function can be of the following form for a second order system

$$G(s) = D + \frac{K_1}{sT_1+1} + \frac{K_2}{sT_2+1} \qquad (4.2)$$

D is zero if not given.

Models of first, second and third order have been identified from the three experiments 1, 2 and 3. Most of the models were found to be of second order. The exception is the airduct model, which turns out to be of first order. All the best discrete time models and its continuous time transferfunction parameters are given in tables in section 7 as shown below.

In the tables the root mean square of the model error u(t), denoted by λ, is given.

Model type input	output	Discrete time model	Continuous time transferfunction
		Table numbers in section 7	
control signal	airtemp.a.heatex.	table 1	table 2
" "	" a.room	table 3	table 4
airtemp.b.duct	airtemp.a.duct	table 5	table 6
" b.room	" a.room	table 7	table 8

In many cases, in particular if the "noise term" v(t) is relatively large, it is advantageous also to model this term:

$$v(t) = \lambda\left(e(t) + c_1\ e(t-1) + \ldots + c_n\ e(t-n)\right)$$

where $\left\{e(t)\right\}$ is supposed to be a sequence of independent random variables with N(0,1) distribution. The resulting model then is

$$\begin{aligned} & y(t) + a_1\ y(t-1) + \ldots + a_n\ y(t-n) = \\ & \quad = b_0\ u(t-k) + b_1\ u(t-k-1) + \ldots + b_n\ u(t-k-n) + \\ & \quad + \lambda\left(e(t) + c_1\ e(t-1) + \ldots + c_n\ e(t-n)\right) \qquad (4.3) \end{aligned}$$

and the model parameters a_i, b_i and c_i can be determined using the maximum likelihood method. This method is thoroughly described in Åström-Bohlin (1965) and in Gustavsson (1969), where it is also described how the model order n can be determined using a hypothesis test.

The result from the maximum likelihood identification is rather simular to the result from the least squares identification. The model parameters differ only a little in most cases. The lossfunction is roughly 10% smaller than the lossfunction from the least squares identification. The residuals were in most cases independent, but not normal. The four best models for different model types from experiment 2 have been simulated. The model output and the model error are shown in one diagram. The residuals are shown in another diagram. The discrete time model parameters, continuous time transferfunctions tables and the simulation diagrams are given in section 7 and 8 as shown below:

Model type input	 output	Discrete time model	Continuous time transferfunction	Simulation diagram number
		Table numbers in section 7		in section 8
control signal	airtemp.a. heatex.	table 9	table 10	diagram 4,5
control signal	airtemp.a. room	table 11	table 12	diagram 6,7
airtemp.b.duct	airtemp.a. duct	table 13	table 14	diagram 8,9
airtemp.b.room	airtemp.a. room	table 15	table 16	diagram 10,11

5 Comparison and remarks

5.1 Control signal to air temperature after heatexchanger

The static gains do not differ much (see table 2 and 10). The timeconstants differ most between the first order models. The second order model obtained from measurements consists of two modes, one fast with wrong (positive) gain and one slow with negative gain. The stepresponse can be looked upon as a first order system with a time delay.

The nonlinearity can also be observed as described in section 3.1. The model error and the residuals have got its highest deviations when the control signal is changed.

The valve in this plant is logaritmic. The rest of the water circuit is also nonlinear. These two process parts are together rather linear over a large range in steady state. This can be seen in figure 5.1. The air temperature after heatexchanger is plotted against the control signal. The control signal has been held constant in 30 minutes before every reading.

Three of the points do not fit into a line. The explanation is that the valve and the positioner are connected by a spring to protect the valve. The spring is compressed in these three points. When the position is changed next then the spring springs out more than the position is changed.

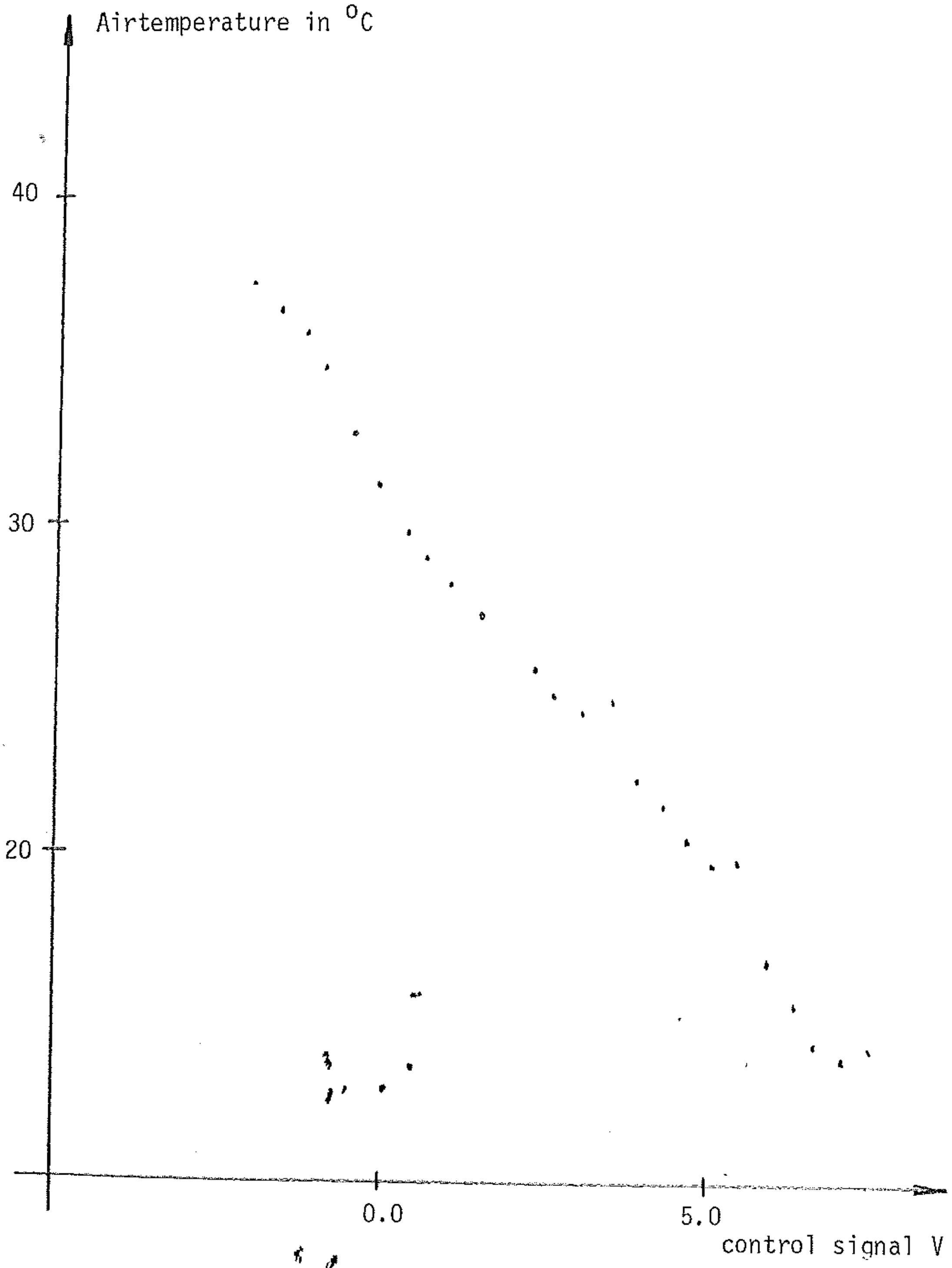

Figure 5.1 Airtemperature after heat exchanger as a function of the control signal in steady state.

5.2 Air temperature before airduct to air temperature after airduct

The model based on construction data contains the assumption that the heatloss to the surroundings is zero. This turns out not to be true. The static gain from the models derived from measurements is about 0.85 (see table 6 and 14). This shows that the loss is about 15% of the heat or cold that is transported through the airduct. The theoretic loss in % can be computed as follows:

$$\frac{\pi\, d\; l\; k\; 100}{\dot{m}\; c}\ \%$$

Where

c = air heat capacity   J/kg °C
d = airduct diameter   m
k = heat transfer coefficient $W/m^2\ {}^oC$
l = airduct length   m
$\dot{m}$ = airmass flow   kg/sec

With actual values one gets

$$\frac{3.14 \cdot 0.4 \cdot 20\ (1.-2.)\ 100}{0.933 \qquad 1000} = 2.7 - 5.4\ \%$$

The only uncertain value is the heat transfer coefficient k, which depends on the isolation of the airduct.

5.3 Air temperature before room to air temperature after room

The static gains from models based on measurements are much smaller than expected (see table 8 and 16). The timeconstants are very close. This is due to the fact that process is mainly influenced by the number of airchanges.

The very low static gain shows that the room will be rather difficult to control. The air inlets and the outlets are situated in the ceiling. The air will always pass the concrete surface of the ceiling. The heat capacity of the ceiling in comparison with the room air is roughly about 100 to 1. This makes it possible for the ceiling to damp the inlet airtemperature and also the outlet airtemperature.

Another fact is that the heat transfer coefficient between the concrete and the air depends on the temperature difference and the air velocity. This will damp large temperature deviations more than small temperature deviations.

5.4 Control signal to air temperature after room

The best models obtained from experiments are of second order and have a delay of two minutes. The model based on construction data has about the same main timeconstant but the static gain is much higher (see table 4 and 12). This is due to the high static gain in the airduct and the room models. In the simple models no try was made to describe the transportation delay.

The pure transportation delay between the valve and the heatexchanger is about 10 seconds. The delay in the airduct is less than 10 seconds. The transportation delay between the air linets and outlets can be estimated to 10-40 seconds. The air velocity is assumed to be 0.1-0.2 m/sec and the distance between inlets and outlets 2.-4. meters.

The positioner has no real delay. The servo motor moves the valve with constant speed until desired position is reached. A full stroke takes 60 seconds. Less than one half of the stroke was used in the experiments. This will give some delay.

The total estimated delay will be less or about one minute.

Consequently there is some agreement between the construction data model and the identified models. However, the former is not very accurate, since it contains several crude approximations. The identified models well describe the experimental data, and are also suitable for designing regulators for the process. This is described in Ekström-Hänsel-Jensen-Ljung (1974).

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7. Tables

Table number 1

Least squares model: control signal to air temperature after heatexchanger

Delay in samples 0

Model order	model parameters	Experiment number 1	2	3
1	a_1	-0.762	-0.746	-0.751
	b_1	-0.560	-0.655	-0.640
	λ	0.488	0.888	0.872
2	a_1	-0.742	-0.742	-0.733
	a_2	0.097	0.097	0.084
	b_1	-0.321	-0.290	-0.291
	b_2	-0.375	-0.562	-0.542
	λ	0.199	0.265	0.279
Number of samples		517	617	510

Table number 2

Least squares model: control signal to air temperature after heatexchanger

Delay none

Model order	model parameter	Experiment number 1	2	3
1	K_1	-2.35	-2.58	-2.57
	T_1	3.68	3.41	3.47
2	K_1	1.28	1.82	1.51
	T_1	0.56	0.56	0.51
	K_2	-3.24	-4.23	-3.88
	T_2	1.79	1.79	1.91

Table number 3

Least squares model: control signal to air temperature after room

Delay in samples 2

Model order	model parameters	Experiment number 1	2	3
1	a_1	-0.935	-0.922	-0.921
	b_1	-0.042	-0.058	-0.055
	λ	0.083	0.089	0.097
2	a_1	-0.683	-0.945	-1.04
	a_2	-0.225	0.037	0.131
	b_1	-0.027	-0.032	-0.026
	b_2	-0.030	-0.031	-0.029
	λ	0.076	0.072	0.075
Number of samples		515	615	508

Table number 4

Least squares model: control signal to air temperature efter room

Delay 2 minutes

Model order	model parameter	Experiment number 1	2	3
1	K_1	-0.65	-0.74	-0.70
	T_1	14.94	12.25	12.20
2	K_1	-*	0.04	0.05
	T_1	-*	0.31	0.52
	K_2	-*	-0.72	-0.66
	T_2	-*	9.91	8.98

* Continuous transfer function does not exist

Table number 5

Least squares model: air temperature before air duct to
air temperature after air duct

Delay in samples 0

Model order	model parameter	Experiment number 1	2	3
1	a_1	-0.721	-0.745	-0.730
	b_o	0.376	0.372	0.379
	b_1	-0.143	-0.156	-0.151
	λ	0.124	0.069	0.101
2	a_1	-0.619	-1.280	-0.873
	a_2	-0.103	0.379	0.084
	b_o	0.351	0.339	0.352
	b_1	-0.044	-0.275	-0.136
	b_2	-0.071	0.021	-0.036
	λ	0.121	0.036	0.090
Number of samples		516	616	509

Table number 6

Least squares model: air temperature before air duct to air temperature after air duct

Delay none

Model order	model parameter	Experiment number 1	2	3
	D	0.38	0.37	0.38
1	K_1	0.46	0.47	0.46
	T_1	3.06	3.40	3.18
	D	-	0.34	0.35
	K_1	-	0.18	0.08
2	T_1	-	1.31	0.45
	K_2	-	0.34	0.42
	T_2	-	4.89	3.68

Table number 7

Least squares model: air temperature before room to air temperature after room

Delay in samples 0

Model order	model parameter	Experiment number 1	2	3
	a_1	-0.727	-0.762	-0.744
1	b_1	0.071	0.066	0.064
	λ	0.075	0.087	0.085
	a_1	-0.434	-0.766	-0.903
	a_2	-0.296	-0.068	0.066
2	b_1	0.114	0.125	0.102
	b_2	-0.037	-0.075	-0.058
	λ	0.069	0.068	0.075
Number of samples		517	617	510

Table number 8

Least squares model: air temperature before room to air temperature after room

Delay none

Model order	model parameter	Experiment number 1	2	3
1	K_1	0.26	0.27	0.25
	T_1	3.13	3.68	3.38
2	K_1	-	-	0.07
	T_1	-	-	3.97
	K_2	-	-	0.20
	T_2	-	-	5.13

Table number 9

Maximum likelihood model: control signal to air temperature after heatexchanger

Delay in samples 0

Model order	model parameter	Experiment number 1	2	3
1	a_1	-0.762	-0.742	-0.745
	b_1	-0.559	-0.665	-0.656
	c_1	0.008	-0.062	-0.104
	λ	0.488	0.887	0.870
2	a_1	-0.697	-0.716	-0.704
	a_2	0.065	0.080	0.064
	b_1	-0.320	-0.289	-0.290
	b_2	-0.404	-0.584	-0.565
	c_1	0.293	0.607	0.568
	c_2	0.176	0.255	0.234
	λ	0.186	0.214	0.232
Number of samples		517	617	510

Table number 10

Maximum likelihood model: control signal to air temperature after heatexchanger

Delay none

Model order	model parameter	Experiment number 1	2	3
1	K_1	-2.35	-2.58	-2.57
	T_1	3.68	3.35	3.39
2	K_1	1.04	1.64	1.36
	T_1	0.45	0.50	0.45
	K_2	-3.01	-4.04	-3.74
	T_2	1.87	1.83	1.94

Table number 11

Maximum likelihood model: control signal to air temperature after room

Delay in samples 2

Model order	model parameter	Experiment number 1	2	3
	a_1	-0.940	-0.921	-0.922
1	b_1	-0.043	-0.059	-0.055
	c_1	-0.255	-0.034	0.074
	λ	0.080	0.089	0.097
	a_1	-1.410	-1.355	-1.350
	a_2	0.462	0.415	0.416
	b_1	-0.028	-0.033	-0.027
2	b_2	-0.0001	-0.006	-0.011
	c_1	-0.919	-0.765	-0.608
	c_2	0.271	0.274	0.205
	λ	0.071	0.064	0.070
Number of samples		515	615	508

Table number 12

Maximum likelihood model: control signal to air temperature after room

Delay 2 minutes

Model order	model parameter	Experiment number 1	2	3
1	K_1	-0.72	-0.76	-0.70
	T_1	16.03	12.20	12.31
2	K_1	0.08	0.10	0.12
	T_1	1.51	1.32	1.34
	K_2	-0.63	-0.74	-0.69
	T_2	8.94	8.35	7.44

Table number 13

Maximum likelihood model: air temperature before air duct to
air temperature after air duct

Delay in samples 0

Model order	model parameter	Experiment number 1	2	3
	a_1	-0.728	-0.735	-0.727
	b_o	0.380	0.360	0.376
1	b_1	-0.150	-0.137	-0.146
	c_1	-0.125	0.433	0.107
	λ	0.123	0.062	0.100
	a_1	-1.286	-1.436	-1.423
	a_2	0.385	0.498	0.489
	b_o	0.360	0.349	0.361
2	b_1	-0.315	-0.354	-0.364
	b_2	0.040	0.059	0.060
	c_1	-0.706	-0.603	-0.749
	c_2	0.028	0.179	0.060
	λ	0.120	0.034	0.086
Number of samples		516	616	509

Table number 14

Maximum likelihood model: air temperature before air duct to air temperature after air duct

Delay none

Model order	model parameter	Experiment number 1	2	3
	D	0.40	0.36	0.38
1	K_1	0.46	0.48	0.47
	T_1	3.15	3.25	3.14
	D	0.36	0.35	0.36
	K_1	0.16	0.27	0.27
2	T_1	1.34	1.87	1.84
	K_2	0.34	0.25	0.23
	T_2	4.80	6.17	5.84

Table number 16

Maximum likelihood model: air temperature before room to
air temperature after room

Delay none

Model order	model parameter	Experiment number 1	2	3
1	K_1	0.27	0.28	0.25
	T_1	3.34	3.63	3.34
2	K_1	0.12	0.18	0.19
	T_1	1.23	1.73	2.09
	K_2	0.19	0.14	0.11
	T_2	8.19	13.07	17.56

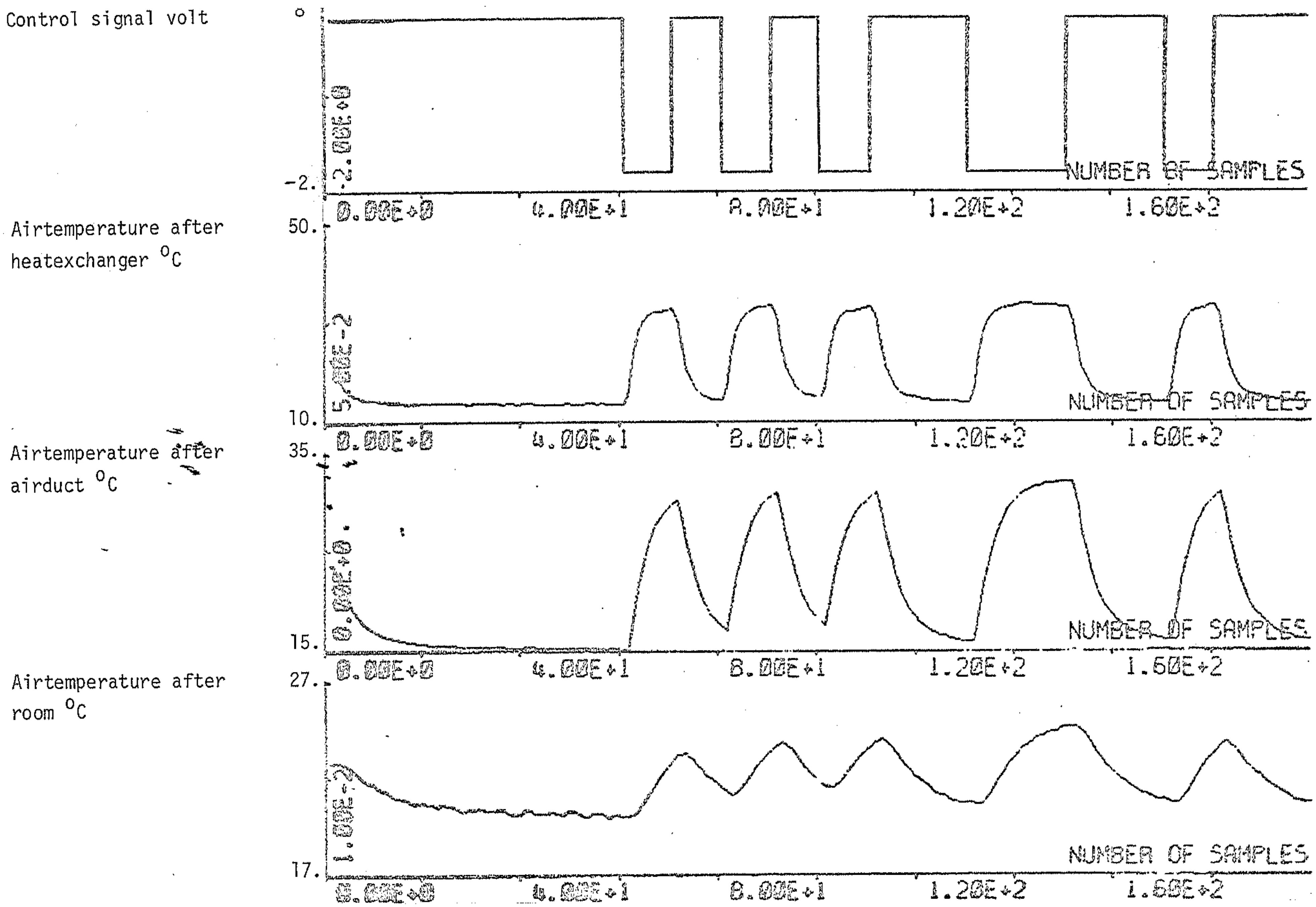


Diagram 1. Samples 1 to 200 from experiment 2.

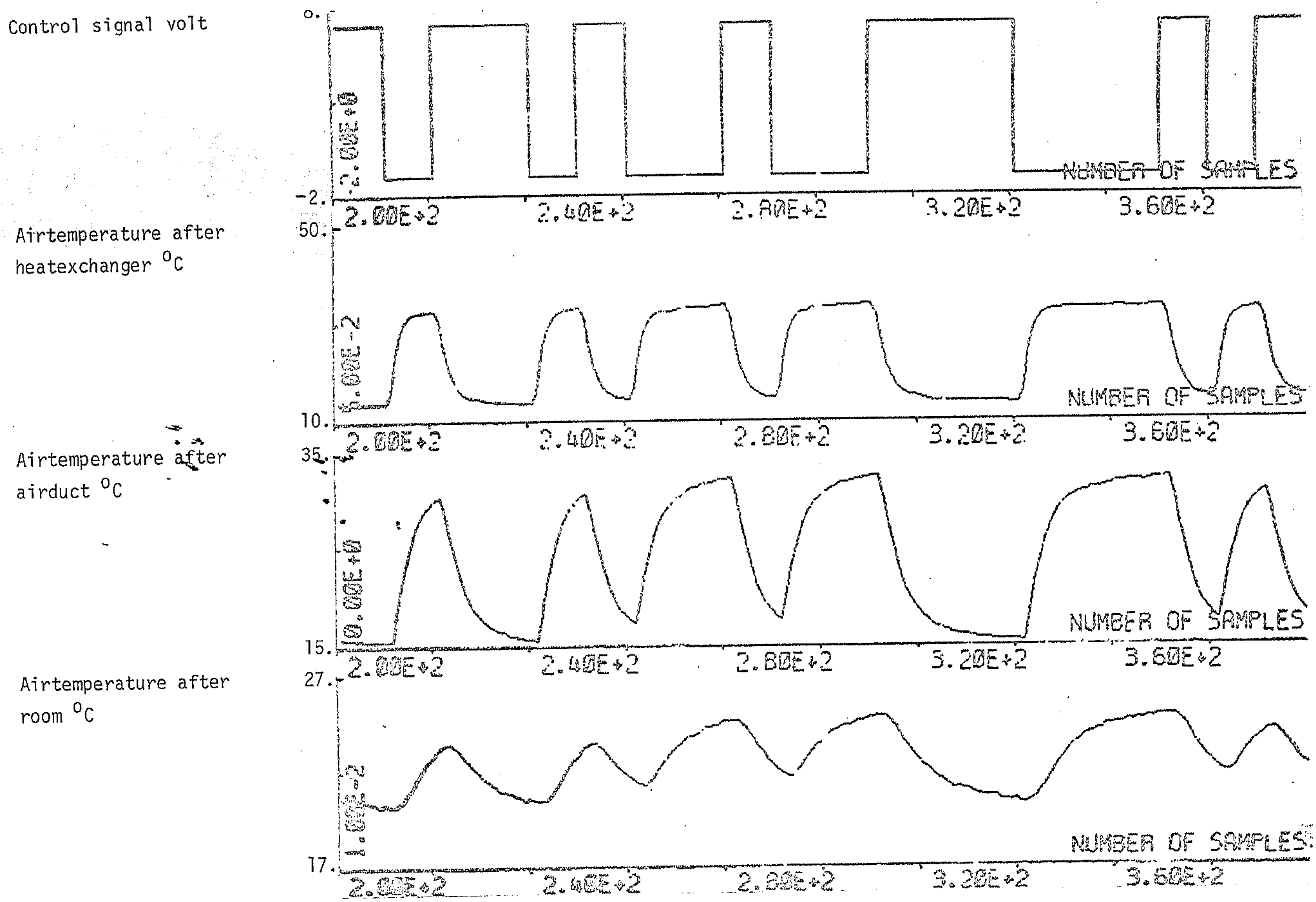


Diagram 2. Samples 201 to 400 from experiment 2.

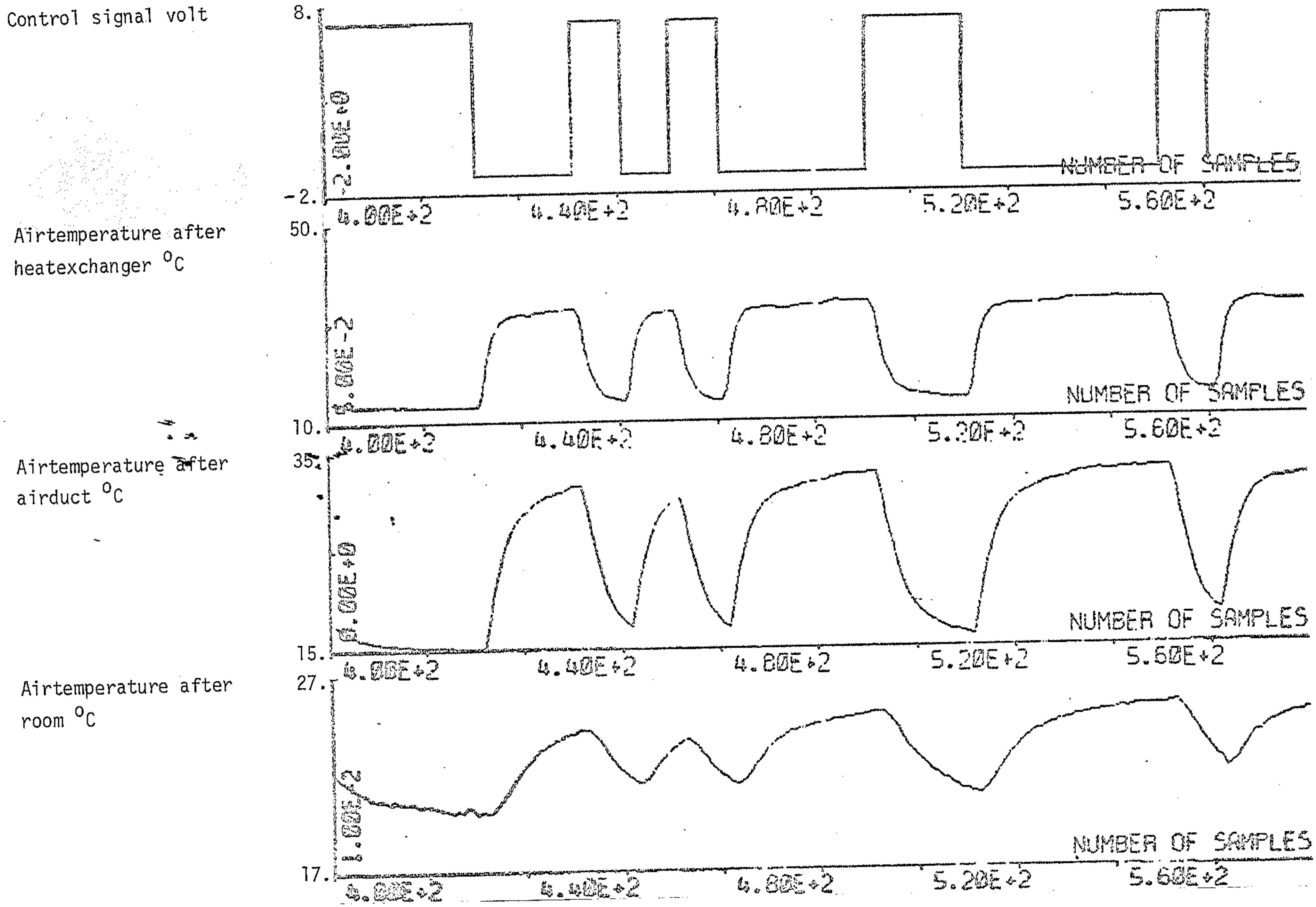


Diagram 3. Samples 401 to 600 from experiment 2.

Diagram 4. Deterministic output and model error from model control signal to airtemperature after heatexchanger from experiment 2. The model is of second order.

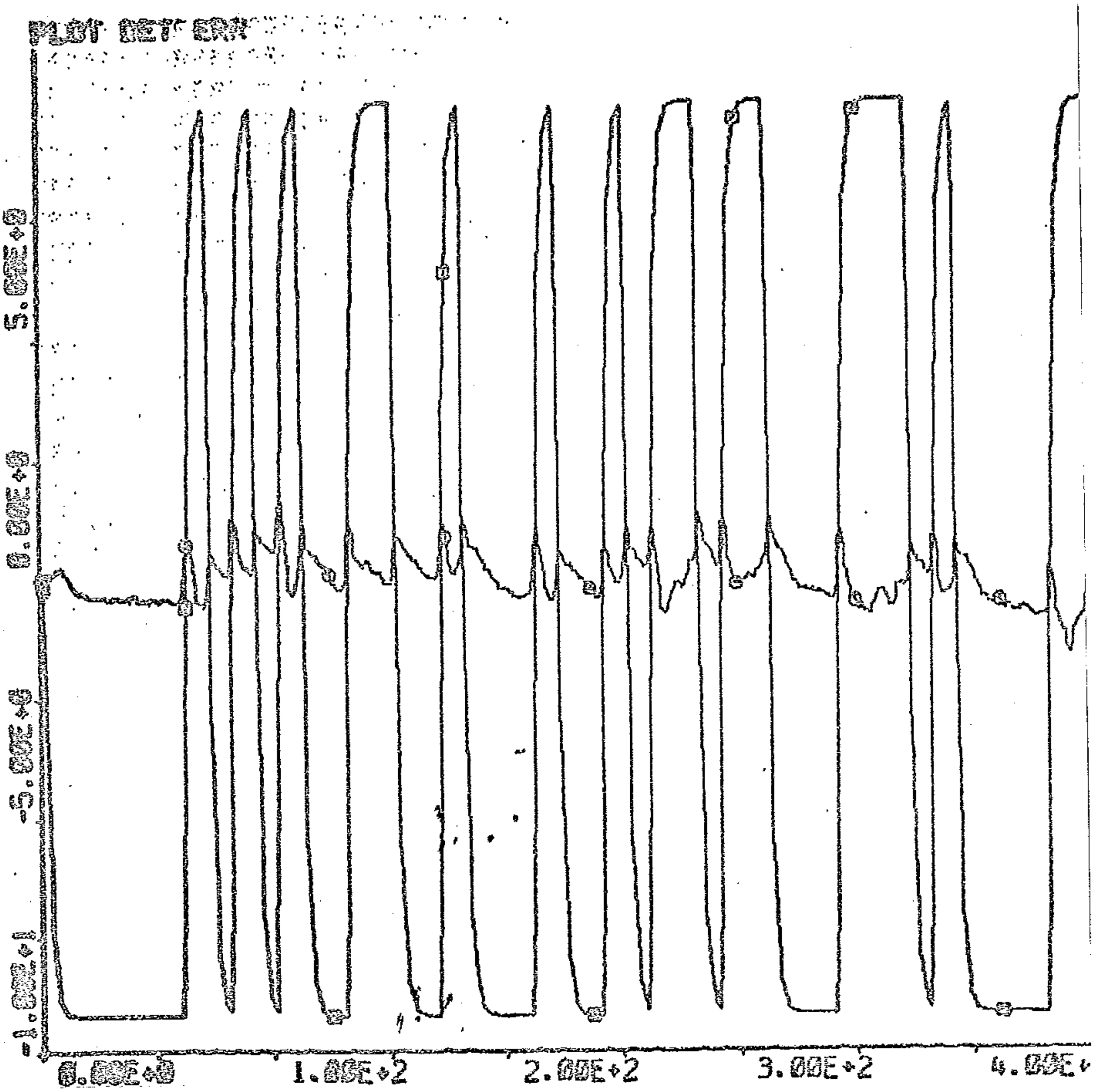


Diagram 5. Residuals from model control signal to air-temperature after heatexchanger from experiment 2. The model is of second order.

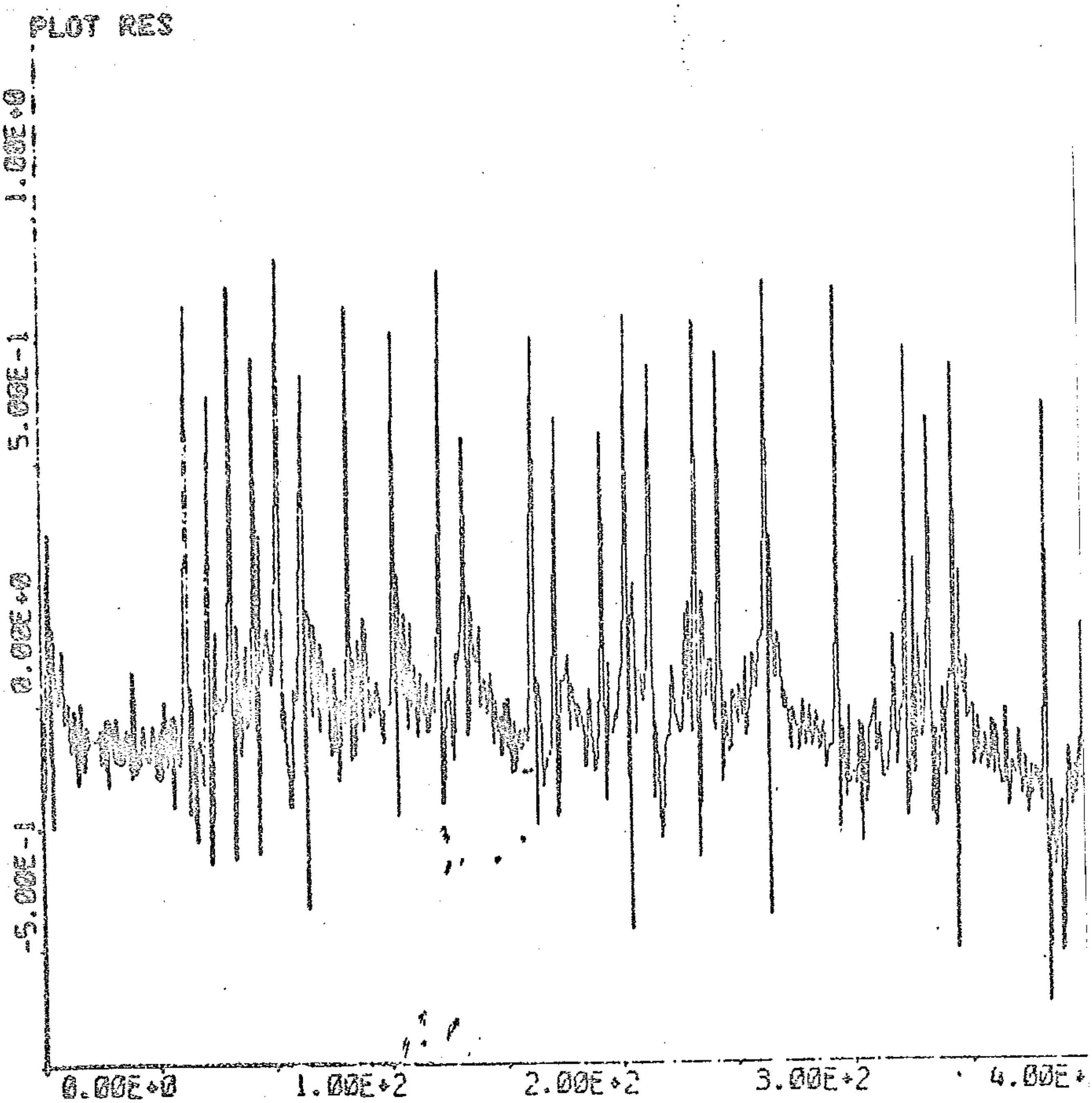


Diagram 6. Deterministic output and model error from model control signal to airtemperature after room from experiment 2. The model is of second order and has a delay of 2 minutes.

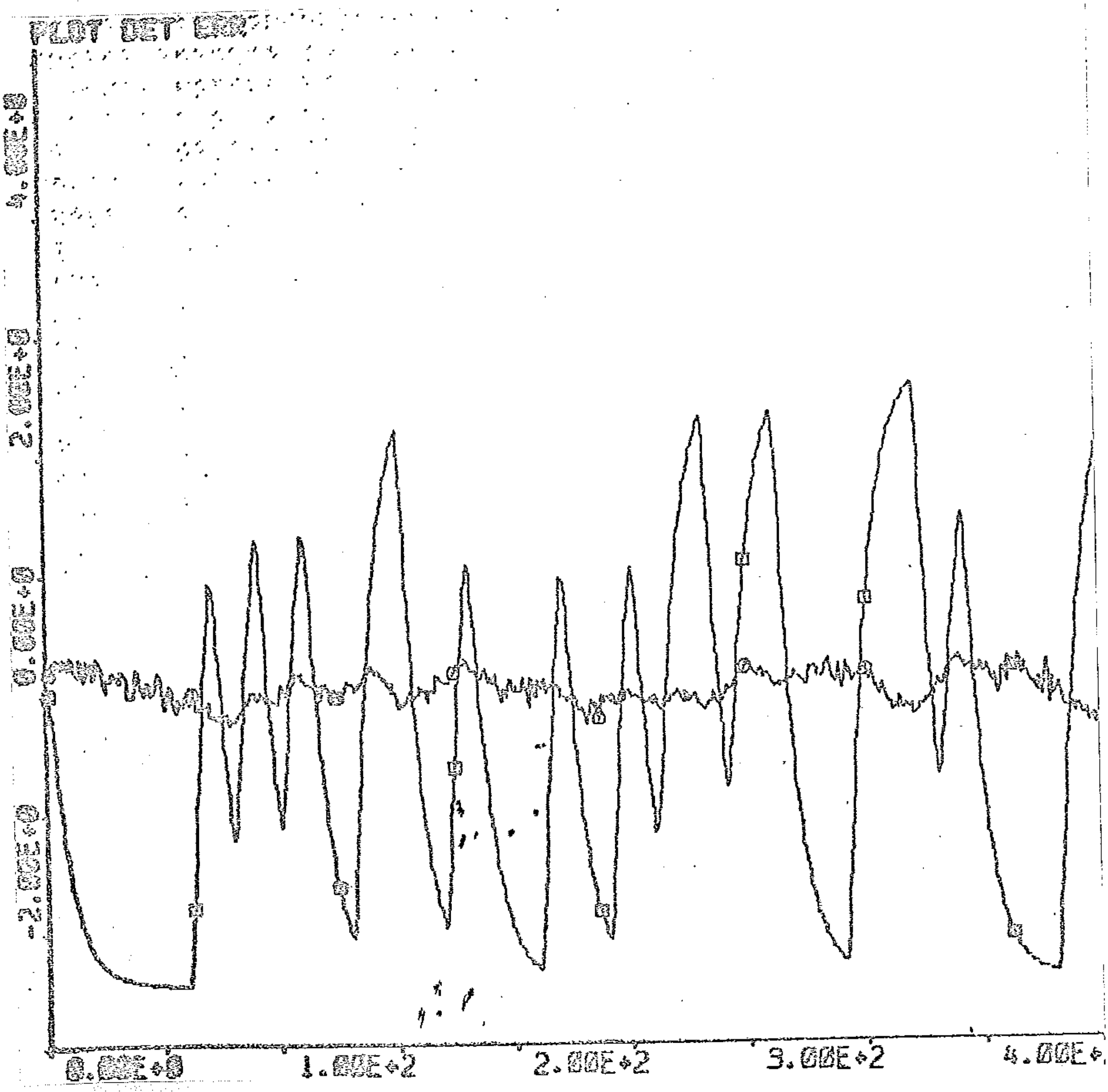


Diagram 7. Residuals from model control signal to air-temperature after room from experiment 2. The model is of second order and has a delay of 2 minutes.

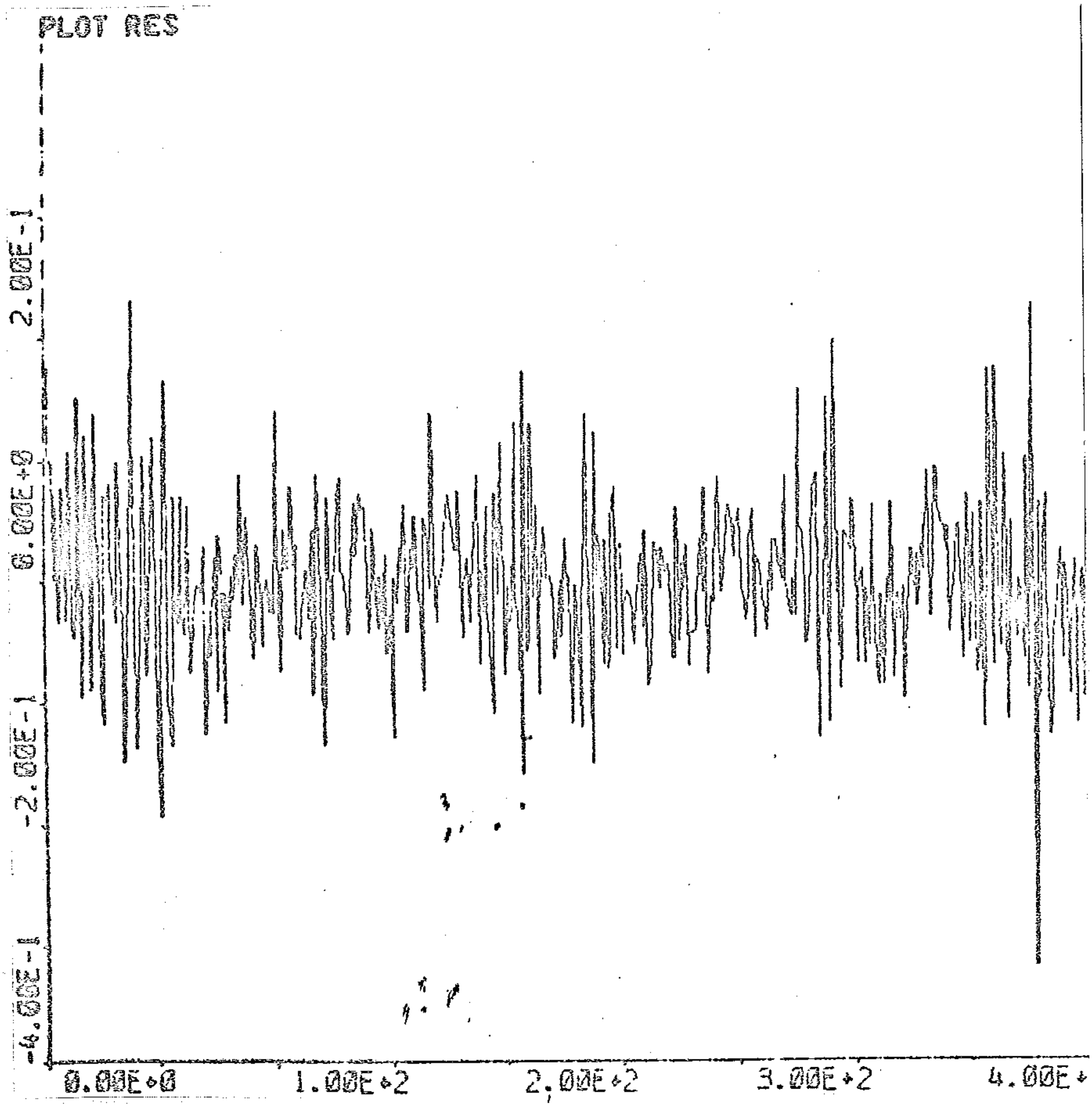


Diagram 8. Deterministic output and model error from model airtemperature before airduct to airtemperature after airduct from experiment 2. The model is of first order with a directterm.

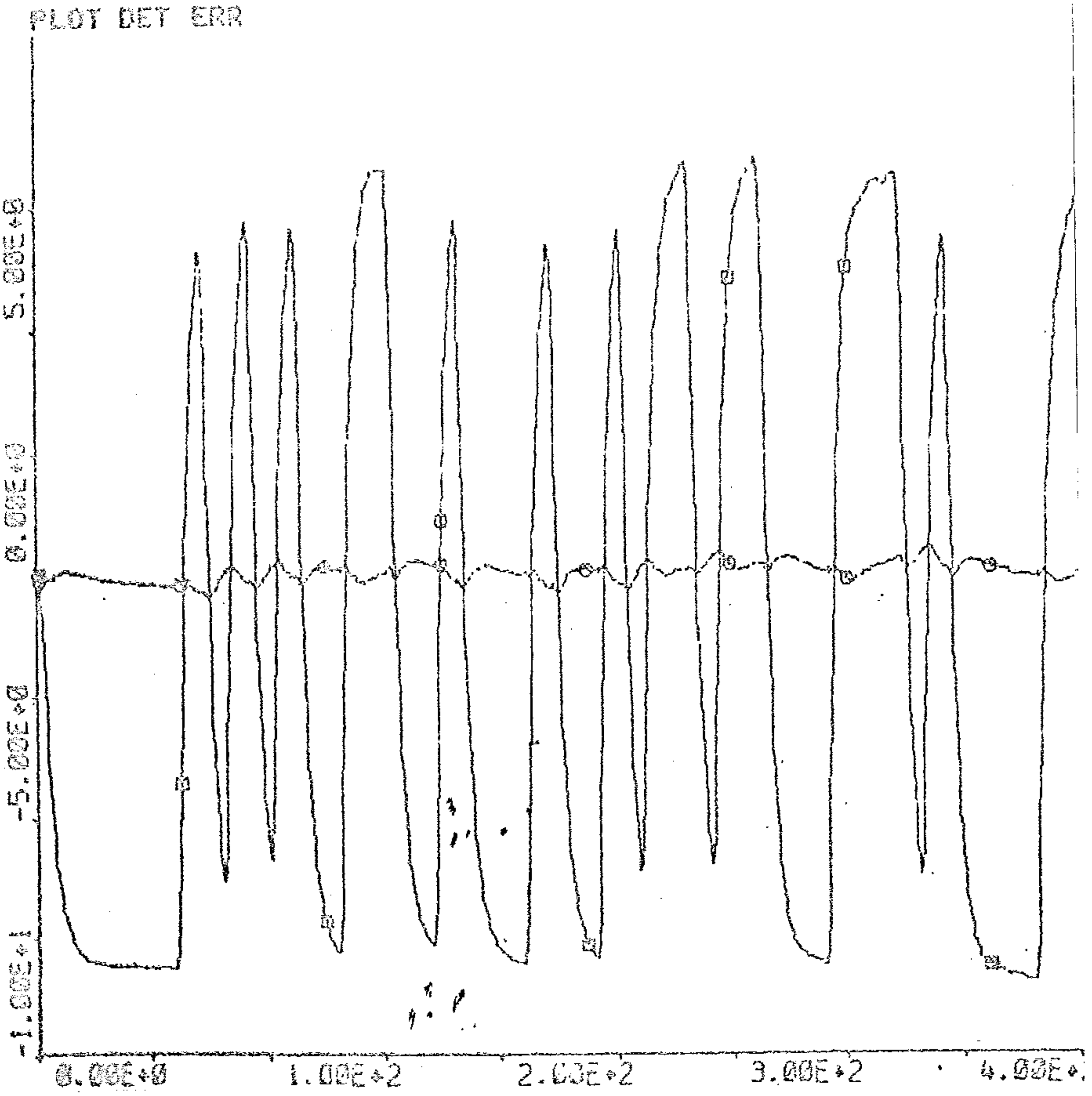


Diagram 9. Residuals from model airtemperature before airduct to airtemperature after airduct from experiment 2. The model is of first order with a directterm.

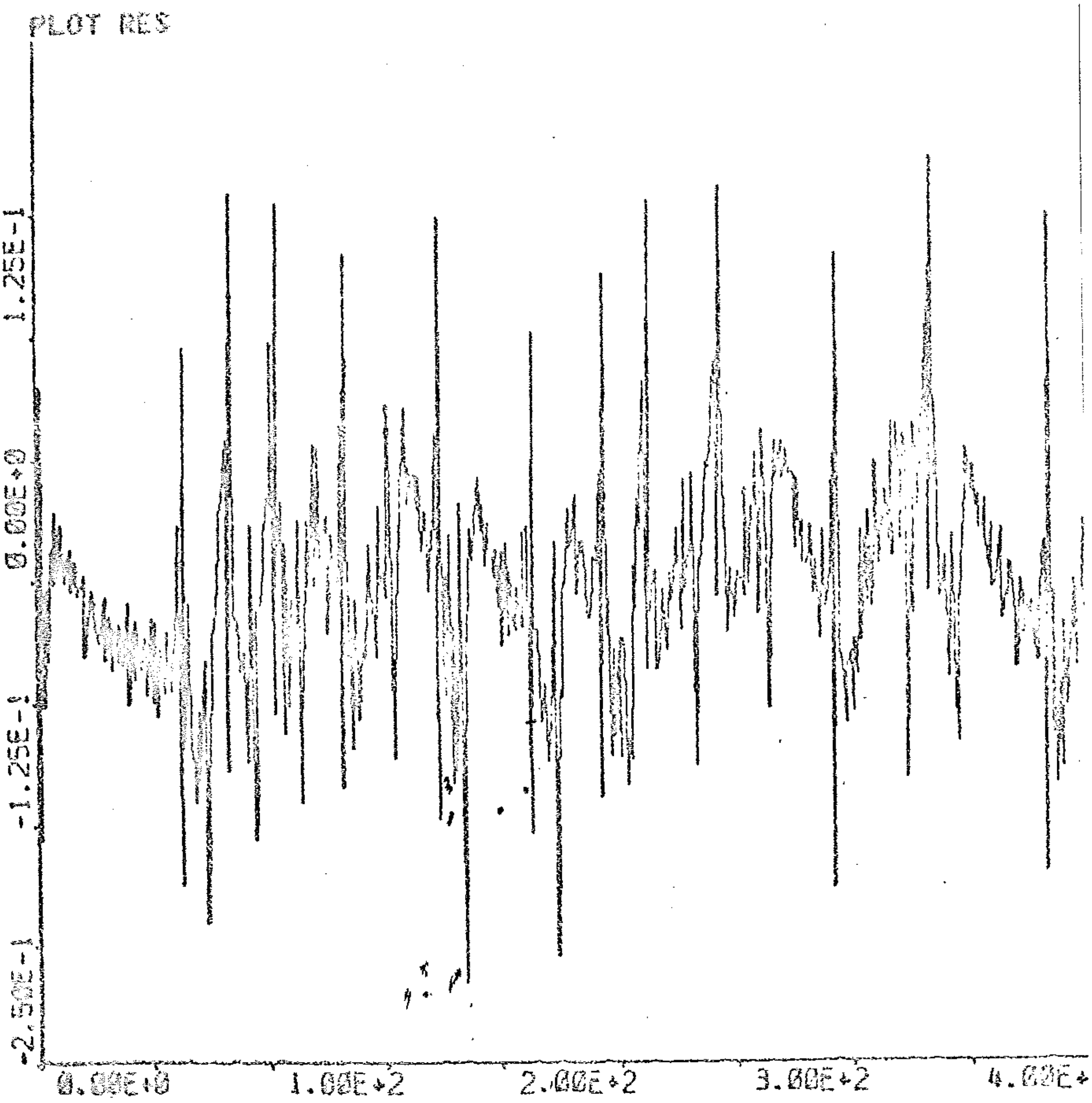


Diagram 10. Deterministic output and model error from model airtemperature before room to airtemperature after room from experiment 2. The model is of second order.

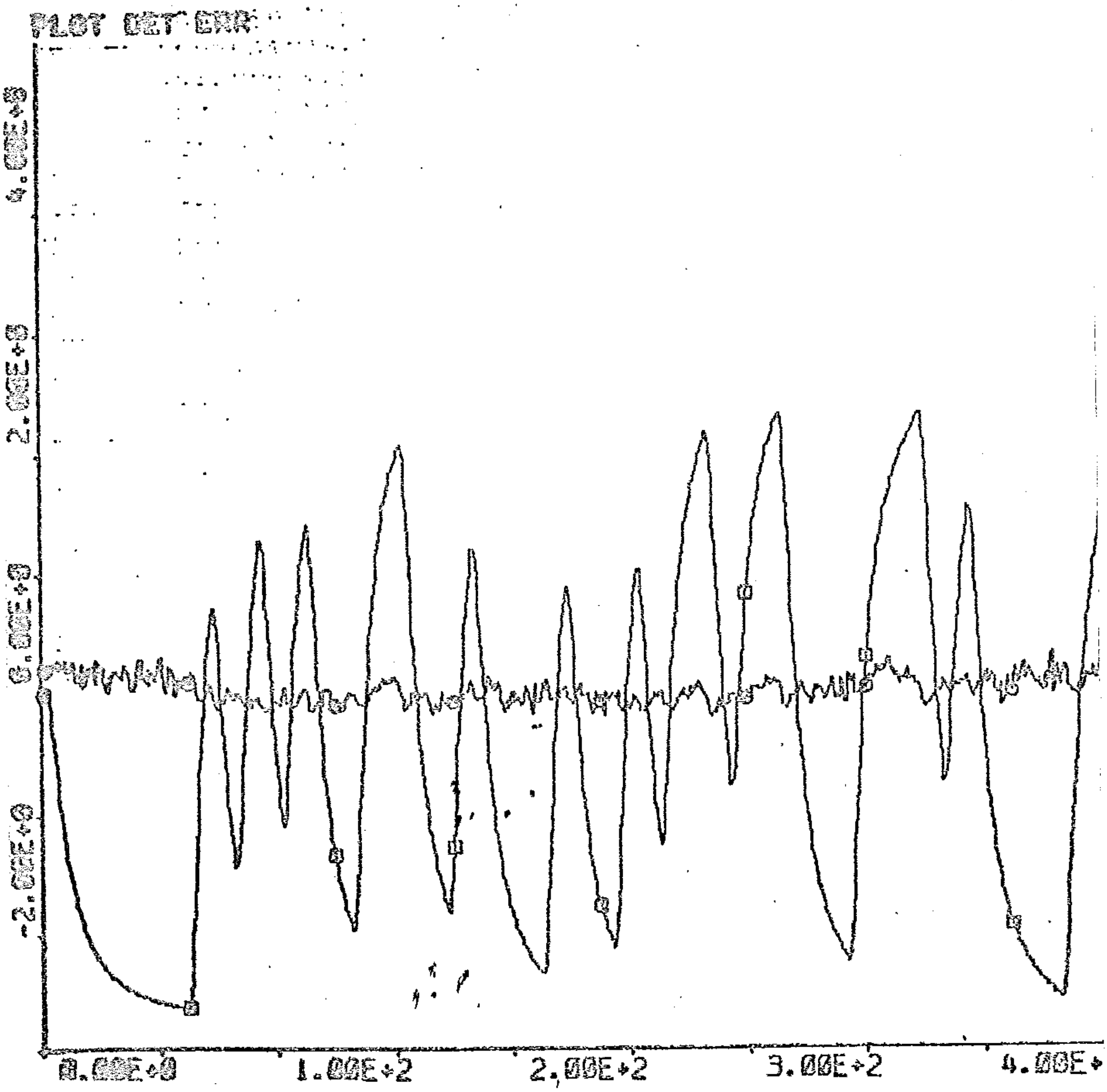
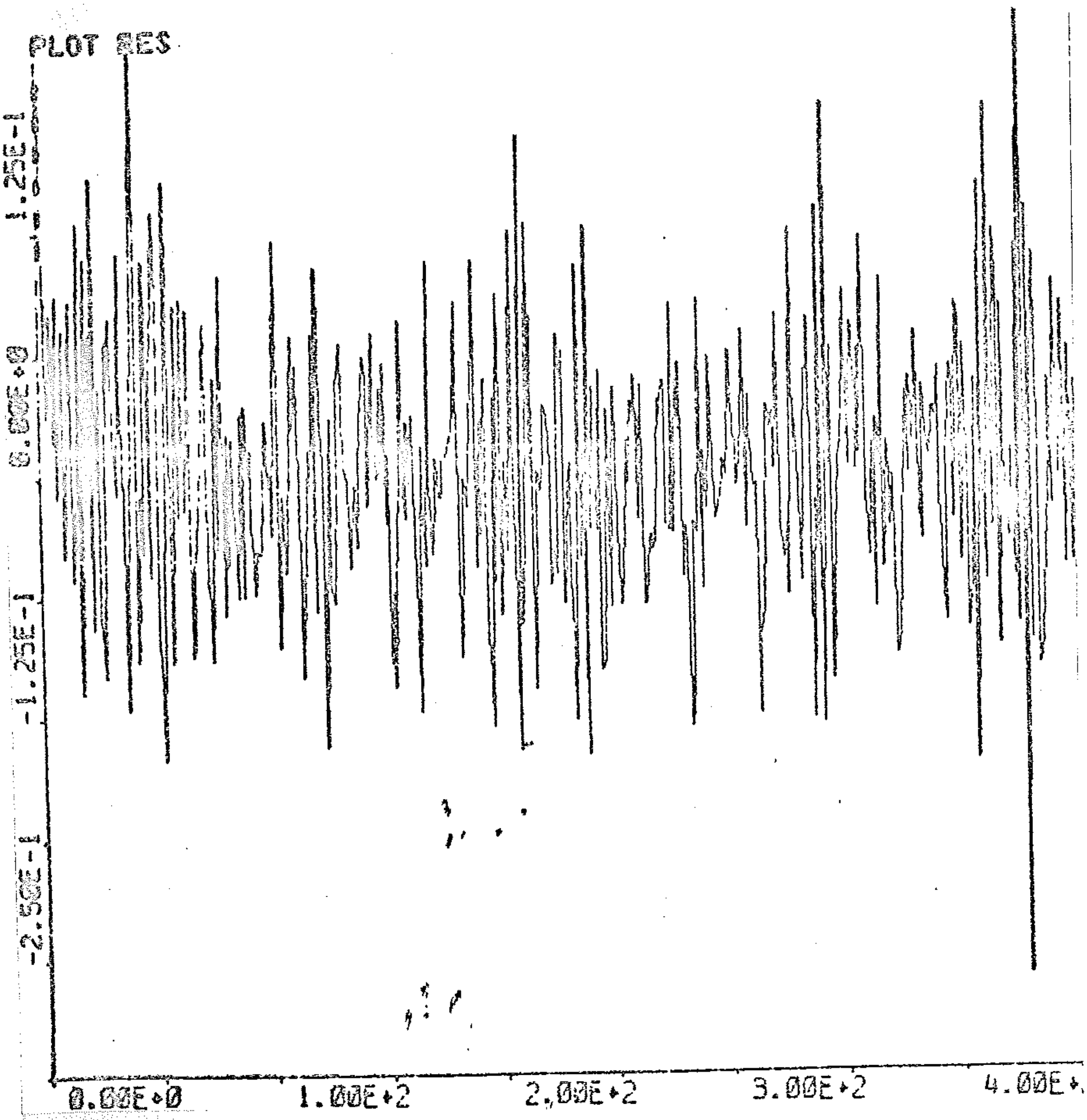


Diagram 11. Residuals from model airtemperature before room to airtemperature after room from experiment 2. The model is of second order.



Appendix 1

Plant data

Valve servo

Honeywell Modutrol M944B

full stroke time 60 seconds

full stroke angle 160 °

Valve

Honeywell V5011A8044

$C_V = 6.3$

connection 3/4"

Recirculation loop with pump

Volume 8 l

Flow 19 l/min

Pump

Vadstena type VM-31F
1450 r/min
Wheel 420

Water to air crossflow heatexchanger

Svenska Fläktfabriken VKBE-01-2-2-2

water temperature in	70 °C
water temperature out	40 °C
air temperature in	-15 °C
air temperature out	24 °C
effect	36.5 kW

Fan

Svenska Fläktfabriken VKBR-01-3-31-1
air flow 2800 m^3/h

Inlet airduct

length	20 m
diameter	405 mm
thickness duct	0.7 mm
thickness isolation	30 mm

Room

length	11 m
width	7.5 m
height	3.2 m
volume	260 m^3
reinforced concrete area	284 m^2
reinforced concrete volume	27 m^3
window area	15.4 m^2

The plant consisted also of another heatexchanger for cooling and a humidifier. These were both turned off.

Appendix 2

Usage of analog input

The location of sensors in the room are given as coordinates in a xyz system. The x-axis follows the back wall of the room and the y-axis the window surface. The z-coordinate is the height above the floor.

Analog input

number	type	location
1	room air temperature air inlet zone	(3,5,5,5,1,6)
2	room air temperature air outlet zone	(3,5,4,0,1,6)
3	inlet duct air temperature	(3,5,5,5,3,0)
4	ceiling air temperature	(3,5,5,8,2,7)
5	outlet duct air temperature	(3,5,1,5,3,0)
6	valve position	-
7	convector temperature	(0,1,4,0,0,2)
8	hot water temperature	-
9	air temperature after heatexchanger and fan	-
10	air temperature before heatexchanger	-

Appendix 3

Usage of outputs

Only one analog output was used as control signal to the valve positioner. The four logical output were used as follows.

Logical output number	open/closed
0	positioner off/on
1	normal control/computer control
2	disturbance 1(1-4 kW) off/on
3	disturbance 2(1-4 kW) off/on