Prediction Error Method for Identification of a Heat Exchanger

by

Ren Qingchang

EUT Report 90-E-237
ISBN 90-6144-237-0

January 1990
PREDICTION ERROR METHOD FOR IDENTIFICATION OF A HEAT EXCHANGER

by

Ren Qingchang

EUT Report 90-E-237
ISBN 90-6144-237-0

Eindhoven
January 1990
予报误差方法用于热交换器模型辨识的研究

中国西安冶金建筑学院访问学者

任庆昌

指导者：P. 艾克霍夫（P. Eykhoff）教授

一九九零年一月

CIP-GEGEVENS KONINKLIJKE BIBLIOTHEEK, DEN HAAG

Ren Qinchang

Prediction error method for identification of a heat exchanger /
by Ren Qingchang. - Eindhoven: Eindhoven University of Technology,
Faculty of Electrical Engineering. - Fig., tab. - (EUT report,
ISSN 0167-9708; 90-E-237)
Met lit. opg., reg.
ISBN 90-6144-237-0
SISO 653.6  UDC 621.565-53:519.71.001.3  NUGI 832
Trefw.: warmtewisselaars; systeemidentificatie.
ABSTRACT

The dynamic behaviour of a shell-and-tube counter flow water-water heat exchanger, the heating power of which can be influenced by varying the water flow, is investigated by experimental identification with Pseudo Random Binary Sequence (PRBS) test signals. It will be shown that it is possible to describe this non-linear distributed parameter system using a linear lumped parametric model. Both Equation Error Model (ARX model) and Output Error Model (OE model) structures based on the Prediction Error Method (PEM) are used in order to do this, and the identification results are compared with each other.

Some estimation techniques for this sort of MIMO process are presented and discussed. The proposed identification scheme has proved to function well and to be convenient. It can be extended to deal with similar kinds of thermal processes.

Supervisor: Professor P. Eykhoff

Address of the author:
Ren Qingchang
Measurement & Control Group
Dept. of Electrical Engineering
Eindhoven University of Technology
P.O. Box 513, 5600 MB Eindhoven
The Netherlands

On leave from Xi’an Institute of Metallurgy and Construction Engineering, Xi’an, P.R. China.

January 1990
CONTENTS

Abstract ........................................... page

1 Introduction .................................... 1
2 Process description ............................. 1
3 Experimental set-up ......................... 6
4 Identification method: Prediction Error Method (PEM) 10
   4.1 SISO System ................................ 10
   4.1.1 ARX model structure and Least Squares method 12
   4.1.2 OE model structure and Gauss-Newton method 16
   4.2 MIMO System ................................ 20
5 Data processing and analyzing .............. 23
6 Conclusions and remarks ...................... 32

Acknowledgment ..................................... 34

References ........................................ 35
Figures 5.1.1 - 5.5.4 .......................... 39
Appendix: "CONTROL EG" program ............ 50
INTRODUCTION

Numerous different kinds of heat exchangers are used in processes such as heating, cooling and economizing processes; they play an important role in industrial plants. A very common type of heat exchanger is the shell-and-tube heat exchanger. It occurs in many forms, as a separate unit in the form of preheaters, coolers and condensers, as an integral part of some other unit. The research work represented in this paper is based on a shell-and-tube counter flow water-water heat exchanger, which is a preheater for an artificial climate chamber.

Before the controlled behaviour of a heat exchanger can be predicted at the design stage, it is necessary to be able to predict the dynamic behaviour of the heat exchanger. Dynamic analysis of heat exchangers has been investigated by many researchers because of their application over a wide range. A heat exchanger is intrinsically a non-linear and distributed parameter process. In line with the different applications its mathematical model can be described in different ways: linear (or non-linear) partial differential equations (Refs. [20] [25]), linear (or non-linear) ordinary differential equations (Refs. [8] [11]).

Previously, some research has been done on a similar heat exchanger (installed in the Eindhoven University of Technology), which involves building up a physical model by means of theoretical analysis and building up an experimental model by means of identification techniques, regarding it as a single input-single output system.

This paper gives a multi input - multi output model of the heat exchanger using an identification method - PEM (Prediction Error Method). For the purpose of control we regard it as a lumped parameter system and linearize it in the different working points. The result shows that such an approximation technique functions well, is convenient and can be extended to deal with similar thermal processes.

2. PROCESS DESCRIPTION

The counterflow water-water heat exchanger, having a shell-and-tube mechanical structure (schematically illustrated in Figure 2.1) is a prehea-
ter of an artificial climate chamber. Its geometrical and physical data are given in table 2.1.

Table 2.1 Data of the investigated heat exchanger

<table>
<thead>
<tr>
<th></th>
<th>shell</th>
<th>inner tubes</th>
</tr>
</thead>
<tbody>
<tr>
<td>length (mm)</td>
<td>1005</td>
<td>1005</td>
</tr>
<tr>
<td>diameter (mm)</td>
<td>Ø58</td>
<td>Ø3</td>
</tr>
<tr>
<td>total cross section</td>
<td>15</td>
<td>6.5</td>
</tr>
<tr>
<td>area (cm²)</td>
<td>inside shell: 1800</td>
<td>inside tubes: 8500</td>
</tr>
<tr>
<td></td>
<td>outside shell: 1850</td>
<td>outside tubes: 11300</td>
</tr>
<tr>
<td>heat transfer area (cm²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>contents (cm³)</td>
<td>1450</td>
<td>640</td>
</tr>
<tr>
<td>velocity at 100 l/h (cm/s)</td>
<td>1.9</td>
<td>4.3</td>
</tr>
<tr>
<td>numbers</td>
<td>1</td>
<td>90</td>
</tr>
</tbody>
</table>
Figure 2.1 Structure of shell-and-tube heat exchanger
Figure 2.2 shows the system configuration. The hot water, produced by the heat exchanger, supplies thermal energy for the artificial climate chamber. Some auxiliary facilities, such as steam generators, steam water heaters, hot and cold water pressure stabilizers, serve the heat exchanger.

From the viewpoint of a control engineer the heat exchanger is characterized by two important parameters which will be taken as the outputs to be controlled:
- outlet temperature of the water on the cold side (denoted by $T_{co}$)
- outlet temperature of the water on the hot side (denoted by $T_{ho}$)

They are influenced by some process conditions, in principle, by the four conditions which are all candidates for controlling inputs. These are:
- flow of the water on the cold side (denoted by $F_c$)
- inlet temperature of the water on the cold side (denoted by $T_{ci}$)
- flow of the water on the hot side (denoted by $F_h$)
- inlet temperature of the water on the hot side (denoted by $T_{hi}$)

In the application of this heat exchanger $T_{hi}$ is pre-controlled in a certain range, i.e. the variation of $T_{hi}$ (denoted by $\Delta T_{hi}$) is very small (see measuring record curve in Figures 5.1.1 - 5.1.3 and $T_{ci}$ is kept at an almost fixed temperature; its variation (denoted by $\Delta T_{ci}$) can be neglected. The outlet temperature of the water on the cold side and the water on the hot side are controlled by regulating the flow of the water on the hot side with that of the water on the cold side. Therefore, it is important to be able to predict the dynamic responses of the outlet temperatures of the water on both sides when both flows are varied. Consequently, the heat exchanger is a real multi-input multi-output (MIMO) system.
Figure 2.2 System Configuration
Neglecting $\Delta T_{hi}$ and $\Delta T_{ci}$ we consider it to be a 2-input 2-output system. Its outputs are outlet temperature of the water on the cold side ($T_{co}$) and the water on the hot side ($T_{ho}$), and its inputs are flow variations of the water on the hot side ($F_h$) and that on the cold side ($F_c$), as shown in Figure 2.3.

![Figure 2.3 Heat Exchanger (MIMO system)](image)

3 EXPERIMENTAL SET-UP

For identification of the dynamic behaviour between the water flow and the outlet temperature, a measuring system was installed at the heat exchanger. This system is schematically illustrated in Figure 3.1.

The heat exchanger, which is constructed as shown in Figure 2.1, has 90 straight brass inner tubes inside the shell. In representing them we draw only one inner tube for brief illustration and easy comprehension.

A process minicomputer (Philips PC 3102) is connected to the heat exchanger via an interface. A computer with RTI-820 I/O boards and a 5B series of conditioners, combined with special software - "CONTROL EG"
(provided by ANALOG DEVICES INC.) was used for the test signal output, the data acquisition and the monitoring of the experiment. For off-line data analysis "MATLAB" software was used on the Philips PC 3102 computer.

Figure 3.1 The measuring system for identification of the heat exchanger
The test signals $u_1$ and $u_2$ which activate the system are given by the process computer as analogue voltages and transferred to the pneumatic valve via a voltage to current converter and a current to pressure converter; they become the signals $F_c$ and $F_h$. In this way the water flow through the heat exchanger is changed. By means of testing the water pressure difference (denoted by $\Delta P$) of both sides of a built-in hole-plate in the pipe, and by converting $\Delta P$ via a pressure to voltage converter, the computer receives the voltage signal which is proportional to the square of the velocity of the water.

Measurements of inlet and outlet temperature of water were obtained by putting RTD resistances at the beginning and end of the tube and shell respectively.

Since the quality of the best possible model is determined by the quality of the data used for its construction, it is important to plan an experiment strategy which results in maximum information on the parameters and thus yields good estimates. The optimal design of experiments for parameter identification considers several questions. These include:

- selection of the duration of the experiment
- selection of a reasonable sampling rate
- selection of the type of test signals to be superimposed on the process

Based on the available a priori knowledge and practical experience, we made the following assumptions which are permitted from the practical point of view, and some choices about experimental parameters.

- The heat exchanger has linear dynamic behaviour around the designated working point
- From the initial step response experiment we measured the following time constant ($T_a$) =

  \[ T_{a11} = 210 \text{s}, \text{ for } \Delta F_c \text{ (input)} - \Delta T_{CO} \text{ (output)} \]

  \[ T_{a12} = 141 \text{s}, \text{ for } \Delta F_h \text{ (input)} - \Delta T_{CO} \text{ (output)} \]

  \[ T_{a21} = 114 \text{s}, \text{ for } \Delta F_c \text{ (input)} - \Delta T_{ho} \text{ (output)} \]
$T_{a22} = 96s$, for $\Delta F_h$ (input) $\Delta T_h$ (output)

In general, it can be stated that an experiment directed to parameter estimation has to cover at least 5-10 times the largest relevant time constant to allow a reliable estimation of the corresponding process eigenvalues. Thus the duration of the experiment should be equal to or greater than

$10 T_{a12} = 10 \times 141 = 1410s$

- Select the pseudo random binary sequences (PRBS) as the test signal with the following parameters:
  - The basic period (the smallest time span between shifts) is $\Delta = 0.3 \times \frac{1}{f_m} = 0.3 \times T_{a22} = 28.8s$, we choose $\Delta = 30s$.
  - The period (the sequence length) $N_p \geq \frac{1}{\Delta f_m} = \frac{T_{a22}}{\Delta} = \frac{96}{30} = 3$, we choose $N_p = 4$.
  - The amplitude of the sequence is $a = 15 \sim 20\%$ full range of the input variables of the process.
  - The sampling interval is $T_s = 5s$.

In this experiment we benefitted from the measurement and control program - "CONTROL EG". "CONTROL EG" is a menu-driven automation software package for use with the RTI-820 series of analog and digital I/O boards, the 3B/5B series of analog signal conditioners. Therefore it is a perfect tool for small to medium (up to 256 analog input channels) laboratory and industrial applications.

For the identification of the heat exchanger we set up the following tables (see Appendix):

- runtime set-up table
- analog input set-up table
- calculated input set-up table
- analog input alarm set-up table
- calculated input alarm set-up table
- analog output set-up table
- sequencer table
- history graph set-up table
In this case, extremely complex formulas can be entered in simple algebraic notation. These calculated values can be displayed in real-time displays (the annunciator display, the history display, the bar graph display, etc.) and logged to a disk and printer, or used to control analog and digital outputs.

4 IDENTIFICATION METHOD

The system identification problem is to estimate a model of a system based on observed input-output data. There are several ways to describe a system to be estimated.

4.1 SISO system

\[ \begin{align*}
  y(k) &= G(z^{-1})u(k) + v(k) \\
  v(k) &= H(z^{-1})e(k) \\
  \end{align*} \]

\[ (4.1.1) \]

\[ (4.1.2) \]

Eq. (4.1.1) and (4.1.2) together give a time domain description of the
system. Where $u(k)$ is the input signal, $y(k)$ is the output signal, $e(k)$ is white noise with variance $\lambda$, $v(k)$ is the additional, unmeasurable disturbance (noise) and can be described as filtered white noise as in Eq. (4.1.2).

$z$ is the shift operator, so that $z^{-1}u(k) = u(k-1)$, $z^{-1}y(k) = y(k-1)$, $z^{-1}e(k) = e(k-1)$.

$$G(z^{-1}) = \sum_{i=1}^{\infty} g(i)z^{-i}$$ (4.1.3)

where $g(i)$ is the weighting function (or impulse response), $G(z^{-1})$ is called the transfer operator or the transfer function of the linear system.

$G(z^{-1})u(k)$ is short for

$$G(z^{-1})u(k) = \sum_{i=1}^{\infty} g(i)u(k-i)$$ (4.1.4)

To be able to estimate the functions $G$ and $H$ in (4.1.1), (4.1.2) they, typically, have to be parametrized, most often as rational functions in the delay operator $z^{-1}$. Let the parameters be the numerator and denominator coefficients. Thus we give a general parametric model structure:

$$A(z^{-1})y(k) = \frac{B(z^{-1})}{F(z^{-1})} u(k-nk) + \frac{C(z^{-1})}{D(z^{-1})} e(k)$$ (4.1.5)

where $A, B, C, D$ are polynomials in the delay operator $z^{-1}$

$$A(z^{-1}) = 1 + a_1 z^{-1} + \ldots + a_{na} z^{-na}$$ (4.1.5a)

$$B(z^{-1}) = b_0 + b_1 z^{-1} + \ldots + b_{nb} z^{-nb}$$ (4.1.5b)

$$C(z^{-1}) = 1 + c_1 z^{-1} + \ldots + c_{nc} z^{-nc}$$ (4.1.5c)

$$D(z^{-1}) = 1 + d_1 z^{-1} + \ldots + d_{nd} z^{-nd}$$ (4.1.5d)

$$F(z^{-1}) = 1 + f_1 z^{-1} + \ldots + f_{nf} z^{-nf}$$ (4.1.5f)

We shall refer to the structure variables $na, nb, nc, nd, nf$ as the orders of the respective polynomials. The number $nk$ is the number of delays from input to output.

For most practical purposes, we may get some different model sets from Eq. (4.1.5) depending on which of the five polynomials $A, B, C, D$ and $F$ are
used. The common special cases of Eq. (4.1.5) are summarized in Table 4.1.1.

Table 4.1.1 Some model sets as special cases of Eq. (4.1.5)

<table>
<thead>
<tr>
<th>Polynomials used in Eq. (4.1.5)</th>
<th>Name of model structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>FIR (Finite Impulse Response)</td>
</tr>
<tr>
<td>A, B</td>
<td>ARX</td>
</tr>
<tr>
<td>A, B, C</td>
<td>ARMAX</td>
</tr>
<tr>
<td>A, C</td>
<td>ARMA</td>
</tr>
<tr>
<td>A, B, D</td>
<td>ARARX</td>
</tr>
<tr>
<td>A, B, C, D</td>
<td>ARARMAX</td>
</tr>
<tr>
<td>B, F</td>
<td>OE (output error)</td>
</tr>
<tr>
<td>B, F, C, D</td>
<td>BJ (Box-Jenkins)</td>
</tr>
</tbody>
</table>

Considering the reality of the heat exchanger, and attempting to compare different model structures as well as different identification methods, we made the following scheme:

- ARX model structure (belonging to the Equation Error model struc-

![Figure 4.2](image1)

**Figure 4.2** The ARX model structure

![Figure 4.3](image2)

**Figure 4.3** The Process and model for Equation Error Method
Consulting Table 4.1.1 and comparing Eq. (4.1.1), (4.1.2) and (4.1.5), the ARX model can be written as:

\[ A(z^{-1})y(k) = B(z^{-1})u(k-nk) + e(k) \tag{4.1.6a} \]

\[ G(z^{-1}) = \frac{B(z^{-1})}{A(z^{-1})} \quad H(z^{-1}) = \frac{1}{A(z^{-1})} \tag{4.1.6b} \]

In this case, the adjustable parameters are:

\[ \theta = [a_1 a_2 \ldots a_{na} b_0 b_1 \ldots b_{nb}]^T \tag{4.1.7} \]

The signal flow can be depicted as in Figure 4.2. The following linear difference equation corresponds to (4.1.6)

\[ y(k) + a_1 y(k-1) + \ldots + a_{na} y(k-na) = b_0 u(k-nk) + b_1 u(k-1-nk) + \ldots + b_{nb} u(k-nb-nk) + e(k) \tag{4.1.8} \]

Since the white-noise term \( e(k) \) here enters as a direct error in the difference equation, see Figure 4.3, the model (4.1.6) or (4.1.8) is often called an Equation Error Model (structure).

Such a model set has a very important property that makes it a prime choice in many applications. We shall also call the model (4.1.6) or (4.1.8) an ARX model where AR refers to the autoregressive part \( A(z^{-1})y(k) \) and \( x \) to the extra input \( B(z^{-1})u(k) \).

**Parameter Estimation**

Given a description (4.1.1), (4.1.2) and having observed the input-output data \( u, y \) we can compute one-step-ahead prediction errors \( e(k) \) in (4.1.2)

\[ \hat{y}(k) = [1 - H^{-1}(z^{-1})]y(k) + H^{-1}(z^{-1})G(z^{-1})u(k-nk) \tag{4.1.9} \]

\[ e(k) = y(k) - \hat{y}(k) \]
We call these errors $e(k)$ "prediction errors". They will, for given data $u$ and $y$, be functions of $G$ and $H$. The most common parametric identification method is, naturally enough, to determine estimates of $G$ and $H$ by minimizing

$$V_N(G, H) = \sum_{k=1}^{N} e^2(k)$$

Here $N$ is the length of the observed data.

In a broad sense, a "good" model is one that is good at predicting, that is, one that produces prediction errors as small as possible when applied to the observed data.

Based on this method of estimating parameters, we can construct models of basically any structure. It contains many well-known and much used procedures. We shall give it a general term prediction-error identification methods (PEM).

In this particular situation (ARX model structure) we shall use the special case of PEM - Least Squares Method (LSM).

The Least Squares Method (LSM)

Using process description (4.1.8) we define the Equation Error (EE):

$$e(k) = y(k) + \sum_{i=1}^{na} a_i y(k-i) - \sum_{i=0}^{nb} b_i u(k-i-nk)$$

which is also the Prediction Error. It can be rewritten as

$$e(k) = y(k) - \varphi^T(k, nk) \theta$$

$$\varphi^T(k, nk) = [-y(k), ..., -y(k-na), u(k-nk), ..., u(k-nb-nk)]$$

In order to estimate parameters of the function $G$ and $H$ under consideration of the least squares method, observing the system, taking $N$ samples (e.g. at equidistant times $t = i.Ts$, $i = 1, ..., N$) leads to

$$\hat{y}(N) = \varphi(n) \theta$$
\[ \mathbf{e}(N) = \mathbf{y}(N) - \mathbf{\Phi}(N)\mathbf{\theta} \]  
\text{(4.1.16)}

where

\[ \mathbf{y}(N) = [y(1) \ldots y(N)]^T \]  
\text{(4.1.17)}

\[ \mathbf{\Phi}(N) = [\varphi(1,nk) \ldots \varphi(N,nk)]^T \]  
\text{(4.1.18)}

\[ \mathbf{e}(N) = [e(1) \ldots e(N)]^T \]  
\text{(4.1.19)}

Using the loss function

\[ V_N(\mathbf{\theta}) = \frac{1}{N} \mathbf{e}^T(N) \mathbf{e}(N) \]

\[ = \frac{1}{N} \sum_{k=1}^{N} e^2(k) \]

\[ = \frac{1}{N} \sum_{k=1}^{N} [A(z^{-1})y(k) - B(z^{-1})u(k-nk)]^2 \]  
\text{(4.1.20)}

and minimizing the loss function leads to the least squares method with the well-known solution

\[ \mathbf{\Phi}^T(N)\mathbf{\varphi}(N)\hat{\mathbf{\theta}} = \mathbf{\Phi}^T(N)\mathbf{y}(N) \]  
\text{(4.1.21a)}

where \( \hat{\mathbf{\theta}} \) is the estimate of the parameter vector \( \mathbf{\theta} \). If \([\mathbf{\Phi}^T(N)\mathbf{\varphi}(N)]\) is non-singular we get the unique solution of \( \hat{\mathbf{\theta}} \)

\[ \hat{\mathbf{\theta}} = [\mathbf{\Phi}^T(N)\mathbf{\varphi}(N)]^{-1} \mathbf{\Phi}^T(N)\mathbf{y}(N) = \mathbf{p}(N)\mathbf{y}(N) \]  
\text{(4.1.21b)}

where

\[ \mathbf{p}(N) = [\mathbf{\Phi}^T(N)\mathbf{\varphi}(N)]^{-1} \mathbf{\Phi}^T(N) \]  
\text{(4.1.21c)}

The above non-recursive solution of the problem is called Least Squares algorithm.

Note that the unique feature of the least squares criterion (4.1.20), developed from the linear parametrization and the quadratic criterion, is
that it is a quadratic function in $\theta$. Therefore it can be minimized analytically.

### 4.1.2 OE model structure and Gauss-Newton Method

Consulting table 4.1.1 and comparing Eq. (4.1.1), (4.1.2) and (4.1.5), the output error (OE) model can be written as

\[ y(k) = \frac{B(z^{-1})}{F(z^{-1})} u(k-nk) + e(k) \]  

(4.1.22a)

\[ G(z^{-1}) = \frac{B(z^{-1})}{F(z^{-1})}, \quad H(z^{-1}) = 1 \]  

(4.1.22b)

The parameter vector to be determined is

\[ \theta = [b_0, b_1, \ldots, b_{nb}, f_1, f_2, \ldots, f_{nf}]^T \]  

(4.1.23)

The signal flow of this model is shown in Figure 4.4. The error $e(k)$ in Figure 4.5 and Eq. (4.1.22a) is the so-called output error.

This model structure has the following characteristics:

- In the ARX model (Equation Error model Structure) the transfer function $G$ and $H$ have the polynomial $A$ as a common factor in the
denominators. From a physical point of view it may seem more natural to parametrize these transfer functions independently. The OE model structure just satisfies such a demand.

If we simulate the process using the same input as in the estimation, the simulated output \( \hat{y}(k) \) is given by

\[
\hat{y}(k) = G(z^{-1})u(k-nk) = \frac{B(z^{-1})}{F(z^{-1})} u(k-nk)
\]

(4.1.24)

and

\[
e(k) = y(k) - \hat{y}(k) = y(k) - \frac{B(z^{-1})}{F(z^{-1})} u(k-nk)
\]

(4.1.25)

is the simulation error.

Here the simulation means calculating the output, based on the model as well as the previous and present input. We see that the simulation error in (4.1.25) just equals the output error in (4.1.22a). Therefore the output error model structure is suitable for the process simulation.

The loss function is given by

\[
V_N(\theta) = \frac{1}{N} \sum_{k=1}^{N} \frac{1}{2} e^2(k) = \frac{1}{N} \sum_{k=1}^{N} \frac{1}{2} [y(k) - \frac{B(z^{-1})}{F(z^{-1})} u(k-nk)]^2
\]

(4.1.26)

Obviously, \( V_N(\theta) \) is non-linear with respect to the parameters of \( F(z^{-1}) \) and cannot be minimized by analytical methods. We have to use a non-linear optimization method to solve the parameter estimation problem. Then the solution has to be found by interactive, numerical techniques. Usually, it is more complex than the Least Squares method as stated above. We now briefly mention the technique which we used in the identification of the heat exchanger.

**Gauss-Newton Method**

Methods for numerical minimization of a function \( V(\theta) \) update the estimate of the minimizing point iteratively. This is usually done according to

\[
\hat{\theta}(i+1) = \hat{\theta}(i) + \alpha f(i)
\]

(4.1.27)

where \( f(i) \) is a search direction based on information about \( V(\theta) \) acquired
at previous iterations, and where $\alpha$ is a positive constant determined so that an appropriate decrease in the value of $V(\theta)$ is obtained. Depending on the information supplied by the user to determine $f^{(i)}$ (using function values, values of its gradient, and of its Hessian (the second derivative matrix)) we can get different numerical minimization methods.

Consider the quadratic criterion from (4.1.26)

$$V_N(\theta, z^N) = \frac{1}{N} \sum_{k=1}^{N} \frac{1}{2} e^2(k, \theta)$$

(4.1.28)

where

$$z^N = \{u(0), y(0), \ldots, u(n), y(n)\}$$

The criterion (4.1.28) has the gradient

$$V'_N(\theta, z^N) = -\frac{1}{N} \sum_{k=1}^{N} \psi(k, \theta) e(k, \theta)$$

(4.1.29)

Here $\psi(k, \theta)$ is the $d \times p$ gradient matrix of $\hat{y}(k|\theta)$ with respect to $\theta (d = \text{dim } \theta, p = \text{dim } y)$.

The general search routine is then given by

$$\hat{\theta}_N^{(i+1)} = \hat{\theta}_N^{(i)} - \mu_N^{(i)} \left( R_N^{(i)} \right)^{-1} V'_N(\hat{\theta}_N^{(i)}, z^N)$$

(4.1.30)

where $\theta_N^{(i)}$ denotes the $i$-th iteration

$R_N^{(i)}$ is a $d \times d$ matrix that modifies the search direction

$\mu_N^{(i)}$ is the step size which is chosen so that

$$V_N(\hat{\theta}_N^{(i+1)}, z^N) < V_N(\hat{\theta}_N^{(i)}, z^N)$$

(4.1.31)

Normally, the minimization problem is a constrained one: $\theta \in D\mu$. The constraint can easily be obeyed by proper selection of $\mu$.

Depending on the way $R_N^{(i)}$ is selected, the following numerical methods can be obtained.
The Gradient or Steepest-descent Method

The choice of $R_N^{(1)}$ is to take it as the identity matrix

$$R_N^{(1)} = I$$

Close to the minimum, this method is fairly inefficient.

The Newton Method

Choose the Hessian as $R_N^{(1)}$. The Hessian is

$$V_N^0(\theta, Z_N) = \frac{1}{N} \sum_{k=1}^{N} \psi(k, \theta) \psi^T(k, \theta) + \frac{1}{N} \sum_{k=1}^{N} \psi'(k, \theta)e(k, \theta) \quad (4.1.33)$$

where $\psi'(k, \theta)$ is the $d \times d$ Hessian of $e(k, \theta)$.

$$R_N^{(1)} = V_N^0(\hat{\theta}_N^{(1)}, Z_N) \quad (4.1.34)$$

Suppose there is a value $\theta_0$ such that the prediction errors $e(k, \theta_0) = e_0(k)$ are independent. Then this value yields the global minimum of $E V_N(\theta, Z_N)$. Close to $\theta_0$ the second sum of (4.1.33) will then be close to zero since $E \psi'(k, \theta_0)e_0(k) = 0$. We have

$$V_N^0(\theta, Z_N) = \frac{1}{N} \sum_{l} \psi(k, \theta) \psi^T(k, \theta) \triangleq H_N(\theta) \quad (4.1.35)$$

We need a good estimate of the Hessian only in the vicinity of the minimum. By omitting the last sum in (4.1.33) the estimate of the Hessian is always assured to be positive semi-definite. This makes the numerical procedure a descent algorithm and guarantees convergence to a stationary point. Consequently, a quite suitable choice for our problem is

$$R_N^{(1)} = H_N(\hat{\theta}_N^{(1)}) \quad (4.1.36)$$

Formulas (4.1.30) and (4.1.36) are known as the Gauss-Newton Method. Sometimes we give a more detailed term for them: Gauss-Newton Method (when the particular choice $\mu_N^{(1)} = 1$ is used), and the Damped Gauss-Newton Method (when an adjusted step size $\mu$ is applied). In the control literature the terms modified Newton-Raphson and quasi-linearization have also been used.
The iterative search for the minimum of the loss function (4.1.28) is accomplished by a special start-up procedure based on least squares and instrumental variables. From the initial estimate, a Gauss-Newton minimization procedure is carried out until the norm of the Gauss-Newton direction is less than a certain tolerance.

4.2 MIMO system

Based on the principle of identification of the single input/single output (SISO) system described above, we extend it to a multi input/multi output (MIMO) system to adapt it to the heat exchanger process.

The first problem we face with a linear MIMO process is what kind of model should we take to describe the multivariable process? We can choose one of the following models:

(a) State space model
(b) Input/output difference equation model
(c) Transfer function matrix
(d) Impulse response matrix (or Markov parameter matrix)

They are equivalent and can be transformed into each other. If the input/output variables can be measured directly, the last three models (b), (c), (d) are suitable. The model (c) will be chosen for solving our problem.

![MIMO process diagram](image)

**Figure 4.6 MIMO process**

The MIMO process (Figure 4.6) can be described by the transfer function
matrix equation:
\[ Y(z) = G(z) U(z) + W(z) \] (4.2.1)

Where \( y(z) \) and \( u(z) \) are \( m \) and \( \gamma \)-dimensional column vectors, \( G(z) \) is an \((mx\gamma)\) dimension transfer function matrix denoted by
\[
G(z) = \begin{bmatrix}
G_{11}(z) & G_{12}(z) & \cdots & G_{1\gamma}(z) \\
\vdots & \ddots & \vdots & \vdots \\
G_{m1}(z) & G_{m2}(z) & \cdots & G_{m\gamma}(z)
\end{bmatrix} \quad (4.2.2)
\]

\( G_{ij}(z) \) (\( i = 1,z,\ldots,m; \ j = 1,2,\ldots,\gamma \)) are transfer functions. In this paper \( z \) is the shifted operator or \( z \)-transfer operator, depending on how it appears in the difference equation or transfer function. Here \( z \) is a \( z \)-transfer operator.

\( G(z) \) can be rewritten as
\[
G(z) = \frac{1}{A^*(z)} \begin{bmatrix}
B_{11}^*(z) & B_{12}^*(z) & \cdots & B_{1\gamma}^*(z) \\
\vdots & \ddots & \vdots & \vdots \\
B_{m1}^*(z) & B_{m2}^*(z) & \cdots & B_{m\gamma}^*(z)
\end{bmatrix} \quad (4.2.3)
\]

Here \( A^*(z) \) is the minimum common factor of \( G_{ij}(z) \)'s denominator and is the characteristic polynomial of the process.

Further we give the more useful form \( G(z) \)
\[
G(z^{-1}) = \frac{1}{A(z^{-1})} \begin{bmatrix}
B_{11}(z^{-1}) & B_{12}(z^{-1}) & \cdots & B_{1\gamma}(z^{-1}) \\
\vdots & \ddots & \vdots & \vdots \\
B_{m1}(z^{-1}) & B_{m2}(z^{-1}) & \cdots & B_{m\gamma}(z^{-1})
\end{bmatrix} \quad (4.2.4)
\]

where
\[
A(z^{-1}) = 1 + a_1 z^{-1} + \ldots + a_n z^{-na}
\]
\[
B_{ij}(z^{-1}) = b_{ij0} + b_{ij1} z^{-1} + \ldots + b_{ijn} z^{-nb}
\]
\( i = 1,2,\ldots,m; \ j = 1,2,\ldots,\gamma \)

then multivariable process can be described by
\[
A(z^{-1}) y(k) = B(z^{-1}) u(k) + V(k) \quad (4.2.6a)
\]
\[ V(k) = A(z^{-1})w(k) \]  

(4.2.6b)

\[ V(k) = [v_1(k) \ v_2(k) \ \ldots \ v_m(k)]^T \]  

(4.2.6c)

By means of the above description we consider the MIMO process to be a number of the independent multi-input/single-output subsystem as shown in Figure 4.7.

![Diagram](image-url)

**Figure 4.7** Description of MIMO process using m subsystems

The i-th subsystem is
\[ A(z^{-1})y_i(k) = \sum_{j=1}^{\gamma} B_{ij}(z^{-1})u(k) + v_i(k) \]  
\[ i = 1, 2, \ldots, m \]  

(4.2.7)

Therefore identification of the MIMO system can be divided into identification of \( m \) different independent subsystems separately. In other words, we can estimate parameters in \( G(z) \) row by row. Every row corresponds to a subsystem, provided we assume the noise contribution at the different rows are uncorrelated. There is no essential difference between such a subsystem and a SISO system in the identification method. The Prediction Error Method (PEM) will be used for every subsystem.

5 DATA PROCESSING AND ANALYZING

For the off-line identification the important steps that greatly influence the final results are not only the identification experiment design and the identification method, but also the ways and means of data processing. Here the data processing was implemented on a "Philips PC 3102", using the System Identification Toolbox, which is a collection of MATLAB functions for all phases of the system identification process. The data processing procedure we used consisted of:

(1) Primary signal processing
A reasonable length of data has to be selected. We did three experiments, resulting in 1022, 944, 746 samples respectively (Figures 5.1.1 - 5.1.3). After observing the record of the data, the first 150-250 samples corresponding to the first part of the PRBS had to be thrown away, because in the initial stage the system is in transient condition. The data in this stage are not reliable. Before the estimation the data are modified by subtracting the mean levels from the input and output sequences.

(2) Determining the structural parameters of the process.
Here the structural parameters mean the order of the characteristic polynomial of the transfer function, or the input-output difference equation, or state space equation of the SISO process. The structural parameters also mean order of the characteristic polynomial of transfer function matrix, or the matrix input-output difference equation, or the state
space equation of the MIMO process, and other parameters for describing the structure of the MIMO process such as Kronecker constants.

Comparatively, the model structure selection for the identification of a SISO system is simple and straightforward, whereas the choice for a multivariable system is quite different and more complex. The topic of model structure selection for a MIMO process has attracted much attention in many publications. Several papers review the most commonly used methods (see A. Niederlinkski and A.K. Hajdasinski [1979], A.J.W. van den Boom [1982], T. Backx [1987], P. Janssen [1988], etc). It is difficult to find a unique and general method for solving such a problem.

In order to estimate the order of the heat exchanger (2 inputs – 2 outputs process) we adopt a loss function method combined with the prior knowledge and model validation. (Paragraph (4) of this section will introduce a method to check whether a certain model is a suitable one, based on model validation).

The loss function method can be used for both SISO and MIMO processes. The loss function is produced by a scalar input-output difference equation in the former case, while the loss function is produced by a matrix input-output difference equation in the latter case. Give a MIMO process

\[
A(z^{-1}) \bar{Y}(k) = B(z^{-1}) \bar{U}(k) + \bar{e}(k)
\]  

(5.1)

Here \(\bar{Y}(k), \bar{U}(k)\) and \(\bar{e}(k)\) are ny, nu and ny dimensional column vectors. \(A(z^{-1})\) is an ny x ny polynomial matrix. That is, it is a square matrix whose entries are polynomials like \(A(z^{-1})\) in (4.1.6a). Similarly, \(B(z^{-1})\) is an ny x nu polynomial matrix. As stated previously the Prediction Error Method (PEM) deals with the minimization of a quadratic loss function with respect to the prediction error. For equation (5.1) the loss function is

\[
V_N(\theta) = \frac{1}{2} \sum_{i=1}^{ny} \sum_{k=1}^{N} e_i^2(k)
\]  

(5.2)

where \([e_1(k) e_2(k) ... e_{ny}(k)]^T = \bar{e}(k)\)

\(ny\) is the dimension of the vector \(\bar{e}(k)\)

\(N\) is the length of the data sequence
The idea of using the loss function for the determination of the parameters can be extended to the selection of the order $n_p$ of the characteristic polynomials of equation (5.1) within the chosen model set. Using the by-products of the estimation algorithm, the calculation of the loss function can be obtained. The value of the loss function $V_N(\theta)$ will decrease for increasing order. Fig. 5.2.1 shows the variation of the value of the loss function with the different orders of the characteristic polynomial of the heat exchanger. $V_N(\theta)$ decreases rapidly when the order is changed from $n_p=1$ to $n_p=5$ whereas $V_N(\theta)$ decreases over a small range when the order $n_p>6$. Considering priori knowledge and model validation we choose the order $n_p=4$.

(3) Calculate parameter estimates according to the established identification method, so that the model of process can be obtained.

Let

$$
T = \begin{bmatrix}
T_{co} \\
T_{ho}
\end{bmatrix}
$$

(5.4a)

$$
F = \begin{bmatrix}
F_c \\
F_h
\end{bmatrix}
$$

(5.4b)

$$
G(z^{-1}) = \begin{bmatrix}
G_{11}(z^{-1}) & G_{12}(z^{-1}) \\
G_{21}(z^{-1}) & G_{22}(z^{-1})
\end{bmatrix}
$$

(5.4c)

$$
H(z^{-1}) = \begin{bmatrix}
h_1(z^{-1}) \\
h_2(z^{-1})
\end{bmatrix}
$$

(5.4d)

Comparing with Eq. (4.1.1) and (4.1.2) the heat exchanger can be described as

$$
T(k) = G(z^{-1})F(k) + H(z^{-1})e(k)
$$

(5.5a)

i.e.
\[
\begin{bmatrix}
T_{co}(k) \\
T_{ho}(k)
\end{bmatrix} =
\begin{bmatrix}
G_{11}(z^{-1}) & G_{12}(z^{-1}) \\
G_{21}(z^{-1}) & G_{22}(z^{-1})
\end{bmatrix}
\begin{bmatrix}
F_c(k) \\
F_h(k)
\end{bmatrix}
+ 
\begin{bmatrix}
h_1(k) \\
h_2(k)
\end{bmatrix} e(k)
\]

(5.5b)

According to the algorithm, which is provided by MATLAB for an ARX model structure, Eq. (5.5) has the form

\[
\begin{bmatrix}
A_1(z^{-1}) & 0 \\
0 & A_2(z^{-1})
\end{bmatrix}
\begin{bmatrix}
T_{co}(k) \\
T_{ho}(k)
\end{bmatrix} =
\begin{bmatrix}
B_{11}(z^{-1}) & B_{12}(z^{-1}) \\
B_{21}(z^{-1}) & B_{22}(z^{-1})
\end{bmatrix}
\begin{bmatrix}
F_c(k) \\
F_h(k)
\end{bmatrix}
+ 
\begin{bmatrix}
1 \\
1
\end{bmatrix} e(k)
\]

(5.6a)

then

\[
G(z^{-1}) = 
\begin{bmatrix}
G_{11}(z^{-1}) & G_{12}(z^{-1}) \\
G_{21}(z^{-1}) & G_{22}(z^{-1})
\end{bmatrix}
\] = 
\[
\begin{bmatrix}
B_{11}(z^{-1}) & B_{12}(z^{-1}) \\
B_{21}(z^{-1}) & B_{22}(z^{-1})
\end{bmatrix}
\begin{bmatrix}
A_1(z^{-1}) & A_1(z^{-1}) \\
A_2(z^{-1}) & A_2(z^{-1})
\end{bmatrix}
\]

(5.6b)

\[
H(z^{-1}) = 
\begin{bmatrix}
h_1(z^{-1}) \\
h_2(z^{-1})
\end{bmatrix}
\] = 
\[
\begin{bmatrix}
1 \\
1
\end{bmatrix}
\begin{bmatrix}
A_1(z^{-1}) \\
A_2(z^{-1})
\end{bmatrix}
\]

(5.6c)

While for the OE model structure Eq. (5.5) has the form

\[
\begin{bmatrix}
T_{co}(k) \\
T_{ho}(k)
\end{bmatrix} =
\begin{bmatrix}
F_{11}(z^{-1}) & F_{12}(z^{-1}) \\
F_{21}(z^{-1}) & F_{22}(z^{-1})
\end{bmatrix}
\begin{bmatrix}
F_c(k) \\
F_h(k)
\end{bmatrix}
+ 
\begin{bmatrix}
1 \\
1
\end{bmatrix} e(k)
\]

(5.7a)

then
The results of estimate-computation are given in table 5.1 (a), (b) - table 5.3 (a), (b). These tables show the parameters of ARX and OE models for the typical working points 1, 2, 3 respectively. We have two kinds of matrix elements $G_{ij}(z^{-1})$, ($i=1,2; j=1,2$): the polynomial ratio and the zero-pole ratio. Fig. 5.3 shows the zero-pole plot of the model at working point 1.

Note that the order of the process represents the minimum factor of the denominator of $G_{ij}(z^{-1})$. In the fig. 5.3 - Fig. 5.5.4 the order written in the title is in accordance with the order of $G_{ij}(z^{-1})$ (matrix element), not with that of the polynomial matrix $G(z^{-1})$. 

\[
G(z^{-1}) = \begin{bmatrix}
G_{11}(z^{-1}) & G_{12}(z^{-1}) \\
G_{12}(z^{-1}) & G_{22}(z^{-1})
\end{bmatrix} = \begin{bmatrix}
\frac{B_{11}(z^{-1})}{F_{11}(z^{-1})} & \frac{B_{12}(z^{-1})}{F_{12}(z^{-1})} \\
\frac{B_{21}(z^{-1})}{F_{21}(z^{-1})} & \frac{B_{22}(z^{-1})}{F_{22}(z^{-1})}
\end{bmatrix}
\] (5.7b)

\[
H(z^{-1}) = \begin{bmatrix}
h_{1}(z^{-1}) \\
h_{2}(z^{-1})
\end{bmatrix} = \begin{bmatrix}
1 \\
1
\end{bmatrix}
\] (5.7c)
### Table 5.1 (a) The Equation Error Model (ARX) of Heat Exchanger

<table>
<thead>
<tr>
<th>Model</th>
<th>Polynomial Ratio Description</th>
<th>Zero-Pole Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{11}(z^{-1})$</td>
<td>$\frac{-0.027-0.025 z^{-1} + 0.009 z^{-2}}{1-0.834 z^{-1} - 0.027 z^{-2}}$</td>
<td>$-0.279 \times (1.375 z^{-1}) (0.282 z^{-1})$ $(0.865 z^{-1}) (0.031 z^{-1})$</td>
</tr>
<tr>
<td>$G_{12}(z^{-1})$</td>
<td>$\frac{-0.006+0.009 z^{-1} + 0.009 z^{-2}}{1-0.834 z^{-1} - 0.027 z^{-2}}$</td>
<td>$0.086 \times (2.283 z^{-1}) (0.702 z^{-2})$ $(0.865 z^{-1}) (0.031 z^{-1})$</td>
</tr>
<tr>
<td>$G_{21}(z^{-1})$</td>
<td>$\frac{-0.003-0.005 z^{-1} - 0.005 z^{-2}}{1-0.876 z^{-1} - 0.043 z^{-2}}$</td>
<td>$-0.196 \times (0.939+0.997 z^{-1}) (0.939-0.997 z^{-1})$ $(0.923 z^{-1}) (0.047 z^{-2})$</td>
</tr>
<tr>
<td>$G_{22}(z^{-1})$</td>
<td>$\frac{-0.011+0.047 z^{-1} - 0.018 z^{-2}}{1-0.876 z^{-1} - 0.043 z^{-2}}$</td>
<td>$0.226 \times (3.996 z^{-1}) (0.419 z^{-2})$ $(0.923 z^{-1}) (0.047 z^{-2})$</td>
</tr>
</tbody>
</table>

### Tables 5.1 (b) The Output Error Model (OE) of Heat Exchanger

<table>
<thead>
<tr>
<th>Model</th>
<th>Polynomial Ratio Description</th>
<th>Zero-Pole Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{11}(z^{-1})$</td>
<td>$\frac{-0.027-0.026 z^{-1} + 0.003 z^{-2}}{1-0.645 z^{-1} - 0.161 z^{-2}}$</td>
<td>$-0.260 \times (1.024 z^{-1}) (0.090 z^{-1})$ $(0.838 z^{-1}) (0.193 z^{-1})$</td>
</tr>
<tr>
<td>$G_{12}(z^{-1})$</td>
<td>$\frac{-0.015+0.027 z^{-1} + 0.003 z^{-2}}{1-1.079 z^{-1} + 0.146 z^{-2}}$</td>
<td>$0.114 \times (4.444 z^{-1}) (0.060 z^{-2})$ $(0.920 z^{-1}) (0.159 z^{-2})$</td>
</tr>
<tr>
<td>$G_{21}(z^{-1})$</td>
<td>$\frac{-0.002-0.003 z^{-1} + 0.002 z^{-2}}{1-1.712 z^{-1} + 0.747 z^{-2}}$</td>
<td>$-0.115 \times (1.205 z^{-1}) (0.434 z^{-2})$ $(0.856+0.120 j z^{-1}) (0.856-0.120 j z^{-2})$</td>
</tr>
<tr>
<td>$G_{22}(z^{-1})$</td>
<td>$\frac{-0.021+0.065 z^{-1} - 0.042 z^{-2}}{1-1.561 z^{-1} + 0.577 z^{-2}}$</td>
<td>$0.127 \times (2.146 z^{-1}) (0.917 z^{-2})$ $(0.960 z^{-1}) (0.601 z^{-2})$</td>
</tr>
</tbody>
</table>

Working point 1 for Table 5.1 (a) - (b)
- $F_c = 65.77$ l/h, $T_c = 18.48°C$, $T_{co} = 71.74°C$
- $F_h = 68.17$ l/h, $T_{hi} = 60.12°C$, $T_{ho} = 28.30°C$
Table 5.2 (a) The Equation Error Model (ARX) of Heat Exchanger

<table>
<thead>
<tr>
<th>model</th>
<th>polynomial ratio description</th>
<th>zero-pole description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{11}(z^{-1})$</td>
<td>$-0.011 - 0.027 z^{-1} + 0.013 z^{-2}$</td>
<td>$1 - 0.974 z^{-1} + 0.060 z^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$-291 \times (2.786z^{-1}) (0.420z^{-2})$</td>
<td>$(0.908z^{-1}) (0.066z^{-2})$</td>
</tr>
<tr>
<td>$G_{12}(z^{-1})$</td>
<td>$-0.003 + 0.005 z^{-1} + 0.007 z^{-2}$</td>
<td>$1 - 0.974 z^{-1} + 0.050 z^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$0.107 \times (2.914z^{-1}) (0.915z^{-2})$</td>
<td>$(0.908z^{-1}) (0.066z^{-2})$</td>
</tr>
<tr>
<td>$G_{21}(z^{-1})$</td>
<td>$-0.003 - 0.001 z^{-1} - 0.009 z^{-2}$</td>
<td>$1 - 0.738 z^{-1} - 0.156 z^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$-0.126 \times (0.234+1.830jz^{-1}) (0.234-0.380jz^{-1})$</td>
<td>$(0.909z^{-1}) (0.171z^{-2})$</td>
</tr>
<tr>
<td>$G_{22}(z^{-1})$</td>
<td>$-0.026 + 0.022 z^{-1} - 0.029 z^{-2}$</td>
<td>$1 - 0.738 z^{-1} - 0.156 z^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$0.150 \times (1.335z^{-1}) (0.535z^{-2})$</td>
<td>$(0.909z^{-1}) (0.171z^{-2})$</td>
</tr>
</tbody>
</table>

Table 5.2 (b) The Output Error Model (OE) of Heat Exchanger

<table>
<thead>
<tr>
<th>model</th>
<th>polynomial ratio description</th>
<th>zero-pole description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{11}(z^{-1})$</td>
<td>$-0.014 - 0.028 z^{-1} + 0.006 z^{-2}$</td>
<td>$1 - 0.766 z^{-1} - 0.075 z^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$-0.228 \times (2.196+0.088jz^{-1}) (0.199z^{-2})$</td>
<td>$(0.854z^{-1}) (0.068z^{-2})$</td>
</tr>
<tr>
<td>$G_{12}(z^{-1})$</td>
<td>$-0.015 + 0.038 z^{-1} - 0.023 z^{-2}$</td>
<td>$1 - 1.948 z^{-1} + 0.949 z^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$0.115 \times (1.492z^{-1}) (0.989z^{-2})$</td>
<td>$(0.974+0.006jz^{-1}) (0.974-0.006jz^{-1})$</td>
</tr>
<tr>
<td>$G_{21}(z^{-1})$</td>
<td>$-0.027 - 0.024 z^{-1} + 0.017 z^{-2}$</td>
<td>$1 - 1.965 z^{-1} + 0.967 z^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$0.053 \times (2.247z^{-1}) (1.007z^{-2})$</td>
<td>$(0.983+0.030jz^{-1}) (0.983-0.030jz^{-1})$</td>
</tr>
<tr>
<td>$G_{22}(z^{-1})$</td>
<td>$-0.024+0.006 z^{-1} - 0.039 z^{-2}$</td>
<td>$1 - 0.250 z^{-1} - 0.620 z^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$0.165 \times (1.419z^{-1}) (1.154z^{-2})$</td>
<td>$(0.922z^{-1}) (0.672z^{-2})$</td>
</tr>
</tbody>
</table>

Working point 2 for Table 5.2 (a) - (b):

$F_C = 48.32 \ell/h$, $T_{CL} = 21.63\degree C$, $T_{CO} = 72.73\degree C$

$F_h = 52.78 \ell/h$, $T_{hi} = 78.72\degree C$, $T_{ho} = 30.30\degree C$
Table 5.3 (a) The Equation Error Model (ARX) of Heat Exchanger

<table>
<thead>
<tr>
<th>model</th>
<th>polynomial ratio description</th>
<th>zero-pole description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_1(z^{-1}) )</td>
<td>(-0.012+0.009 z^{-1} - 0.005 z^{-2} )</td>
<td>( 0.287 \times (0.970+0.930 z^{-1}) (0.370-0.555 z^{-1}) (0.920-z^{-1}) (0.123-z^{-2}) )</td>
</tr>
<tr>
<td>( G_2(z^{-1}) )</td>
<td>(-0.003+0.007 z^{-1} + 0.009 z^{-2} )</td>
<td>( 0.084 \times (0.314-z^{-1}) (0.122-z^{-2}) (0.920-z^{-1}) (0.123-z^{-2}) )</td>
</tr>
<tr>
<td>( G_3(z^{-1}) )</td>
<td>(-0.005+0.005 z^{-1} - 0.019 z^{-2} )</td>
<td>( -0.217 \times (0.455+0.862 z^{-1}) (0.455-0.862 z^{-1}) (0.925-z^{-1}) (0.206+z^{-1}) )</td>
</tr>
<tr>
<td>( G_4(z^{-1}) )</td>
<td>(-0.012+0.035 z^{-1} - 0.011 z^{-2} )</td>
<td>( 0.262 \times (0.856-z^{-1}) (0.221-z^{-1}) (0.925-z^{-1}) (0.206+z^{-1}) )</td>
</tr>
</tbody>
</table>

Table 5.3 (b) The Output Error Model (OE) of Heat Exchanger

<table>
<thead>
<tr>
<th>model</th>
<th>polynomial ratio description</th>
<th>zero-pole description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_1(z^{-1}) )</td>
<td>(-0.022+0.024 z^{-1} - 0.012 z^{-2} )</td>
<td>( 0.040 \times (0.455+0.521 z^{-1}) (0.455-0.521 z^{-1}) (0.850+0.228 j-z^{-1}) (0.850-0.228 j-z^{-1}) )</td>
</tr>
<tr>
<td>( G_2(z^{-1}) )</td>
<td>(-0.019+0.024 z^{-1} - 0.004 z^{-2} )</td>
<td>( 0.091 \times (0.653-z^{-1}) (0.175-z^{-1}) (0.937-z^{-1}) (0.855-z^{-1}) )</td>
</tr>
<tr>
<td>( G_3(z^{-1}) )</td>
<td>(-0.010+0.020 z^{-1} - 0.021 z^{-2} )</td>
<td>( -0.109 \times (0.981-1.032 j-z^{-1}) (0.981-1.032 j-z^{-1}) (0.823+0.260 j-z^{-1}) (0.823-0.260 j-z^{-1}) )</td>
</tr>
<tr>
<td>( G_4(z^{-1}) )</td>
<td>(-0.042+0.012 z^{-1} + 0.037 z^{-2} )</td>
<td>( 0.086 \times (0.116-z^{-1}) (0.813 z^{-1}) (0.941-z^{-1}) (0.692+z^{-1}) )</td>
</tr>
</tbody>
</table>

Working point 3 for Table 5.3 (a) - (b):
- \( F_e = 33.66 \) L/h, \( T_{ci} = 20.31^\circ C \), \( T_{co} = 73.39^\circ C \)
- \( F_h = 36.59 \) L/h, \( T_{hi} = 77.76^\circ C \), \( T_{ho} = 28.26^\circ C \)
(4) Model validation

Model validation is the heart of the identification problem and no absolute procedure for approaching it can be given. It is wise to be equipped with several different tools by which model qualities can be evaluated. The following techniques were adopted by us.

- Noise-free simulations
- Akaike's Final Prediction Error criterion (FPE)
- Testing the residuals for independence of past inputs and possibly for whiteness.

A. Noise-free simulations

In order to evaluate the performance of the PEM method applied to such a multivariable system, simulation techniques were used. The simulation is such that the model we have obtained in (3) is driven by the actual input PRBS sequences used in the experiment. The purpose of simulation is to check whether a model is capable of reproducing the observed output under the same input conditions.

As a typical illustration, we give the simulation result for one of the working points (working point 1). The response obtained from simulation are plotted together with the experimental data in Fig. 5.4.1 - Fig. 5.4.2. The solid lines show the measured values, the dotted lines are the simulation values given by the model. The error between measured and simulated value is less than 0.6°C, i.e. less than 8% over the whole measuring range.

The data comparison shows that the calculated data obtained by the simulation agree well with the experimental data. Further, comparing the ARX and the OE model, the OE model leads to smaller deviations than ARX model, thus giving a more reasonable description of the system.

B. Akaike's Final Prediction Error Criterion

Based on the minimum value $V_N(G,H)$ of the criterion function (4.1.11), the Akaike's Final Prediction Error Criterion (FPE) can be formed as

$$FPE = \frac{1 + \frac{n}{N}}{1 - \frac{n}{N}} \cdot V_N$$  \hspace{1cm} (5.8)

where $n$ is the total number of estimated parameters, and $N$ is the length
of the data record. This criterion reflecting the prediction-error variance says that in a collection of different models the one with the smallest value of FPE should be chosen.

Fig. 5.2.2 shows the FPE for the heat exchanger model at working point 1. It gives a similar result to that in the paragraph (2) of this section.

C. Residual analysis
The residuals associated with the data and a given model, as in (4.1.10), should ideally be white and independent of the input, for the model to be a "correct" description of the system.

Fig. 5.5.1 - 5.5.4 provide valuable insight into residual analysis of the heat exchanger model at working point 1. Using MATLAB the correlation function of residuals $e$ and the cross correlation function between $e$ and input $u$ are computed up to lag 25. Also the 95% confidence intervals for these variables can be given, assuming that $e$ is indeed white and independent of $u$. The confidence limits is a horizontal line in the Figures.

The data comparison shows that the correlation function of the ARX model's residuals $e$ is better than that of the OE model. Considering both the correlation and cross correlation function the OE model has better results of residual analysis than the ARX model.

Primarily we are interested in the dynamics $G(z)$ of the process, and the OE-structure model focuses on the dynamics $G(z)$ and is less interested in the noise properties $H(z)$. In this case we should be more concerned about the independence between noise $e$ and input $u_1$, $u_2$. The cross correlation results of the OE model prove to be satisfactory (see Fig. 5.5.3 - 5.5.4).

It should be pointed out that we give the model validation results at working point 1 as stated above. The model at working point 2 and 3 also were checked and proved to be valid using the same methods.

6. CONCLUSION AND REMARKS

A model is obtained, which gives a good representation of the character-
istics of the Shell-and-tube counter flow water-water heat exchanger.

For describing the dynamic behaviour of the heat exchanger the Equation Error Model (ARX) and Output Error Model (OE) are adopted, the Prediction Error Method (PEM) has been presented (in the least squares sense). The OE model is obtained by minimizing the simulation error, the ARX model is obtained by minimizing the one-step prediction error. In the case of an ARX model the PEM method is an analytical one, whereas in the case of an OE model the PEM method is based on the non-analytical optimization which consists of two parts: Obtaining the prediction of the Output and the gradient through a selected predictor model, updating the parameter estimate with a Gauss-Newton Search procedure.

The "true system" is an esoteric entity that cannot be attained in practical modelling. We have to be content with partial descriptions that are adequate for our applications. For the given problem we work with several models of the same system that are to be used for different typical operating points. This way makes it possible to attain linear lumped models of the heat exchanger, described by nonlinear equations with distributed parameters.

It is necessary to use a suitable order for the model (4th order for the transfer function matrix, 2nd order for the individual transfer functions) in order to achieve good representation of the process. The validation results for the identified models, especially for the OE model, indicate good simulation characteristics and residual analysis.

The mathematical model obtained is considered for the purpose of simulation and control system design. Current research efforts are directed towards ITAE optimal control \( (J = \int_0^\infty t|e(t)|dt \rightarrow \text{min}) \) of the heat exchanger and to predictive control of the indoor temperature in the climate chamber.

Further studies in Recursive Prediction Error Method (RPEM) are needed in order to continuously update the parameters, and in order that it can be incorporated in an on-line monitoring and control scheme.

Finally, the procedure described above can be used for similar thermal processes.
ACKNOWLEDGEMENTS

The report has been accomplished in Eindhoven University of Technology under the supervision of Professor P. Eykhoff. The author would like to express much gratitude to him for his guidance and encouragement. The author is indebted to the staff members and Ph.D. students of the Group ER, who helped the author in completing this project.

The author would also like to thank ir. A.M.M. Bottram, Mr. J.W. van Drie and Mr. Sijberden, who were involved in the experiment, for their kind cooperation.

Furthermore, the author would like to express thanks to Mrs. B. Cornelissen-Milner and Mrs. M.A. Simon for their excellent typing.
REFERENCES

[1] Åström, K.J.
Maximum likelihood and prediction error methods.

[2] Backx, A.C.P.M.

[3] Backx, Ton and Ad Damen
Identification of industrial MIMO processes for fixed controllers.
Part 1: General theory and practice.

[4] Backx, Ton and Ad Damen
Identification of industrial processes for fixed controllers.
Part 2: Case studies.

Equation error versus output error methods in system identification.
Measurement and Control Group, Department of Electrical Engineering,
Internal Report ER 85/06.

[6] Eykhoff, P.
System identification: Parameter and state estimation.

IFAC series for graduates, research workers & practising engineers,
Vol. 1.

[8] Franck, G. and H. Rake
Identification of a large water-heated crossflow heat exchanger
with binary multifrequency signals.
In: Identification and systems parameter estimation. Proc. 7th
IFAC/IFORS Symp., York, 3-7 July 1985. Ed. by H.A. Barker and
P.C. Young.

Fault detection in a tubular heat exchanger based on modelling and
parameter estimation.
In: Identification and systems parameter estimation. Proc. 7th
IFAC/IFORS Symp., York, 3-7 July 1985. Ed. by H.A. Barker and
P.C. Young.

[10] Gieles, P.
Modelvorming van een tegenstroomwarmtewisselaar. Stageverslag.
In Dutch. System and Control Engineering Group, Department of
Physics, Eindhoven University of Technology, 1980.
MWR approximation and modal control of parallel - and counter-flow heat exchangers.

[12] Janssen, P.H.M.
On model parametrization and model structure selection for identification of MIMO-systems.

[13] Law, W.M.
The dynamic response of shell - and - tube heat exchangers to flow changes.
Central Instrument Laboratory, Imperial Chemical Industries Ltd. (ICI), Bozedown House, Whitchurch Hill, Near Reading, Berks., England. 1962.

[14] Ljung, L.
System identification: Theory for the user.
Prentice-Hall information and system sciences series

Theory and practice of recursive identification.

[16] McGreavy, C. and A. Guidoum
Identification of heat transfer parameters in fixed-beds.

Identificatie van een tegenstroomwarmtewisselaar. Stageverslag.
In Dutch. System and Control Engineering Group, Department of Physics, Eindhoven University of Technology, 1985.

[18] Niederliński, A. and A. Hajdasiński
Multivariable system identification. A survey.

Version 2.5.
Quinn-Curtis, 1191 Chestnut Street, Unit 2-5, Newton, MA 02164, U.S.A. 1989.
Some recent applications of distributed parameter systems theory -
a survey.

[21] Söderström, T. and P. Stoica
System identification.
Prentice-Hall international series in systems and control engineering

Practical aspects of industrial multivariable process identification.
In: Identification and system parameter estimation. Proc. 7th
IFAC/IFORS Symp., York, 3-7 July 1985. Ed. by H.A. Barker and
P.C. Young.

[23] Boom, A.J.W. van den
System identification: On the variety and coherence in parameter-
and order estimation methods.

[24] Linden, R.J.P. van den and W.A. Renes, O. Rademaker
PRIMAL: A package for real-time interactive modelling, analysis
and learning.

Identification of distributed parameter systems using the least
square output method applied to a heat-exchanger.
Abstract in: Benelux Meeting on Systems and Control, Brussels,
8-10 March 1989. Organized by the Control Engineering Laboratory,
Université Libre de Bruxelles, Belgium (R. Hanus and M. Kinnaert).
P. 206.
FIGURES
Figure 5.1.1 Heat Exchanger Input-Output signals at working point 1:

\[ F_c = 65.77 \text{ l/h}, \quad T_{ci} = 18.48^\circ\text{C}, \quad T_{co} = 71.74^\circ\text{C} \]
\[ F_h = 68.17 \text{ l/h}, \quad T_{hi} = 80.12^\circ\text{C}, \quad T_{ho} = 28.30^\circ\text{C} \]
Figure 5.1.2 Heat Exchanger Input-Output Signals at working point 2:

\[ \begin{align*}
F_C &= 48.32 \text{ l/h}, & T_{ci} &= 21.63{}^\circ \text{C}, & T_{co} &= 72.73{}^\circ \text{C} \\
F_h &= 52.78 \text{ l/h}, & T_{hi} &= 78.72{}^\circ \text{C}, & T_{ho} &= 30.30{}^\circ \text{C}
\end{align*} \]
Figure 5.1.3  Heat Exchanger Input-Output Signals at working point 3:

- $F_c = 33.68 \text{ l/h}$,  $T_{ci} = 20.31^\circ\text{C}$,  $T_{co} = 73.39^\circ\text{C}$
- $F_h = 36.59 \text{ l/h}$,  $T_{hi} = 77.76^\circ\text{C}$,  $T_{ho} = 28.26^\circ\text{C}$
Figure 5.2.1 The value of the loss function as a function of the model structure
(ARX model, working point 1)

Figure 5.2.2 Model validation, FPE method
(ARX model, working point 1)
Figure 5.3  Zero-pole plot of the Heat Exchanger (working point 1)
Figure 5.4.1: Simulation for model validation. ARX model, working point 1.
Figure 5.4.2
Simulation for model validation

*Figure 5.4.2* Simulation for model validation
Figure 5.5.1
Residual analysis
ARX model, working point 1

Cross correlation function between input 1 and residuals

Cross correlation function between input 2 and residuals

Correlation function of residuals

Deg.c Residuals 2nd order ARX model(1)
Figure 5.5.2
Residual analysis
ARX model (2), working point 1

Cross correlation function between input 1 and residuals

Cross correlation function between input 2 and residuals

Deg. c Residuals 2nd order ARX model (2)

Correlation function of residuals
Figure 5.5.3

Residual analysis

Cross correlation function between input 1 and residuals

Cross correlation function between input 2 and residuals

Correlation function of residuals

Residuals 2nd order OE model
Figure 5.5.4
Residual analysis

OE model (2), working point 2
APPENDIX: "CONTROL EG" PROGRAM

(1) Runtime setup table 51

(2) Analog output setup table 51

(3) Analog input setup table 52

(4) Calculated Input setup table 52

(5) Analog Input alarm setup table 53

(6) Calculated input alarm setup table 53

(7) Sequencer table 54

(8) History graph setup table 56
### Runtime Setup Table 1

<table>
<thead>
<tr>
<th>Run Title</th>
<th><strong>CONTROL EG</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Scan and Control Period</td>
<td>5.00</td>
</tr>
<tr>
<td>Display Update Period</td>
<td>15.00</td>
</tr>
<tr>
<td>Sequencer Update Period</td>
<td>5.00</td>
</tr>
<tr>
<td>Disklog Update Period</td>
<td>5.00</td>
</tr>
<tr>
<td>Printlog Update Period</td>
<td>15.00</td>
</tr>
<tr>
<td>Disklog Filename</td>
<td></td>
</tr>
<tr>
<td>File Type (0,1)</td>
<td></td>
</tr>
<tr>
<td>Operator Log Filename</td>
<td></td>
</tr>
<tr>
<td>Group A Title</td>
<td></td>
</tr>
<tr>
<td>Group B Title</td>
<td></td>
</tr>
<tr>
<td>Group C Title</td>
<td></td>
</tr>
<tr>
<td>Group D Title</td>
<td></td>
</tr>
<tr>
<td>Group E Title</td>
<td></td>
</tr>
<tr>
<td>Group F Title</td>
<td></td>
</tr>
<tr>
<td>Group G Title</td>
<td></td>
</tr>
</tbody>
</table>

**Group A**

Press PgDn to advance page, PgUp to backup page, Esc to exit, ? for Help

### Analog Output Setup Table - Page 1

<table>
<thead>
<tr>
<th>Ch</th>
<th>Tag</th>
<th>LowClmp</th>
<th>HiClmp</th>
<th>MaxRate</th>
<th>DL</th>
<th>PL</th>
<th>Grp</th>
<th>Formula</th>
<th>Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>ST.Fc</td>
<td>0.00</td>
<td>0.50</td>
<td>X</td>
<td>Y</td>
<td>N</td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>ST.Fh</td>
<td>0.00</td>
<td>0.50</td>
<td>X</td>
<td>Y</td>
<td>Y</td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>B1C2</td>
<td>0.00</td>
<td>1.00</td>
<td>X</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>B1C3</td>
<td>0.00</td>
<td>1.00</td>
<td>X</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Fc-%</td>
<td>0.00</td>
<td>1.00</td>
<td>X</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Fh-%</td>
<td>0.00</td>
<td>1.00</td>
<td>X</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Tco-rec</td>
<td>0.00</td>
<td>1.00</td>
<td>X</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>(AI8/100)-0.7</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Tho-rec</td>
<td>0.00</td>
<td>1.00</td>
<td>X</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>(AI10/100)-0.2</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>B1C8</td>
<td>0.00</td>
<td>1.00</td>
<td>X</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>B1C9</td>
<td>0.00</td>
<td>1.00</td>
<td>X</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>B1C10</td>
<td>0.00</td>
<td>1.00</td>
<td>X</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>B1C11</td>
<td>0.00</td>
<td>1.00</td>
<td>X</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>B1C12</td>
<td>0.00</td>
<td>1.00</td>
<td>X</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>B1C13</td>
<td>0.00</td>
<td>1.00</td>
<td>X</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>B1C14</td>
<td>0.00</td>
<td>1.00</td>
<td>X</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>B1C15</td>
<td>0.00</td>
<td>1.00</td>
<td>X</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**ST.Fc**

Press PgDn to advance page, PgUp to backup page, Esc to exit, ? for Help
Analog Input Setup Table - Page 1

<table>
<thead>
<tr>
<th>AI Ch</th>
<th>Tag</th>
<th>Units</th>
<th>Type</th>
<th>BgLow</th>
<th>BgHigh</th>
<th>M x</th>
<th>+ B</th>
<th>DL</th>
<th>PL</th>
<th>Grp</th>
<th>Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>B1C0</td>
<td>Volts</td>
<td>L1</td>
<td>-5.00</td>
<td>5.00</td>
<td>1.00</td>
<td>0.000</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>X</td>
</tr>
<tr>
<td>1</td>
<td>Flc</td>
<td>Volts</td>
<td>SB30-02</td>
<td>-5.00</td>
<td>5.00</td>
<td>1.00</td>
<td>0.856</td>
<td>N</td>
<td>N</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>B1C2</td>
<td>Volts</td>
<td>L1</td>
<td>-5.00</td>
<td>5.00</td>
<td>1.00</td>
<td>0.000</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>B1C3</td>
<td>Volts</td>
<td>L1</td>
<td>-5.00</td>
<td>5.00</td>
<td>1.00</td>
<td>0.000</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>B1C4</td>
<td>Volts</td>
<td>L1</td>
<td>-5.00</td>
<td>5.00</td>
<td>1.00</td>
<td>0.000</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>X</td>
</tr>
<tr>
<td>5</td>
<td>B1C5</td>
<td>Volts</td>
<td>L1</td>
<td>-5.00</td>
<td>5.00</td>
<td>1.00</td>
<td>0.000</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>X</td>
</tr>
<tr>
<td>6</td>
<td>B1C6</td>
<td>Volts</td>
<td>L1</td>
<td>-5.00</td>
<td>5.00</td>
<td>1.00</td>
<td>0.000</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>X</td>
</tr>
<tr>
<td>7</td>
<td>Tci</td>
<td>c</td>
<td>SB34-02</td>
<td>0.00</td>
<td>100.00</td>
<td>20.000</td>
<td>0.000</td>
<td>Y</td>
<td>Y</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>8</td>
<td>Tco</td>
<td>c</td>
<td>SB34-02</td>
<td>0.00</td>
<td>100.00</td>
<td>20.000</td>
<td>0.000</td>
<td>Y</td>
<td>Y</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>9</td>
<td>Thi</td>
<td>c</td>
<td>SB34-02</td>
<td>0.00</td>
<td>100.00</td>
<td>20.000</td>
<td>0.000</td>
<td>Y</td>
<td>Y</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>10</td>
<td>Tho</td>
<td>c</td>
<td>SB34-02</td>
<td>0.00</td>
<td>100.00</td>
<td>20.000</td>
<td>0.000</td>
<td>Y</td>
<td>Y</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>11</td>
<td>B1C11</td>
<td>Volts</td>
<td>L1</td>
<td>-5.00</td>
<td>5.00</td>
<td>1.000</td>
<td>0.000</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>X</td>
</tr>
<tr>
<td>12</td>
<td>B1C12</td>
<td>Volts</td>
<td>L1</td>
<td>-5.00</td>
<td>5.00</td>
<td>1.000</td>
<td>0.000</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>X</td>
</tr>
<tr>
<td>13</td>
<td>B1C13</td>
<td>Volts</td>
<td>L1</td>
<td>-5.00</td>
<td>5.00</td>
<td>1.000</td>
<td>0.000</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>X</td>
</tr>
<tr>
<td>14</td>
<td>FLh</td>
<td>Volts</td>
<td>SB30-02</td>
<td>-5.00</td>
<td>5.00</td>
<td>1.000</td>
<td>0.946</td>
<td>N</td>
<td>N</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>15</td>
<td>B1C15</td>
<td>Volts</td>
<td>L1</td>
<td>-5.00</td>
<td>5.00</td>
<td>1.000</td>
<td>0.000</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>X</td>
</tr>
</tbody>
</table>

B1C0

Edit:
Press PgDn to advance page, PgUp to backup page, Esc to exit, ? for Help

Calculated Input Setup Table - Page 1

<table>
<thead>
<tr>
<th>Calc</th>
<th>Tag</th>
<th>Units</th>
<th>BgLow</th>
<th>BgHigh</th>
<th>DL</th>
<th>PL</th>
<th>Grp</th>
<th>Formula</th>
<th>Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>CALC 0</td>
<td>None</td>
<td>0.00</td>
<td>100.00</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>NONE</td>
<td>X</td>
</tr>
<tr>
<td>1</td>
<td>CALC 1</td>
<td>None</td>
<td>0.00</td>
<td>100.00</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>NONE</td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>CALC 2</td>
<td>None</td>
<td>0.00</td>
<td>100.00</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>NONE</td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>CALC 3</td>
<td>None</td>
<td>0.00</td>
<td>100.00</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>NONE</td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>CALC 4</td>
<td>None</td>
<td>0.00</td>
<td>100.00</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>NONE</td>
<td>X</td>
</tr>
<tr>
<td>5</td>
<td>CALC 5</td>
<td>None</td>
<td>0.00</td>
<td>100.00</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>NONE</td>
<td>X</td>
</tr>
<tr>
<td>6</td>
<td>CALC 6</td>
<td>None</td>
<td>0.00</td>
<td>100.00</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>NONE</td>
<td>X</td>
</tr>
<tr>
<td>7</td>
<td>CALC 7</td>
<td>None</td>
<td>0.00</td>
<td>100.00</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>NONE</td>
<td>X</td>
</tr>
<tr>
<td>8</td>
<td>Fc</td>
<td>1/h</td>
<td>0.00</td>
<td>100.00</td>
<td>Y</td>
<td>Y</td>
<td>B</td>
<td>52.53*SQRT(ABS(A11))</td>
<td>X</td>
</tr>
<tr>
<td>9</td>
<td>Fh</td>
<td>1/h</td>
<td>0.00</td>
<td>100.00</td>
<td>Y</td>
<td>Y</td>
<td>B</td>
<td>51.77*SQRT(ABS(A114))</td>
<td>X</td>
</tr>
<tr>
<td>10</td>
<td>ST.Fcp</td>
<td>1/h-%</td>
<td>0.00</td>
<td>100.00</td>
<td>Y</td>
<td>Y</td>
<td>B</td>
<td>AD0*200</td>
<td>X</td>
</tr>
<tr>
<td>11</td>
<td>ST.Fhp</td>
<td>1/h-%</td>
<td>0.00</td>
<td>100.00</td>
<td>Y</td>
<td>N</td>
<td>B</td>
<td>AD0*200</td>
<td>X</td>
</tr>
<tr>
<td>12</td>
<td>CALC12</td>
<td>None</td>
<td>0.00</td>
<td>100.00</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>NONE</td>
<td>X</td>
</tr>
<tr>
<td>13</td>
<td>CALC13</td>
<td>None</td>
<td>0.00</td>
<td>100.00</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>NONE</td>
<td>X</td>
</tr>
<tr>
<td>14</td>
<td>CALC14</td>
<td>None</td>
<td>0.00</td>
<td>100.00</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>NONE</td>
<td>X</td>
</tr>
<tr>
<td>15</td>
<td>CALC15</td>
<td>None</td>
<td>0.00</td>
<td>100.00</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>NONE</td>
<td>X</td>
</tr>
</tbody>
</table>

CALC 0

Edit:
Press PgDn to advance page, PgUp to backup page, Esc to exit, ? for Help
**Analog Input Alarm Setup Table - Page 1**

<table>
<thead>
<tr>
<th>Ch</th>
<th>Tag</th>
<th>LowLim</th>
<th>HiLim</th>
<th>Low Alarm Msg</th>
<th>High Alarm Msg</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>B1C0</td>
<td>-3.75</td>
<td>3.75</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>1</td>
<td>FLc</td>
<td>-5.00</td>
<td>5.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>2</td>
<td>B1C2</td>
<td>-3.75</td>
<td>3.75</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>3</td>
<td>B1C3</td>
<td>-3.75</td>
<td>3.75</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>4</td>
<td>B1C4</td>
<td>-3.75</td>
<td>3.75</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>5</td>
<td>B1C5</td>
<td>-3.75</td>
<td>3.75</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>6</td>
<td>B1C6</td>
<td>-3.75</td>
<td>3.75</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>7</td>
<td>Tci</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>8</td>
<td>Tco</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>9</td>
<td>Thi</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>10</td>
<td>Tho</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>11</td>
<td>B1C11</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>12</td>
<td>B1C12</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>13</td>
<td>B1C13</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>14</td>
<td>FLh</td>
<td>-5.00</td>
<td>5.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>15</td>
<td>B1C15</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
</tbody>
</table>

**B1C0**

Press PgDn to advance page, PgUp to backup page, Esc to exit, ? for Help

---

**Calculated Input Alarm Setup Table - Page 1**

<table>
<thead>
<tr>
<th>Ch #</th>
<th>Tag</th>
<th>LowLim</th>
<th>HiLim</th>
<th>Low Alarm Msg</th>
<th>High Alarm Msg</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>CALC0</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>1</td>
<td>CALC1</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>2</td>
<td>CALC2</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>3</td>
<td>CALC3</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>4</td>
<td>CALC4</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>5</td>
<td>CALC5</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>6</td>
<td>CALC6</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>7</td>
<td>CALC7</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>8</td>
<td>Fc</td>
<td>-5.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>9</td>
<td>Fl</td>
<td>-5.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>10</td>
<td>ST.Fcp</td>
<td>-5.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>11</td>
<td>ST.Fhp</td>
<td>-5.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>12</td>
<td>CALC12</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>13</td>
<td>CALC13</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>14</td>
<td>CALC14</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
<tr>
<td>15</td>
<td>CALC15</td>
<td>0.00</td>
<td>100.00</td>
<td>Low Alarm</td>
<td>High Alarm</td>
</tr>
</tbody>
</table>

**CALC 0**

Press PgDn to advance page, PgUp to backup page, Esc to exit, ? for Help
Sequencer Table # 0

<table>
<thead>
<tr>
<th>Step</th>
<th>Action</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>WAIT(30)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>SET(AOO, 0.10)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>WAIT(600)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>SET(AOO, 0.25)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>WAIT(120)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>SET(AOO, 0.10)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>WAIT(90)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>SET(AOO, 0.25)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>WAIT(30)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>SET(AOO, 0.10)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>WAIT(60)</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>SET(AOO, 0.25)</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>WAIT(60)</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>SET(AOO, 0.10)</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>WAIT(30)</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>SET(AOO, 0.25)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>WAIT(30)</td>
<td>END</td>
</tr>
</tbody>
</table>

Edit:
Press PgDn to advance page, PgUp to backup page, Esc to exit, ? for Help

Sequencer Table # 0

<table>
<thead>
<tr>
<th>Step</th>
<th>Action</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>WAIT(30)</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>SET(AOO, 0.10)</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>WAIT(30)</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>GOTO(3)</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td></td>
<td>END</td>
</tr>
</tbody>
</table>

Edit:
Press PgDn to advance page, PgUp to backup page, Esc to exit, ? for Help
### Sequencer Table # 1

<table>
<thead>
<tr>
<th>Step</th>
<th>Action</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>WAIT(90)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>SET(A01, 0.10)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>WAIT(600)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>SET(A01, 0.25)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>WAIT(120)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>SET(A01, 0.10)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>WAIT(90)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>SET(A01, 0.25)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>WAIT(30)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>SET(A01, 0.10)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>WAIT(60)</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>SET(A01, 0.25)</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>WAIT(60)</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>SET(A01, 0.10)</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>WAIT(30)</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>SET(A01, 0.25)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>WAIT(90)</td>
<td></td>
</tr>
</tbody>
</table>

**Comment:**
Press PgDn to advance page, PgUp to backup page, Esc to exit, ? for Help.
### History Graph Setup Table - Graph # 1

<table>
<thead>
<tr>
<th>Plot #</th>
<th>Channel ID</th>
<th>Color</th>
<th>LineStyle</th>
<th>Plot Type</th>
<th>Y-min</th>
<th>Y-max</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>AI1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>-0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>1</td>
<td>AI7</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>100.00</td>
</tr>
<tr>
<td>2</td>
<td>AI8</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>100.00</td>
</tr>
<tr>
<td>3</td>
<td>AI9</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>100.00</td>
</tr>
<tr>
<td>4</td>
<td>AI10</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>100.00</td>
</tr>
<tr>
<td>5</td>
<td>AI14</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>-0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>6</td>
<td>AD0</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>7</td>
<td>AD1</td>
<td>14</td>
<td>0</td>
<td>0</td>
<td>-0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>8</td>
<td>NULL</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>10.00</td>
</tr>
<tr>
<td>9</td>
<td>NULL</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>10.00</td>
</tr>
<tr>
<td>10</td>
<td>NULL</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>10.00</td>
</tr>
<tr>
<td>11</td>
<td>NULL</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>10.00</td>
</tr>
<tr>
<td>12</td>
<td>NULL</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>10.00</td>
</tr>
<tr>
<td>13</td>
<td>NULL</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>10.00</td>
</tr>
<tr>
<td>14</td>
<td>NULL</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>10.00</td>
</tr>
<tr>
<td>15</td>
<td>NULL</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>10.00</td>
</tr>
</tbody>
</table>

### AI1

**Edit:**

Press PgDn to advance page, PgUp to backup page, Esc to exit, ? for Help
(205) Butterweck, H.J. and J.H.F. Ritzerfeld, M.J. Werter
FINITE WORDLENGTH EFFECTS IN DIGITAL FILTERS: A review.

(206) Bollen, M.H.J. and G.A.P. Jacobs
EXTENSIVE TESTING OF AN ALGORITHM FOR TRAVELLING-WAVE-BASED DIRECTIONAL
DETECTION AND PHASE-SELECTION BY USING TWONFIL AND EMTP.

(207) Schuurman, W. and M.P.H. Weenink
STABILITY OF A TAYLOR-RELAXED CYLINDRICAL PLASMA SEPARATED FROM THE WALL
BY A VACUUM LAYER.

(208) Lucassen, F.H.R. and H.H. van de Ven
A NOTATION CONVENTION IN RIGID ROBOT MODELLING.

(209) Józwiak, L.
MINIMAL REALIZATION OF SEQUENTIAL MACHINES: The method of maximal
adjacencies.

(210) Lucassen, F.H.R. and H.H. van de Ven
OPTIMAL BODY FIXED COORDINATE SYSTEMS IN NEWTON/EULER MODELLING.

(211) Boom, A.J.J. van den
Hc-CONTROL: An exploratory study.

(212) Zhu Yu-Cai
ON THE ROBUST STABILITY OF MIMO LINEAR FEEDBACK SYSTEMS.

(213) Zhu Yu-Cai, M.H. Driessen, A.A.H. Damen and P. Eykhoff
A NEW SCHEME FOR IDENTIFICATION AND CONTROL.

(214) Bollen, M.H.J. and G.A.P. Jacobs
IMPLEMENTATION OF AN ALGORITHM FOR TRAVELLING-WAVE-BASED DIRECTIONAL
DETECTION.

(215) Hoeijmakers, M.J. en J.M. Vleeshouwers
EEN MODEL VAN DE SYNHROE MACHINE MET GELIJKRICHTER, GESCHIKT VOOR
RECEPDOELEN.

(216) Pineda de Gyvez, J.

(217) Duarte, J.L.
MTMST: An algorithm for systematic state assignment of sequential
machines - computational aspects and results.

(218) Kamp, M.M.J.L. van de
SOFTWARE SET-UP FOR DATA PROCESSING OF DEPOLARIZATION DUE TO RAIN
AND ICE CRYSTALS IN THE OLYMPUS PROJECT.

(219) Koster, C.J.P. and L. Stok
FROM NETWORK TO ARTWORK: Automatic schematic diagram generation.

(220) Williams, F.H.J.
CONVERSES FOR WRITE-UNIDIRECTIONAL MEMORIES.

(221) Kalasek, V.K.I. and W.M.C. van den Heuvel
L-SWITCH: A PC-program for computing transient voltages and currents during
switching off three-phase inductances.
(222) Jóźwiak, L.
THE FULL-DECOMPOSITION OF SEQUENTIAL MACHINES WITH THE SEPARATE REALIZATION OF THE NEXT-STATE AND OUTPUT FUNCTIONS.

(223) Jóźwiak, L.
THE BIT FULL-DECOMPOSITION OF SEQUENTIAL MACHINES.


(225) Hoeijmakers, M.J.
A POSSIBILITY TO INCORPORATE SATURATION IN THE SIMPLE, GLOBAL MODEL OF A SYNCHRONOUS MACHINE WITH RECTIFIER.

(226) Dahiya, R.P. and E.M. van Veldhuizen, W.R. Rutgers, L.H.Th. Rietjens
EXPERIMENTS ON INITIAL BEHAVIOUR OF CORONA GENERATED WITH ELECTRICAL PULSES SUPERIMPOSED ON DC BIAS.

(227) Bastings, R.H.A.
TOWARD THE DEVELOPMENT OF AN INTELLIGENT ALARM SYSTEM IN ANESTHESIA.

(228) Hekker, J.J.
COMPUTER ANIMATED GRAPHICS AS A TEACHING TOOL FOR THE ANESTHESIA MACHINE SIMULATOR.

(229) Oostrom, J.H.M. van
INTELLIGENT ALARMS IN ANESTHESIA: An implementation.

(230) Winter, M.R.M.
DECTON OF A UNIVERSAL PROTOCOL SUBSYSTEM ARCHITECTURE: Specification of functions and services.

(231) Schenmann, M.F.C. and H.C. Heyker, J.J.M. Kwaspen, Th.G. van de Roer
MOUNTING AND DC TO 18 GHz CHARACTERISATION OF DOUBLE BARRIER RESONANT TUNNELING DEVICES.

(232) Sarma, A.D. and M.H.A.J. Herben
DATA ACQUISITION AND SIGNAL PROCESSING/ANALYSIS OF SCINTILLATION EVENTS FOR THE OLYMPUS PROPAGATION EXPERIMENT.

(233) Nederstigt, J.A.
DECTON AND IMPLEMENTATION OF A SECOND PROTOTYPE OF THE INTELLIGENT ALARM SYSTEM IN ANESTHESIA.

(234) Philippens, E.H.J.
DECTONING DEBUGGING TOOLS FOR SIMPLEXYS EXPERT SYSTEMS.

(235) Heffels, J.J.M.
A PATIENT SIMULATOR FOR ANESTHESIA TRAINING: A mechanical lung model and a physiological software model.