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A Unified Approach to System Data Handling in CAD System for Designing Control Systems

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Synopsis

System data handling in CAD system for designing control systems is discussed. A man-oriented data description method for a wide sense block diagram and its automatical transformation into the state space description is proposed. This work is a part of CAD system: CADPACS-T which has been under development for designing control systems in our laboratory.

The proposal data description for a wide sense block diagram has the following features: 1) to correspond nicely to the block diagram and to be suitable for a man-oriented expression, 2) to express even a large scale system compactly by partitioning into some subsystems defined externally, 3) to be easy to add /or alter the input-output terminals, parameters or elements, and 4) to need not to assign the connection relationship explicitly owing to adopting the input-output terminal/line names.

Moreover, system data handling in designing the PI controller for an actual boiler system expressed in a block diagram is taken up as an example.

1. Introduction

For designing control systems, heretofore a lot of CAD systems have been developed based on the frequency domain [1], [2], but

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recently those based on the state space method become to be developed owing to development of the modern control theories and also owing to ripe opportunities to try to apply these theories to actual systems [3].

Well, in CAD systems, it is important to release a control system designer not only from complicated numerical calculations but also from a lot of troublesome data-handling. In this point of view, most of CAD systems ([1]-[3]) are seemed to have been developed with sufficient considerations, but, as long as the authors know, there seems to be few which can directly handle system data expressed with a block diagram that is often adopted as a suitable expression for a man in designing actual control systems.

Therefore, a man has to work something to transform its block diagram data into the state space description and so it has long been desired to release a designer from its troublesome data handlings. Very recently, one which can directly treat a block diagram data using a graphical terminal has been presented [4], but owing to its enormous processing programs, it is feared that its CAD system can not operate in small scale computers.

In this paper, so as to treat directly a block diagram data in the wide sense we will discuss its describing method which nicely corresponds to the block diagram expression and its automatical transformation into the state space description. This is one of modules in the CAD system :CADPACS-T which has been under development for designing multivariable control systems in our laboratory[5].

In section 2, we will deal with a describing method of block diagram data in the wide sense which include partially the state space description defined externally. In section 3, we will discuss its automatical transformation into the state space description in a unified approach to regard it as a connection among subsystems in the wide sense.

And in section 4, taking up system data handling for designing PI controller of a drum type boiler system expressed with a block diagram, we will illustrate the effectiveness of the proposal approach.

2. Description of Block Diagram Data

Block diagram description is often used to a lot of actual systems as a man-oriented data description because it is easy to grasp mutual relationships among physical variables in parts of an actual system and physical means of the system parameters, but is not suitable to apply control theories based on the state space method to, or to analyze in the time domain with a digital computer.

On the other hand, the state space description has the reverse properties to it.

By the way, in a large scale system, it is not easy to transform the block diagram description into the state space description because it is difficult and troublesome to input a block diagram data into a computer with no mistake.

For the sake of it, it is important to consider a suitable describing method for block diagram data.

Here, we will propose a describing method of block diagram data in the wide sense which include partially the state space description defend externally.

In a large scale system, it is very natural and convenient that some parts of it are described simply with only the names of which substances have been defined externally and the other parts are described in detail. This is the reason why we should consider the wide sense block diagram.

This is method that we describe block diagram data as a program style free format data with the following five basic terms.

1) DEFINE SYSTEM

This is the term to specify the identify name, the input terminal names and the output terminal names of the overall system under consideration.

2) SYSTEM

This is the term to specify the identity name, the input terminal /line names and the output terminal /line names of the each subsystem of which substance is defined externally (in the other DEFINE SYSTEM).

3) DYNAMICS

This is the term to specify the identity name, the transfer function, the input line name and the output line name of each single input-single output transfer element. And its transfer function is described with a rational polynomial of s(Laplace operator) + a constant or a exponential function of s.

4) COEFFICIENT

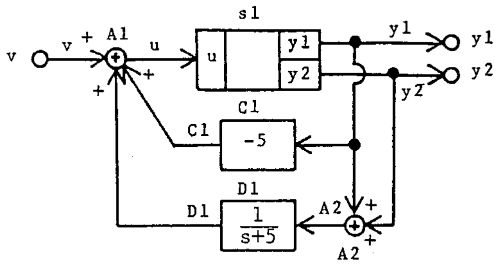
This is the term to specify the identity name , the real value, the input line name and the output line name of each scalar coefficient.

5) ADDER

This is the term to specify the identity name , the signed input line names and the output line name of each adder.

Here, the specifications of the input-output line names are used for the purpose of expressing the relationships among the elements in the block diagram.

Therefore, any descriptions for connecting are not necessary but this. (The syntax-summary is in Appendix A.) And Fig.1 shows an example of the description of a block diagram data.




```
DEFINE SYSTEM  EX1 (V; Y1,Y2);
  SYSTEM
    S1 (U; Y1,Y2);
  DYNAMICS
    D1 (A2; D1) = (1)/(s+5);
  COEFFICIENT
    C1 (Y1; C1) = -5;
  ADDER
    A1 (V,C1,D1; U), A2 (Y1,Y2; A2)
END
```

(a) block diagram (b) description

Fig.1 An example of the description of a block diagram

The features of this describing method are listed up as follows;

1) to correspond nicely to the block diagram and to be suitable for a man-oriented expression,
2) to express even a large scale system compactly and easily by partitioning into some subsystems defined externally in each DEFINE SYSTEM and then arranging their names in the SYSTEM term,
3) to be easy to add /or alter the input-output terminals, parameters or elements,
4) to need not to assign the connection relationship explicitly owing to adopting the input-output terminal /line names.

3. Unified Approach of System Data Handling

3.1 Basic Principle

It is considered that any system data described in a wide sense block diagram consists of some subsystems which are classified into two levels. That is to say, we call one whose substance is defined externally level 1, and call one whose substance is described internally in the DEFINE SYSTEM level 0. SYSTEM is level 1, and DYNAMICS, COEFFICIENT and ADDER are level 0. Where, COEFFICIENT and ADDER are the 0-th order subsystems of the single input single-output and multi input-single output, respectively. Moreover, a block diagram which consists of only level 0 subsystems is considered as a usual block diagram. A system defined in a DEFINE SYSTEM can be made use of as a level 1 subsystem in any other DEFINE SYSTEM as it is. Thus, since in general, a system has a reflexive structure in itself, the above describing method is seemed to be much more for a man-oriented data description owing to its reflexive structure.

Now, consider to obtain the state space description of a system defined in a DEFINE SYSTEM corresponding to a block diagram.

Since as the above discussion, all the elements in a block diagram can be considered as subsystems, respectively, the system can be represented as So in eq.(1).

<u>Open System</u> : So(Ao,Bo,Co,Do) ; input:uo, output:yo

$$\dot{x}(t) = Ao*x(t) + Bo*uo(t) , \qquad \text{--- (1.a)}$$
$$y(t) = Co*x(t) + Do*uo(t) , \qquad \text{--- (1.b)}$$

where,

$$Ao = \text{block diag } (A1,A2,...,Am) , \qquad \text{--- (2.a)}$$
$$Bo = \text{block diag } (B1,B2,...,Bm) , \qquad \text{--- (2.b)}$$
$$Co = \text{block diag } (C1,C2,...,Cm) , \qquad \text{--- (2.c)}$$
$$Do = \text{block diag } (D1,D2,...,Dm) , \qquad \text{--- (2.d)}$$

and also, m denotes the number of the subsystems, i.e., the elements and the sizes of Ai, Bi, Ci, i=1,...,m may be zero corresponding to the 0-th order subsystems.

The connection relationship among these subsystems are automatically determined with the input-output line names added in each element. Represent this relationship as a matrix F (whose elements are all 0 or 1). Then, the overall system is shown as Fig 2.

Connection : F ; input: (u', yo')', output: (y', uo')'

$$\begin{pmatrix} y \\ uo \end{pmatrix} = F*\begin{pmatrix} u \\ yo \end{pmatrix} = \begin{pmatrix} F11 & F12 \\ F21 & F22 \end{pmatrix}*\begin{pmatrix} u \\ yo \end{pmatrix} \qquad \text{--- (3)}$$

Here, eliminating the secondary variables uo, yo in eq.(1)-(3), the state space description of the closed system is obtained as eq.(4),(5).

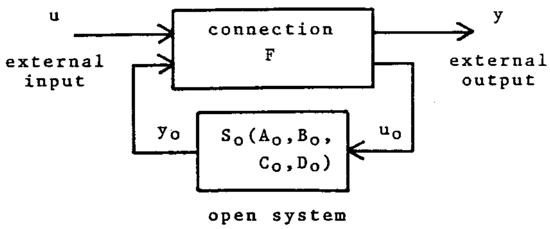


Fig.2 The overall system

Closed System : Sc(A,B,C,D) ; input: u, output: y

$$\dot{x}'(t) = A*x(t) + B*u(t) \qquad \text{--- (4.a)}$$
$$y(t) = C*x(t) + D*u(t) \qquad \text{--- (4.b)}$$

where,

$$A = Ao + Bo*F22*inv(Q)*Co \quad , \qquad \text{--- (5.a)}$$
$$B = Bo + Bo*F22*inv(Q)*Do*F21 \quad , \qquad \text{--- (5.b)}$$
$$C = F12*inv(Q)*Co \quad , \qquad \text{--- (5.c)}$$
$$D = F11 + F12*inv(Q)*Do*F21 \quad , \qquad \text{--- (5.d)}$$
$$Q = I - Do*F22 \quad , \qquad \text{--- (5.e)}$$

and here only the case det.Q$\neq$0 in which a phisical meaning exists is considered.

Thus, in a principle, the numerical calculations have only to be carried out. However, since the sizes of the matrices (Ao,Bo,Co,Do,F) are usually very large, the above calculations are not practical in the points of the cpu time and the working memories.

Then, the fo;;owing practical approach is proposed.

3.2 Practical Approach

In order to operate the calculations corresponding to eq.(5) with the less sizes' matrices, the following practical approach is proposed : It is the approach that separating the 0-th order static subsystems (COEFFICIENT, ADDER, 0-th order SYSTEM and DYNAMICS) from the open system So, and including these informations into the relationship matrix F, and then the closed system is to be obtained using the resulting open system Sd and the connection $\hat{F}$. Where, Sd and $\hat{F}$ are introduced as follows. Now, assuming that So is suitably sorted in order of the more than one-th order dynamic parts (sufix: d) and the 0-th order static parts (sufix: s), eq.(2) can be expressed as follows.

$$Ao = Ad \quad , \quad Bo = [\ Bd \ \vdots\ 0\ ] \ ,$$
$$Co = \begin{pmatrix} Cd \\ \hdashline 0 \end{pmatrix}, \quad Do = \begin{pmatrix} Dd & \vdots & 0 \\ \hdashline 0 & \vdots & Ds \end{pmatrix} \qquad \text{--- (6)}$$

where, 0 denotes a zero matrix with a proper size and Ds denotes the overall of the 0-th order subsystems. And separating uo and yo corresponding to the above separation, and considering the relation ys = Ds*us, the connection $\hat{F}$ is obtained as follows.

Connection : $\hat{F}$; input:(u', yd', ys')' output:(y', ud', ys')'

$$\begin{pmatrix} y \\ ud \\ ys \end{pmatrix} = \hat{F} * \begin{pmatrix} u \\ yd \\ ys \end{pmatrix} = \begin{pmatrix} I & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & Ds \end{pmatrix} * F * \begin{pmatrix} u \\ yd \\ ys \end{pmatrix}$$

Fig.3 shows the results of the above disdussion.

Therefore, the first phase of the module for automatical transformation into the state space description is to interpret the block diagram description (DEFINE SYSTEM), and to set Ad, Bd, Cd, Dd and $\hat{F}$ shown in Fig. 3.

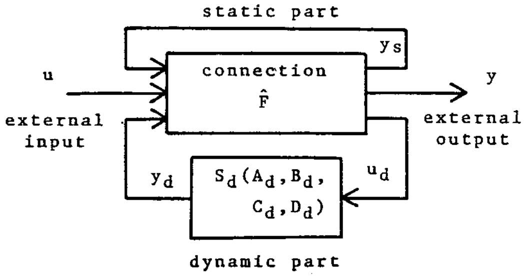


Fig.3 The overall system separating the static parts

Now, on eliminating the secondary variables ys, the direct components Dd in the dynamical parts Sd have to be considered at the same time. (Otherwise, it may occur that the inverse of a matrix can't be calculated or the numerical calculations turn unstable.)

Decomposing yd into the term of Cd and the term of Dd, the connection is expressed as follows.

Connection : $\bar{F}$; input: (u', $\bar{yd}$')', output: (y', ud')'

$$\begin{pmatrix} y \\ ud \end{pmatrix} = \bar{F} * \begin{pmatrix} u \\ \bar{yd} \end{pmatrix} = \begin{pmatrix} \bar{F}11 & \bar{F}12 \\ \bar{F}21 & \bar{F}22 \end{pmatrix} * \begin{pmatrix} u \\ \bar{yd} \end{pmatrix} \qquad \text{--- (9)}$$

where,

$$\bar{F} = \begin{pmatrix} \hat{F}11 & \hat{F}12 \\ 0 & 0 \end{pmatrix} + \begin{pmatrix} \hat{F}12*Dd & \hat{F}13 \\ I & 0 \end{pmatrix} * \begin{pmatrix} I-\hat{F}22*Dd & -\hat{F}23 \\ -\hat{F}32*Dd & I-\hat{F}33 \end{pmatrix}^{-1} * \begin{pmatrix} \hat{F}21 & \hat{F}22 \\ \hat{F}31 & \hat{F}32 \end{pmatrix} \qquad \text{--- (10)}$$

Fig.4 shows the results of the above discussion.

Next, eliminating the secondary variables ud and yd in Fig.4, the state space description of the closed system can be obtained as eq.(11).

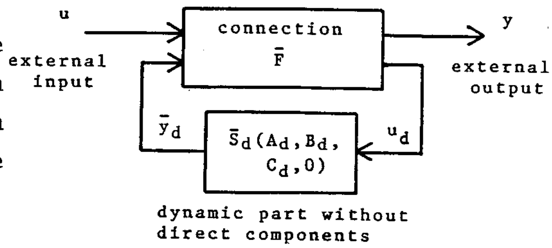


Fig.4 The overall system closed wrt the static components

Closed System : Sc(A,B,C,D) ; input: u, output: y

$$A = Ad + Bd*\bar{F}22*Cd \qquad \text{--- (11.a)}$$
$$B = Bd*\bar{F}21 \qquad \text{--- (11.b)}$$
$$C = \bar{F}12*Cd \qquad \text{--- (11.c)}$$
$$D = \bar{F}11 \qquad \text{--- (11.d)}$$

Although A, B, C and D in eq.(11) are equivalent to those of eq.(5), respectively, the sizes of the matrices on the right hand side turn smaller than those of eq.(5).

Last, the above procedures (by the module DEFSYS) are arranged as follows.

(Phase 1) interpretation of an input data
block diagram description ==> Sd(Ad,Bd,Cd,Dd), $\hat{F}$
(DEFINE SYSTEM) shown in Fig.3

(Phase 2) elimination of the static secondary variables
Sd(Ad,Bd,Cd,Dd), $\hat{F}$ ==> $\bar{S}$d(Ad,Bd,Cd,0), $\bar{F}$
shown in Fig.3 shown in Fig.4

(Phase 3) elimination of the dinamic secondary variables
$\bar{S}$d(Ad,Bd,Cd,0), $\bar{F}$ ==> Sc(A,B,C,D)
shown in Fig.4 shown in eq.(11)

4. Example

Taking up the system data handling for designing PI controller of an actual system described with a block diagram, we will illustrate the effectiveness of the proposal approach. The object system is a drum type boiler with the steam flow rate of 200 ton/hour. (Its block diagram is shown in Appendix B.[6]) Fig.5 shows the block diagram of the boiler system with the PI controller[6]. Fig.6 shows the block diagram description proposed in this paper corresponding to Fig.5. this does nicely correspond to Fig.5 and so it may be said that this is surely a man-oriented description.

Here, #1, #2, #3 and #4 denote the parameters to be altered. Besides, the block diagram descriptions of ECDR,.., SHNO3 in the term of SYSTEM are shown in Appendix C.

Fig.7 shows a consecutive operation example of the reiteration of 1) parameter alteration of the PI controller, 2) automatical transformation into the state space description and 3) simulation for a step response. Fig.8 shown an example of the step responses

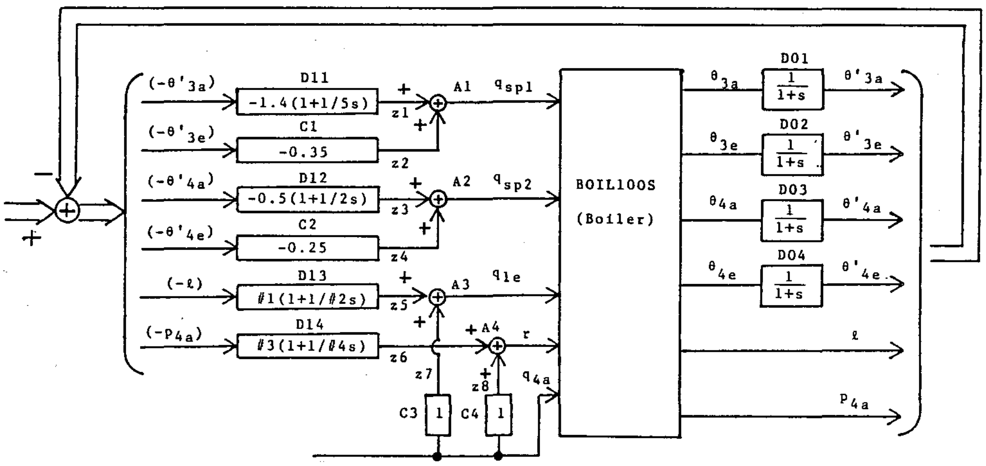


Fig.5 The block diagram of a boiler system with PI controller

```
DEFINE SYSTEM BOIL100S (R,Q1E,QSP1,QSP2,Q4A; L,TH3A,TH3E,TH4A,TH4E,P4A);
  SYSTEM
    ECDR   (Q1E,R,Q2E; PD,L),
    SHN01  (PD,R,Q3E,QSP1; I2A,Q2A,P2A,Q2E),
    SHN02  (I2A,R,Q2A,P2A,Q4E,QSP1,QSP2; TH3A,TH3E,Q3A,P3A,Q3E),
    SHN03  (TH3A,Q3A,P3A,R,QSP2,Q4A; TH4A,P4A,Q4E,TH4E)
END

DEFINE SYSTEM BOILSYS (Q4A; TH3A1,TH4A1,L,P4A,QSP1,QSP2,Q1E,R);
  SYSTEM
    BOIL100S (R,Q1E,QSP1,QSP2,Q4A; L,TH3A,TH3E,TH4A,TH4E,P4A);
  DYNAMICS
    D01 (TH3A; TH3A1) = (1)/(1+s),
    D02 (TH3E; TH3E1) = (1)/(1+s),
    D03 (TH4A; TH4A1) = (1)/(1+s),
    D04 (TH4E; TH4E1) = (1)/(1+s),
    D11 (TH3A1;    Z1) =  1.4*(5s+1)/(5s),
    D12 (TH4A1;    Z3) =  0.5*(2s+1)/(2s),
    D13 (L;        Z5) = -#1 *(#2s+1)/(#2s),     '#1 = 0.5, #2 = 2'
    D14 (P4A;      Z6) = -#3 *(#4s+1)/(#4s);     '#3 = 5.0, #4 = 5'
  COEFFICIENT
    C1 (TH3E1; Z2) = 0.35,  C3 (Q4A; Z7) = 1,
    C2 (TH4E1; Z4) = 0.25,  C4 (Q4A; Z8) = 1;
  ADDER
    A1 (Z1,Z2; QSP1),  A2 (Z3,Z4; QSP2),
    A3 (Z5,Z7; Q1E) ,  A4 (Z6,Z8; R)
END
```

Fig.6 The block diagram description corresponding to Fig.5

```
*RUN ALTER

source, destination ? BOILSYS, BOILSYS1
alter data ? 0.5, 2, 5.0, 5

*RUN DEFSYS

source file name ? BOILSYS1
system name = BOILSYS  (nx = 31, nu =  1, ny =  8)
comment ? boiler system with PI controller.

*RUN SIMULT

system name ? BOILSYS
<< comment >> boiler system with PI controller.
 (nx = 31, nu =  1, ny =  8)
 input name
 Q4A
output name
 TH3A1    TH4A1    L        P4A      QSP1     QSP2     Q1E      R
input data (at + b) ?
 Q4A      ? 0, 0.113
simulation time, no. of output, step length ? 20, 200, 0.0002
output file name ? BOILSYS1
print results ? N
graphic display ? Y

*RUN ALTER

source, destination ? BOILSYS, BOILSYS1
alter data ? 0.4, 1.5, 4.0, 4
```

Fig.7 An operation example for a sort of system data handling

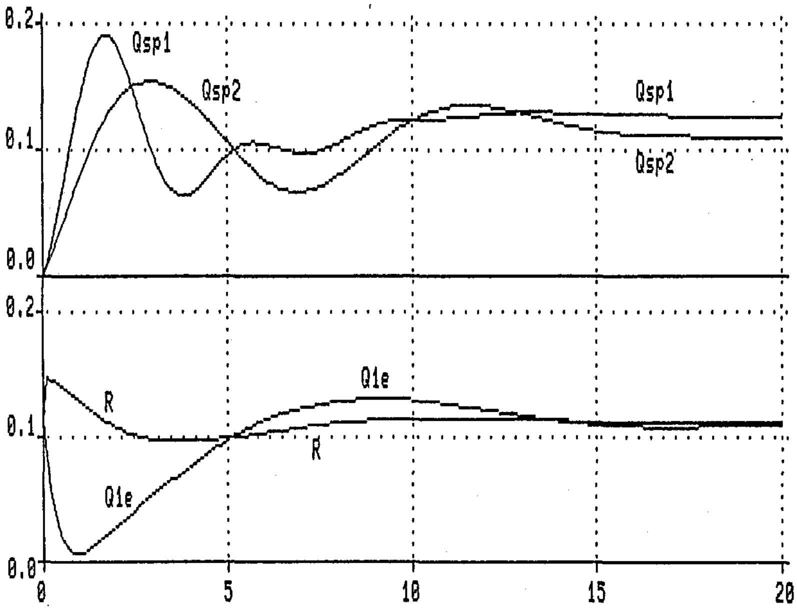


Fig.8 An example of the step responses in the process shown as Fig.7

resulting in the above process (case : #1=0.5, #2=2, #3=5.0 and #4=5). *1

From the above example, it may be said that our CAD system releases a designer from troublesome system data handling and realizes a quick design of the more desirable controller.

5. Conclusion

System data handling in CAD system for designing control systems has been discussed. And a describing method for a wide sense block diagram that is a man-oriented data description and its automatical transformation into the state space description has been proposed.

At that time, a unified concept treating the reflexive structure of system data has been introduced.

Moreover, taking up the design of the PI controller for an actual system expressed in a block diagram, it has been shown that our CAD system does surely release a designer from troublesome data handling.

It may be thought that our CAD system has been achieved satisfactorily with respect to system data handling.

In the future, it is thought important that with respect to data handling, a man-oriented data descriptions to even other kind of data but system data should be developed , and in packaging control theories, numerically stable algorithms should be developed considering inaccuracy of the parameters.

Acknowledgement

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The computer processings have been carried out with Okayama Univ. C.C. Acos-700S System.

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*1 Fig.8 corresponds to Fig.E in pp.147 of reference [6].

References

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Appendix A

The syntax summary for the block diagram description.

The syntax summary is described using an extention version of Backus-Naur Form.

Notice:

(a) Braces enclose a repeated item. The item may appear zero or more times.

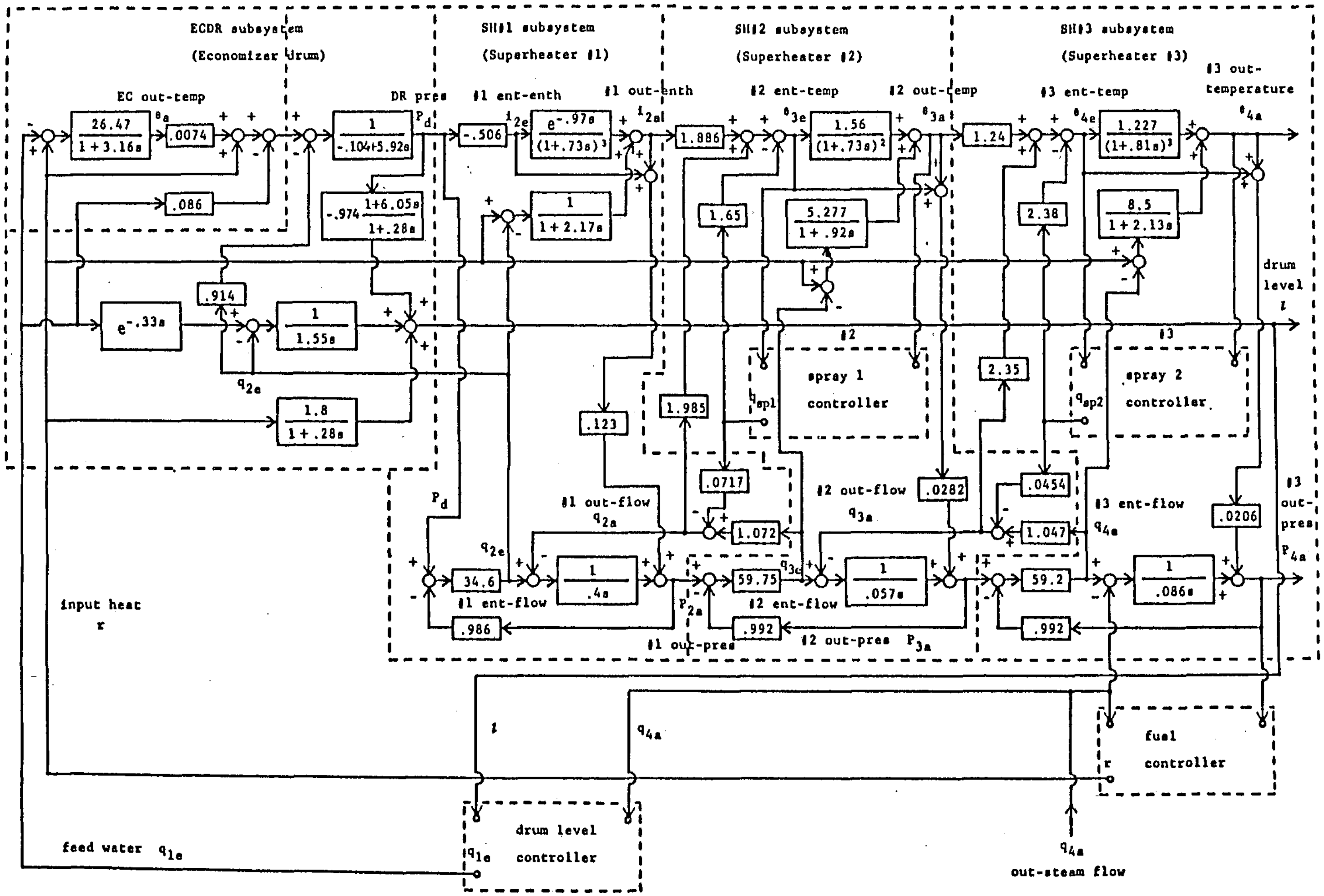
(b) Upper case words underlined denotes reserved words.

Besides, upper case words and lower case words are not discriminated in the description. And the string enclosed by "’" denotes a comment.

```
<define system> ::= DEFINE SYSTEM <system name> <io list 1> ;
                    <declaration> { ; <declaration> } END
<declaration> ::= <system dec>       | <dynamics dec> |
                  <coefficient dec> | <adder dec>

<system dec> ::= SYSTEM <sytem> { , <system> }
<system> ::= <system name> <io list 1>
<dynamics dec> ::= DYNAMICS <dynamics> { , <dynamics> }
<dynamics> ::= <dynamics name> <io list 2> = <function of s>
<coefficient dec> ::= COEFFICIENT <coefficient> { , <coefficient> }
<coefficient> ::= <coefficient name> <io list 2> = <real>
<adder dec> ::= ADDER <adder> { , <adder> }
<adder> ::= <adder name> <io list 3>

<io list 1> ::= ( <input list> ; <output list> )
<input list> ::= <term line> { , <term line> }
<output list> ::= <term line> { , <term line> }
<term line> ::= <terminal name> [ / <line name> ]
<io list 2> ::= ( <line name> ; <line name> )
<io list 3> ::= ( <adder input list> ; <line name> )
<adder input list> ::= [<sign>] <line name> { , [<sign>] <line name> }

<function of s> ::= [<sign>] [ <unsigned real> * ] <simple function>
                    [ <adding operator> <unsigned real> ]
<simple function> ::= <fraction type> | <exponent type>
<fraction type> ::= ( <polynomial> )/( <polynomial> )
                    [ ^ <unsigned integer> ]
<polynomial> ::= [<sign>] <factor> { <adding operator> <factor> }
<factor> ::= <unsigned real> |
             [ <unsigned real> ] s [ <unsigned integer> ]
<exponent type> ::= EXP ( <real> s )
<adding operator> ::= + | -

<real> ::= [<sign>] <unsigned real>
<unsigned real> ::= <unsined integer> [ . <unsigned integer> ]
                    [ e [<sign>] <unsigned integer> ]
<unsigned integer> ::= <digit> { <digit> }
<sign> ::= + | -

<system name> ::= <name>
<dynamics name> ::= <name>
<coefficient name> ::= <name>
<adder name> ::= <name>
<terminal name> ::= <name>
<line name> ::= <name>

<name> ::= <letter> { <letter or digit> }
<letter or digit> ::= <letter> | <digit>
<letter> ::= a |b |c |d |e |f |g |h |i |j |k |l |m |n |o |p |q |r |s |t |u |v |w |x |y |z
<digit> ::= 0 |1 |2 |3 |4 |5 |6 |7 |8 |9
```

Appendix B

The block diagram of the drum type boiler with steam flow rate 200 ton/hour linearized at 75 % load.



Appendix C The block diagram descriptions of subsystems ECDR, SHNO1, SHNO2 and SHNO3 of the boiler system in Appendix B.

```
DEFINE SYSTEM ECDR (Q1E,R,Q2E; PD,L);
  DYNAMICS
    D1 (A1; THA) = (26.47)/(1 + 3.16s),
    D2 (A2;  PD) = (1)/(-0.104 + 5.92s),
    D3 (PD;  D3) = -0.974*(1 + 6.05s)/(1 + 0.28s),
    D4 (Q1E; D4) = EXP(-0.33s),
    D5 (A3;  D5) = (1)/(1.55s),
    D6 (R;   D6) = (1.8)/(1 + 0.28s);
  COEFFICIENT
    C1 (THA; C1) = 0.0074,
    C2 (Q1E; C2) = 0.086,
    C3 (Q2E; C3) = 0.914;
  ADDER
    A1 (R ,-Q1E; A1), A2 (C1,R,-C2,-C3; A2),
    A3 (D4,-Q2E; A3), A4 (D3,D5,D6; L)
END

DEFINE SYSTEM SHNO1 (PD,R,Q3E,QSP1; I2A,Q2A,P2A,Q2E);
  DYNAMICS
    D1 (I2E; D1) = (1)/(1 + 0.73s)^3,
    D2 (D1;  D2) = EXP(-0.97s),
    D3 (A3;  D3) = (1)/(2.17s+1),
    D4 (A6;  D4) = (1)/(0.4s);
  COEFFICIENT
    C1 (PD;   I2E) = -0.506,
    C2 (A2;    C2) =  0.123,
    C3 (QSP1;  C3) =  0.0717,
    C4 (Q3E;   C4) =  1.072,
    C5 (A5;   Q2E) =  34.6,
    C6 (P2A;   C6) =  0.986;
  ADDER
    A1 (D2,D3; I2A),  A2 (I2E,I2A; A2), A3 (R,-Q2E; A3),
    A4 (-C3,C4; Q2A), A5 (PD,-C6; A5),  A6 (Q2E,-Q2A; A6),
    A7 (D4,C2; P2A)
END

DEFINE SYSTEM SHNO2 (I2A,R,Q2A,P2A,Q4E,QSP1,QSP2;
                                  TH3A,TH3E,Q3A,P3A,Q3E);
  DYNAMICS
    D1 (TH3E; D1) = (1.56)/(1 + 0.73s)^2,
    D2 (A4;   D2) = (5.277)/(1+0.92s),
    D3 (A7;   D3) = (1)/(0.057s);
  COEFFICIENT
    C1 (I2A;  C1) = 1.886,   C5 (QSP2; C5)  = 0.0454,
    C2 (QSP1; C2) = 1.65,    C6 (Q4E;  C6)  = 1.047,
    C3 (Q2A;  C3) = 1.985,   C7 (A6;   Q3E) = 59.75,
    C4 (A3;   C4) = 0.0282,  C8 (P3A;  C8)  = 0.992;
  ADDER
    A1 (C1,C3,-C2; TH3E), A2 (D1,D2; TH3A), A3 (TH3A,TH3E; A3),
    A4 (R,-Q3E; A4),      A5 (-C5,C6; Q3A), A6 (P2A,-C8; A6),
    A7 (Q3E,-Q3A; A7),    A8 (D3,C4; P3A)
END

DEFINE SYSTEM SHNO3 (TH3A,Q3A,P3A,R,QSP2,Q4A; TH4A,P4A,Q4E,TH4E);
  DYNAMICS
    D1 (TH4E; D1) = (1.227)/(1 + 0.81s)^3,
    D2 (A4;   D2) = (8.5)/(1 + 2.13s),
    D3 (A6;   D3) = (1)/(0.086s);
  COEFFICIENT
    C1 (TH3A; C1) = 1.24,  C4 (A3;  C4)  = 0.0206,
    C2 (QSP2; C2) = 2.38,  C5 (A5;  Q4E) = 59.2,
    C3 (Q3A;  C3) = 2.35,  C6 (P4A; C6)  = 0.992;
  ADDER
    A1 (C1,C3,-C2; TH4E), A2 (D1,D2; TH4A), A3 (TH4A,TH4E; A3),
    A4 (R,-Q4E;      A4), A5 (P3A,-C6; A5), A6 (Q4E,-Q4A;  A6),
    A7 (D3,C4;      P4A)
END
```