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A 10TH ORDER LINEAR DRUM BOILER TURBINE MODEL

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DEPARTMENT OF AUTOMATIC CONTROL
LUND INSTITUTE OF TECHNOLOGY
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K J Åström
R D Bell

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A 10th Order Linear Drum Boiler Turbine Model.

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A linear state space model for a drum boiler turbine unit is given. The model is based on a medium sized model developed by Eklund. This model is changed to describe drum level dynamics better. The model has 5 inputs, 7 outputs, and 10 state variables. The model was developed for the purpose of design and evaluation of multivariable control schemes. It has been compared with measurements from plant data.

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Contents

1. INTRODUCTION

A medium sized model of a drum boiler turbine unit was described in Eklund (1971). This model takes the major physical phenomena into account. The model was derived from first principles. It was validated against plant data. The measurements were made on the P16/G16 unit of Öresundsverket, Sydkraft AB, Malmö, Sweden. The validation showed that the model described the boiler-turbine unit quite well. There were, however, some deficiencies in the description of the drum level. The shrink and swell effect in Eklunds model was for example much smaller than for the real boiler. In this report Eklund's model is modified to describe the shrink and swell phenomena better. This requires that an additional state variable is introduced. A few other minor changes have also been made to Eklunds model. The modifications introduced are described in Section 2. The major characteristics of the model are described in Section 3. Results from validation against plant measurements are given in Section 4. A simulation program which gives the model in full detail is presented in the Appendix A.

2. MODIFICATIONS OF EKLUND'S MODEL

It is assumed that the reader is familiar with the derivation of the linear boiler model in Chapter 4 of Eklund (1971). Eklund gives two models a 9th order model and a 15th order model. The models differ mainly in the degree of aggregation used to model the superheater. The 9th order model gives a reasonable fit to the experimental data for most signals except the drum water level. The bad fit can be traced to the fact that the influence of the steam bubbles in the risers is poorly described. An improved description of these are given in the modified model. Some minor modifications are also made.

Drum Level Model

A new state variable x_3 is introduced. This variable is the volume of the steam bubbles in the risers divided by the drum area. The drum level is therefore given by

$$y_5 = x_2 + x_3. \tag{2.1}$$

Inspired by Bell and Åström (1979) the following model is introduced for x:

$$\frac{dx_3}{dt} = \left(\alpha \frac{da}{dt} - x_3\right) / T, \tag{2.2}$$

where a is the steam quality, T approximately the mean residence time in the risers, and α a parameter. The amount of swell is easily adjusted by changing the parameter α. The circulation time is about 10 s. Order of magnitude calculation using the parameters of the non-linear model in Bell and Åström (1979) indicates that a value of α = 100 is reasonable. Preliminary simulations indicated that this value was probably a bit too high because the shrink and swell effects were larger in the model than in the process for this value. Since a large shrink and swell does not make the control problem simpler it was decided to use α = 100.

Minor Modifications

Some minor modifications to Eklund's model were also made. Since an extra state variable x_3 was introduced the remaining state variables of Eklund's model were renumbered.

A cross check on Eklund's model also revealed that some parameters should be changed. The numbers b_{13}, b_{14}, b_{23}, b_{24}, b_{43}, b_{44}, and b_{63} were all set to zero. These numbers describe the influences of the spray water flows on the rates of changes of the state variables drum pressure, drum liquid level, drum water temperature and steam quality. The nonzero values were due to the lumping of the system. The parameter b_{12} in Eklund's model is erroneous. The value was changed to

$$b_{12} = - 4.4 \times 10^{-4} \times 3.6 = - 1.6 \times 10^{-3}$$

based on linearization of the nonlinear model Åström and Eklund (1972). There is also a sign error in the coefficient b_{84} which has been corrected.

Finally, all numbers in Eklund's model have been rounded off to four decimal places.

3. CHARACTERISTICS OF THE MODEL

The model is intended to give a reasonable overall description of a drum boiler unit. It has the standard state space format

$$\frac{dx}{dt} = Ax + Bu$$

$$y = Cx + Du.$$

The input signals are

u_1 fuel flow

u_2 feedwater flow

u_3 spray flow 1

u_4 spray flow 2

u_5 steam valve position.

The output signals are

y_1 output power

y_2 power from low pressure turbine

y_3 power from high pressure turbine

y_4 steam flow

y_5 drum level

y_6 drum pressure

y_7 steam temperature.

The state variables are

x_1 drum pressure

x_2 drum liquid level

x_3 drum steam bubble level

x_4 drum water temperature

x_5 riser wall temperature

x_6 mean value of steam quality

x_7 wall temperature of superheater 1

x_8 wall temperature of superheater 2

x_9 wall temperature of superheater 3

x_{10} wall temperature of reheater.

The numerical values of the matrices A, B, C, and D are given in Appendix A.

4. COMPARISONS WITH MEASURED PLANT DATA

The model has been validated against plant data. Three different experiments were performed by Eklund (1969) at two different load levels, full load and half load. Eklund's model was originally developed for the full load operating conditions. The input variables, fuel flow, feedwater flow and steam valve opening were changed in the experiments. In each experiment there was a perturbation in one of the signals and small corrections in the other input signals. The corrections were made manually to maintain a reasonable drum level. To get a feel for the dependence on operating conditions comparisons with plant data at a lower load are also given.

Experiments at Half Load

Figure 1 shows the results obtained at low load when the fuel flow is perturbed. A comparison with Fig. 4 indicates that the drum pressure is modeled as well as in the case of full load. The fluctuations in output power are, however, smaller which reflects the nonlinear properties of the plant. Notice that the model predicts the drum water level fluctuations very well.

Figure 2 shows the results obtained in the experiment when feedwater flow is perturbed. The fluctuations in pressure and power are comparatively small. Notice, however, that the model gives larger fluctuations in these variables and that it also gives more shrink and swell than the real process.

Figure 3 shows the results obtained when the steam valve is changed. The model predicts the pressure variations well. As expected, there are however discrepancies in output power. The shrink and swell is also exaggerated.

The control variables are normalized in the figures. 1 unit in fuel flow corresponds to 14 kg/s and 1 unit of feedwater flow corresponds

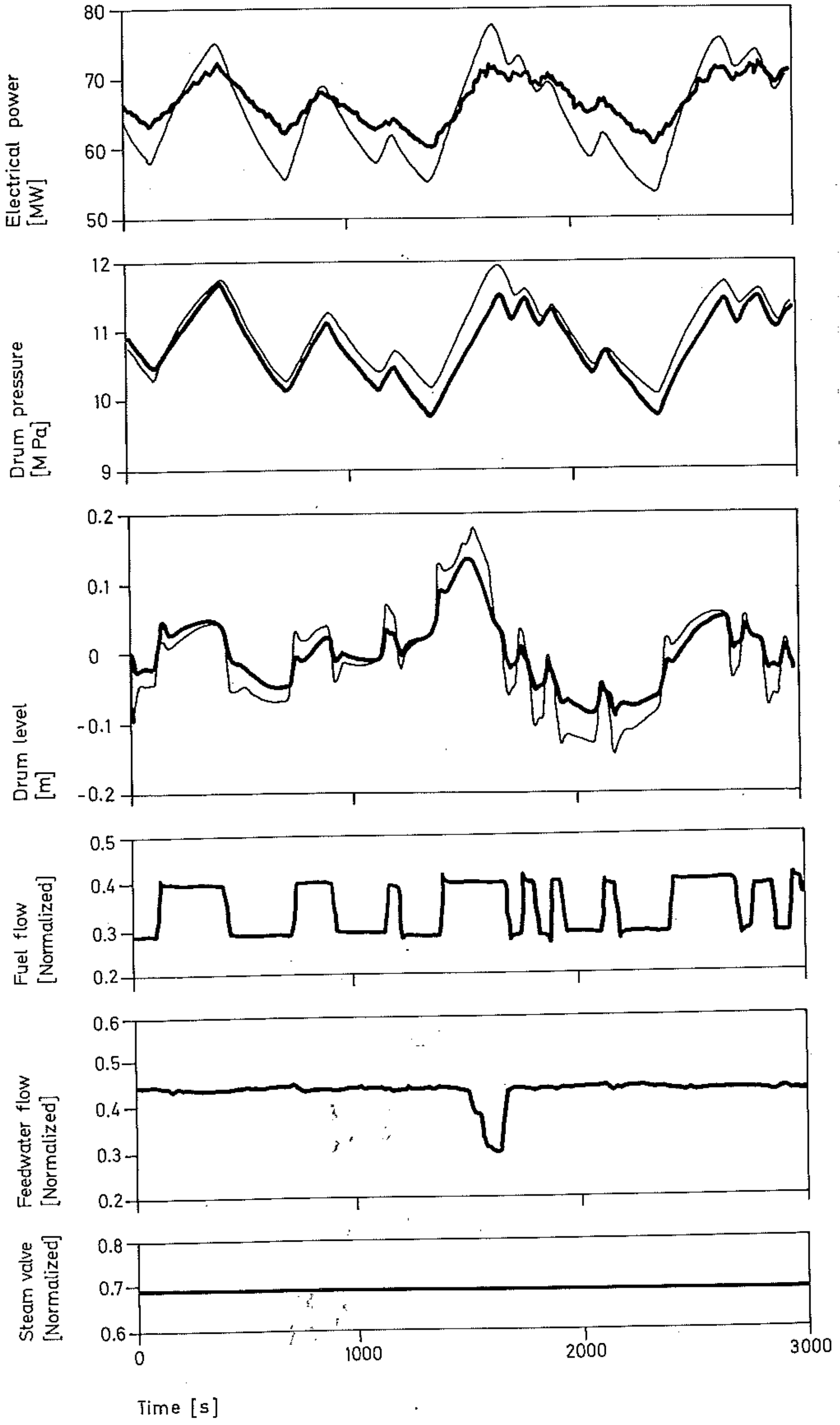

Fig. 1 - Comparison of model outputs (thin lines) with experimental data (thick lines) at half load with fuel flow perturbations.

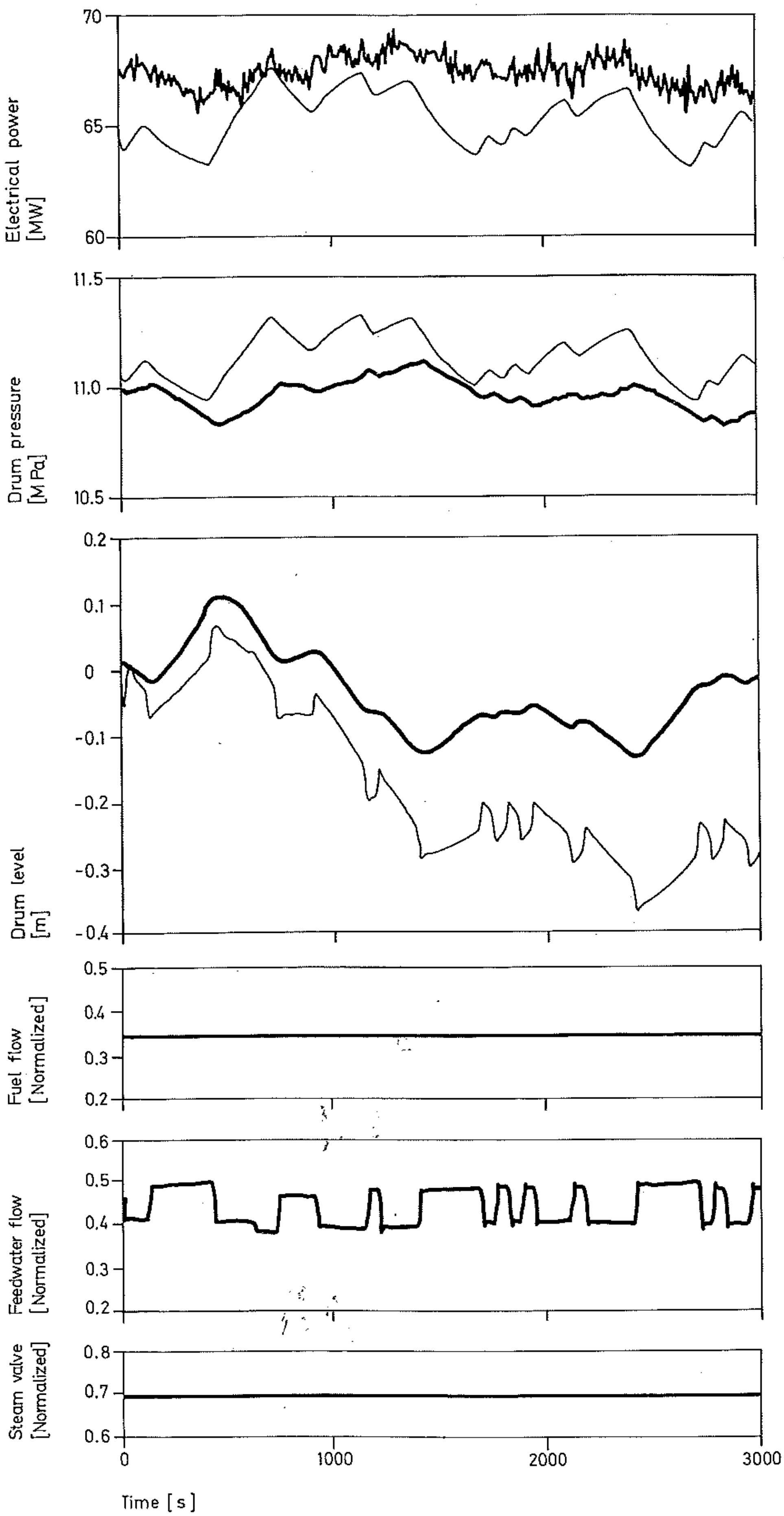

Fig. 2 - Comparison of model outputs (thin lines) with experimental data (thick lines) at half load with feedwater flow perturbations.

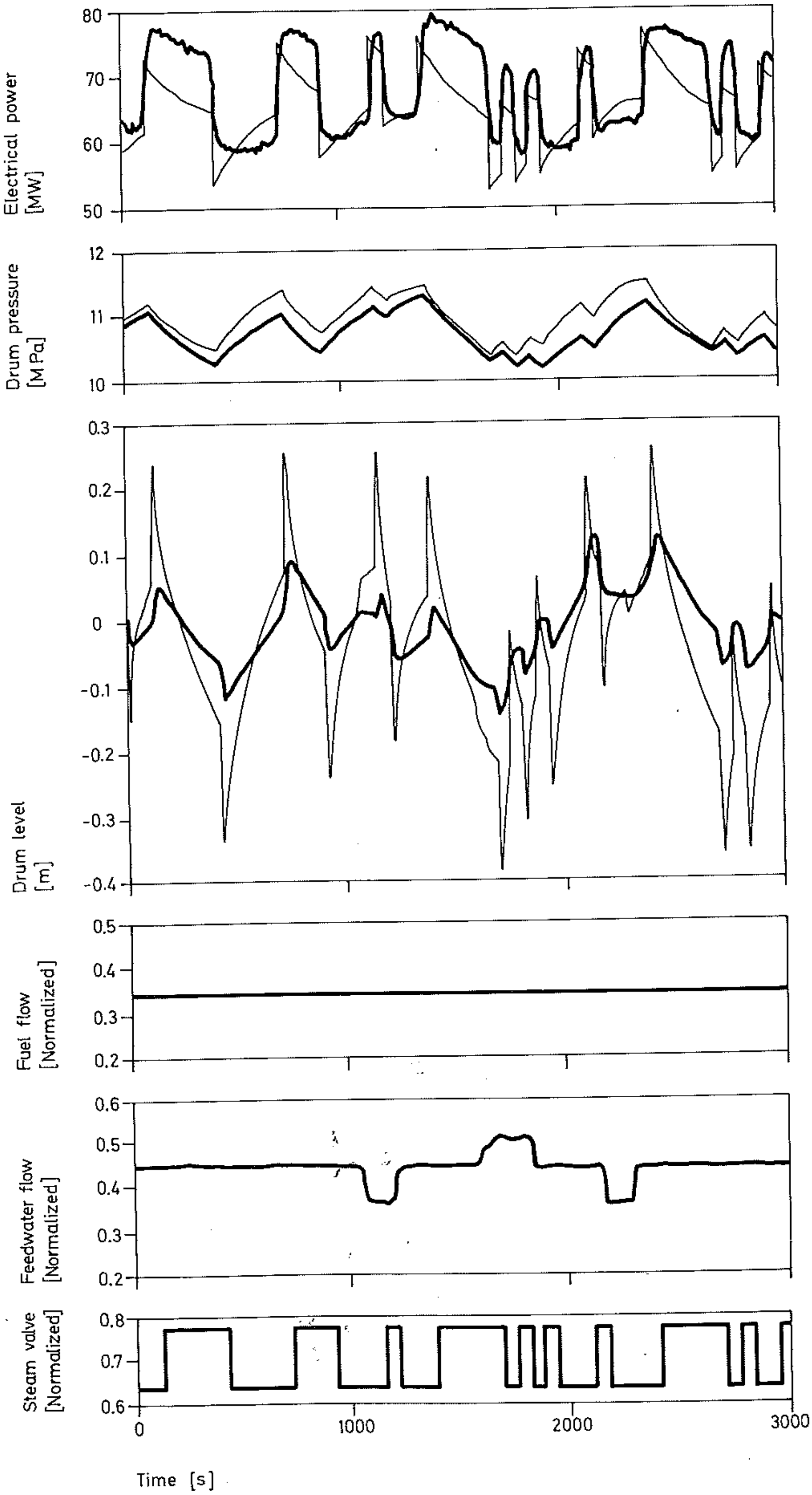

Fig. 3 - Comparison of model output (thin lines) with experimental data (thick lines) at half load with steam valve perturbations.

to 140 kg/s. The steam valve is nonlinear. The linearized gain at full load is twice as large as the linearized gain at half load.

Experiments at Full Load

Figure 4 shows the outputs of the plant model and the measured outputs in the experiment when the fuel flow is perturbed. There is a good agreement with the drum pressure and the output power. The drum level is also described well. The shrink and swell is however larger in the model than in the plant.

Figure 5 shows the results for the experiment when the feedwater flow is perturbed. In this case the changes in drum pressure and output power are fairly small. This is seen e.g. in the noise level in the power signal. There are discrepancies in the drum pressure signal. The main characteristics of the drum level fluctuations are captured fairly well. The shrink and swell is, however, again larger in the model than in the plant.

Figure 6 shows the results for the experiment when the steam valve is perturbed. Notice that there is good agreement for drum pressure and output power. The shrink and swell effect is larger in the model.

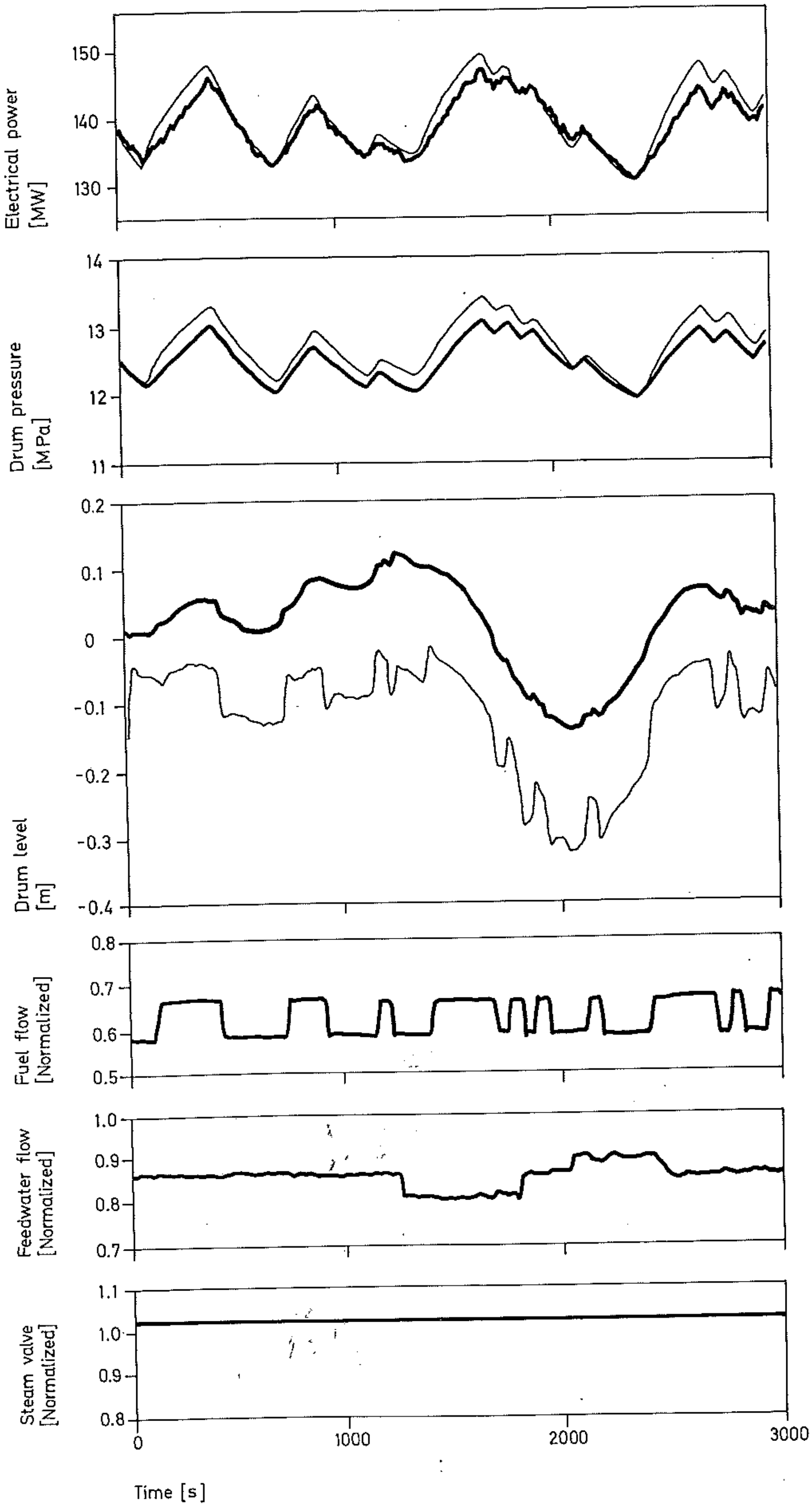

Fig. 4 - Comparison of model outputs (thin lines) with experimental data (thick lines) at full load with fuel flow perturbations.

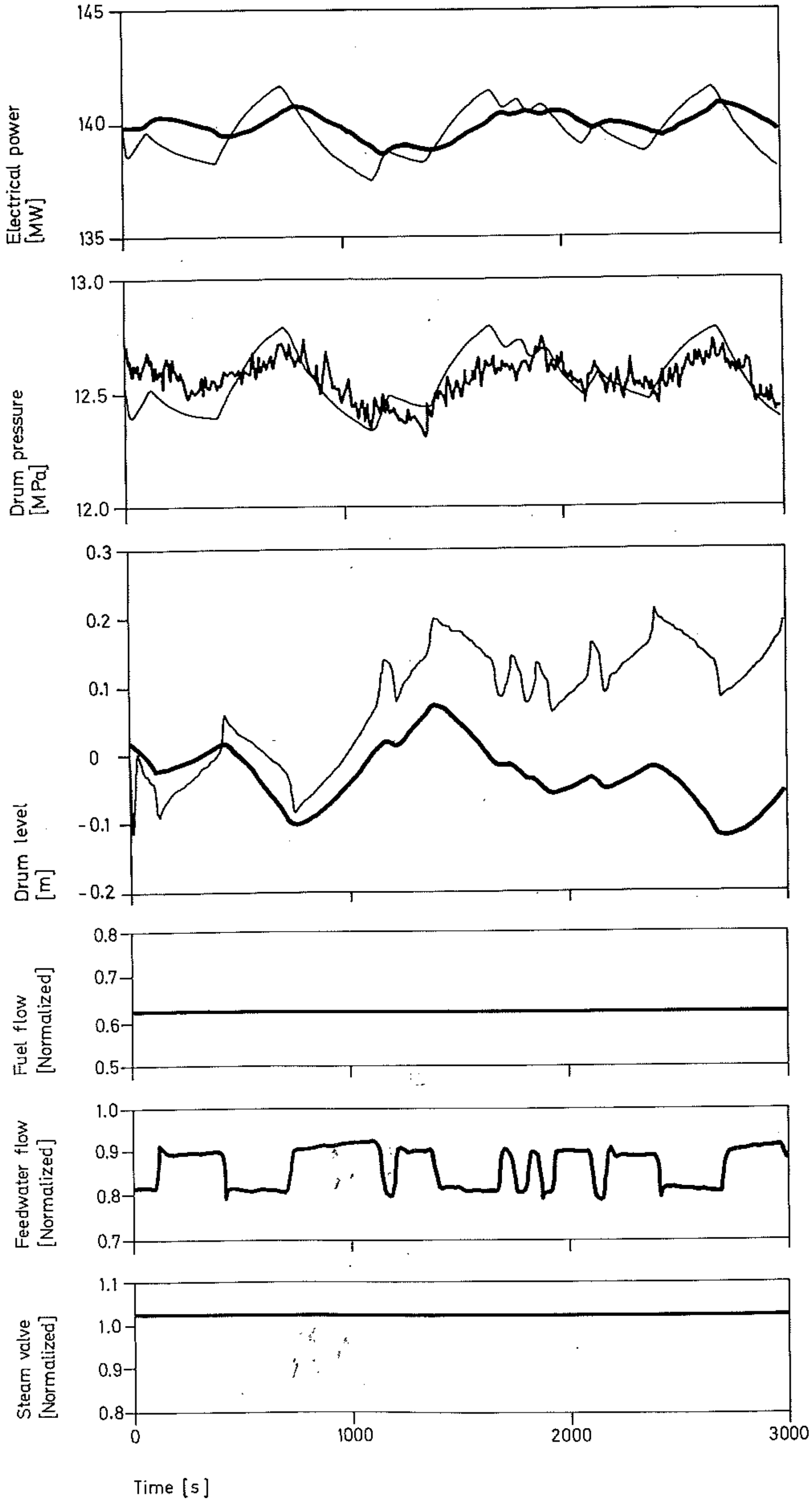

Fig. 5 - Comparison of model outputs (thin lines) with experimental data (thick lines) at full load with feedwater flow perturbations.

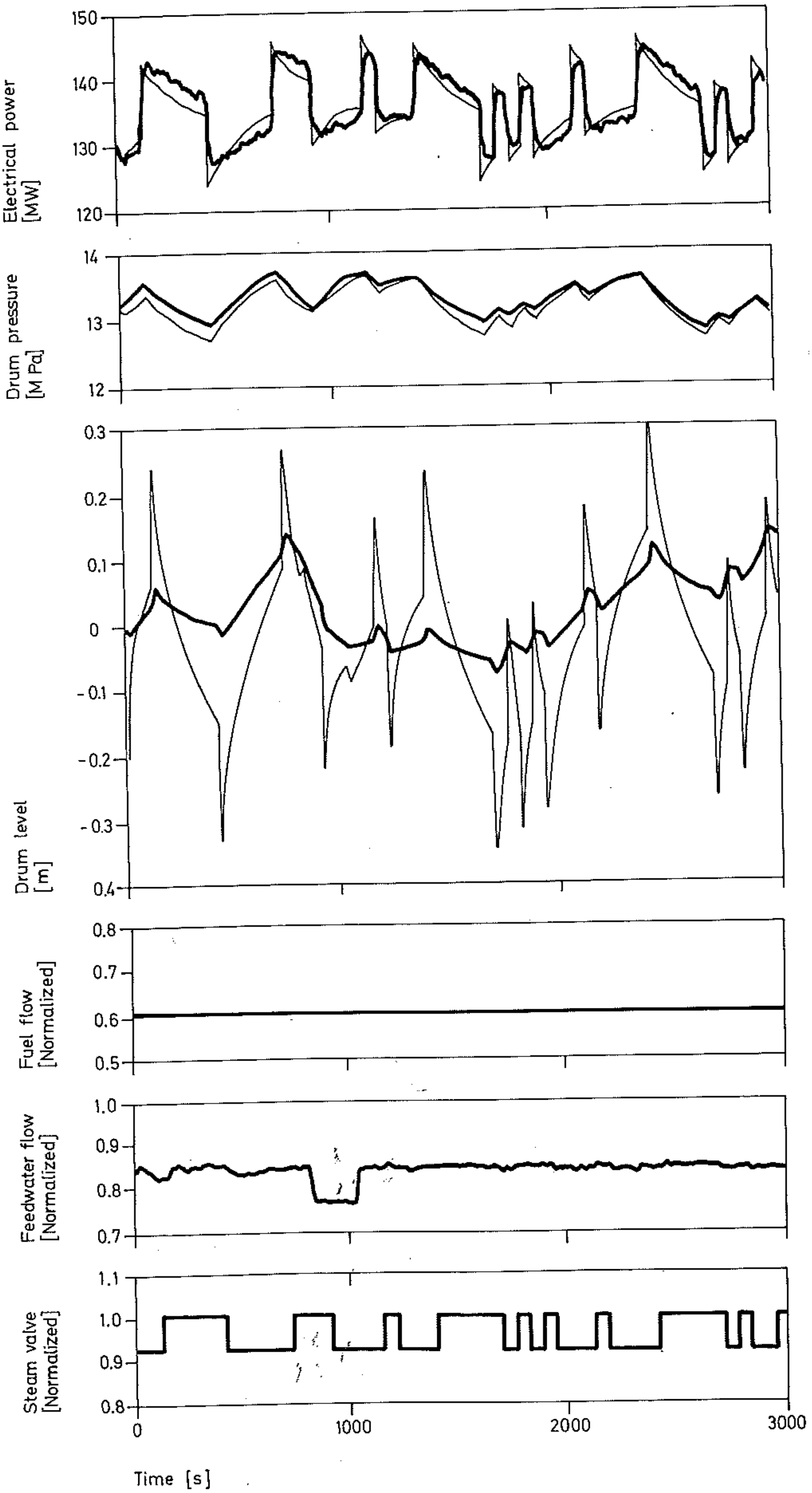

Fig. 6 - Comparison of model output (thin lines) with experimental data (thick lines) at full load with steam valve perturbations.

5. CONCLUSIONS

The comparisons with plant data show that the model describes the main properties of the plant reasonably well. The shrink and swell phenomena is, however, exaggerated in the model. This means that the difficulties in drum level control will not be underestimated when the model is used. It is easy to reduce the shrink and swell by decreasing the parameter α given by Equation (2.2). It is also clear that the model does not describe the influence of all inputs equally well. A comparison with experiments at full load and at half load shows that it is desirable to have a nonlinear model to describe the output power and the drum level well over the whole operating range. Further work is needed to obtain a good model for a particular plant. The results indicate, however, that a model of the chosen complexity is sufficient to describe experiments of the type used in the report. It would also be of interest to estimate the parameters of the model to improve the fit to the data. It is, however, believed that the presented model captures many features of a real plant and that it is accurate enough to be used for testing multivariable control strategies.

6. REFERENCES

Eklund K (1969): Measurements on the P16/G16 unit at Öresundsverket, Sydkraft AB, Malmö, Sweden (Internal memorandum, Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden).

Eklund K (1971): Linear drum boiler-turbine models. Report TFRT-1001, Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Åström K J and Eklund K (1972): A simplified non-linear model of a drum foiler-turbine unit. *Int. J. Control* 16, 145-169.

APPENDIX A

SIMULATION MODEL

```
CONTINUOUS SYSTEM PG16

"          ************************************************
"          *                                              *
"          *                                              *
"          *      LINEAR DRUM BOILER TURBINE MODEL        *
"          *                                              *
"          *                                              *
"          ************************************************

"LINEAR MODEL FOR 160 MW BOILER TURBINE UNIT P16G16 OF
"ORESUNDSVERKET SYDKRAFT AB
"THE MODEL IS BASED ON
"       EKLUND : LINEAR DRUM BOILER MODELS TFRT 1001
"EKLUNDS MODEL HAS BEEN MODIFIED BY INTRODUCING AN EXTRA
"STATE X4 TO MODEL THE SHRINK AND SWELL EFFECT BETTER
"THE FOLLOWING COEFFICIENTS HAVE ALSO BEEN ALTERED TO GET
"BETTER AGREEMENT WITH MEASUREMENTS
"       B13 B14 B23 B24 B43 B44 B63 B84

"AUTHORS K J ASTROM ROD BELL 781206

INPUT U1 U2 U3 U4 U5
OUTPUT Y1 Y2 Y3 Y4 Y5 Y6 Y7
STATE X1 X2 X3 X4 X5 X6 X7 X8 X9 X10
DER DX1 DX2 DX3 DX4 DX5 DX6 DX7 DX8 DX9 DX10

"U1     FUEL FLOW                   10      [1]     KG/S
"U2     FEEDWATER FLOW              120     [10]    KG/S
"U3     SPRAY FLOW 1                0-4     [1]     KG/S
"U4     SPRAY FLOW 2                0-1     [1]     KG/S
"U5     STEAM VALVE POSITION        1-10    [1]

"Y1     OUTPUT POWER                150     [20]    MW
"Y2     POWER FROM LP TURBINE       100     [15]    MW
"Y3     POWER FROM HP TURBINE        50     [ 5]    MW
"Y4     STEAM FLOW                  130     [10]    KG/S
"Y5     DRUM LEVEL                +-300     [100]   MM
"Y6     DRUM PRESSURE               130     [10]    BAR
"Y7     STEAM TEMPERATURE           530     [20]    DEG C
```

```
"X1      DRUM PRESSURE                        140      [10]     BAR
"X2      DRUM LIQUID LEVEL                    +-0.3    [0.1]    M
"X3      DRUM STEAM BUBBLE LEVEL              1        [0.1]    M
"X4      DRUM WATER TEMPERATURE               320      [20]     DEG C
"X5      RISER WALL TEMPERATURE               450      [20]     DEG C
"X6      MEAN VALUE OF STEAM QUALITY          0.1      [0.05]
"X7      WALL TEMPERATURE SUPERHEATER 1       480      [20]     DEG C
"X8      WALL TEMPERATURE SUPERHEATER 2       515      [20]     DEG C
"X9      WALL TEMPERATURE SUPERHEATER 3       570      [20]     DEG C
"X10     WALL TEMPERATURE REHEATER            570      [20]     DEG C

"THE ACTUATORS ARE CHARACTERIZED BY
"    FUEL FLOW U1:
"        TYPICAL START UP TIME FOR BURNER 80 S
"        TYPICAL TIME TO OPEN FUEL VALVE 25 S
"        MAXIMUM RATE OF CHANGE 0.1 KG/(S*S)
"    FEEDWATER FLOW U2:
"        MAXIMUM RATE OF CHANGE 2 KG/(S*S)
"    SPRAY FLOWS U3,U4:
"        MAXIMUM RATE OF CHANGE 0.16 KG/(S*S)
"    STEAM VALVE U5:
"        MAXIMUM RATE OF CHANGE +2/S -20/S

OUTPUT
Y1=C11*X1+C17*X7+C18*X8+C19*X9+C110*X10+D13*U3+D14*U4+D15*U5
Y2=C21*X1+C27*X7+C28*X8+C29*X9+D23*U3+D24*U4+D25*U5
Y3=C31*X1+C37*X7+C38*X8+C39*X9+C310*X10+D33*U3+D34*U4+D35*U5
Y4=C41*X1+C47*X7+C48*X8+C49*X9+D43*U3+D44*U4+D45*U5
Y5=C52*X2+C53*X3+C56*X6
Y6=C61*X1
Y7=C71*X1+C77*X7+C78*X8+C79*X9+D73*U3+D74*U4+D75*U5

DYNAMICS
S1=B12*U2+B15*U5
DX1=A11*X1+A14*X4+A15*X5+A16*X6+A17*X7+A18*X8+A19*X9+S1
S2=B22*U2+B25*U5
DX2=A21*X1+A24*X4+A25*X5+A26*X6+A27*X7+A28*X8+A29*X9+S2
S3=B32*U2+B35*U5
DX3=A31*X1+A33*X3+A34*X4+A35*X5+A36*X6+A37*X7+A38*X8+A39*X9+S3
S4=B42*U2+B45*U5
DX4=A41*X1+A44*X4+A45*X5+A46*X6+A47*X7+A48*X8+A49*X9+S4
DX5=A51*X1+A55*X5+B51*U1
S6=B62*U2+B65*U5
DX6=A61*X1+A64*X4+A65*X5+A66*X6+A67*X7+A68*X8+A69*X9+S6
DX7=A71*X1+A77*X7+A78*X8+A79*X9+B71*U1+B75*U5
DX8=A81*X1+A87*X7+A88*X8+A89*X9+B81*U1+B83*U3+B85*U5
DX9=A91*X1+A97*X7+A98*X8+A99*X9+B91*U1+B93*U3+B94*U4+B95*U5
S10=B101*U1+B103*U3+B104*U4+B105*U5
DX10=A101*X1+A107*X7+A108*X8+A109*X9+A110*X10+S10


A11:-4.368E-2
A14: 1.922E-2
A15: 4.964E-2
A16:-5.094E-1
```

A17: 7,300E-5
A18: 1,380E-4
A19: 5,102E-4
A21:-1,046E-4
A24: 3,394E-4
A25: 2,252E-4
A26:-2,467E-1
A27:-9,980E-7
A28:-1,874E-6
A29:-6,929E-6
A31:-9,853E-3
A33:-0,2
A34:1,533E-2
A35:1,703E-2
A36:-8,633
A37:-3,405E-5
A38:-6,395E-5
A39:-2,364E-4
A41: 1,143E-2
A44:-2,276E-2
A45: 2,533E-3
A46:-3,887
A47:-1,123E-5
A48:-2,108E-5
A49:-7,794E-5
A51: 2,814E-2
A55:-5,024E-2
A61:-9,853E-5
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A71:-1,327E-2
A77:-7,644E-3
A78: 1,429E-4
A79: 5,281E-4
A81:-1,023E-2
A87: 1,561E-2
A88:-1,683E-2
A89: 3,846E-4
A91:-9,515E-3
A97: 4,463E-3
A98: 8,382E-3
A99:-1,190E-2
A101:-3,127E-3
A107: 2,131E-4
A108: 4,002E-4
A109: 1,479E-3
A110:-2,293E-3

B12:-1.584E-3
B15:-1,734E-1
B22: 3,350E-5
B25: 2,354E-5
B32:-9,055E-4
B35:8,032E-2
B42:-3,286E-3
B45: 2,648E-2
B51: 1,200E-1
B62:-9,055E-6
B65: 8,032E-4
B71: 2,132E-1
B73: 1,296E-2
B74: 1.163E-2
B75:-1,794E-1
B81: 2,328E-1
B83:-9,502E-2
B84:-8,470E-3
B85:-1,307E-1
B91: 2,596E-1
B93:-2,749E-2
B94:-7,938E-2
B95:-1,179E-1
B101: 5,643E-2
B103:-1,444E-3
B104:-4,032E-3
B105:-4,920E-4

C11:1,1406
C17:1,726E-3
C18:3,241E-3
C19:1.198E-2
C110:9,844E-2
C21: 1.135E-1
C27: 7,562E-3
C28: 1,420E-2
C29: 5,250E-2
C31: 1,027
C37:-5,836E-3
C38:-1,096E-2
C39:-4,052E-2
C310: 9,844E-2
C41: 7,908E-1
C47:-5,447E-3
C48:-1,023E-2
C49:-3,782E-2
C52:1000
C53:1000
C56:10000
C61:1
C71:-6,971E-2
C77: 1,030E-1
C78: 1,935E-1
C79: 7.153E-1

```
D13:4.573E-2
D14:7.268E-2
D15:1.86E1
D23:-4.019E-2
D24:-1.228E-1
D25: 1.913
D33: 8.592E-2
D34: 1.955E-1
D35: 1.669E1
D43: 7.195E-2
D44: 1.673E-1
D45: 1.285E1
D73:-6.272E-1
D74:-1.819
D75:-2.768E-1

END
```

APPENDIX B

CONNECTING SYSTEM FOR COMPARISON WITH PLANT DATA

```
CONNECTING SYSTEM LMCPD

TIME T

"CONSTANTS FOR DATA D107A

U1[PG16]=(C9[CFILE]-U1A)*CF1
U2[PG16]=(C2[CFILE]-U2A)*CF1
U3[PG16]=(U3C-U3A)
U4[PG16]=(U4C-U4A)
U5[PG16]=IF C10[CFILE]>WSSW THEN U2M+U2R ELSE U2M-U2R
PDVP[PG16]=(C13[CFILE]-PO)/PR
XWP[PG16]=C3[CFILE]/XWSC
POVP[PG16]=(C8[CFILE]-MO)/MR

U3C:5.35
U4C:4.1
U1A:17.2
U2A:220
U3A:5.35
U4A:4.1
WSSW:0
U2M:0
U2R:0.0
XWSC:1
PO:110
PR:1.0
MO:65
MR:1.0
CF1:0.282

END
```