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A LINEAR QUADRATIC CONTROL OF A DRUM BOILER TURBINE

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This paper describes a control of a drum boiler turbine based on linear quadratic theory. The model used is of 10:th order, multivariable and linear. The control consists of a feedback loop and a feedforward strategy. The feedforward part is used to obtain a fast response to the power demand signal.

The work is done by means of the synthesis package SYNPAC.

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Contents

1. INTRODUCTION

A drum boiler-turbine unit is a typical example of an industrial multivariable system. Several attempts have been made to design boiler controls based on different theories for multivariable control, e.g. Eklund (1971), McDonald and Kwatny (1973), Dettinger et al (1974), Marshall and Owens (1976), Lindahl (1976), Chou et al (1977), Sandor and Willamson (1977), Lecrique et al (1978) and Tyssö and Brembo (1978). In this paper linear quadratic theory is used.

In Åström and Bell (1979) a modification of a linear drum boiler turbine model developed by Karl Eklund is described. This new model will be used here.

The work is done by means of the synthesis package SYNPAC. To possibly simplify later use of SYNPAC, the commands used and the method of working are described rather detailed.

For low order systems, there are usually no problems to find suitable penalty matrices in a linear quadratic design. For high order systems however, difficulties often arise. Some of these are clearly shown in this paper. The final control strategy makes the system behave well with respect to disturbances as well as changes in the power demand signal.

The control consists of a feedback loop and a feedforward strategy. The feedback loop is described in section 2. Feedforward is useful to obtain a fast response to command signals. Design at feedforward from an output power demand signal is described in section 3. The boiler turbine model used is given in the appendix.

2. THE FEEDBACK LOOP

It is desired to obtain a well behaved closed loop system using state feedback. Figure 1 shows the feedback loop. The plant, i.e. in this case the model given in the appendix, is denoted by S. The feedback matrix to be designed is L.

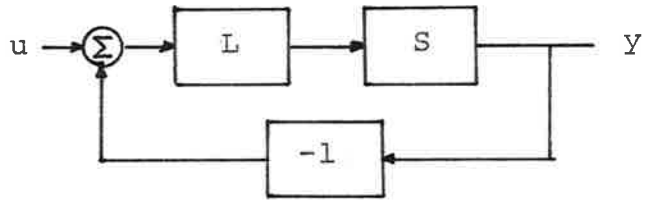


Fig. 1 - The feedback loop

Entering the System Description

We start by making a system description in SYNPAC. Since the system is continuous, the global variable DELTA., denoting the sampling period, should be set to zero. This is done by the command

```
LET DELTA. = 0
```

In our case, there are lots of zeroes in the system matrices. It is then most convenient to introduce the matrices with the commands ZEROM and ALTER. With the command ZEROM a zeromatrix is created. The elements in a matrix can be changed by the command ALTER. The A-matrix is e.g. introduced by the commands

The Lossfunction

SYNPAC also requires a lossfunction on the form

$$J = X(t_1)^T Q0\ X(t_1) + \int_0^{t_1} \left[X(t)^T Q1\ X(t) + X(t)^T Q12\ U(t) + U(t)^T Q2\ U(t) \right] dt$$

i.e. a function of the state and the control variables. Sometimes it is more natural to think of the lossfunction as a function of other variables, i.e. the output and control variables. For this purpose, there is in SYNPAC a possibility to define an extended lossfunction, and then with the command PENLT transfer the extended lossfunction to the ordinary form above. In our case it was convenient to use a lossfunction on the form

$$J = \int_0^{t_1} \left[X(t)^T EQ1\ X(t) + U(t)^T EQ2\ U(t) + Y(t)^T EQ4\ Y(t) \right] dt$$

where the matrix EQ1 is a zeromatrix at the beginning.

Our goal is to keep the output power, Y(1), Y(2) and Y(3), and the steam temperature, Y(7), as undisturbed as possible, with the control variables and the other output variables only varying within reasonable ranges. With this in mind, EQ2 and EQ4 were first chosen as

EQ2 = diag(2.5 0.025 2.5 2.5 2.5)
EQ4 = diag(0.4 0.8 7 0 0 0 0.4)

Each element in the matrices is inversely proportional to the square of the typical variation in the corresponding variable, and the product of the nonzero elements in each matrix is equal to one. In EQ4, the 4:th, 5:th and 6:th diagonal element were set equal to zero.

The matrices in the extended lossfunction are created and placed in an aggregate, here called ESLOSS, an the same way as the system matrices.

Now we have an aggregate S which contains the system matrices, and an aggregate ESLOSS which contains the extended lossfunction matrices. With the command SYST, these aggregates can be tied together into a system description. This system description must also contain an aggregate, here called SLOSS, which contains the matrices of the ordinary lossfunction. SLOSS is created by the command PENLT. The commands in our case are

```
SYST(SC) S < ABCDX0
  AG(L) SLOSS
  AG(E) ESLOSS
  IN Q1
  IN Q12
  IN Q2
  IN EQ1
  IN EQ2
  IN EQ4
  X
PENLT S
```

(written in this way, there is no need for subcommands to insert the aggregate S).

Preleminary Design

In the first design, I put the matrix Q12 equal to zero, since I wanted a lossfunction consisting of just a Q1 and a Q2 matrix.

The system S now contains all information needed to calculate the optimal feedback matrix L. This is done by the command

```
OPTFB L M < S
```

The matrix M is the solution to the stationary Riccati equation.

It is now possible to calculate the closed system, since both L and S in figure 1 are known. With the command SYSOP, L and S can be tied together creating the closed system, here put into the section CLOSED inside S. The commands are

```
SYSOP S(CLOSED)< SM /M/L
  IN U1< U-Y2
  IN U2< X1
  OUT Y< Y1
  OUT Z < U-Y2
  X
```

All variables indicated with "1" originates from S, and the variables indicated with "2" originates from L. The variable Z is introduced just to give a possibility to look at the input signal to S. The input signal U must be present, but will in our case be set to zero. It is created by the command INSI. Before creating U, the global variable DELTA. must be changed to a nonzero value. In this case DELTA. was set to 1. If the system shall be simulated during 200 seconds, the input datafile U must have five columns with 200 elements in each. The commands are

```
LET DELTA.=1
INSI U 200
  ZERO
  ,
  ,
  ,
  ,
  X
```

Finally the variables can be simulated and plotted using the commands SIMU and PLOT. The commands are

```
SIMU Y Z X < S(CLOSED) U
PLOT Y Z X
```

It appeared that the first attempted lossfunction gave too high gains, and that the "free" output signals had too large variations. Therefore the lossfunction was modified to

EQ2 = diag(25 0.25 25 25 25)

EQ4 = diag(0.5 0.5 10 0.01 0.01 0.01 0.5)

Now the problem became more difficult. If one tries to suppress one signal, at least one other will blow up. It was not possible to make all signals wellbehaved, just by modifying EQ2 and EQ4. If we introduce a penalty on the state variables (EQ1), we get some more degrees of freedom, since the system is of 10:th order, while there are only seven output variables. The greatest problem was to get a good behavior of the drum level, Y(5). It appeared that it was very dependent on the drum steam bubble level, X(3). Therefore the extended lossfunction matrix EQ1 was introduced, with the value corresponding to X(3) nonzero. With this strategy, there was no problem to suppress the drum level.

Final choice

After several iterations like the one above, it appeared that the lossfunction having the matrices

EQ1 = diag(100 0 10^5 0 0 0 0 0 0 0)

EQ2 = diag(1000 5 25 100 50 000)

EQ4 = diag(0.5 0.5 10 0.01 0.01 0.01 0.5) gave reasonable well behaved signals. Some of the most interesting are shown in figure 2. The feedback matrix, L, was

$$
L = \left[\begin{array}{ccccc}
7.945364-002 & .404479 & .960021 & .148191 & .193830 \\
-3.984979-002 & 37.7930 & -35.7746 & -1.37060 & -1.88465 \\
7.116503-003 & -1.336705-002 & .285758 & 5.970158-002 & 3.691968-002 \\
-3.780187-003 & 1.873944-002 & 6.687419-002 & 1.747565-002 & 8.154916-003 \\
-1.379024-002 & -.225579 & .287677 & 4.416674-003 & 5.201262-003
\end{array}\right.
$$

$$
\left.\begin{array}{ccccc}
-41.7535 & 2.123553-003 & 1.740163-003 & 3.307226-003 & 2.626547-003 \\
120.586 & 1.419594-002 & 6.536979-003 & 1.627329-002 & -1.260155-002 \\
-49.6910 & -1.805023-002 & -1.332770-002 & -2.689688-002 & 2.934883-004 \\
-15.7990 & -3.900134-003 & -3.498717-003 & -7.769091-003 & -5.238223-004 \\
.509854 & 9.302246-005 & 1.114948-005 & -7.714274-005 & -7.457150-005
\end{array}\right]
$$

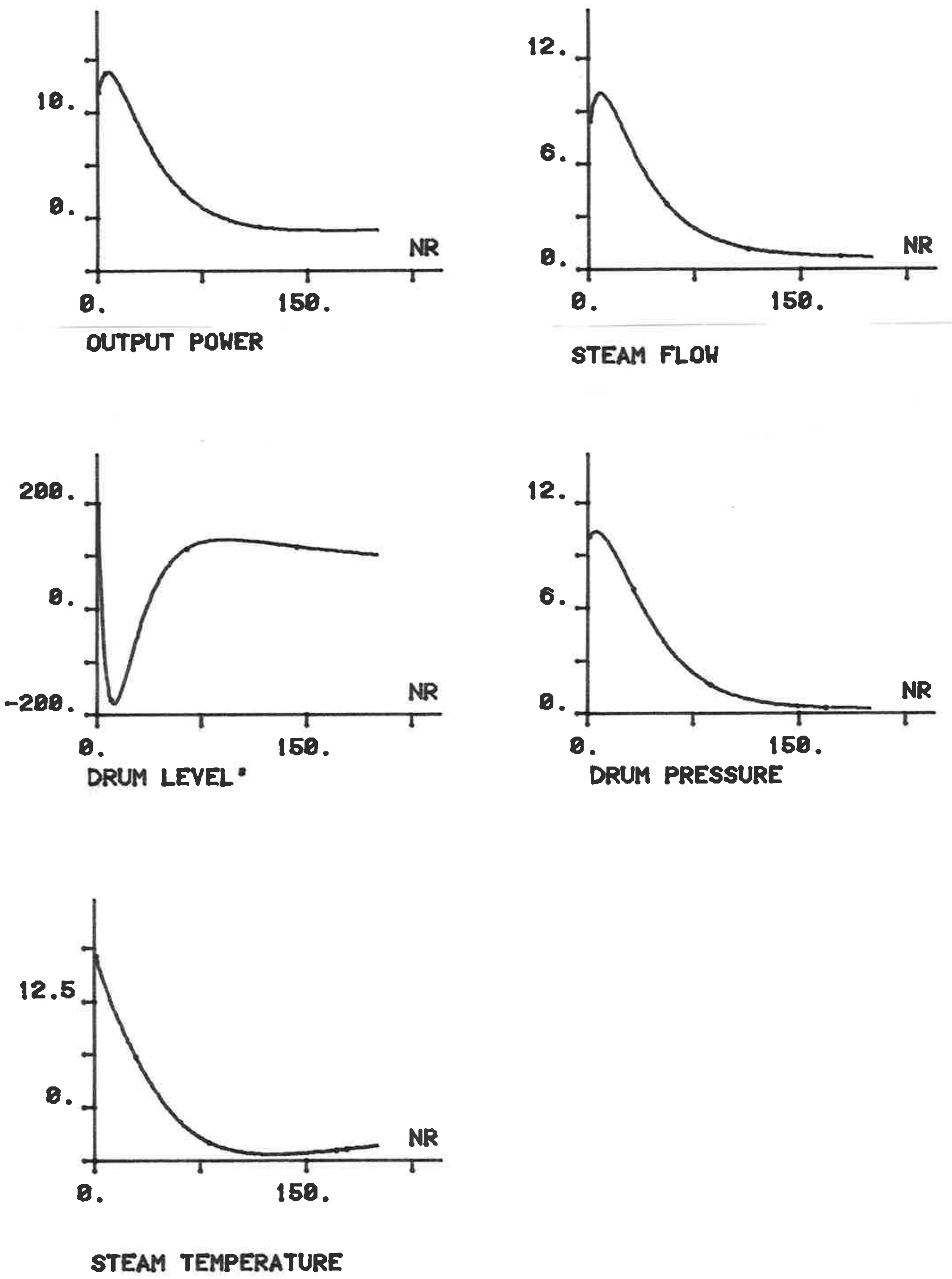


Fig 2.a - Some output signals due to an initial disturbance in the state vector.

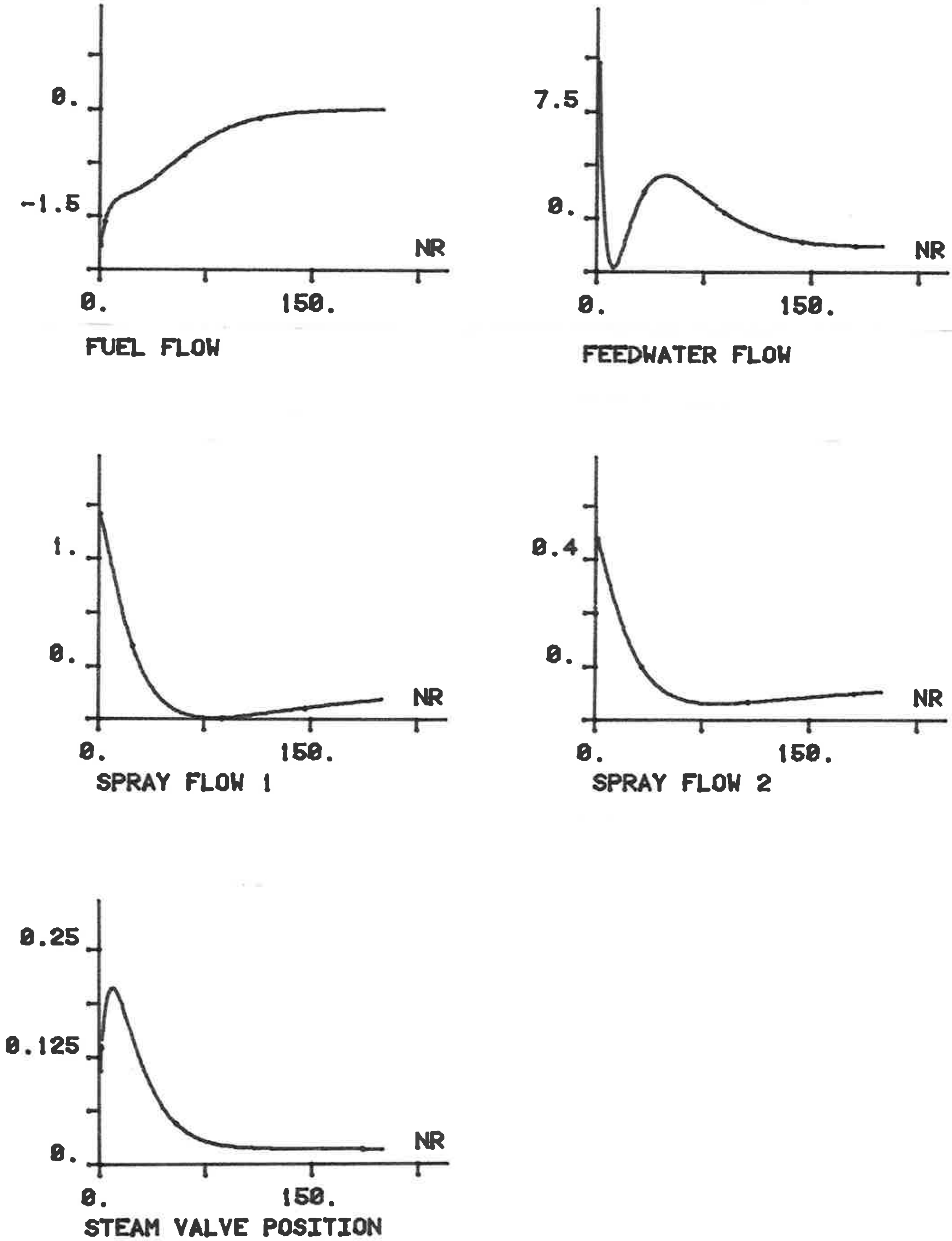


Fig 2.b - The control signals due to an initial disturbance in the state vector.

3. THE FEEDFORWARD STRATEGY

A block diagram showing the feedforward strategy is shown in figure 3.

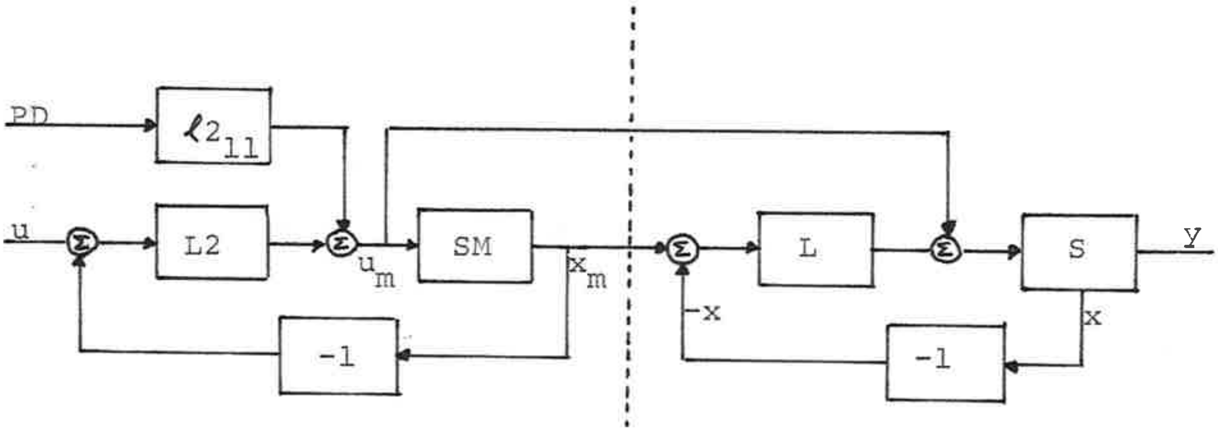


Fig. 3 - The feedforward strategy

The right-hand loop is the feedback loop designed in section 2. The desired plant model is SM, i.e. in our case it is exactly the same model as S. The power demand signal is PD. U will be set to zero as in section 2. L2 and $\ell 2_{11}$ are feedback and feedforward matrices to be designed using linear quadratic theory.

If the power demand signal is constant, the total system will react exactly as the system designed in section 2 with respect to disturbances in S. On the other hand, if there are no disturbances in S, and we change PD, there will be no signals in front of L, since x_m and x will become identical. Hence the reaction of the total system to a change in PD is only dependent on the matrices L2 and $\ell 2_{11}$. Since S and SM are identical, it is no restriction to cut the system at the dotted line shown in figure 3, and just look at the left half when we design our feedforward strategy.

The power demand signal is discussed in Lindahl (1976). Suppose that the output power shall be increased from 100 MW to 150 MW. Then a good choice of PD is one that starts with a step of 5 MW followed by a ramp with a rate of 9 MW/min during 5 minutes. However, a step will cause large pulses in the signals, since there is nothing in the model describing the maximum rate of change in the valves. Therefore the step was replaced by a ramp, which forced PD from 0 to 5 MW in ten seconds. The power demand signal was created by the following commands

```
INSI R 10
  RAMP 0 0.5
  X
INSI S 300
  RAMP 5 0.15
  X
INSI T 190
  STEP
  X
SCLOP T<T*50
CONC PD<R S
CONC PD<PD T
```

In order to be able to compute the matrices L2 and $\ell 2_{11}$ using OPTFB, the power demand input is modeled by introducing an extra state. PD is placed as the 11:th column in U. The new state space representation becomes

$$\begin{bmatrix} \dot{x} \\ \dot{x}_{11} \end{bmatrix} = \begin{bmatrix} A & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ x_{11} \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u_m$$

$$y = \left(C \quad \begin{matrix} -1 \\ 0 \\ \vdots \\ 0 \end{matrix} \right) \begin{bmatrix} x \\ x_{11} \end{bmatrix} + D\, u_m$$

$$u_m = (L2 \quad \ell 2_{11}) \left(\begin{bmatrix} x \\ x_{11} \end{bmatrix} + \begin{bmatrix} u \\ PD \end{bmatrix} \right)$$

where A,B,C and D are the system matrices given in the appendix. If the extended lossfunction is chosen as in section 2, with a relatively high value in the upper left position of EQ4, the output power will approximately follow the power demand signal, since x_{11} is zero.

It appeared that it was impossible for me to solve this design problem with the Q12 matrix equal to zero. When I finally allowed Q12 to keep the value computed by PENLT, the problem got much easier to solve. The final lossfunction having the matrices

$$EQ1 = \mathrm{diag}(20\ 000 \quad 0 \quad 10^7 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0)$$
$$EQ2 = \mathrm{diag}(10\ 000 \quad 5 \quad 30\ 000 \quad 40\ 000 \quad 0.0001)$$
$$EQ4 = \mathrm{diag}(100\ 000 \quad 0 \quad 0 \quad 0 \quad 3 \quad 0.1 \quad 5\ 000)$$

gave the feedback/feedforward marices

$$L2 = \left[\begin{array}{ccccc}
.857247 & 14.4542 & -.617801 & .130837 & .392006 \\
-35.5902 & 206.632 & -1154.07 & -5.30096 & -27.5642 \\
.115219 & 2.84235 & -.181365 & 2.611723-002 & 5.867752-002 \\
7.084967-002 & 1.34536 & -.123872 & 1.222674-002 & 3.096824-002 \\
5.470542-002 & -.103613 & 2.692262-002 & -7.278736-004 & -2.329807-003
\end{array}\right.$$
$$\left.\begin{array}{ccccc}
26.7780 & 1.553063-002 & 7.956760-002 & .295709 & 7.194247-002 \\
-17567.4 & 1.75572 & 1.38012 & 2.93081 & -2.16280 \\
-1.16464 & -2.167459-002 & -2.404664-002 & -7.468785-002 & 1.183309-002 \\
.187110 & -2.311016-002 & -3.646459-002 & -.127710 & 4.691435-003 \\
-2.994910-002 & 6.439474-004 & 5.628531-004 & 1.611786-003 & 4.765919-003
\end{array}\right]$$

$$\ell 2_{11} = \begin{bmatrix} -1.00326 \\ 24.0071 \\ -.164720 \\ -6.063950-002 \\ -4.645291-002 \end{bmatrix}$$

Some interesting signals are shown in figure 4. In Lindahl (1976), the same change in the output power is done in a nonlinear turbine model. The agreement of the curves in figure 4 and those given in that report is good. The only considerable differences are that we seem to have a smaller steam flow and greater spray flows in the attemperators.

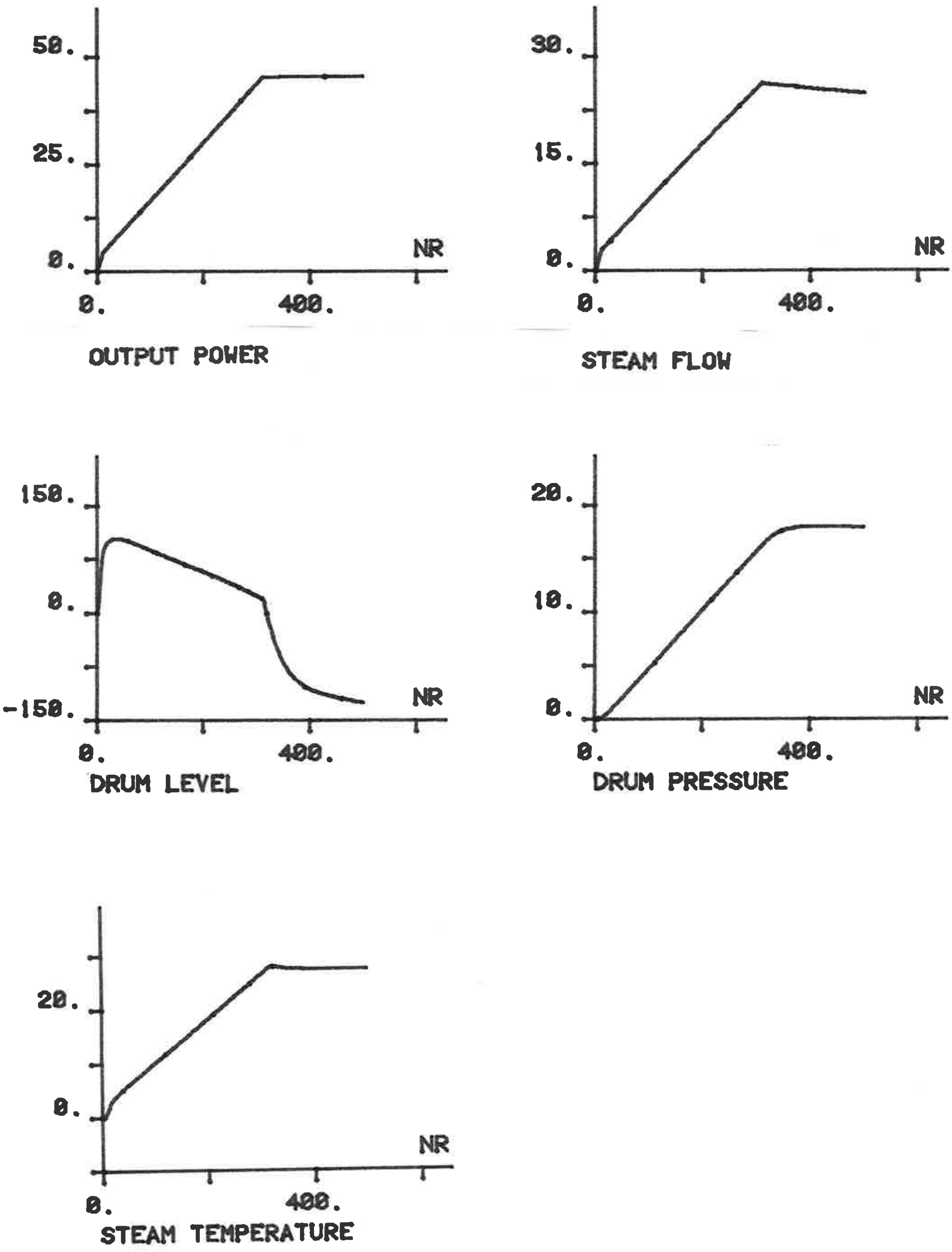
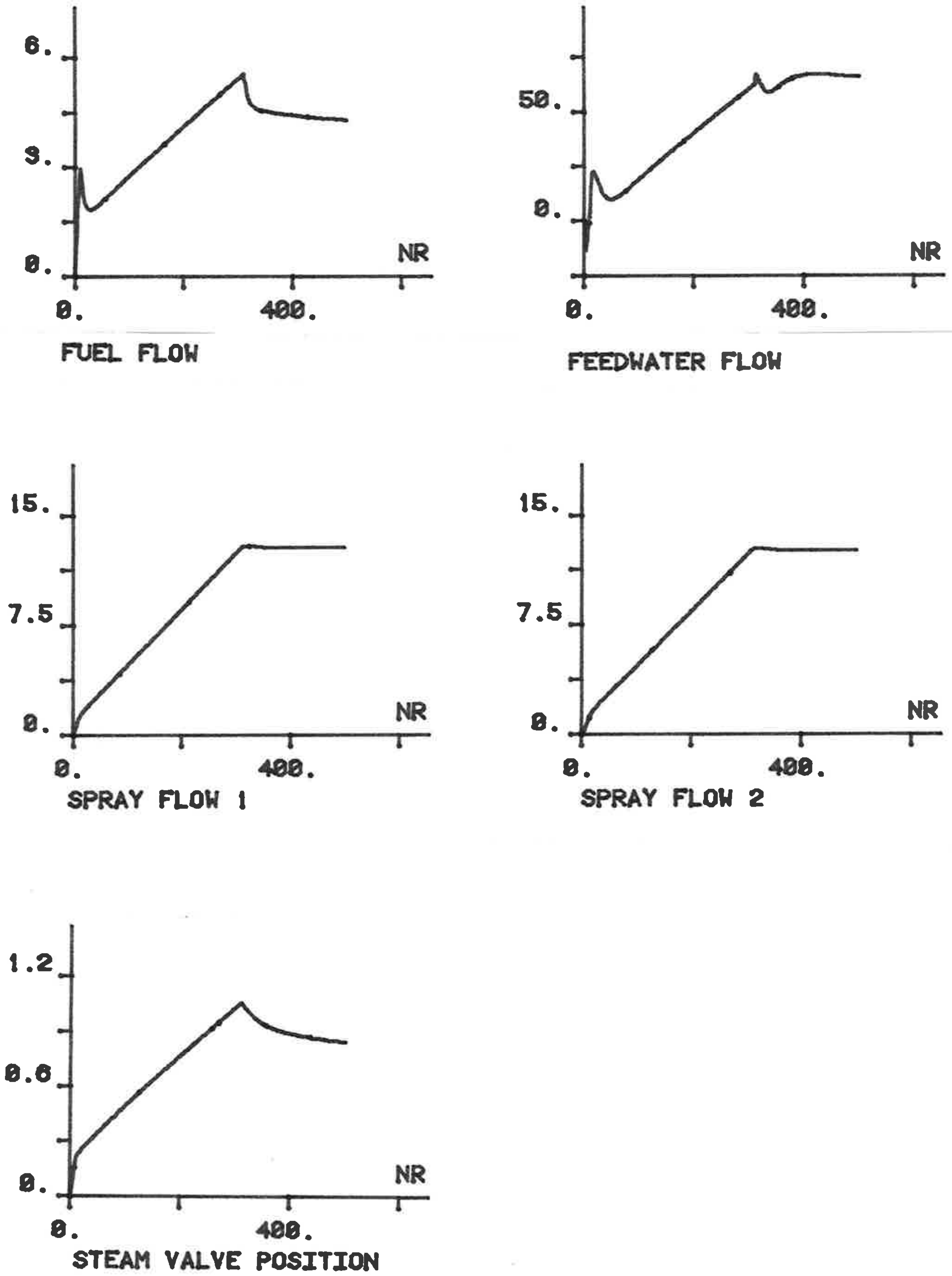


Fig 4.a - Some output signals due to an increase in the output power.



<u>Fig 4.b</u> - The control signals due to an increase in the output power.

4. EXPERIENCES

Standard textbooks in linear quadratic theory usually deal with low order systems. In these cases there are few difficulties in choosing suitable penalty matrices. This problem has taught me that the selection of suitable lossfunctions in the linear quadratic design can be quite difficult.

Most theory of linear quadratic design assume that there is no term in the lossfunction which contains cross-products of states and control variables ($Q12 = 0$). In this case it turned out to be crucial to have $Q12 \neq 0$.

Finally, I have been convinced that problems like this are unsolvable in practice, if one doesn't have access to a synthesispackage like SYNPAC.

5. ACKNOLEDGEMENT

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McDonald J P and Kwatny H G (1973): Design and analysis of boiler-turbine-generator controls using optimal linear regulator theory. IEEE AC <u>18</u>.

Sandor J and Willamson D (1977): Optimal nonlinear control theory with applications to boiler-turbine control. IFAC Symposium, Melbourne, Australia.

Tyssö A and Brembo J C (1978): Installation and operation of a multivariable ship boiler control system. Automatica <u>14</u>.

Wieslander J (1980): SYNPAC commands. Report TFRT-3159, Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden.

$$D = \begin{bmatrix} .000000 & .000000 & 4.573000\text{-}002 & 7.268000\text{-}002 & 18.6000 \\ .000000 & .000000 & -4.019000\text{-}002 & -.122800 & 1.91300 \\ .000000 & .000000 & 8.592000\text{-}002 & .195500 & 16.6900 \\ .000000 & .000000 & 7.195000\text{-}002 & .167300 & 12.8500 \\ .000000 & .000000 & .000000 & .000000 & .000000 \\ .000000 & .000000 & .000000 & .000000 & .000000 \\ .000000 & .000000 & -.627200 & -1.81900 & -.276800 \end{bmatrix}$$