A Simple Drum Level Model

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A simple drum level model.

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A simple model which relates drum level to fuel flow, feedwater flow, steam flow, and drum density is derived from first principles. The model has two states which are chosen as the total amount of water in the drum, downcomers, and risers and the average steam quality in the risers. Preliminary validation against plant measurements is presented.

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1. INTRODUCTION

One reason why complex regulators may give better results than ordinary three term controllers is that they can anticipate plant behaviour better. To do so it is necessary to base the design of the regulators on good process models. The choice of a reasonable model complexity is largely a matter of engineering judgement and experience. For control system design it is therefore useful to have an hierarchy of models available. This report is part of a long range project aimed at developing such a model hierarchy for boilers, both conventional and nuclear. A simple model which only accounts for energy storage was developed in Åström and Eklund (1972, 1975). A comparatively simple model which also describes the drum level was given in Bell and Åström (1979). In this paper a very simple nonlinear model for drum level is given. The model is based on the insight obtained from Bell and Åström (1979). In terms of number of state variables it is probably the simplest possible model. It has only two states which are chosen as drum level and average steam quality. The model is based on simple balance equations which are stated in Section 2. The state equations are given in Section 3. The equations are linearized in Section 4 where the transfer functions for the important loops are also given. An advantage with a simple model is that it is easy to relate model behaviour directly to physical parameters. The shrink and swell phenomena is discussed in Section 5 where it is shown how the gross characteristics relate to major physical properties of the plant. The simple model is characterized by four parameters, the drum area, the riser volume, the total volume of drum risers and down comers, and the friction coefficient in the downcomer riser loop. In Section 6 it is shown how well the model fits experimental data. The measurements made by Eklund (1971) were used for the comparison. A SIMNON program for simulating the model is included in an Appendix.

the density in the downcomers there will be a force which drives the circulation in the downcomer riser drum system. To describe the drum level it is necessary to account for the total amount of water in the system and the total amount of steam below the drum level. In this simple model it is assumed that there is only steam in the risers and that the steam in the drum can be neglected.

Notations

a	average steam quality in risers [volume ratio]
A_d	area of wet surface in drum [m^2]
$b = 1+aV_r/V_s$	dimensionfree parameter
h_c	evaporation enthalpy of water [J/kg]
k	friction coefficient in downcomer riser loop
P	power supplied to water in risers from fuel [W]
q	circulation flow [kg/s]
q_{fw}	feedwater flow [kg/s]
q_s	steam flow to turbine [kg/s]
ρ_s	steam density [kg/m^3]
ρ_w	water density [kg/m^3]
V_r	volume of risers [m^3]
V_s	volume of steam in drum [m^3]
V_t	total volume of drum risers and downcomers [m^3]
V_w	volume of water in drum downcomers and risers [m^3]
x	drum level [m]
x_r	average steam quality at riser outlet [mass ratio]

3. STATE EQUATIONS

The balance equations will now be reduced to state space form. It is assumed that the inputs to the system are

P power supplied by the fuel

q_{fw} feedwater flow

q_s steam flow

The state variables are chosen as ρ_s, V_w, and a. Neglecting the variations of water density with temperature and pressure the equations (2.1), (2.2), and (2.3) can be written as

$$\begin{cases} V_s \dfrac{d\rho_s}{dt} - \rho_s \dfrac{dV_w}{dt} - \rho_s V_r \dfrac{da}{dt} = x_r q - q_s \\ \rho_w \dfrac{dV_w}{dt} = q_{fw} - q_s \\ a V_r \dfrac{d\rho_s}{dt} + \rho_s V_r \dfrac{da}{dt} = P / h_c - x_r q. \end{cases} \tag{3.1}$$

The time derivatives of the state variables can be solved with simple calculations. We get

$$\begin{cases} b V_s \dfrac{d\rho_s}{dt} = P / h_c + (\rho_s/\rho_w) q_{fw} - (1+\rho_s/\rho_w) q_s \\ \rho_w \dfrac{dV_w}{dt} = q_{fw} - q_s \\ \rho_s b V_r \dfrac{da}{dt} = P/h_c - qx_r + a(V_r/V_s)(q_s - x_r q) + \\ \qquad + a(V_r/V_s)(\rho_s/\rho_w)(q_s - q_{fw}) \end{cases} \tag{3.2}$$

where

$$b = 1 + aV_r/V_s \tag{3.3}$$

and q is given by (2.5). Notice that the equation for steam quality

4. LINEARIZATION

The state equations will now be linearized. The linearized equations will then be used to obtain insight into the properties of the model. Before the equations are linearized an appropriate stationary solution will be determined.

Stationary Solutions

It is easier to determine the stationary solutions directly from the balance equations. It follows from (2.1) and (2.3) that in steady state we have

$$q_s = q_{fw} = x_r q = 2a(\rho_s/\rho_w)\ q.$$

Furthermore equation (2.4) implies

$$P = h_c\ x_r\ q = h_c\ q_{fw}.$$

The circulation flow can be determined by eliminating a from (2.5) and (4.1). Hence

$$\frac{1}{2}(\rho_w - \rho_s)\ V_r\ q_s\ (\rho_w/\rho_s) = \frac{1}{2} k\ q^3.$$

This implies that

$$q = \sqrt[3]{(\rho_w - \rho_s)\ (\rho_w/\rho_s)\ V_r\ q_s / k}.$$

Summarizing we find that the control variables must satisfy the following conditions to achieve steady state.

$$q_s = q_{fw} \tag{4.1}$$

$$P = h_c\ q_{fw} \tag{4.2}$$

The circulation flow is

$$q = \sqrt[3]{(\rho_w - \rho_s)\ (\rho_w/\rho_s)\ V_r\ q_s / k} \tag{4.3}$$

and the steady state value of the steam quality is then given by

$$b_{12} = \frac{\rho_s}{\rho_w[V_s + aV_r]}$$

$$b_{13} = -\frac{1 + \rho_s/\rho_w}{V_s + aV_r}$$

$$b_{22} = 1 / \rho_w$$

$$b_{23} = -1 / \rho_w$$

$$b_{31} = \frac{1}{h_c\rho_s V_r[1 + aV_r/V_s]}$$

$$b_{32} = -\frac{a}{\rho_w[V_s + aV_r]}$$

$$b_{33} = \frac{a[\rho_w + \rho_s]}{\rho_s\rho_w[V_s + aV_r]} \tag{4.6}$$

Simplifications

The number a_{31} in the linearized model is very small. The number becomes even smaller if it is also taken into account that there is a mass exchange between the water and the steam in the drum. Water condenses if the steam temperature is higher than the drum water temperature and water evaporates if the steam temperature is lower than the drum water temperature. If the number a_{31} can be neglected the model simplifies considerably because the differential equation for drum density can be decoupled from the other equations. The amount of water in the system and the steam quality are thus given by

$$\frac{d}{dt}\begin{pmatrix}\delta V_w \\ \delta a\end{pmatrix} = \begin{pmatrix}0 & 0 \\ 0 & a_{33}\end{pmatrix}\begin{pmatrix}\delta V_w \\ \delta a\end{pmatrix} + \begin{pmatrix}0 & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{32}\end{pmatrix}\begin{pmatrix}\delta P \\ \delta q_{fw} \\ \delta q_s\end{pmatrix}. \tag{4.7}$$

5. THE SHRINK AND SWELL PHENOMENA

Having obtained the transfer function (4.11) relating drum level to steam flow it is now possible to discuss the shrink and swell phenomena quantitatively. The transfer function is given by

$$G(s) = K\left[-\frac{1}{s} + \frac{c}{s+\alpha}\right] \qquad (5.1)$$

where

$$\alpha = \frac{3q}{\rho_w V_r} \qquad (5.2)$$

$$c = \frac{aV_r(1+\rho_w/\rho_s)}{V_s + aV_r} \qquad (5.3)$$

$$K = \frac{1}{A_d \rho_w} . \qquad (5.4)$$

The step response is given by

$$H(t) = K\left[-t + \frac{c}{\alpha}(1-e^{-\alpha t})\right] \qquad (5.5)$$

After a positive step change in steam flow the drum level will thus increase initially if $c > 1$ i.e.

$$a \rho_w V_r > \rho_s V_s \qquad (5.6)$$

which is the condition that swell occurs. If this condition is satisfied the step response has a maximum

$$\max_{0 \leq t \leq \infty} H(t) = K(c + \ln c - 1) / \alpha \qquad (5.7)$$

at

$$t = \frac{\ln c}{\alpha}. \qquad (5.8)$$

The step response changes sign approximatively at

$$t_1 = c(1-e^{-c}) / \alpha. \qquad (5.9)$$

6. VALIDATION

The model is characterized by the following parameters:

A_d wet area in drum

V_r volume of risers

V_t total volume of downcomers, risers and drum

k friction coefficient in risers.

The first three parameters are easily determined from physical data. The friction coefficient can be determined if the circulation flow is known. For the P16 - G16 boiler turbine unit of Öresundsverket the following numerical values are appropriate for full load operating conditions:

$A_d = 27 \text{ m}^2$

$V_r = 37 \text{ m}^3$

$V_t = 72 \text{ m}^3$

$k = 0.01.$

See Larsson and Öhbom (1969).

Step Responses

The responses of the model to 4 step changes in the inputs are shown in Figs. 6.1, 6.2, and 6.3. The Simnon programs used to generate these curves are given in Appendix A. In these simulations the density of the steam in the drum has been regarded as an input.

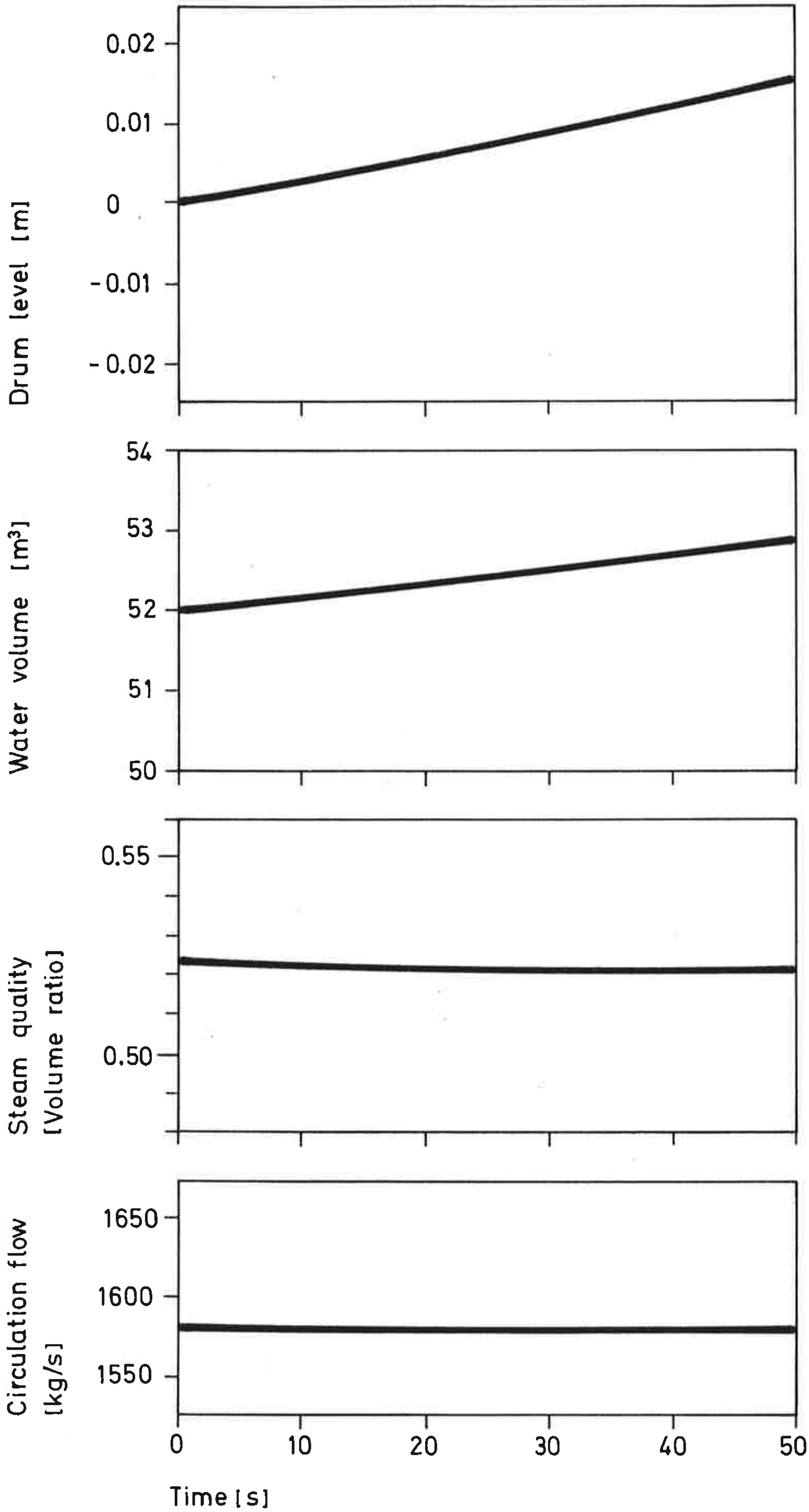

Fig. 6.2 - Responses of the model to a 10 % step change in feedwater flow.

Plant Measurements

Extensive plant experiments were performed by Eklund (1971). The simple drum level model has been validated using Eklund's data. Measured values of fuel flow, feedwater flow, steam flow, and drum pressure were used as inputs to the model. The power supplied to the boiling water was assumed to be proportional to the fuel flow. The drum density was calculated from drum pressure using a simple approximation. The details and the specific numbers used are found in the connecting system NLCPD in Appendix B. The drum level was then calculated from the model and the values obtained were compared with the measured drum level.

Fuel flow perturbations

In experiment A of Eklund (1971) there was a PRBS-like perturbation in fuel flow at full power operating conditions. The result obtained when calculating the drum level from the data of experiment A is shown in Fig. 6.4.

Feedwater flow perturbations

In experiment B of Eklund (1971) there was a PRBS-like perturbation in fuel flow at full load operating conditions. The results obtained when calculating the drum level from the data of experiment B using the model are shown in Fig. 6.5.

Steam flow perturbations

In experiment E of Eklund (1971) there was a PRBS-like perturbation of the steam value at full load operating conditions. The results obtained when calculating the drum level from the data of experiment E is shown in Fig. 6.6.

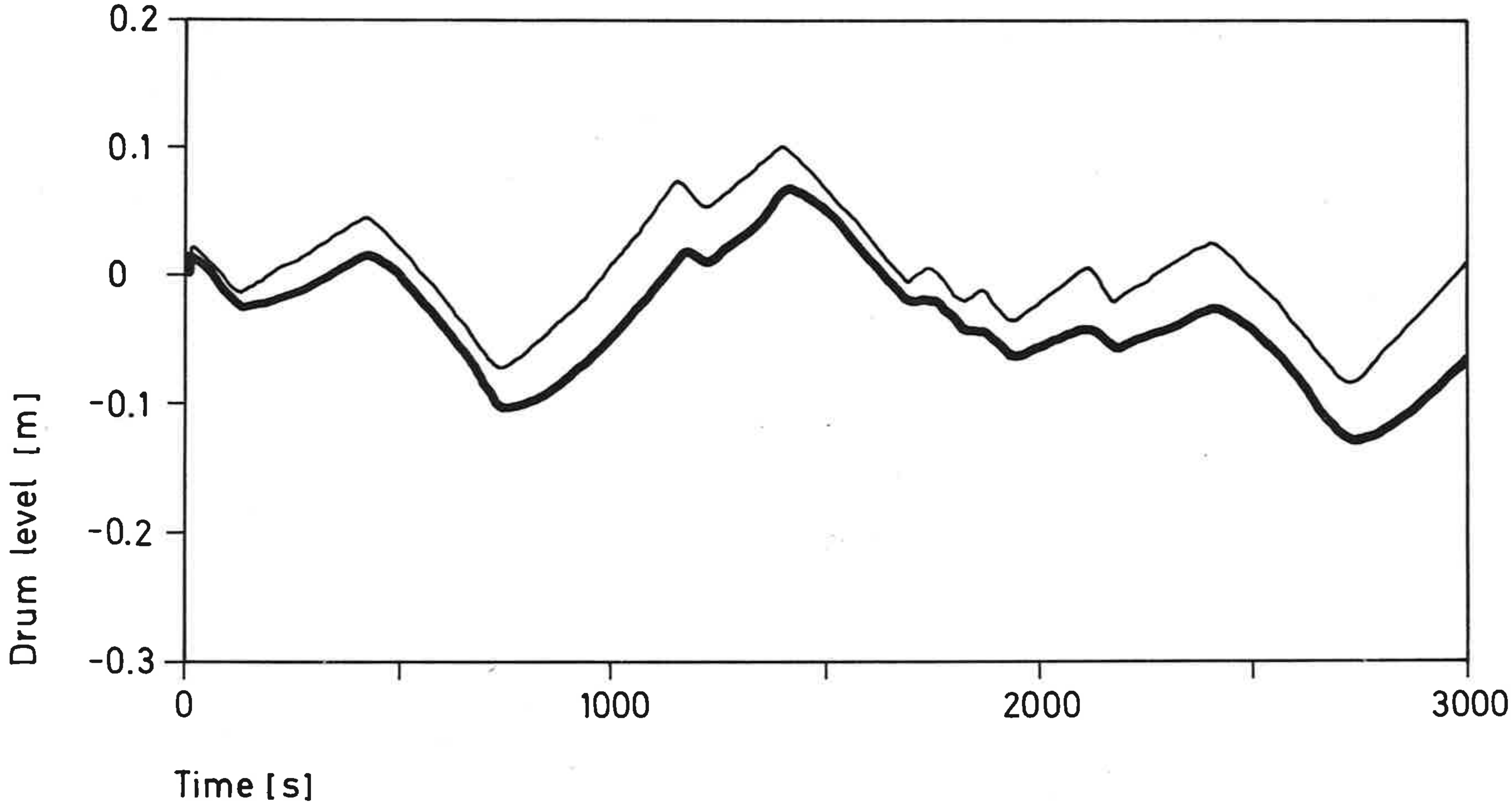

Fig. 6.5 - Drum level computed from the model (thin line) and measured drum level (thick line) from experiment B of Eklund (1971) with feedwater flow perturbations.

Conclusions

The simple model appears to give a reasonable description of drum level. Notice that nominal values were used for the parameters A_d, V_d, and V_r and that only a crude estimate of k was used. Some improvement can be expected if the friction coefficient is estimated more accurately. It is, however, not possible to adjust the parameter k so that both the circulation flow q and the steam quality at the riser outlet x_r have reasonable values. If x_r is reasonably 0.15 - 0.20 then the circulation flow is too high. This drawback can be eliminated by replacing Equation (4.4) which is an approximation by the more accurate expression

$$a = \frac{\rho_w}{\rho_w - \rho_s}\left[1 - \frac{\rho_s}{x_r(\rho_w - \rho_s)} \ln\left(1 + \frac{x_r(\rho_w - \rho_s)}{\rho_s}\right)\right].$$

APPENDIX A

A listing of the Simnon program used to simulate the model is given below.

```
CONTINUOUS SYSTEM DRUM1
"MODEL FOR DRUM-DOWNCOMER-RISER
"DATA FOR ORESUNDSVERKET P16/G16

"AUTHOR K J ASTROM 790504

INPUT POW QFW QS RS
OUTPUT DL Q XR
STATE VW A
DER DVW DA

INITIAL
A:0.523375
VW:52

OUTPUT
DL=(VW+A*VR)/AD-DL0
Q=SQRT(2*(RW-RS)*A*VR/K)
XR=2*A*RS/RW
ALPHA=3*Q/(RW*VR)
VS=VT-VW
C=A*VR*(1+RW/RS)/(VS+A*VR)

DYNAMICS
DVW=(QFW-QS)/RW
B=1+A*VR/VS
DA=(-2*A*B*(RS/RW)*Q+POW/HC-A*VR/VS*((RS/RW)*QFW-
    -(1+RS/RW)*QS))/(RS*B*VR)

AD:27
VT:72
VR:37
K:0.01

DL0:2.64318
RW:700
HC:1.3E6

END
```

APPENDIX B

Eklund's measurements are stored on a file. To calculate the model response the following connecting system was used.

```
CONNECTING SYSTEM NLCPD

"CONNECTING SYSTEM FOR SIMULATING DRUM1 WITH EKLUNDS DATA

TIME T

POW[DRUM1]=C9[CFILE]*CF1
QS[DRUM1]=(C10[CFILE]+C11[CFILE])/CF2
QFW[DRUM1]=C2[CFILE]/3.6
P=C4[CFILE]
RS[DRUM1]=IF P<100 THEN 55.43 ELSE 55.43+.7136*(C4[CFILE]-100)
XWP=C3[CFILE]/XWSC

CF1:1.5E7
CF2:3.7
XWSC:1000


END
```

A special Simnon version stored on disc 9 was used for the CFILE system. The following procedures and system commands were used.

```
$PIP
>T RK-RK <EXT> SIMNON XXX (D)
>T RK-RK <EXT> SIMNON XCT (B)
>T RK-RK <ROD> SYSTEM XXX (D)
>T RK-RK <ROD> SYSTEM XCT (B)

Back to DOS
$A RK 3/RK <EXT> 4/NON 5,7,15,16
$BUFFS 6
$E SIMNON
 >LET N.CFILE = 13                       "number of columns in Eklund's data
 >LET FNAME.CFILE = D201A                "data file name
 >SYST CFILE DRUM1 NLCPD
 >
```

Different experimental data is picked out simply by changing the global variable FNAME.CFILE. The names for the different experiments are listed below.

Pärmprov