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MULTIVARIABLE CONTROL OF A BOILER

K. Eklund

ABSTRACT

A summary of a study covering both modelling and control of a drum boiler is presented. A systematic approach to the modelling problem - numerical modelbuilding - is introduced. This technique was applied to the modelling of the drum of the boiler. The dynamics of different order models were compared. The load disturbances were modelled from measurements as a stationary stochastic process with rational spectral density function. Linear quadratic control theory was applied to design control laws for the drum pressure and level control. A Kalman filter for estimation of the state vector as well as the load disturbance was included. The boiler control was simulated on a hybrid computer.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

The thesis consists of this summary and the reports

- Linear mathematical models of the drum-downcomer-riser loop of a drum boiler
- Numerical modelbuilding
- Multivariable control of a boiler - An application of linear quadratic control theory

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1. INTRODUCTION

Control theory has developed considerably during the last ten years. The results seem to offer great potential possibilities to solve practical control problems which up till now have not been possible. The development of process control computers has also made it feasible to implement control strategies for complex industrial processes at a reasonable cost.

In this thesis we will explore the application of some of the recent results for the control of a complex industrial process. The idea has been to take an industrial problem and to carry out the whole design procedure.

A thermal boiler was chosen as an example of a multivariable process. Boiler control is of interest because of the changes in the use of power resources in Sweden during the coming period. There are several interesting control problems, for example the steady state control and the start-up. In this thesis we will only consider the steady state control . To obtain a problem which can be tackled with a reasonable amount of work we have concentrated on the drum of the boiler which is a very complex part of the process.

To be able to control a process a mathematical model is needed. No matter what approach is used the effort for the modelling of an industrial process is a very tedious work. The model can be developed using two different approaches

- physical equations
- process identification

In the thesis we have used the approach of physical equations. Partly for the fact that no measurements were available.

The thesis consists of the reports

- Linear mathematical models of the drum-downcomer-riser loop of a drum boiler {8}
- Numerical modelbuilding {7}
- Multivariable control of a boiler - An application of linear quadratic control theory {9}.

The first two reports deal with modelling. Although the original set of equations only give a 6:th order system the work to compute steady state solutions, coefficients of linearized equations and the reduction to state space form is very extensive. For the investigation of the influence of various physical approximations and model parameters on the model dynamics this work must be repeated many times. This led to the development of a systematic approach to the modelling problem. The idea is to have a computer to do all the tedious work. The procedure is straight forward in principle but numerical difficulties may arise. There is, however, one principle problem involved namely the assignment of the smallest possible number of state variables to the set of linearized equations. Again the boiler is a good example. It is a reasonably simple process which clearly exhibits this principle difficulty. The method developed to solve this problem is believed to be new. However, the approach of numerical modelbuilding should be pursued further.

There are some step response measurements on boiler dynamics available {1} {13}. Due to the large amount of disturbances these measurements do only give the gross features of the dynamics. If the boiler model of this thesis is completed with models of superheaters the dynamics obtained give roughly the same responses {16}. However, to make more detailed comparisons with the real process a much more refined method than step responses must be used. It seems essential that such measurements are done. This may also answer if it is possible to predict the boiler dynamics from construction data.

The third phase of the thesis is concerned with the control of the drum pressure and level of the boiler. The idea has been to use linear quadratic control theory for the design. In principle this method will give no special difficulties when applied to multivariable processes. This is in strong contrast with conventional control theory. In the boiler application there is no rational a priori choice of the parameters of the loss functional. For the final choice of the parameters the designer is left with some freedom. Various ways to exploit this fact have been looked into. Different methods to eliminate steady state errors were also investigated. This problem, which is of great interest for the practical applications, seems to have been overlooked to a great extent in existing literature on optimal control. Further research on this subject might be fruitful.

The hybrid simulations were originally planned as a pure verification. It turned out, however, that the simulation gave a very good insight into the sensitivity of the optimal controller. A straight forward digital simulation would certainly not give the same information, because it is usually very difficult to know a priori where the main problems with respect to computing accuracy are to be found. In this particular case we found that a direct computation gave a Kalman filter which was very sensitive. Ways to diagnosticate this as well as to avoid it were found. The conclusion with respect to practical applications is that the sensitivity of the optimal controller is very essential.

The control algorithm for the boiler control was programmed in assembler language. Fixed point arithmetic and scaling procedures were used. The requirements on the process control computer, an EAI 640, were quite modest. For a system with 2 inputs and 2 outputs we have the following characteristic figures

Order of the system	6	15
Storage requirements	385 words	682 words
Computing time	6.7 ms	∿ 35 ms

The results show that it seems very attractive to design a controller using linear quadratic control theory. There are no difficulties with the cross couplings in the boiler. Load disturbances are easily taken into account. The storage space and computing time required for a on-line computer are very modest. Using a digital computer it is also easy to adjust controller parameters with respect to load variations.

2. BACKGROUND

Fig. 1 illustrates the predicted percentile distribution of energyproduction and power in Sweden for 1980 {10}. The situation shown in this figure is entirely different from the present one. The available nuclear power is still small. This means that

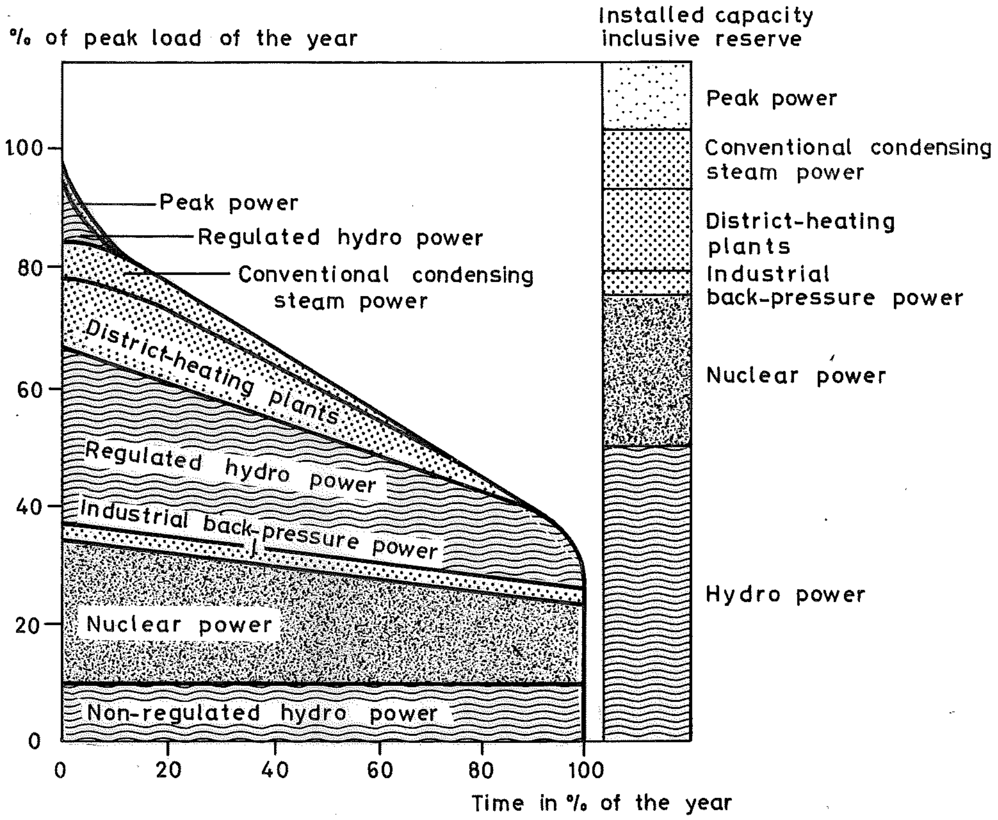

Fig. 1 - The predicted percentile distribution of energyproduction and power in Sweden for 1980.

the place of nuclear power at present is occupied by conventional thermal power and water power. The mains frequency is essentially maintained using the hydro-electric power stations and the thermal power stations do only contribute slightly.

In the future power system one predict in average one failure of a thermal power station at least every two weeks. These failures create stability disturbances which affect the entire system. The time to eliminate the effect of such a disturbance is quite long which increases the risk for additional failures. It is then important that both the hydro-electric and remaining thermal power stations are used to meet the demand for power.

This predicted situation implies that the operating conditions for the conventional thermal power stations will change drastically during the coming period. Characteristic for the new operating conditions is

- a large number of start-up and shut-down operations
- mains frequency control

A fast start-up is then desirable both for the internal efficiency and for the reliability of the entire system.

The conventional thermal power stations must participate in the control of the mains frequency. It is then desirable that the stations have a fast response to load changes.

Due to these factors the design criteria for boilers will change from pure high performance requirements in the steady state to rigid requirements on dynamics and control.

3. BOILER MODELS

There are several models for different types of boilers available in literature. One of the first systematic works presented was due to Chien et.al. {4}. In this paper a drum boiler with natural circulation and one superheater is considered. The linearized model is of the 9:th order. The model is not simplified by neglecting some very fast dynamical effects. Chien's approach has been used by several others {1} {8} {17}.

In {1} large power station boilers of the drum typ with natural circulation are considered. Two models which hold for different boilers are discussed. The order of the models are 19 and 31 respectively. Desuperheaters, economizers and several superheaters are included. The model step responses have been compared with the responses of the real process. The differences are not neglectable. No attempt to derive a model from measurements is presented.

Both the drum and once-through boilers are analysed in {20}. Transfer functions for the different components of the boilers are derived. This approach have been used in {13} {25}. The complete models are of very high order and not very attractive for the design of control laws. In {13} a drum boiler is considered. Measured step responses are converted to Nyquist diagrams and compared to those given by the model. The agreement in the Nyquist diagrams is very good but if Bode diagrams were used large differences at higher frequencies would appear. Transfer function time constants and gains are often adjusted by empirical formulas. Additional references are {5}, which considers a boiler-turbine unit and {21}, where a model of a once-through boiler is presented.

The dynamics of boiling channels have been thoroughly investigated in connection with nuclear boilers {3} {12} {22}. In these studies the two phase flow of the boiling channel is usually described by partial differential equations. In {3} these equations are approximated by a large number of ordinary differential equations and the solution is obtained by the use of a digital computer. The dynamics of superheaters have also been seperately investigated by several authors {11} {20} {23}.

The model report {8} of this thesis covers the drum-downcomer-riser loop of a drum boiler with natural circulation. This loop is a complex part of the boiler. In order to design regulators using state space techniques it is very essential to keep the order of the model as low as possible. It was then important to investigate the influence of various physical approximations and model parameters on the model dynamics. To meet the complexity of the modelling problem a digital computer was used. Once the basic physical equations have been derived the computation of steady state solutions, coefficients of linearized equations and the reduction to state space form was performed on a digital computer. The essential difficulty with this approach is to assign the smallest number of state variables to the linearized set of equations in order to reduce this set to state space form. A method to solve this problem was developed and is presented in {7}. The model program input is boiler construction parameters and thermal data determined by the drum pressure.

Using lumped parameters linear models of the 4:th, 5:th and 6:th order were derived. The original set of equations gave a 6:th order model. These equations are essentially the same equations considered by {1} {4}. The order was reduced to 5 by neglecting the acceleration terms in the momentum equations for the downcomers and the risers. Considering the steam-water mixture of the risers as a rigid body we get a 4:th order model. The input variables are the heat flow to the risers, the feedwater flow and the drum outlet steam flow. The state variables correspond to the following physical quantities

x_1 drum pressure
x_2 drum liquid level
x_3 drum liquid temperature
x_4 riser wall temperature
x_5 steam quality
x_6 a linear combination of the mass flows of the downcomers and risers.

The output variables equals the first two state variables.

The responses of the state variables to a step change of the drum outlet steam flow are given in Fig. 2. Notice the non-minimum phase characteristics of the drum level response. This means physically that we take the bubble formation effect at least qualitatively into account. This is in strong contrast with {13} where this effect is just added to the model with no direct physical interpretation. The agreement between the 5:th and 6:th order model is extremely good. The 4:th order model differs considerably from the other models. Especially there is no non-minimum phase behaviour of the drum level. The indicated large difference in gain is mostly due to a distinction of the unstable mode of the models. The cause of this unstable model is the assumption of constant outlet steam flow.

The model has been expanded in {16} with two superheaters and one desuperheater. The resulting model is of the 7:th order. The work will be further extended by the modelling of a specific power station boiler of 160 MW.

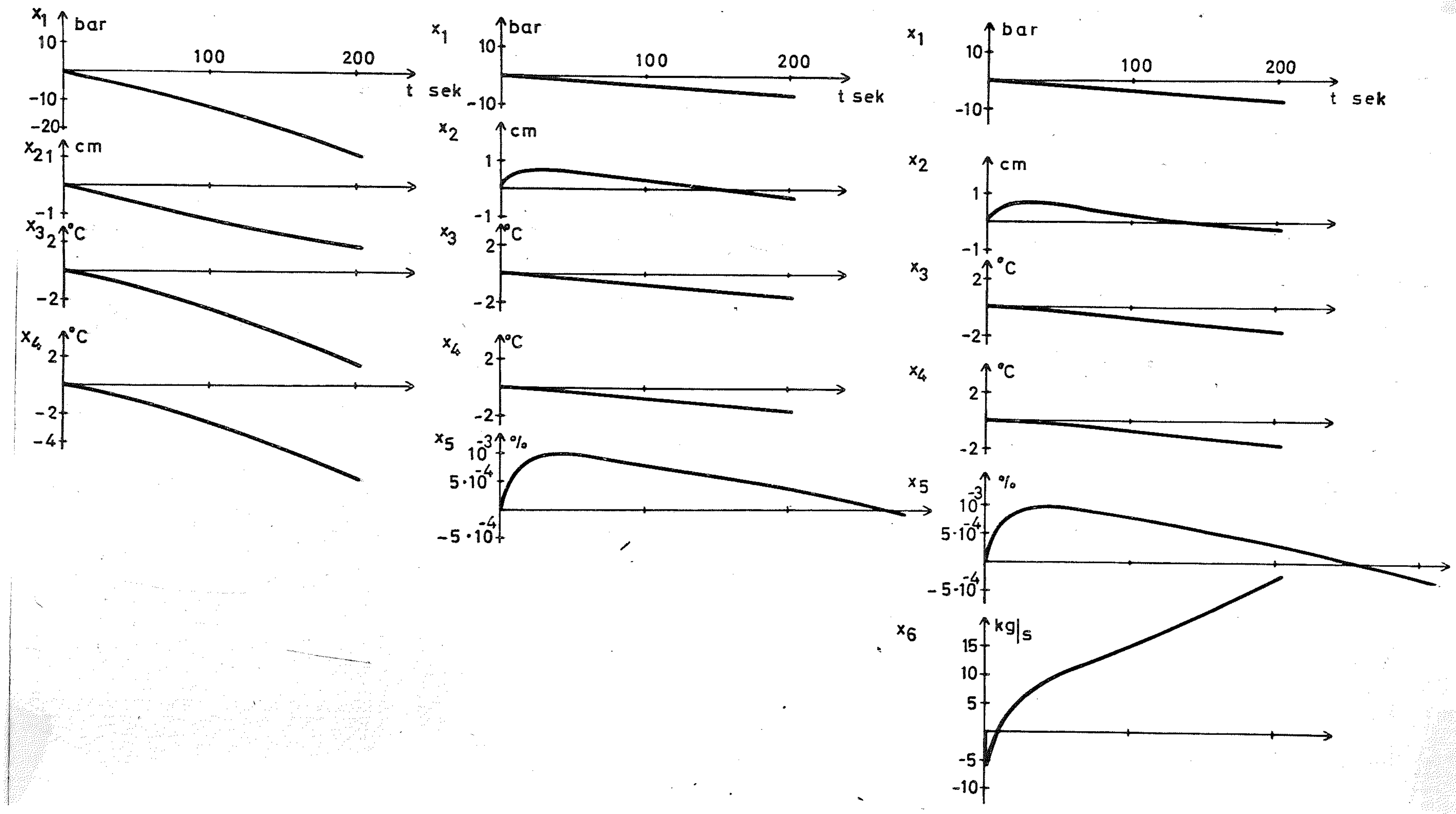

Fig. 2 - Open loop responses of the state variables of the 4:th, 5:th and 6:th order models to a step change in the outlet steam flow of 2 kg/s (∼ 1%)

4. BOILER CONTROL

We will here consider the steady state control of a boiler. The boiler is described with a linear model. It is generally agreed that for load variations of about ± 10% linear models can be used.

There are different ways to approach the multivariate control problem. The choice of synthesizing method depends on if we are going to implement the control law with ordinary PI-regulators or using a process control computer. Using PI-regulators it is essential to find the dominating cross coupling in the process and include this in the synthesis. It is then important to determine the interaction between the parameter settings of the regulators and the stability limits. This approach has been taken in {15}, {24}. Using a process control computer we have to determine a control algorithm.

We will here take the last approach. This looks reasonable since a number of digital computers have been installed in power stations to perform functions such as data logging, performance calculations and automatic start-up and shut-down of the plant {6}. In such cases computer control offers the possibilities of capital savings by reduced analog equipment. It is also possible to take nonlinearities of boiler dynamics into account in a simple way.

To design the control law it seems attractive to use linear quadratic control theory. This has to some extend been done before {2 } {17} {18} {19}. In {2 } {17} and {19} it is assumed that all state variables can be measured. In {18} a state estimation is included and the load disturbance is a deterministic signal with added white noise. Both {2 } and {17} compare their results with conventional control. In {17} a significant improvement of the control was achieved. In {2 } no such improvement was obtained and a discussion of this fact is presented. The simulations in these works have been done on digital computers. No implementations on real processes are presented.

In the control part {9 } of this thesis linear quadratic control theory was used to design control laws for the drum pressure and level control. This differs from earlier works in the sense that a model for the load disturbance based on actual measurements and a Kalman filter for the estimation was included.

Models

The 5:th order boiler model was used. The superheater were simulated by a restriction and the pressure before the turbine was taken as a measure of the load changes. These approximations gave a fast system compared with the real process. The disturbances included were the load changes and the measurement noise. The model of the load disturbance was based on a set of measurements of the power generated by four hydro-electric power stations in the north of Sweden. An example is shown in Fig. 3.

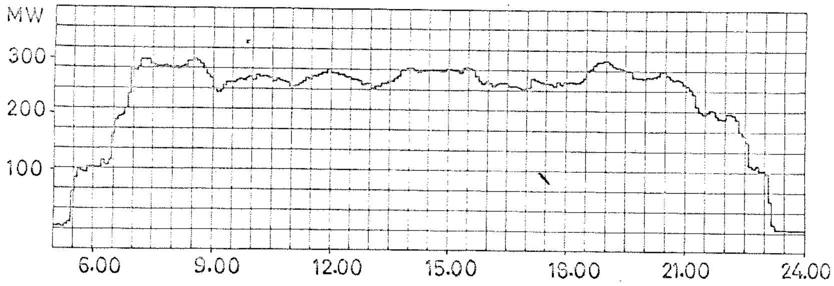

Fig. 3 - The power generated by four hydro-electric power stations in the time interval 5^{00}-24^{00} on a weekday.

The power variations in the interval 7^{00}-21^{00} are for the main part due to the control of the mains frequency. The sampling interval of the measurement is 300 seconds. The disturbance was successfully modelled as a stationary stochastic process with rational spectral density function. It was shown that the disturbance could approximately be described as a Wiener process. The frequency content of the model disturbance signal above 10^{-3} rad/s was small. The measurement errors were assumed to be independent and the covariances were chosen to match the state vector estimation errors.

Structure of solution

The structure of the solution given by linear quadratic control theory is illustrated in Fig. 4.

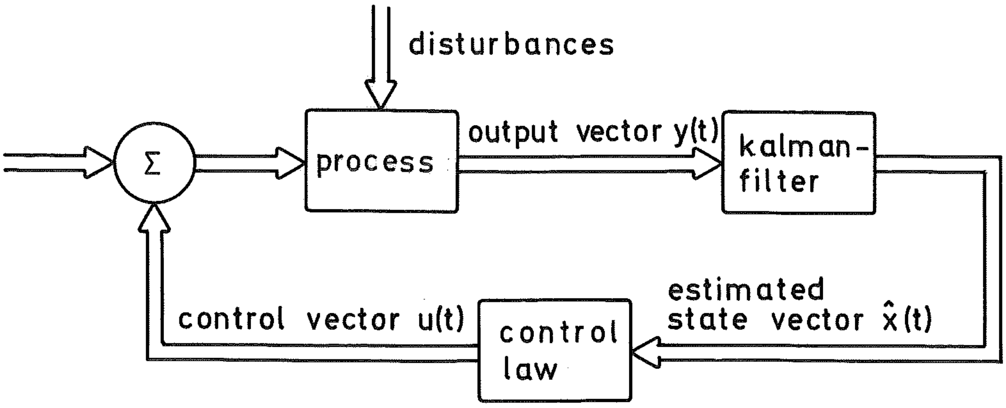

Fig. 4 - The structure of the solution to the design problem given by linear quadratic control theory

The solution is composed of two parts. The Kalman filter gives the minimum mean square estimate $\hat{x}(t)$ of the state vector based on measurements of the output vector y(t). The control law which is a linear feedback from all state variables minimizes a quadratic loss functional. We have used the stationary values of the feedback and filter gains. As the model was based on physical equations the state variables have a simple physical interpretation. In such cases the estimated state vector might also be useful for other purposes than control.

Choice of loss functional

One difficulty in the application of linear quadratic control theory to a process is to find the parameters of the loss functional. In many cases there is no rational a priori choice of these parameters. Starting with an initial guess of the parameters the control law was evaluated by simulation. The change of the parameters was judged from the results of these simulations. No special difficulties were experienced with this procedure and the final choice was achieved after couple of iterations.

Elimination of steady state errors

Steady state errors of the output variables were eliminated using a concept of feedforward control. A procedure similar to this method has been used in {2 }. The method simply means that also the disturbance is included in the control law. As the disturbance is also estimated using a Kalman filter, we need not to measure it directly . The guaranteed stability of the closed loop system associated with linear quadratic control theory is not affected.

Sensitivity

It was shown that the optimal system was very sensitive to parameter variations. This is essentially due to the sensitivity of the Kalman filter obtained when load changes are the only disturbances. By introducing uncertainties in the model simply by adding independent errors in all model equations it was shown that the sensitivity could be reduced significantly. It is believed that this approach can always be used to reduce the sensitivity of the Kalman filter.

Sampling interval

The discrete form of the model equations, control law and Kalman filter was needed for the implementation on a hybrid computer. The choice of the sampling interval was based upon an estimate of the increase of the loss functional when the length of the sampling interval was increased. The sampling interval was chosen to 10 seconds.

Simulation

Some results of the hybrid simulations are given in Fig. 5, 6 and 7 The closed loop responses of the state variables and the estimated state and disturbance variables to a step change of the load are given in Fig. 5. The load changes are simulated by the pressure before the turbine which is called v_1. The control variables and estimated state and disturbance variables are zero during the first two sampling intervals since the control algorithm is given starting values of these variables which equals zero. In Fig. 6 and 7 the load disturbance is described as a Wiener process. The

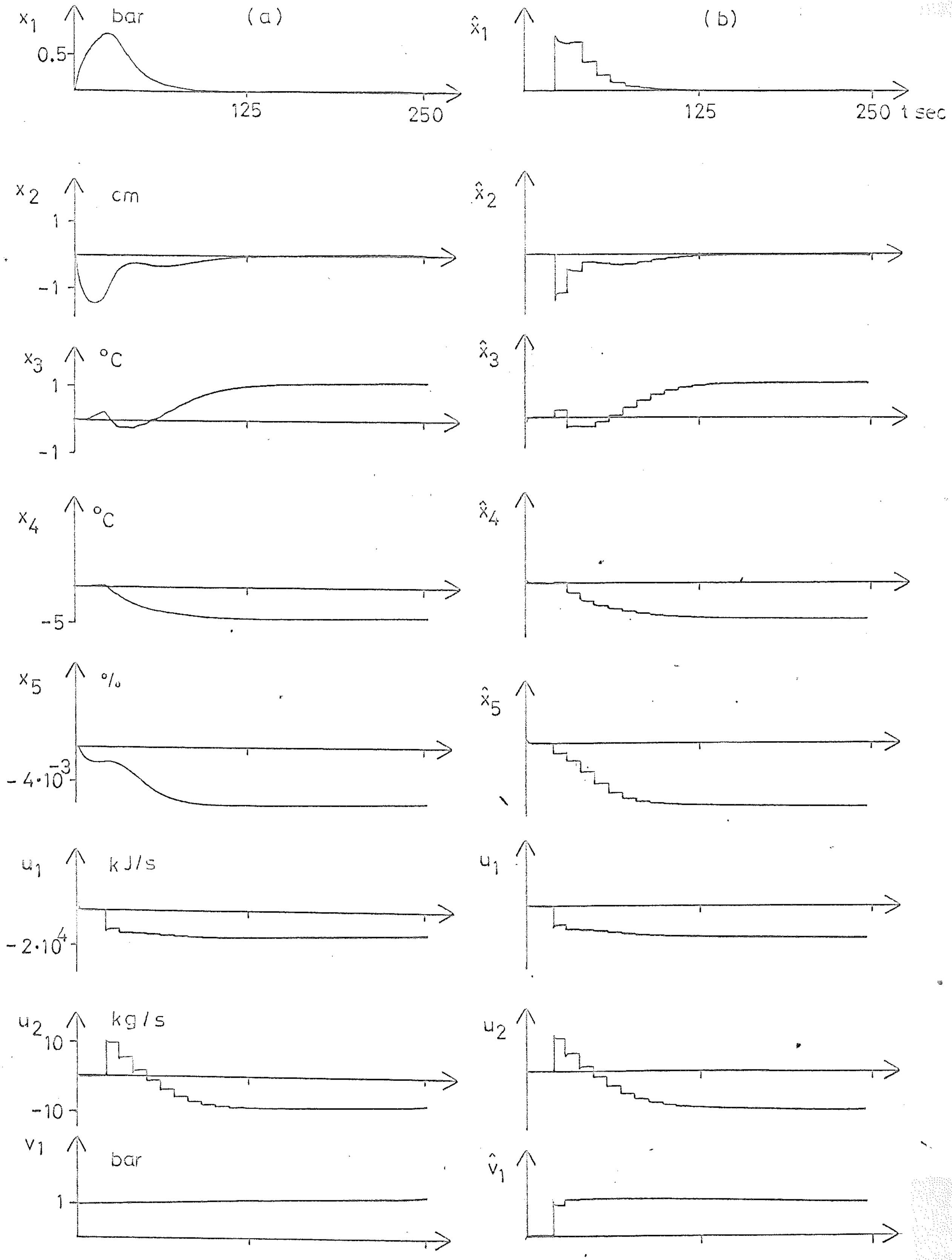

Fig. 5 - Closed loop responses of state variables (a) and estimated state and disturbance variables (b) to a step change of 1 bar of load disturbance $v_1(t)$.

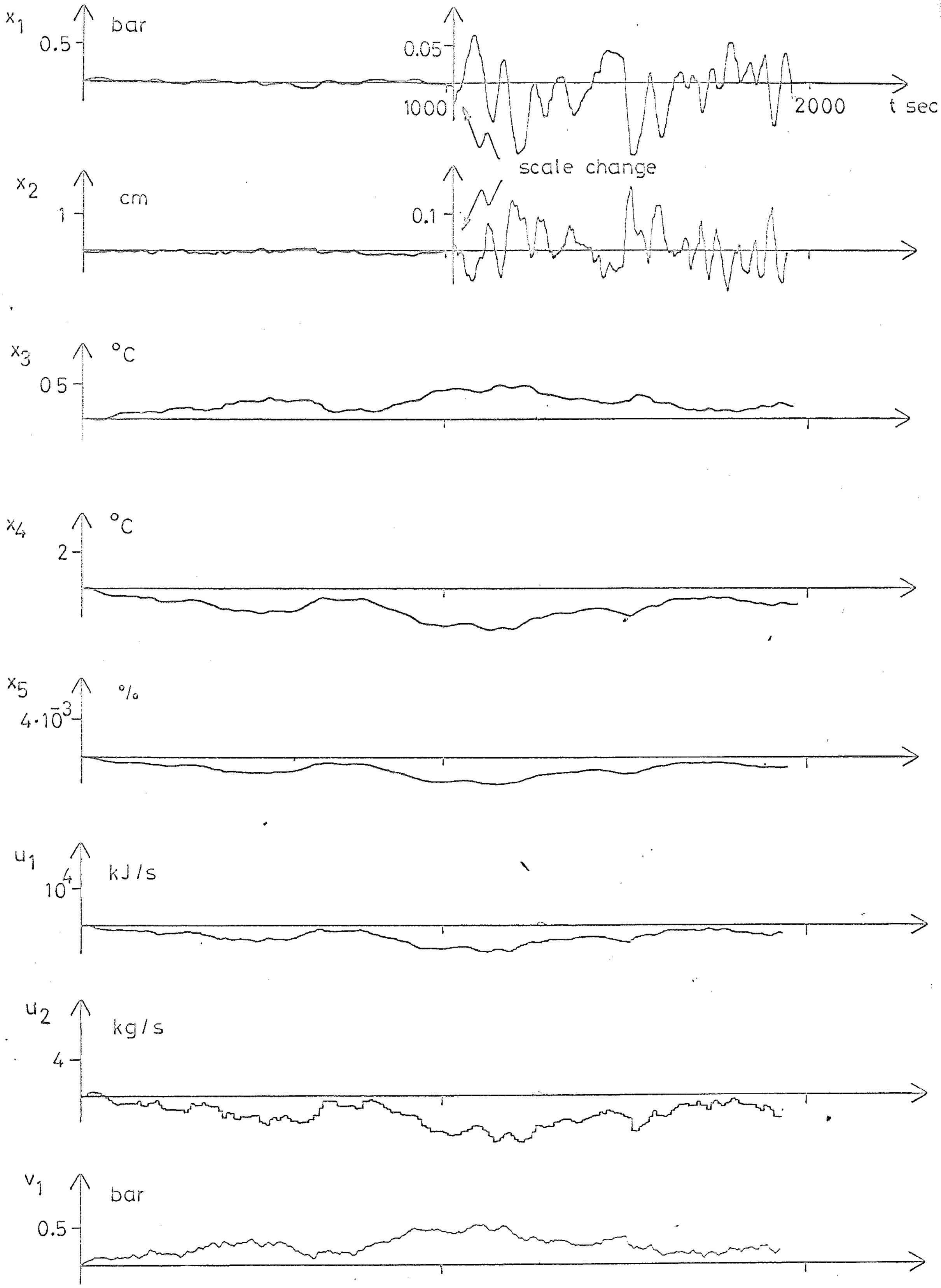

Fig. 6 - Closed loop responses of state variables when the load disturbance $v_1(t)$ is a Wiener process.

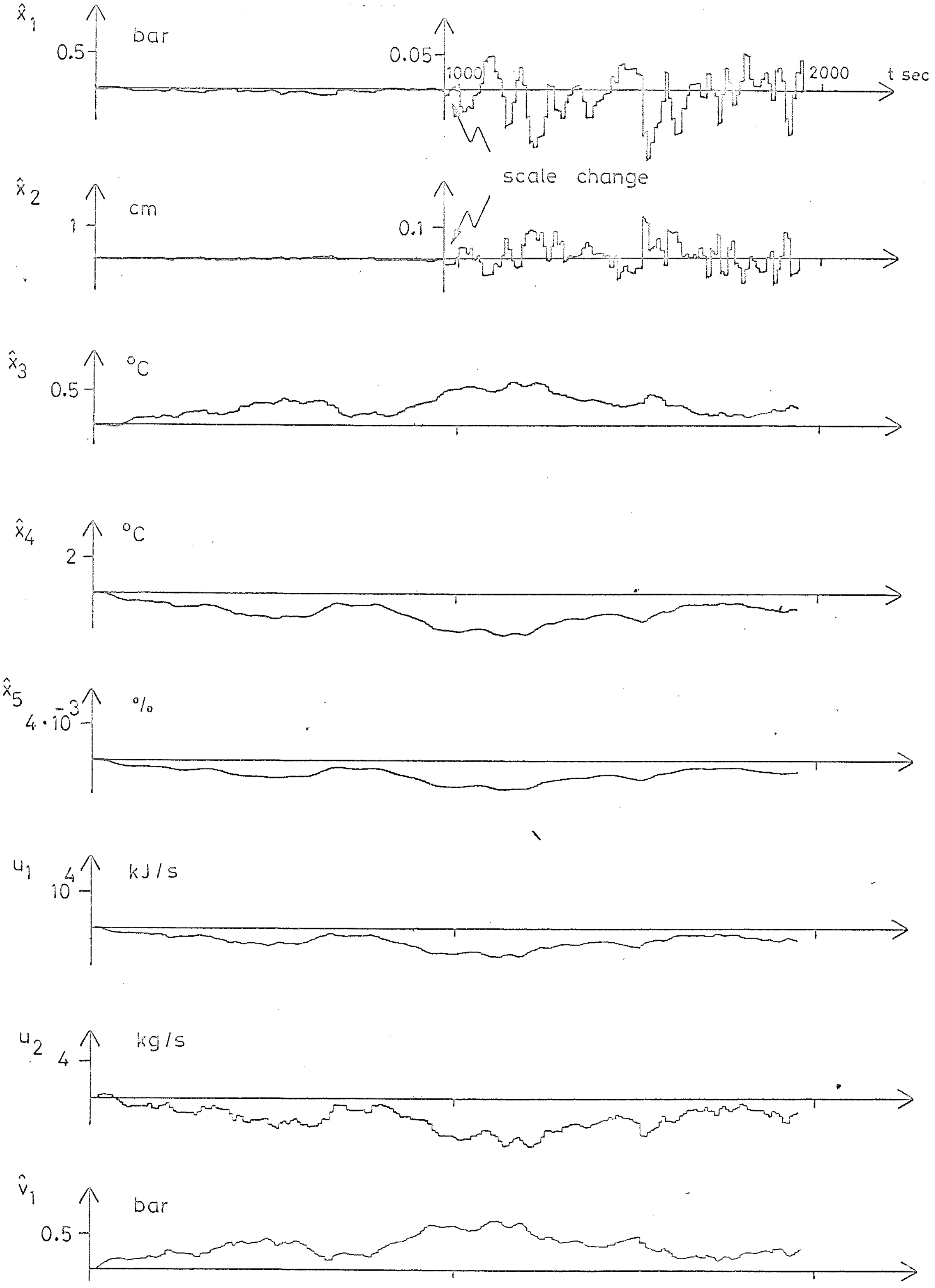

Fig. 7 - Responses of estimated state and disturbance variables when the load disturbance $v_1(t)$ is a Wiener process.

figures give the state variables and estimated state and disturbance variables respectively. Compared with the continuous case where it was assumed that all state variables could be measured directly, the variances of the drum pressure and level have increased with a factor 2 and 10 respectively.

Requirements on process control computer.

The process control computer was an EAI 640. Some characteristic features for this machine are

Cycle time	1.65 μs
Word length	16 bits
Add fix point	3.3 μs
Mult -"-	18.5 μs

The control algorithm was written in assembler language and fixed point arithmetic was used. For a 6:th order system with two inputs and two outputs the core memory requirement was 385 words. If the order of the system was increased to 15 the necessary storage requirement increased to 682 words. The execution time of the control algorithm for a 6:th order system was 6.7 ms.

5. REFERENCES

1. Anderson J.H., Kwan H.W., Qualtrough G.H., Dynamic models for power station boilers, Paper presented at the Third U.K.A.C. Control Convention 2-4:th April 1968.

2. Anderson J.H., Dynamic control of a power boiler. Control Systems Centre Report No. 27. April 1968. University of Manchester, Institute of Science and Technology.

3. Becker K.N., Jahnberg S., Haga I., Hansson P.T., Mathisen R.P. Hydrodynamic Instability and Dynamic Burnout in Natural Circulation Two-Phase Flow. An Experimental and Theoretical Study. AB Atomenergi Report No AE-156, Stockholm 1964.

4. Chien K.L., Ergin E.T., Ling C., Lee A., Dynamic Analysis of a Boiler. Paper 58-IRD-4 ASME Instruments and Regulators Conference Newark, Del, April 1958.

5. Daniels J.H., Enns M., Hottenstine R.D., Dynamic representation of a large boiler turbine unit. A.S.M.E. paper No. 61-SA-69 presented at the Summer Annual Meeting, June 1961.

6. Digital computer applications to process control. Proceedings of IFAC/IFIP 1:st International Conference at Stockholm, Sweden 1964.

7. Eklund K.G., Numerical Model Building. Report 6808, November 1968, Lund Institute of Technology, Division of Automatic Control.

8. Eklund K.G., Linear mathematical models of the drum-downcomer-riser loop of a drum boiler. Report 6809, November 1968, Lund Institute of Technology, Division of Automatic Control.

9. Eklund K.G., Multivariable control of a boiler - An application of linear quadratic control theory. Report 6901, January 1969, Lund Institute of Technology, Division of Automatic Control.

10. Elförsörjningen under 1970-talet. 1967 års CDL-studie. Report from Centrala Driftledningen, Dec. 1967.

11. Enns M., Comparison of Dynamic Models of a Superheater. ASME Journal of Heat Transfer, Nov 1962, s. 375-385.

12. Gouse S. William Jr., An Index to the Two-Phase Gas Liquid Flow Literature. MIT Report No 9, 1966.

13. Isermann R., Das regeldynamische Verhalten der Überhitzung bei Berücksichtigung der Koppelungen mit anderen Teilen eines Dampferzeugers. Ph.D. thesis University of Stuttgart 1965.

14. Isermann R., Messung und Berecknung des regeldynamischen Verhaltens eines Überhitzers. VDI-Verlag, Düsseldorf, Fortschr.-Ber. VDI-Z, Reihe 6 No. 9 Oct 1965.

15. Isermann R., The steam temperature control of the multivariable system "Steam Boiler". Preprints of IFAC Symposium on Multivariable Control Systems. 7-8 Oct 1968, Düsseldorf.

16. Lagerlöf B., Linjär matematisk modell av en dompanna med två överhettare. Examensarbete utfört vid institutionen för Regleringsteknik, Lunds Tekniska Högskola 1969.

17. Nicholson H., Dynamic optimization of a boiler, Proc. I.E.E. Vol. III, No. 8, August 1964.

18. Nicholson H., Dual-mode control of a time varying boiler model with parameter and state estimation, Proc. I.E.E. Vol. 112, No. 2, Febr. 1965.

19. Nicholson H, Dynamic optimization of a boiler-turboalternator model, Proc. I.E.E., Vol 113, No. 5, May 1966.

20. Profos P., Die Regelung von Dampfanlagen. Springer Verlag, Berlin/Göttingen/Heidelberg 1962.

21. Ruschinski V.N., Dynamics of the Automatic Control of a Boiler-Turbine Unit. Preprints of IFAC Congress at Moscow 1960.

22. Symposium on Two-Phase Flow, Exeter 21-23 June 1965 Proceeding, Dept of Chemical Engineering, University of Exeter.

23. Thal-Larsen H., Dynamics of Heat Exchangers and their Models. ASME Journal of Basic Engineering, June 1960, s. 489-504.

24. Unbehauen H., The load dependence of the stability and optimal controller settings of the multivariable steam temperature control system in a boiler. Preprints of IFAC Symposium on Multivariable Control Systems. 7-8 Oct 1968 Düsseldorf.

25. Voss K., Das übertragungsverhalten der Strecken eines Zwangsdurchlaufkessels. VDI-Verlag, Düsseldorf, Fortschr.-Ber. VDI-Z. Reihe 6, No. 18, March 1968.