Black Box Modelling of a Boiler System

John V. Ringwood

School of Electronic Engineering
Dublin City University
Glasnevin
Dublin 9

ABSTRACT

This paper describes the successful application of black-box techniques to modelling the dynamics of a 30 tonne/hour boiler system. The procedure for producing a model, with the aid of a CAD package, is straightforward and model validation results indicate the quality of the derived models. The models were used to diagnose problems with the control system and provide a test bed for further control designs.

1. BLACK-BOX MODELLING

Most control design projects consist of determining a model for the system under study, followed by a control design based on the model, and subsequent simulation to examine its effectiveness. However, the modelling phase generally takes a considerable amount of time (in some cases a number of man years), leaving only a small amount for the actual analysis and design. Reduction of the duration of the modelling phase has the benefit of either reducing the overall project time, or allowing more time to be devoted to the design aspects.

Traditionally, most modelling exercises begin with an analysis of the physical laws which govern the process. Then follows a detailed derivation of the system equations, followed by determination of the system parameters. Certainly, the most difficult aspect is finding values for the system parameters so that the response of the general model matches that of the particular plant under examination. Black-box techniques can assist at this stage of the modelling process or, in some cases, eliminate the need for physical modelling altogether.

The approach taken with black box modelling is as follows. Data is logged from the plant in question over, if possible, a wide cross-section of plant operating conditions. Linear, dynamical discrete-time models are then fitted to this data so that the models, when fed with the actual plant inputs, produce the same outputs as the real system. This fitting process is divided into two stages (a) model structure and order determination and (b) identification of the model parameters. Some preliminary physical modelling can be used to assist with stage (a) or the structure and order may be determined using the logged data alone. A combination of these approaches is beneficial. In the identification stage, an overdetermined set of equations is set up, based on the model structure and the logged data. These equations are then solved, usually in a least-squares sense (minimising the difference between the model response and the response from the actual plant), for the unknown parameters (Ljung, 1987). The MATLAB (Matlab, 1991), (Ljung, 1991) suite of mathematical analysis tools provides facilities for each of the steps above.

2. THE BOILER SYSTEM

The boiler plant in question is a set of three 30 tonne/hour boilers, which operate in parallel, supplying high pressure steam to a turbine set for electricity generation and low pressure steam to a dairy plant producing dried milk. Each of the boilers operates independently, the collective setpoints for firing rate being determined from the pressure in the main steam line. A schematic of the boiler is shown in Fig.1. The drum level control system is also shown, for completeness.

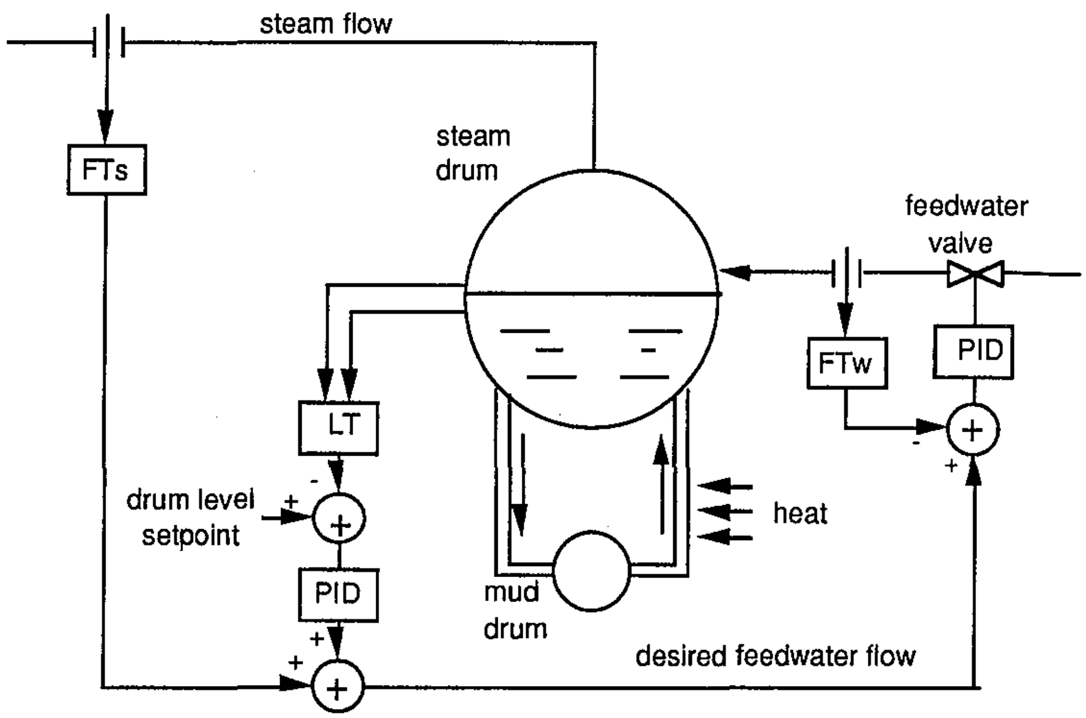


Fig.1: Structure of drum level control scheme

Notation:

FT - flow transducer (s and w denote steam and water respectively)

LT - level transducer

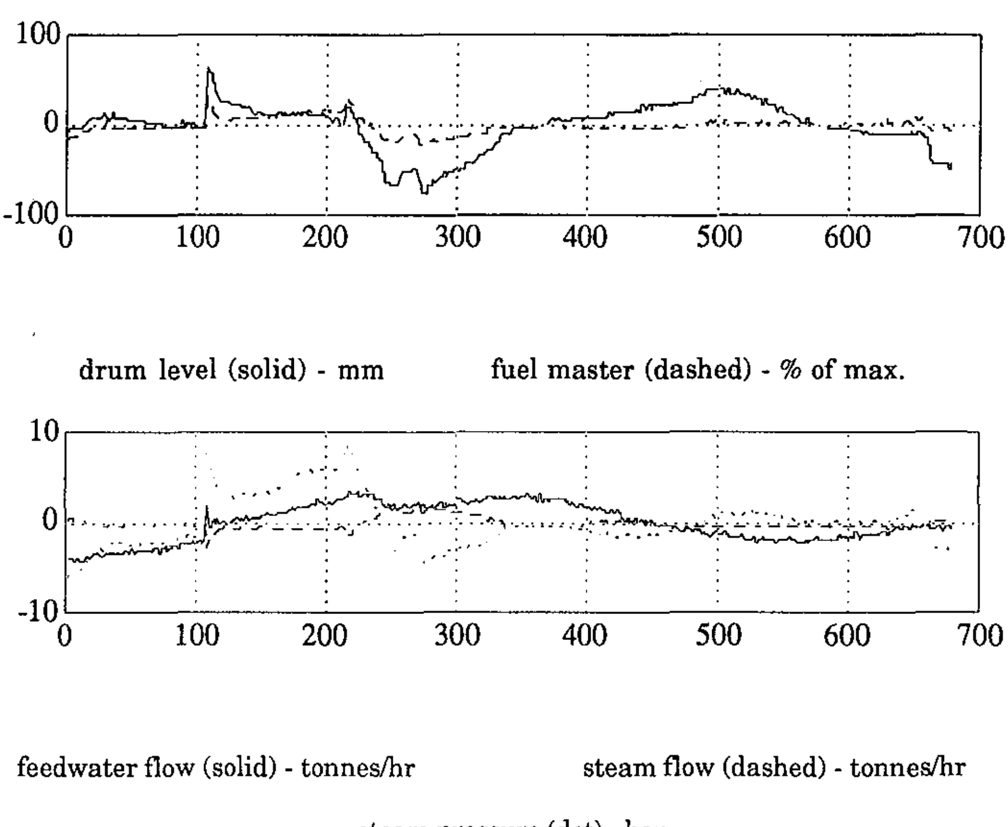
PID - PID controller

The objective of the control system is to maintain the drum level at its setpoint, which is about midway up the steam drum, in spite of variations in steam flow. The operation of the control system is straightforward. Steam flow is measured by the steam flow transducer (FTs) and provides the primary feedwater flow demand. This feedforward action establishes the basic flow balance through the drum. However, due to transport delays and other dynamics in the drum level and associated systems, the feedwater flow input generally does not react quickly enough to changes in steam flow. Corrective action is taken by the drum level PID feedback controller which increases (decreases) feedwater flow in response to a low (high) drum level condition. The feedwater flow loop attempts to maintain the feedwater flow at the desired rate. Its presence is required due to the nonlinearity of the valve and variations in feedwater pressure.

3. DATA LOGGING

Fortunately, the distributed computer control system used with the boiler facilitated data logging. The recorded data was subsequently uploaded to an IBM PC/AT and imported into MATLAB (Matlab, 1991) for analysis. In the data logging exercise, all the system variables deemed to be related to the boiler drum level were recorded, including steam flow, feedwater flow, main steam pressure, fuel master (firing rate), and drum level itself. The data logging was performed over four different runs, where an attempt was made to excite the dynamics of the system as much as possible. Since the dairy plant was in operation, certain restrictions on the variations in the system variables were imposed, but a reasonable cross-section of responses was obtained, some from artificially induced signals and some from natural variations in steam demand.

Fig.2: Data logged from Test 1

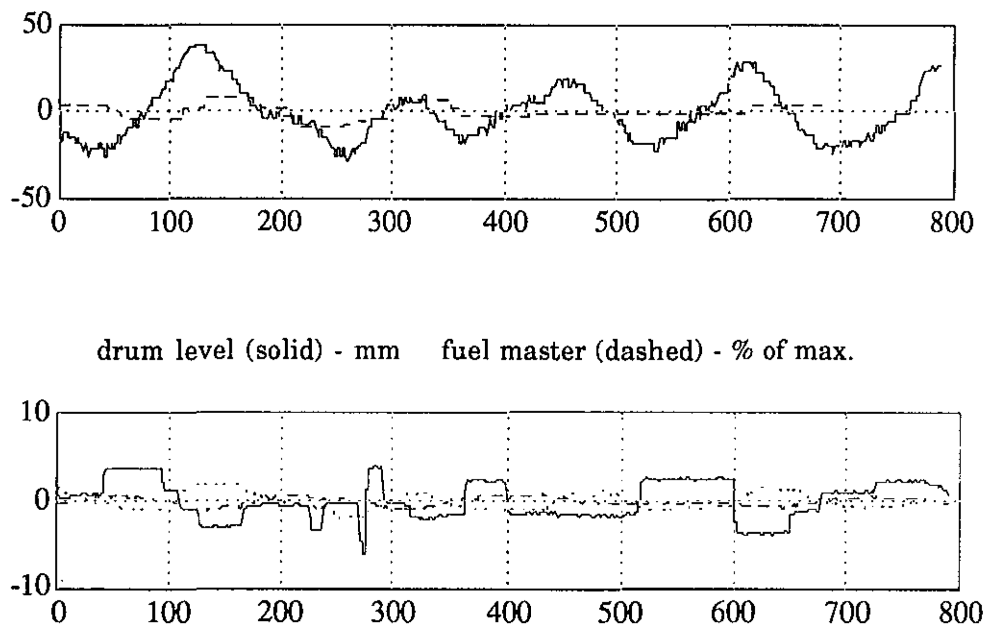


The logged data (with a sampling period of 3 seconds) was obtained in four sections, with graphs shown for two sections, as examples:

Test 1:	Contains large steam flow variations (up to 31 tons/hour)	Fig.2
Test 2:	Normal plant operation (small variations in steam flow)	
Test 3:	Manual input to feedwater flow (open loop system response)	Fig.3
Test 4:	Variation in feedwater pressure (electric pump switched in and out)	

This variety of logged data allows mathematical models to be evaluated over a range of boiler operating conditions and allows models evaluated for particular sets of data to be validated against others, giving an indication of their accuracy.

Fig.3: Data logged from Test 3



feedwater flow (solid) - tonnes/hr steam flow (dashed) - tonnes/hr

steam pressure (dot) - bar

4. A DYNAMICAL BOILER MODEL

Although a physical modelling exercise was initially undertaken, this was abandoned due to time constraints. It did, however, provide some insight into the system in terms of model structure and order. Concurrently, a black box model was determined, based on the following procedure:

1. For a given output (e.g. drum level), an initial guess is made as to the input variables which affect this output (e.g. feedwater flow, steam flow, etc). It is better, if unsure at this stage, to include too many inputs rather than too few, since the sections of the

model representing surplus inputs will have insignificant parameters (small coefficients with large variances). Correlation techniques may also be used to evaluate the significance of inputs.

2. The model orders for the autoregressive (AR) and input terms are specified separately. The number of steps delay for each input term must also be specified.

3. An identification technique is utilised to determine the coefficients of the chosen model structure which minimise, in a least squares sense, the difference between the actual boiler output variable and that predicted from the model (Ljung, 1987).

4. The output of the model is compared to that from the actual boiler, where the model is fed with inputs which were logged from the plant. If poor similarity is achieved steps (2) or (1) are repeated, until no further improvement is possible.

A set of three models, covering all the plant variables of interest (drum level, steam flow and steam pressure), are now produced. For brevity, the full procedure for the determination of the drum level model only will be shown.

4.1 The Drum Level Model

The inputs deemed to influence drum level (dl) were feedwater flow (fwf), steam flow (sf) and, to a lesser extent, main steam pressure (msp). Some preliminary tests, coupled with experience gained with the physical modelling exercise, indicated that the fuel master (fm) signal was not a significant input to this subsystem. The discrete time ARX (AutoRegressive with eXogenous inputs) model (Ljung, 1991) is of the form:

$$A_{dl}(q)\, dl(t) = B_{fwf}(q)\, fwf(t-dfwf) + B_{sf}(q)\, sf(t-dsf) + B_{msp}(q)\, msp(t-dmsp) \quad (1)$$

where:

$$A_{dl}(q) = 1 + a_1 q^{-1} + \dots\dots + a_{na} q^{-na}$$

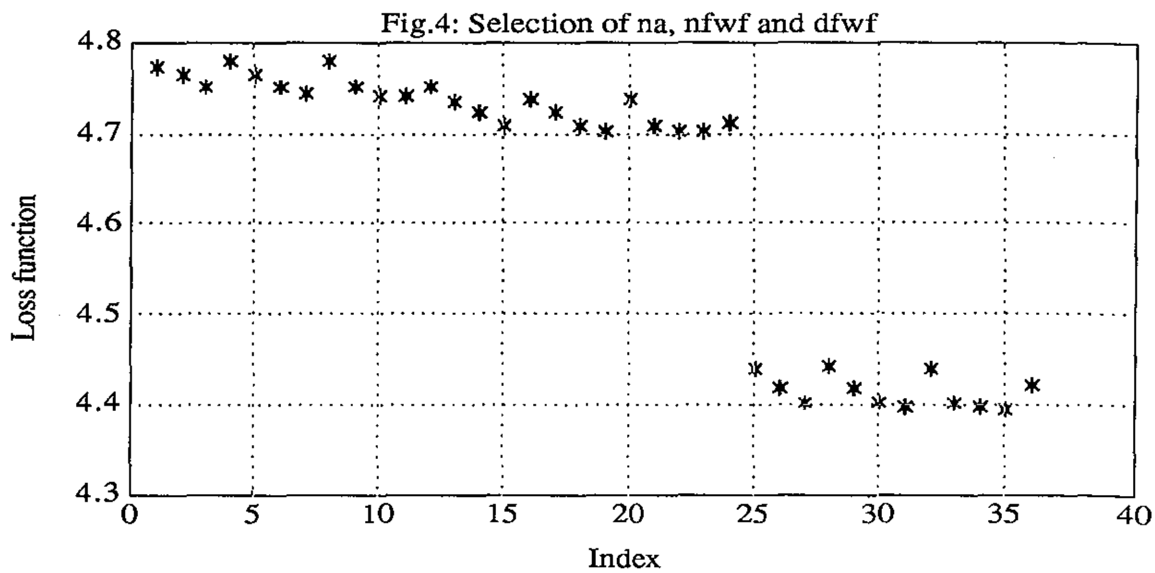
$$B_{fwf}(q) = b_{0fwf} + b_{1fwf} q^{-1} + \dots\dots + b_{nbfwf} q^{-nbfwf}$$

$$B_{sf}(q) = b_{0sf} + b_{1sf} q^{-1} + \dots\dots + b_{nbsf} q^{-nbsf}$$

$$B_{msp}(q) = b_{0msp} + b_{1msp} q^{-1} + \dots\dots + b_{nbmsp} q^{-nbmsp}$$

and q is the discrete time forward shift operator (q^{-1} corresponds to one step delay). The terms dfwf, dsf and dmsp correspond to the pure delays in the respective inputs (feedwater, steam flow and main steam pressure).

Having specified the basic model structure (step 1), the model orders na, nbfwf, nbsf, nbmsp and the delays dfwf, dsf and dmsp must now be determined. The software tools used [3] allowed the loss function, which is a measure of the difference between the model and actual system outputs, to be evaluated for one input at a time, using different model orders and delays.



Since Test 3 was specifically designed to introduce variations into the drum level, the data from that test will be used in the determination of the drum level model. Starting with variations in na, nbfwf and dfwf, the loss function is plotted in Fig.4. *Index* describes the variation in na, nfwf and dfwf as follows:

Index	1	2	3	4	5	6	7	..	36
na	1	1	1	1	1	1	1	..	3
nbfwf	1	1	1	1	2	2	2	..	3
dfwf	2	3	4	5	2	3	4	..	5

A clear downward drop in the loss function occurs at na = 3. Similarly, low values of the loss function (ignoring the influence of na) occur at indices 15, 19, 23, 27 and 31 clearly selecting dfwf as 4. The best choice for nbfwf is not immediately clear, but re-examination of the loss function variations for changes in nbfwf of 0 to 3 (with na set to 3 and dfwf set to 4) leaves nbfwf = 3 as a good choice. It is interesting to note that the physical modelling exercise also suggested values of na = 3 (from the equation orders) and dfwf = 4 (from consideration of the transport delay in the feedwater system).

A similar exercise is now carried out on the other two input terms using a value of na = 3. The table below summarises the order selection results:

Input	Order(A)	Order(B)	delay
FWF	3	3	4
SF	3	2	0
MSP	3	1	1

A prediction-error based identification algorithm (Ljung 1987, 1991) is now used to determine the parameter values for a model with the structure in equation (1) and the orders as above. The parameter values are given in the table below:

Polynomial	Coeff. of q^0	Coeff. of q^{-1}	Coeff. of q^{-2}	Coeff. of q^{-3}	delay
A	1.0	-0.5755	-0.9469	0.5176	n/a
B_{fwf}	0.0	0.1862	0.0876	-0.1359	4
B_{sf}	0.0	3.7860	-0.8372	0	0
B_{msp}	0.0	0.0382	0.0	0.0	1

4.2 <u>The Steam Pressure Model</u>

In a manner similar to that for the drum level model, steps 1 to 4 in the modelling procedure were also performed for a steam pressure model. In this case, the appropriate inputs were found to be fuel master, steam flow, feedwater flow and drum level. Since the most significant variations in steam pressure were observed in Test 1, the data from that test is used in the determination of the steam pressure model. Using a loss function analysis, the following orders and delays were determined:

Input	Order(A)	Order(B)	delay
FM	3	2	0
SF	3	2	0
FWF	3	2	0
DL	3	2	0

Application of the identification algorithm yielded the following parameters:

Polynomial	Coeff. of q^0	Coeff. of q^{-1}	Coeff. of q^{-2}	Coeff. of q^{-3}	delay
A	1.0	-1.0238	-0.0296	0.0857	n/a
B_{fm}	0.0	-0.0268	0.0243	0.0	0
B_{sf}	0.0	-0.0723	0.0746	0.0	0
B_{fwf}	0.0	-0.0296	0.0310	0.0	0
B_{dl}	0.0	-0.0045	0.0045	0.0	0

4.3 The Steam Flow Model

Finally, a steam flow model was determined using feedwater flow, fuel master, drum level and steam pressure as inputs. Again, Test 1 data was used in the determination, due to the amount of variation in the steam flow signal. The results for this case are as follows:

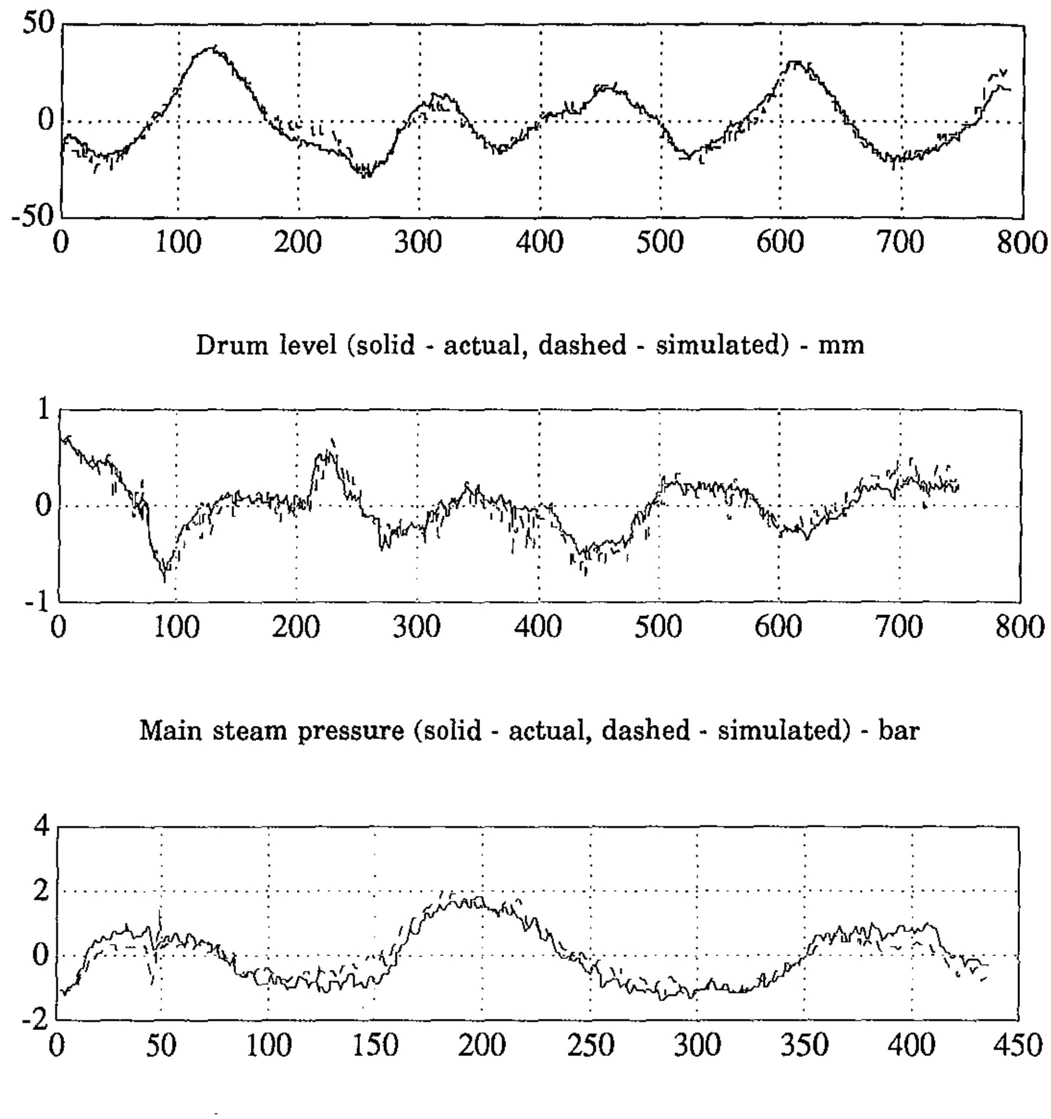
Input	Order(A)	Order(B)	delay
FWF	3	2	0
FM	3	2	0
DL	3	2	0
MSP	3	2	0

Polynomial	Coeff. of q^0	Coeff. of q^{-1}	Coeff. of q^{-2}	Coeff. of q^{-3}	delay
A	1.0	-1.0135	-0.0316	0.0544	n/a
B_{fwf}	0.0	0.2217	-0.2255	0.0	0
B_{fm}	0.0	0.0219	-0.0165	0.0	0
B_{dl}	0.0	0.0545	-0.0542	0.0	0
B_{msp}	0.0	-0.5700	0.6036	0.0	0

5. MODEL VALIDATION

The models presented in Sections 4.1, 4.2 and 4.3 are the result of a comprehensive study of a wide range of models validated against all the sets of data recorded. In some cases, the model was reiterated based on validation results, corresponding with step 4 in the model determination procedure. The validation results presented in this section are representative of the range of tests performed. Fig.5 shows a sample of the model validation performed. Validation results for all three models are given, with cross-validation examples being shown in the case of the main steam pressure (validated against Test 2 data) and steam flow models (validated against Test 4 data). These results give an indication of the quality of the models over a wide range of plant operating conditions.

Fig.5: Validation of dynamical models

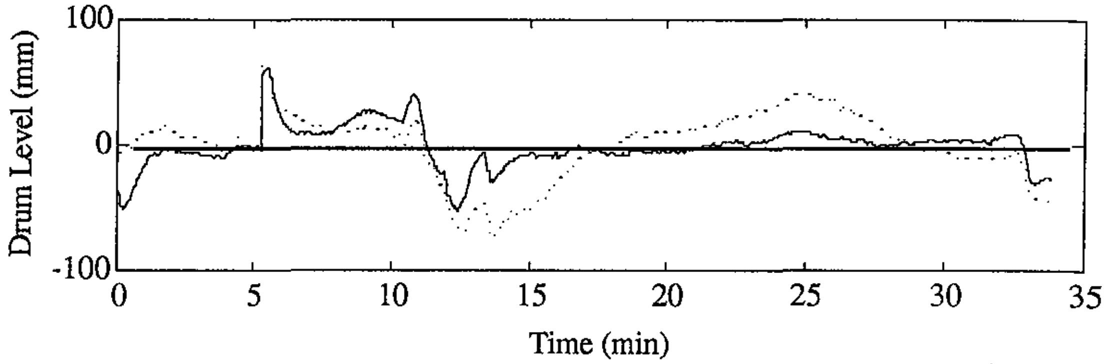


6. CONTROL SYSTEM DESIGN

A study of the model derived above facilitated diagnosis of the problems associated with the boiler control system. An analysis of the the data revealed errors in the feedwater and steam flow measurement. Simulation of the system also revealed poor tuning of both the feedwater and drum level PID controllers. In particular the drum level model was seen to contain a pole at unity (a pure integrator term), eliminating the need for the excessive integral action present in the current drum level PID, which was contributing to a highly underdamped response under certain conditions. A simulation of the system, based on the model, allowed retuning of the PID values in a completely controlled environment and provided the basis for further model-based control design studies (Ringwood, Noell and Austin, 1992). Fig.6

shows the response of the retuned controller (solid line) compared to that for the original settings.

Fig.6: Drum level variations for original and retuned controller



7. CONCLUSIONS

This paper demonstrates the use of black-box modelling techniques as a possible alternative or complement to basic physical modelling. Although most plants are described by sets of non-linear equations, the general approach is to determine a linearised model, upon which control design studies are based. In some cases it may not be possible to determine a linear model which approximates the operation of the plant over a wide range of conditions. Such a condition may be identified from poor model validation results. Where linearisation is possible, however, black box modelling provides a mechanism for determining the optimal linearised model (in a least squares sense), given the range of logged data available.

ACKNOWLEDGEMENT

The author is grateful for the helpful comments and assistance of Dr. Paul Austin and Mr. Ian Noell of the Production Technology Department at Massey University, New Zealand. Thanks must also go to the staff of Anchor Products, Te Rapa, New Zealand for their co-operation.

REFERENCES

Ljung, L. (1987) *System Identification - Theory for the User*, Prentice-Hall.

Ljung, L. (1991) *System Identification Toolbox (for use with MATLAB^{TM})*, The Math Works Inc.

Matlab (1991) *Matlab^{TM} for Macintosh Computers*, The Math Works Inc.

Ringwood, J.V., Noell, I.H. and Austin, P.C. (1992) *Modelling, Redesign and Analysis of a Boiler Control System*, submitted for publication, Journ. I. Chem. E.