THE USE OF THE ÅSTRÖM-BELL MODEL FOR THE DESIGN OF DRUM LEVEL CONTROLLERS IN POWER PLANT BOILERS

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Abstract: This paper is concerned with the study of drum water level control using the well established single element and 3 element controllers. The study is based on the Åström-Bell (A-B) interpretation model of the boiler, which is used to simulate a 160 MW plant P16-G16 in Sweden and a 500 MW plant WW500 in Australia.

Keywords: Drum Level Control; Åström-Bell Model; Power Plant Simulation.

1. INTRODUCTION

An important issue in power plant control is the control of drum water level in the boiler. Under steady operating conditions drum level control is usually not a problem, but for power plants that are frequently changing load or subject to sudden load disturbances, which are common in current market driven electricity industry, this is not the case. In such circumstances poor control can result in a costly plant trip, or even serious damage by boiling the drum or carrying water over into the turbine.

Most drum boilers around the world have level controlled by the so-called 3 element controllers. By balancing steam mass to the turbine against feedwater mass to the drum and then trimming the drum level error by a second controller, good level control is achieved. It is thought however that one fixed controller cannot control the level adequately over all the operating conditions and that at very low loads control instability can occur, requiring the control system to be switched to simple level feedback control - the so-called single element controller.

In recent years engineers in the power industry have come to accept the role of computer simulation in plant analysis and control design. In the boiler area, many models now exist ranging from complex knowledge based models to experimental models derived from special plant tests. In the middle of this range are so-called 'interpretation' models [Maffezzoni (1997), Rees and Lu (2002)]. These models are complex enough to capture the essential physics whilst at the same time have good control design features. The control studies described in this paper are based on one such model developed by Åström and Bell for a Swedish power station. This model is used to examine the performance of a 3 element controller over a wide range of plant operating conditions. The model is then fitted to a much larger 500MW plant unit with forced rather that natural circulation and the control studies repeated. In addition the limitations of the model and how these might affect the results are examined.

2. THE PLANT, ÅSTRÖM-BELL MODEL AND EXTENSIONS

2.1 The Plant

The plant under study is the drum water circulation system of a power plant boiler as shown in Fig.1. The main inputs to the plant are feedwater flow and temperature, steam flow and the heat Q to the risers. The main outputs are drum pressure and level. Later in this section the extent of the plant and the number of key variables will be discussed.

2.2 The Åström-Bell model (A-B Model)

The A-B Model is a non-linear physically based model of Fig.1

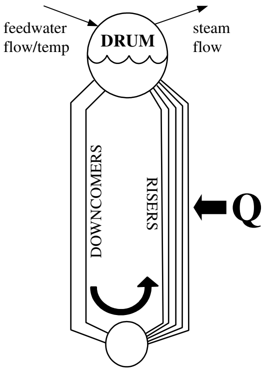

Fig. 1. The Drum Circulation System

The model equations are built up from global mass and energy balances. These overall balances when applied to Fig.1 lead to a simple second order model which quite accurately represents the pressure dynamics of the drum. But the serious deficiency in this simple model lies in its failure to model drum water level. Although it does determine the total amount of water in the system it does not take into account the steam in the risers and below the water surface level in the drum. To do this separate mass and energy balances must be written for the risers and the drum. Details of how this is done and what assumptions are made are given in Åström and Bell (2000). When a circulation flow equation and drum geometric equation are added to the above the resulting equations can be manipulated into a 4th order Åström-Bell state space representation of drum dynamics given by

$$e_{11}\frac{dV_{wt}}{dt} + e_{12}\frac{dp}{dt} = q_f - q_s \tag{1}$$

$$e_{21}\frac{dV_{wt}}{dt} + e_{22}\frac{dp}{dt} = Q + q_f h_f - q_s h_s \tag{2}$$

$$e_{32}\frac{dp}{dt} + e_{33}\frac{d\alpha_r}{dt} = Q - \alpha_r h_c q_{dc} \tag{3}$$

$$e_{42}\frac{dp}{dt} + e_{43}\frac{d\alpha_r}{dt} + e_{44}\frac{dV_{sd}}{dt} = \frac{\rho_s}{T_d}(V_{sd}^0 - V_{sd}) + \frac{h_f - h_w}{h_c} q_f \tag{4}$$

where the variables in the equations are defined in the Table 1 and the coefficients e_{ij} in the state matrix are non-linear functions of the states and the thermodynamic properties of water and steam. In addition to the

Table 1. Nomenclature

Parameters	Subscripts
V: volume	s: steam
ρ: specific density	w: water
p: pressure	f: feedwater
h: specific enthalpy	m: metal
t: temperature	d: drum
q: mass flow rate	dc: downcomer
Q: heat input	sh: superheater
T: time constant	t: total
α_r: steam quality	cd: condensation
α_v: steam volume ratio	r: riser
m_t: total metal mass of drum and tubes	

4 state variables in Equations (1)-(4) other important variables describing the behaviour of the boiling channel and drum can be easily displayed. As discussed in section 4, these variables are important in understanding channel behaviour and hence validation of the model.

2.3 Model Extensions

A number of relatively simple extensions can make the model applicable to a much broader range of plants. These include forced circulation, drum geometry, throttle valve pressure and auxiliary and sensor modelling. The later variables are essential for realistic plant simulation.

In the A-B model natural circulation is assumed with downcomer and riser flow dependent on density changes. Forced circulation assumes that the pump determines the flow. In the extension a linear combination of these factors is used. For plants that are not regulated about the centre line, non-linear geometry need to be used to determine drum level from the states. A simple interactive procedure has been added to solve the level.

Most operating plants base pressure control on the throttle valve ($TSVP$) or first stage turbine pressure; this can be determined by a steady state momentum balance, added to the model. Finally it is necessary to consider the important dynamics associated with sensors and actuators. Simple and multiple first order dynamics are used for the modelling of the actuators; saturation and rate limits are available if required. Further details on the extensions are in Donaldson (2003).

3. CONTROL OPERATION AND SIMULATION

3.1 Drum Level Control

The plant control of water level is carried out using either single element control or three-element control. Single element control is essentially level feed back PID control and does not generally handle fast load changes well due to the shrink and swell effect. Three

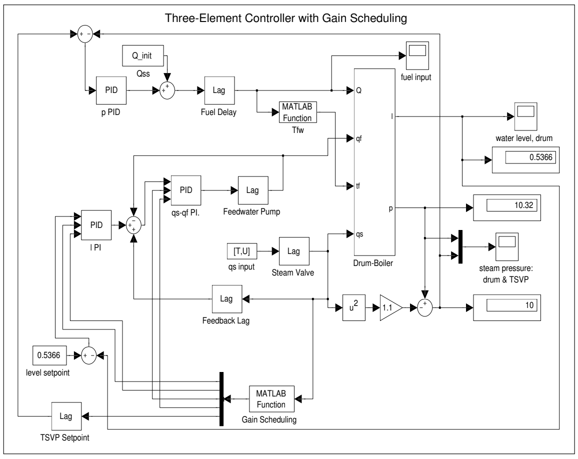

Fig. 2. Plant and Control Simulation

element control is essentially a form of cascade control in which the inner loop is a fast acting loop to follow load changes and the outer loop a slower trim loop for water level.

3.2 Pressure Control

The basic pressure control loop is a PID loop based on $TSVP$ error. The plant can be operated using fixed pressure but is more likely to operate using a modified form of sliding pressure which has been programed into the simulation. In Fig.2 the plant is shown operating in boiler follow mode. Section 5 will discuss a mode of co-ordinated control and a more complicated pressure controller.

3.3 Gain Scheduling

In Section 5 it will be shown that it is not possible to operate the plant over a wide range using fixed parameter pressure and water level controllers. Results using gain scheduling will be described briefly in Section 6.

3.4 Plant and Control System Simulation

Fig.2 shows a Matlab/Simulink implementation of the plant and control systems.

The drum boiler block masks the A-B Model Eq.(1)-(4) to which the forced circulation and geometry extensions have been added. Below the drum boiler module is the superheater and throttle valve pressure loss extension. To the left the auxiliary are added including fuel system, feedwater pump and throttle valve. Sensor lags are also put into the feedback loops but not shown in the figure. In addition two Matlab modules carry out the gain schedule, sliding pressure function and also account for the variation fo the feedwater temperature with load.

4. MODEL FITTING AND VALIDATION

4.1 Model Fitting

A key feature of the A-B model is that it can be fitted to plant data using only a small number of physically meaningful parameters. These are

- *D*rum, riser and downcomer volumns V_d,V_r,V_{dc}.
- *D*rum area at normal operating level A_d.
- *T*otal metal mass m_t at riser mass m_r.
- *F*rictional coefficient in the riser loop, k.
- *V*olume of steam in the drum with no condensation V_{sd}^0 and residence time of the steam T_d.

When the model extensions are included the experimenter must also know the frictional coefficient in the superheater, the physical dimensions of the drum, the forced-natural circulation coefficient k_g and the major time constants of the auxiliaries.

For the P16-G16 plant all the necessary parameters have been determined in Åström and Bell[2000]. The model performance has also been tested against open loop and closed loop data. For the WW500 plant we have estimated the above parameters from limited available data. The required volumes, masses, area and k have been estimated from engineering drawings and handbooks. V_{sd}^0 and T_d cannot be estimated directly. Instead they have been scaled up from their P16-G16 values. Since open loop data was available for P16-G16 the original valves of V_{sd}^0 and T_d are fairly reliable. Finally the auxiliaries have been estimated from operational data.

4.2 Model Validation for WW500

Open Loop Validation In Donaldson (2003) extensive open loop simulation results have been conducted for step changes in steam flow, feedwater flow and heat input. Since no open loop plant data is available the only way these tests can be validated is by examining all the physical variables in the simulation and using physical and thermodynamics principles to show that their behaviour is meaningful. In addition, since some confidence exists about the P16-G16 open loop results a comparison of the WW500 results with these also gives some confidence as shown in Fig.3.

Note that the operating pressure for WW500 is much greater than P16-G16 hence there is a smaller shrink and swell effect, which is also reflected in V_{sd} and V_{wd}. Since WW500 has forced circulation its flow q_r is more constant and significantly less than in P16-G16. Since the heat input has not changed and q_r is much smaller for WW500, α_r must be larger as shown. Note also that the higher pressure causes a greater condensation flow q_{cd}.

Closed Loop Validation Whilst the open loop results give some confidence about the model, the final test

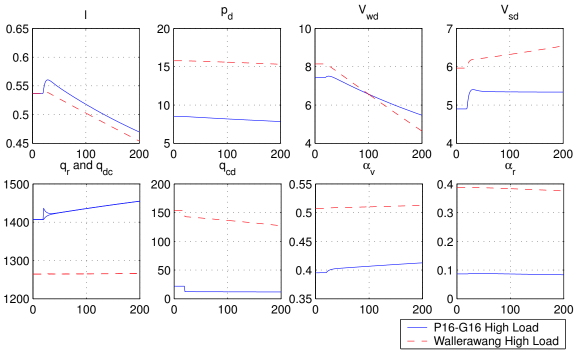

Fig. 3. WW500 vs.P16-G16 for a 10kg/s step in q_s at high load

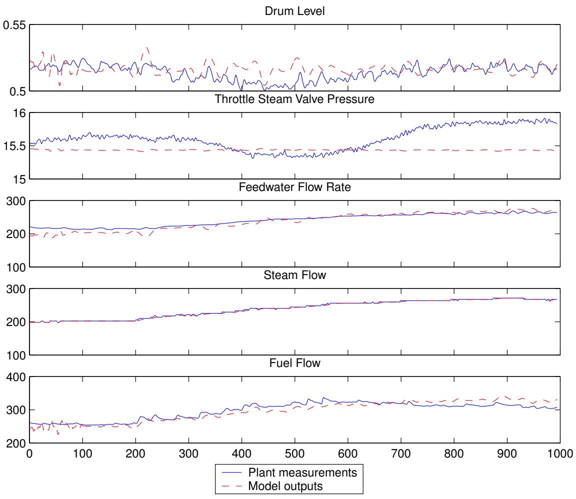

Fig. 4. WW500 Closed Loop Response to a step in q_s

needs to be closed loop performance. Fig.4 shows the results of a benchmark test in boiler follow mode. In this test both the plant and the model are driven by the same steam flow input.

Note that the steam, feedwater and fuel flows results match well but there is more error in drum level and $TSVP$. This is partly due to the fact that in the model, the pressure loop was tightly tuned and this was not so in the real plant. This lack of tight control can be seen in both level and $TSVP$ measures. It also accounts for some of the discrepancy in the fuel flow where $TSVP$ dropping below its set point around 500 secs cause the real plant to demand more heat.

Whilst the open loop and closed loop results described here are far from ideal they do give some confidence that the WW500 model is basically correct. To fully validate the model however and to get good parameter estimation well designed experiments need to be carried out. These experiments will require not only careful recording of what is done during the experiments but also control structures and settings. Such experiments are costly to the industry and time consuming, and will only be possible where management sees advantages from carrying the tests out.

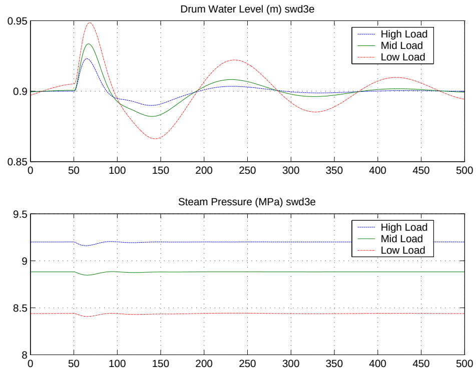

Fig. 5. Fixed 3 Element Controller at High/Mid/Low Loads for P16-G16

5. CONTROL RESULTS

In this section the fitted models for P16-G16 and WW500 will be used to investigate the controlled behavior of the two plants. The aim is not only to control the plants, but also to understand the fundamental issues underlying the drum level control, i.e. what is it that makes the control difficult? Since both plants are highly non-linear the studies will be carried out for high, medium and low load operation ranges. The initial conditions for each of these cases are determined by the steady state solution of Eq.(1)-(4).

Controller tuning is carried out following standard engineering practice, i.e. assume no interaction between loops and then get initial control settings from a control design procedure, usually Ziegler-Nichols. Tuning is then modified by trial and error making allowances for the strength of the interaction and rate and position limits on the controllers. This is much more easily done in simulation than in practice and after some experience the designer can quite quickly produce good results.

5.1 P16-G16 Plant

In this plant the auxiliaries are rather fast with 10 seconds lags for the fuel system and feedwater pump. Results with single element control show consistent poorer performance than the 3 element control. Fig.5 shows the results from a 3 element controller. The plant is in boiler follow mode and the simulations show high (85%), medium (50%) and low (15%) load performance following a 10% step load change using a fixed parameter controller with parameters tuned for high load.

The results suggest that whilst medium and high load performance of the water level is about acceptable (25mm) low load performance is poor (50mm) and lacks robustness. This should be contrasted with later results for the 500MW plant where more realistic longer time constants of the auxiliaries and the lags

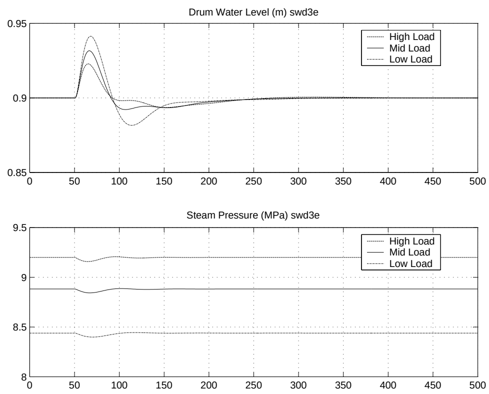

Fig. 6. Separately Tuned 3 Element Controllers at High/Mid/Low Loads for P16-G16

from the sensors make the control, especially pressure control difficult.

In Fig.6 the controllers have been tuned at each load level. The results show improved level control especially settling time, however low load results are still not good enough. Pressure remains easy to control since it is not strongly influenced by water performance. The next section will show how water level performance can be improved using a coordinated approach.

5.2 WW500 Plant

The A-B model with parameters fitted as in Section 4 is supplemented with a much realistic longer time constants and multiple dynamics in the auxiliaries especially in the coal fired fuel model. This makes the control of drum pressure much more difficult using only one PID controller as shown in Fig.7.

In Fig.7 the controllers have been tuned for each load. The water level is performing well but pressure control is poor with large amplitude low frequency oscillations that would not be acceptable for load pressure and temperature controls.

A method of overcoming these pressure variations by the use of steam flow feed forward is suggested in DiDomenico (1983) and this has been improved upon by Hussin (2001). In essence the method creates a cascaded pressure control loop in which the inputs to the inner controller are pressure errors and the imbalance between the steam signal and the heat input to the furnace. The results of this ’combined’ coordinated control are shown in Fig.8.

Fig.8 shows that pressure control is now very good and level control is much faster. At low load however drum water excursion is large. This is due to that fact that although pressure changes are small the rate of change of the pressure is very high causing a much geater swell effect especially at low loads.

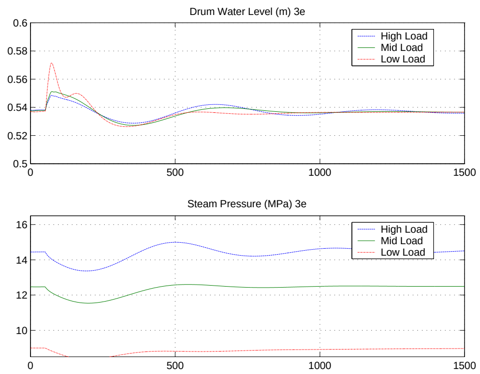

Fig. 7. Separately Tuned 3 Element Controllers at High/Mid/Low Loads for WW500

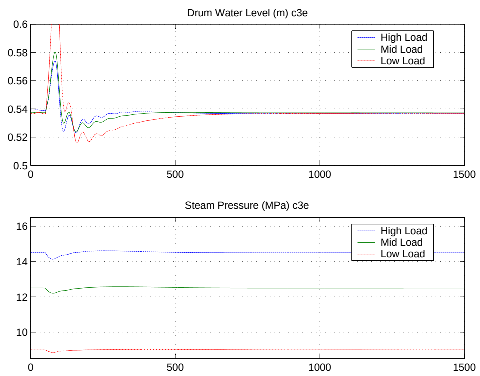

Fig. 8. Separately Tuned Combined 3 Element Control at High/Mid/Low Loads for WW500

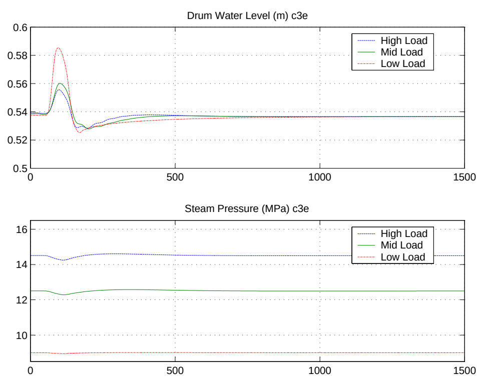

Fig. 9. Separately Tuned Combined 3 Element Control at H/M/L Loads for WW500 with Ramp Load Change

It may be possible to get a better balance between level deviation and pressure by proper tuning but it is also worth mentioning that most load changes follow a ramp rather than step input. When using a 10%/min load ramp change the results are shown in Fig.9 with almost halved level deviation of 40mm at low load.

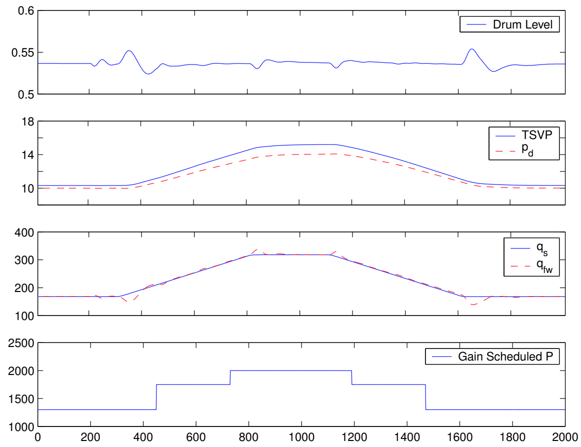

Fig. 10. Gain Scheduling with Sliding Pressure

6. CONCLUSION AND FUTURE WORK

This paper describes a simulation study of drum water level control. The two plants under study are a 150MW oil fired plant in Sweden and a 500MW coal fired plant in Australia. The plants have been modelled using the so called Åström and Bell model and it has been shown that with suitable data this model can be fitted to both plants. Extensions to the A-B model to take in to account non-linear drum design, forced water circulation, the throttle valve and other issues have been described.

The control design has followed engineering practice and the results generally confirm that 3 element control of drum water level is a fairly satisfactory method of control over a wide range. However even if the controller is tuned for different load levels 3 element control still needs improvement at low loads. Ways of achieving this are discussed in the paper. The paper also tries to understand the complex non-linearities and interaction between pressure and water level in the drum.

As already mentioned although it is not the complete answer, some type of gain scheduling certainly improves wide range control. Fig.2 outlines the gain scheduling system used in this study. The gain scheduling block takes steam flow as input determines from this generated load and then computes the two sets of PI controller setting and the sliding pressure set point. Fig.10 shows results of this proceedure for ramp up and ramp down steam flow changes from 30% load to 75% load.

The drum water level results show all the points we have been making in the paper such as control being harder at low load and drum water disturbances being smaller for ramp changes. The results of the control studies suggest that non-linear multivariable control might well be usefully applied to the problem.

The A-B model certainly seems a useful model to study power plant dynamics. Realistic results will however only really be available when the actuator and sensor dynamics are included and we have tried to highlight this in our study. The A-B model is an attractive model because of its compactness and familiarity to control theorists. It does seem to catch major events, however, at low loads although it reflects the much greater swell effects it is not such a fundamental analyses as that made by Kwatny and Berg (1993). Since the Kwatny and Berg work is particularly concerned with operation below 30% load this might not be a problem. More work needs to be done on this question but this would imply rather expensive plant studies.

7. ACKNOWLEDGEMENTS

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REFERENCES

Åström K.J. and Bell R.D. (2000), Drum-Boiler Dynamics. *Automatica* vol.36, pp363-378.

DiDomenico, Peter N. (1983), Practical Application of Feedforward Control for a Ultility Type Drum Boiler. *American Control Conference*, San Francisco, Session WA3-B.

Donaldson S.C. (2003), Drum-Boiler Water Level - Simulation and Control. *B.E. Thesis*. UNSW, Sydney, Australia.

Hussin F.A. (2001), Drum Water Level Control - A Study by Simulation. *M.Eng. Sci. Thesis*. UNSW, Sydney, Australia.

Kwatny H.G. and Berg J. (1993), Drum Level Regulation at All Loads. *12th IFAC World Congress*, Sydney, Australia vol.3, pp405-408.

Maffezzoni C. (1997), Boiler-Turbine Dynamics in Power-Plant Control. *Control Engineering Practice*, vol.9, pp.301-312.

Rees N.W. and Lu C.X. (2002), Some Thoughts on the Advanced Control of Electrical Power Plants. *Transaction of the Institute of Measurement and Control*, vol.24, No.2, pp87-106.