

A Novel Approach to Develop the Lower Order Model of Multi-Input Multi-Output System

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Abstract— A mathematical model is a virtual entity that uses mathematical language to describe the behavior of a system. Mathematical models are used particularly in the natural sciences and engineering disciplines like physics, biology, and electrical engineering as well as in the social sciences like economics, sociology and political science. Physicists, Engineers, Computer scientists, and Economists use mathematical models most extensively. With the advent of high performance processors and advanced mathematical computations, it is possible to develop high performing simulators for complicated Multi Input Multi Output (MIMO) systems like Quadruple tank systems, Aircrafts, Boilers etc. This paper presents the development of the mathematical model of a 500 MW utility boiler which is a highly complex system. A synergistic combination of operational experience, system identification and lower order modeling philosophy has been effectively used to develop a simplified but accurate model of a circulation system of a utility boiler which is a MIMO system. The results obtained are found to be in good agreement with the physics of the process and with the results obtained through design procedure. The model obtained can be directly used for control system studies and to realize hardware simulators for boiler testing and operator training.

Keywords: *Mathematical Model, Multi-Input Multi Output (MIMO) system, Lower Order Model, Utility Boiler, Circulation System..*

I. INTRODUCTION

Modeling and Simulation is a discipline for developing a level of understanding of the interaction of the parts of a system, and of the system as a whole. The level of understanding which may be developed via this discipline is seldom achievable via any other discipline.

A system is understood to be an entity which maintains its existence through the interaction of its parts. A model is a simplified representation of the actual system intended to promote understanding. Whether a model is a good model or not depends on the extent to which it promotes understanding. Since all models are simplifications of reality there is always a trade-off as to what level of detail is included in the model. If too little detail is included in the model one runs the risk of missing relevant interactions and the resultant model does not promote understanding. If too much detail is included in the model the model may become overly complicated and actually preclude the development of understanding. One simply cannot develop all models in the context of the entire universe. Mathematical models can take many forms, including but not limited to dynamical systems, statistical models, differential equations, or game theoretic models. These and other types of models can overlap, with a given model involving a variety of abstract structures.

Mankind has always desired to develop intelligent systems that mimic the biological systems and also obey his commands. The invention of aircraft systems, robots and industrial automations systems and many others has been inspired by this desire. In order to make cost-effective systems for such applications, advancements in computer technology plays an important role. Simulation softwares like Matlab provide a platform to simulate and test the performance of simulator systems before they are implemented on a hardware simulator. This paper deals with the methodology adopted to develop the model of the circulation system of a 500MW utility boiler as a MIMO system. Precise and sustained control of the steam generation system is vital for increasing the boiler efficiency. In order to develop and analyze the control strategies, it is essential to develop an accurate and valid boiler model. A few methods to develop such models are available in literature, but these methods are often plant specific. The objective of this paper is to present a methodology to develop the reduced order model of the circulation system of a boiler.

The behavior of the model described in this paper accurately represents the significant dynamics of the 500 MW utility boiler at Bharath Heavy Electricals Limited, Vishakapatnam, India. Upon review of the currently available models, this paper presents a



simple approach to model the circulation system of the 500MW utility boiler based on system identification and lower order modeling philosophies.

II. MATHEMATICAL MODELING

Mathematical Modelling of any system is important to describe its dynamic behavior. It is a challenging task to accurately model complex real time systems like utility boilers which involve a lot of subsystems. A mathematical model basically establishes the relationship between the input and output of a system. The relationship may be

- Linear or Non-linear Algebraic Equations
- Linear or Non-linear Differential/Partial Differential/Time Varying Equations
- Transfer functions
- State Space Models

Generally, there are two modeling approaches that are adopted in order to determine the dynamic model of a system:

- First Principle or Physical model Approach
- Black Box model Approach

In the physical model approach, the system/process is assumed to be well understood. The modeling philosophy is based on the laws of conservation of mass, energy and momentum as is applicable to the physical process under consideration. This approach usually results in non-linear model equations consisting of differential and algebraic terms. The coefficients that are derived from the model equations have a wide range of validity and are related to the physical process to a great extent.

In the Black Box model approach, the process may not be completely known or may be too complicated to be modeled by physical laws. Hence, the system under study is modeled using its input output relationship. Experiments are performed and field measurements are obtained for input-output responses, from which the process dynamics are determined. This approach is useful for the overall study of various systems.

Many attempts have been made by researchers to derive the lower order model of a thermal power plant. In the case of field measurements, it is found that performing experiments are expensive, time consuming and are prone to error due to measurement noise and the delays introduced due to the sensing devices. Physical model, on the other hand is more reliable and justified since it is derived from fundamental physical laws. Therefore, when such a detailed physical model is available, it is relatively easy to derive the lower order model of the various subsystems or the overall plant. The model thus obtained can be tested for a step or any other disturbance and the response analyzed without having to bother about the complexity involved in the system.

There are many detailed models available in literature for coal-fired thermal power plants. Some of the papers to be mentioned are the ones by Mc Donald and Kwatny [1], Kwan and Anderson [2] in which the authors have derived the physical model of a 100 MW power plant. Reduced order or Lower order modeling of the subsystems in a power plant is necessary because it leads to reduced memory requirements and easy implementation. It can be used to study the effect of controller settings on a system without having to study the detailed mathematical model. It also helps one to realize a hardware simulator that can be used for stability analysis of the power plant and various diagnostic studies.

III. LITERATURE BACKGROUND

Many attempts have been made by researchers to derive the lower order model of a thermal power plant. Eklund and Gustavsson [3] have used the physical knowledge of the system to derive the structure of the model and identified the transfer function parameters by performing experiments on the boiler. Lower order modeling using mathematical approaches like Newton Raphson method, Jacobian method and many more have been attempted by researchers, but these are found to be computationally complex and time consuming [4 to 20]. Ponnusamy et.al [21] have derived a lower order dynamic model of a complete thermal power plant. Sivakumar and Rajalakshmy have derived a model of a utility boiler furnace using heuristic approach. [22]. In order to derive

the lower order model of a system, one needs the input – output measurements obtained from the field or the values generated from the detailed physical model of the plant.

With a detailed physical model is at one's disposal, it is relatively easy to derive the lower order model of the various subsystems or the overall plant. The input-output data can be precisely obtained for a given region of interest from which the lower order models can be derived to fit these input-output relations using appropriate system identification techniques. The model thus obtained can be tested for a step or any other disturbance and the response analyzed without having to bother about the complexity involved in the system.

In contrast with the methods available in literature, the authors have attempted to derive the simplified model of the complex Multiple Input Multiple Output (MIMO) circulation system using the input output data generated from the validated model of a 500 MW thermal power plant at BHEL, Vishakapatnam, India on the basis of literature survey on modeling, plant data knowledge, system identification methodology and heuristic adjustments. The detailed description of the system identification method is discussed and the results are presented.

IV. SYSTEM UNDERSTANDING

In this paper, a pulverized coal corner fired furnace is considered. There are nine elevations through which coal can be sent to the furnace. For a full load 500MW, fuel is fired through six elevations with appropriate burner tilt. The number of elevations and burner tilt vary depending upon the part load. The net heat input to the furnace is decided by the calorific value and coal flow rate and the sensible heat brought in by primary and secondary air. The feed water from economizer goes to the drum and gets converted into steam in the circulation system (drum – down comers and water walls). The different heat exchangers like panel super heater, platen super heater and re heater which are located at the top of the furnace in the flue gas path. The steam from the drum gets super-heated in various super heaters and enters the high pressure turbine.

The most important subsystems of the thermal power plant are the Boiler Feed Pumps, high pressure boiler (including boiler furnace, Circulation System, Economizer, Super heaters, Reheater) High Pressure, Intermediate Pressure and Low Pressure Turbine, Condenser and De-aerator. The following section describes the methodology and principle behind lower order modeling of the circulation system of a 500 MW coal fired utility boiler. The overall schematic diagram of a boiler system is shown in Fig. 1. [23]

V. LOWER ORDER MODELING OF CIRCULATION SYSTEM

Reduced order or lower order modeling of various subsystems in a power plant is necessary and useful in a number of situations, because it leads to reduced memory requirements for computation. A low-order model of a power plant has a number of uses:

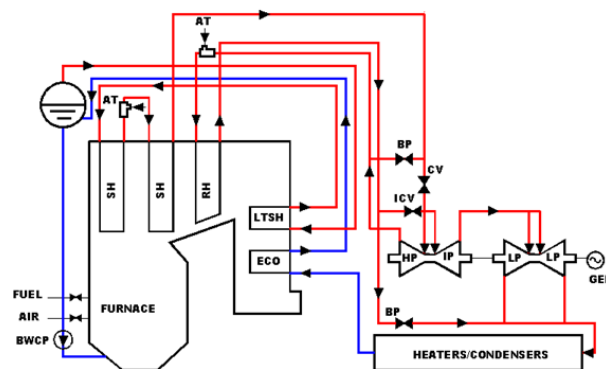


Fig. 1. Overall Schematic diagram of a 500 MW Boiler

- It can be used for various system analysis studies and to study the effect of controller settings on a system without having to study the detailed mathematical model.
- It also helps one to realize a hardware simulator using analog, digital or hybrid hardware.
- It can be used for the study of power plant malfunction or upset conditions within the limits of the model.
- It can be used for long term stability analysis of the power plant and various diagnostic studies.

In summary, it may be inferred that low-order models for the power plant or its subsystems may be derived using input-output responses obtained from field measurements or from the detailed physical model of the power plant, by employing appropriate system identification techniques in each case. Performing experiments are expensive and time consuming and may involve risk to the physical system; hence they are not easy to conduct. Appropriate input signals, such as a step disturbance in only one input, are not easy to introduce. Moreover, in real time situations, all inputs may vary simultaneously even though disturbance was initially introduced only in one of the input variables. Thus in a multi-input, multi-output system, the output recorded would be the result of simultaneous disturbances in several inputs. This makes the identification job more difficult. Also, the field measurements may be corrupted by noise and also be affected by the response lags in transducers and measuring instruments. These factors also have to be taken care of in the identification algorithms. All of these make the generation of input-output data and the subsequent identification process difficult.

This paper adopts the black box model approach and acknowledges the authorities of Bharat Heavy Electrical Limited for permitting access to the input – output responses obtained from the Predicted Performance Data of their Simhadri Power Plant. Predicted Performance of the boiler at different loads will usually be supplied by OEMs. In order to derive the lower order model, the circulation system is considered as a Black Box with multiple inputs and multiple outputs. The system may be considered to behave linearly for small input variations around a steady state operating point. Therefore, the inputs and outputs can be related by suitable transfer functions that are derived from the input-output data of the circulation system. In the proposed methodology, it is observed that the behavior of input and outputs are quite simple and the general form of transfer function can be estimated with ease just by inspection of the input output curves. Once the order is known, then the other parameters like gain, poles and zeros can be easily determined. Software Simulated system identification tool box has been used to estimate the parameters.

The circulation system consists of the drum, down comers and water walls. The feed water that returns from the condenser picks up heat in the High Pressure Heaters and the Economizer before entering the drum at a temperature that is lower than its saturation temperature. Steam that has attained its saturation temperature is drawn out of the drum by adjusting the throttle valve provided at turbine inlet according to the load requirements. The water walls that also form the furnace walls receive heat by direct radiation.

The steps involved in the low-order modeling of the subsystems are obtained and illustrated by considering the circulation system. These low-order models have been implemented in hardware and in a training simulator. The following sections describe the methodology and principle behind lower order modeling of the circulation system of the 500 MW boiler.

The detailed model of the circulation system is quite non-linear. It consists of coupled non-linear differential equations associated with algebraic equations for heat transfer and steam-water properties. These equations can be used to compute the changes in the drum pressure and drum level for any changes in the input variables. Around a given steady state, say the full-load operating point, the incremental changes in the inputs and outputs can be linearly related and the circulation system can be characterized by

$$\begin{bmatrix} G_{11} & G_{21} & G_{31} & G_{41} \\ G_{12} & G_{22} & G_{32} & G_{42} \end{bmatrix} \begin{bmatrix} \Delta T_{weco} \\ \Delta W_{weco} \\ \Delta Q_{gww} \\ \Delta W_{sdro} \end{bmatrix} = \begin{bmatrix} \Delta P_{DR} \\ \Delta V_{DR} \end{bmatrix}$$

Where $G_{xi}(s)$ is the transfer function relating the output at port x to the input at port i.

Thus, the circulation system is perceived as a multi-input multi-output system as shown in Fig. 2.

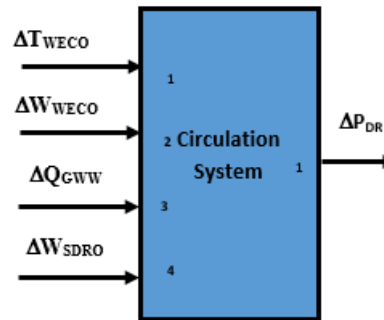


Fig. 2 Circulation System with the input - output variables

The schematic representation of the circulation system is shown in Fig.3.[22]

The inputs to the circulation system are

- Feed water Temperature at the Economizer outlet. (T_{WECO})
- Feed water flowrate at the Economizer outlet. (W_{WECO})
- Heat flow rate to water walls. (Q_{GWW})
- Steam flow rate from drum. (W_{SDRO})

The output from the circulation system are

- P_{DR} – Drum Pressure
- V_{DR} – Drum Volume

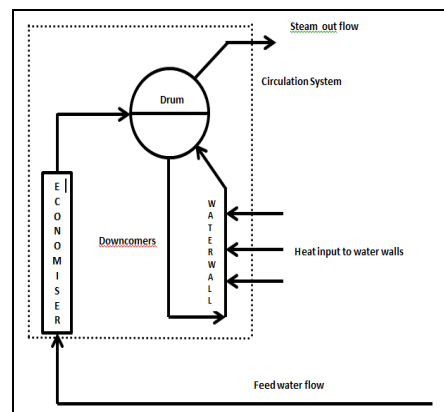


Fig. 3. Schematic Diagram of Circulation System

VI. MODEL DESCRIPTION

There exists a detailed non linear mathematical model developed for a 500MW capacity thermal plant in “The Centre of Excellence for Simulators”, BHEL, Vishakapatnam, India. [23] This model includes various subsystems such as mills, Primary fans, Secondary fans, Induced draft fans, Boiler feed pumps, furnace and super heating sections as well as reheating sections. The volume and pressure responses of the circulation system model for a step increase in the four input variables are shown in Fig. 4.

This model has been extensively validated from experimental results obtained including field dynamic experiments carried out and used to build plant simulator. The data required for system identification of the circulation system has been generated from this validated model.

The graphs have been plotted against time in seconds. The pressure and volume response for a step increase in the four input variables is observed and a general form of the transfer function is thus estimated.

Now, by using the system identification toolbox, the coefficients are estimated. Fig. 5.a and 5.b. depicts the transfer function representation of the input-output variations.

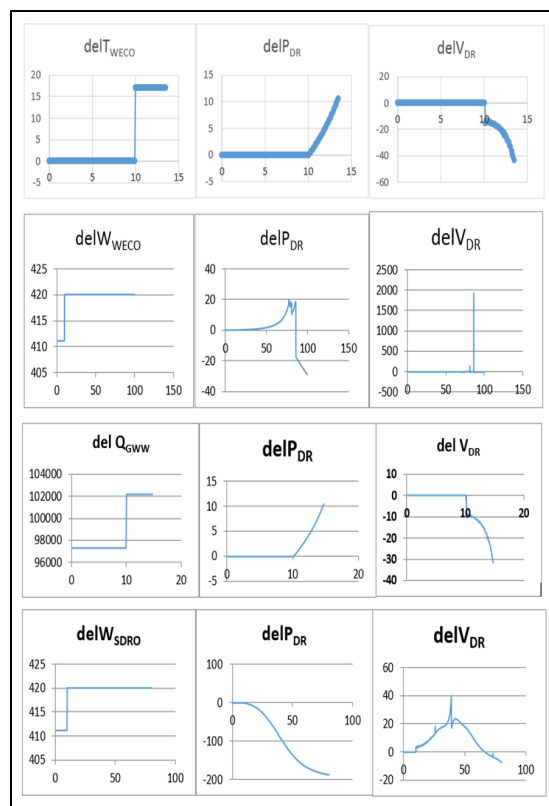


Fig. 4. Input – Output behavior of a circulation system

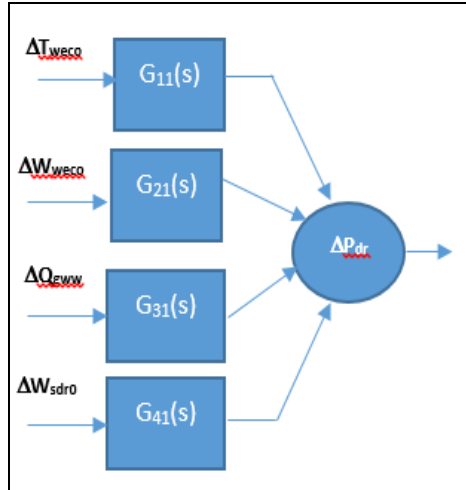


Fig. 5a. Transfer function model of Input Vs Drum Pressure

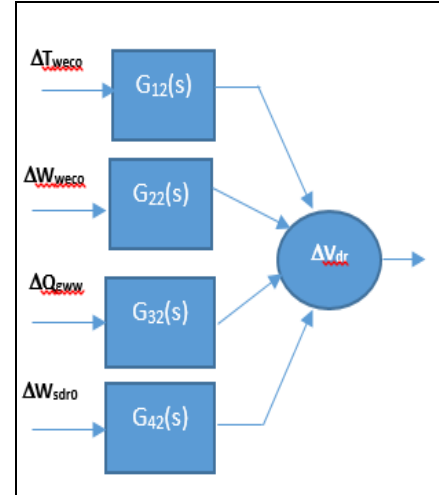


Fig. 5b. Transfer function model of Input Vs Drum Volume

The system parameters identified are listed in Table 1 and 2.

Table 1- System parameters for Input Vs P_{DR}

S. No.	TF Model	TF Structure	Parameter Identified
			K
1	$G_{11}(s)$	$\frac{K}{s}$	0.017719
2	$G_{21}(s)$	$\frac{K}{s}$	0.0013798
3	$G_{31}(s)$	$\frac{K}{s}$	2.1007×10^{-6}
4	$G_{41}(s)$	$\frac{K}{s}$	-7.22×10^{-4}

VII. RESULTS AND DISCUSSION

By observing the response curves of drum Pressure P_{DR} and drum volume V_{DR} for step changes in one of the input variables namely, W_{sdro}, as shown in Fig. 6a&b, it may be noted that the transfer function relates to the behavior of the system.

The required transfer functions thus obtained can be used for control and simulation studies of the circulation system and further be integrated with the lower order models of the other subsystems to obtain a complete lower order model of a thermal power plant. The transfer functions derived were tested for a step change in the input parameters for drum pressure response and the response obtained is shown in Fig. 7., where G₁₁, G₂₁, G₃₁, G₄₁ are the transfer functions derived above.

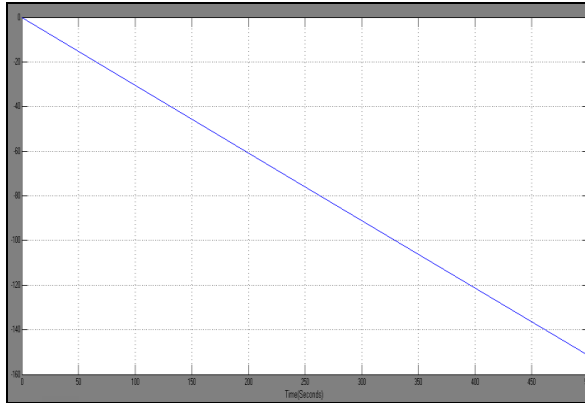


Fig. 6a. Drum Pressure Response for a step change in Wsdro

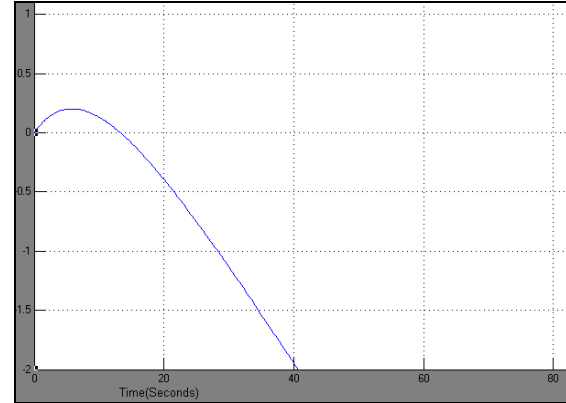


Fig. 6b. Drum Volume Response for a step change in Wsdro

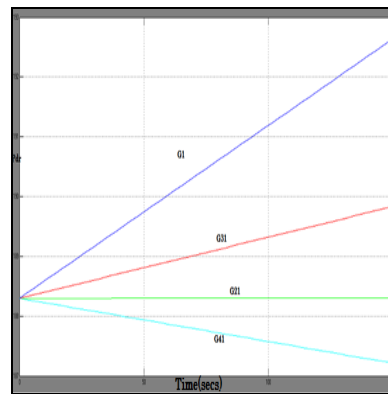


Fig. 7. Drum Pressure output for a step change in input parameters

It is observed that the drum pressure response for a step change in the input parameters Tweco, Wweco, Qgww, Wsdro is well within the industrial standards. The simulation has been carried out for a 500MW boiler when the boiler demand is 100%.

The lower order modeling of the complete boiler has been dealt with in two steps. The first step is to develop the mathematical model of the circulation system based on system identification studies. The transfer function obtained is validated by plotting the drum pressure response for varying loads and verifying that they conform to the response of the detailed mathematical model. The response curves of drum pressure P_{DR} for step changes in the boiler input parameters is shown in Fig. 8. It may be noted from the response that the system behavior conforms to the transfer function obtained. For example, the transfer function relating the input step change in the steam flow rate at the outlet of the drum, ΔW_{sdro} and the output drum pressure, ΔP_{DR} is defined as

$$\Delta W_{sdro} \frac{\Delta P_{DR}(s)}{\Delta W_{sdro}(s)} = G_{41}(s) = \frac{K_4}{s}$$

The value of K_4 obtained using the system identification technique is -7.22×10^{-4} . The negative sign indicates that the step response hence obtained exhibits a negative slope. This behavior of the circulation system conforms to the physical system behavior. This is because the drum pressure decreases for a step increase in the flowrate of steam from the outlet of the drum. In a similar manner, all transfer functions that have been developed in this mode can be tested and validated and the results are quite promising.

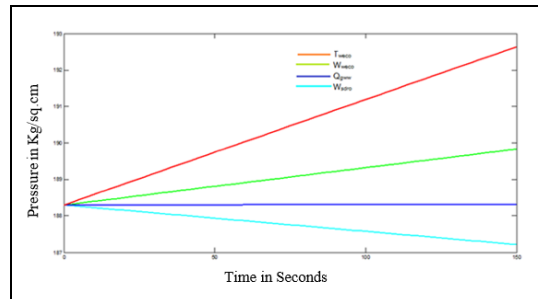


Fig. 8. Drum Pressure Response for step changes in various loads

The boiler components are integrated and the entire system is simulated in software for inputs at various loads. The simulation result for 500MW load is shown in Fig. 9. It is the main steam temperature obtained at the output of the platen super-heater

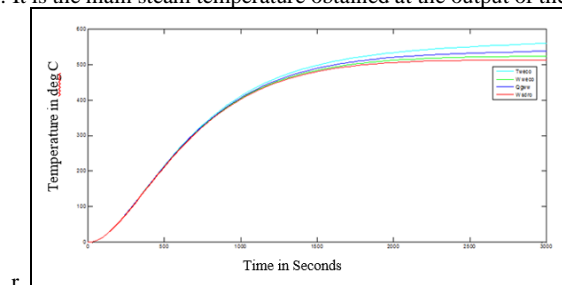


Fig. 9. Main Steam Temperature Response of Super-heaters for a step change in input variables.

VIII.CONCLUSIONS

This paper aims at emphasizing the usefulness of mathematical model in obtaining the lower order model of a circulation system. The required input and output data are accurately generated from the detailed mathematical model of the circulation system and the lower order system parameters are evaluated from these data by employing conventional system identification tool box. The transfer functions obtained can be used for dynamic stability analysis of the system. The methodology can be extended to other MIMO systems like aircrafts, four tank systems as well.

IX.ACKNOWLEDGEMENTS

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