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Neural Network Approach for Predicting Drum Pressure and Level in a Coal-fired Subcritical Power Plant

Eni OKO and Meihong Wang

Process and Energy Systems Research Group, School of Engineering
University of Hull HU6 7RX, United Kingdom

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Outline

- ❑ Background
- ❑ Boiler Drum Data
- ❑ NARX Model
- ❑ NARX Model Training
- ❑ Results
- ❑ Conclusion and Future Work

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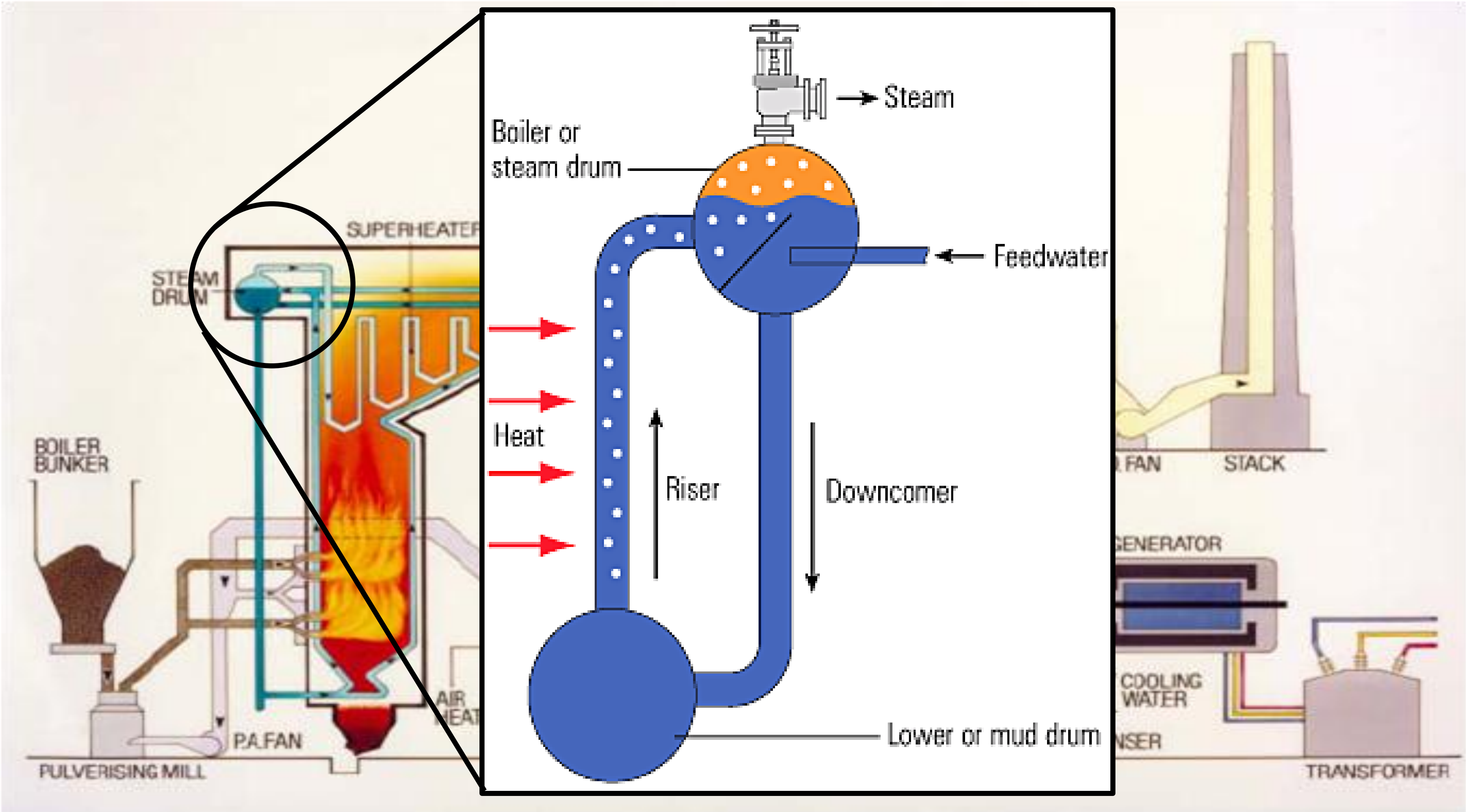
Background



Layout of Coal-fired Subcritical Power Plant[1]

Background

- Boiler Drum is a critical component of a coal-fired subcritical power plant:
  - acts as energy reservoir in the plant enabling it to cope with short term load changes
  - dictates overall plant dynamics due to the slower dynamics compared to the steam turbine dynamics
- Due to tightening regulations, deserves study of the dynamics for operation and control purposes
- Data-based approach such as neural networks less laborious than physical modelling

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Boiler Drum Process

- Represented by a detailed first principle model according to Åström and Bell [3] using gPROMS tool.
  - Inputs: Feedwater flowrate, Steam flowrate and heat energy input
  - Outputs: Drum pressure and drum water level
- Thermodynamic properties of water/steam were obtained using IAPWS-95 formulation in Aspen Properties via COThermo interface.
- Thermodynamic property derivatives were obtained using polynomial approximations of steam table calculations from NIST REFPROP V9.1.

Boiler Drum Process

Global Conservation Equations

$$\frac{d}{dt}[\rho_s V_{st} + \rho_w V_{wt}] = m_{fw} - m_{st}$$

$$\frac{d}{dt}[\rho_s h_s V_{st} + \rho_w h_w V_{wt} - pV_t + M_t C_p T_{sat}] = Q + h_{fw} m_{fw} - h_s m_{st}$$

$$V_{st} + V_{wt} = V$$

Drum Dynamics

$$\frac{d}{dt}\rho_s V_{sd} = \alpha_r m_r - m_{sd} - m_{cd}$$

$$m_{sd} = \frac{\rho_s}{T_d}(V_{sd} - V_{sd}^0) + \alpha_r m_{dc} + \alpha_r \beta (m_{dc} - m_r)$$

$$V_{wd} = V_{wt} - V_{dc} - (1 - \overline{\alpha_v}) V_r$$

$$m_{cd} = m_{fw}\frac{h_w - h_{fw}}{h_s - h_w} + \frac{1}{h_s - h_w}[\rho_s V_{sd}\frac{dh_s}{dt} + \rho_w V_{wd}\frac{dh_w}{dt} - (V_{sd} + V_{wd})\frac{dp}{dt} + m_d C_p \frac{dT_{sat}}{dt}]$$

$$L_d = \frac{V_{wd} + V_{sd}}{A_d}$$

Downcomer-Riser Dynamics

$$\frac{d}{dt}[\rho_s \overline{\alpha_v} V_r + \rho_w (1 - \overline{\alpha_v}) V_r] = m_{dc} - m_r$$

$$\frac{d}{dt}[\rho_s h_s \overline{\alpha_v} V_r + \rho_w h_w (1 - \overline{\alpha_v}) V_r - pV_r + M_r C_p T_{sat}]$$
$$= Q + m_{dc} h_w - (\alpha_r (h_s - h_w) + h_w) m_r$$

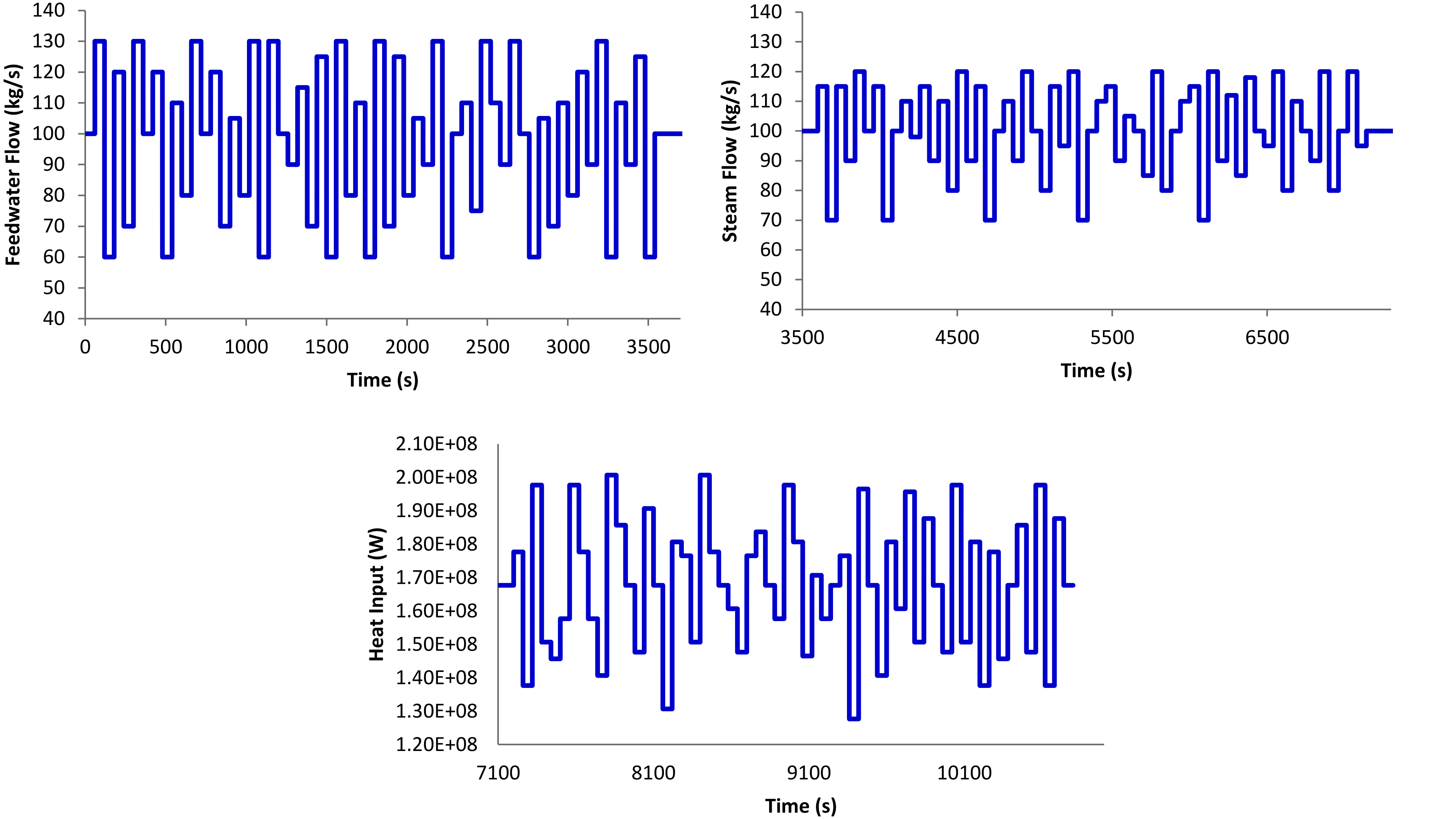
$$\overline{\alpha_v} = \frac{\rho_w}{\rho_w - \rho_s}[1 - \frac{\rho_s}{\alpha_r(\rho_w - \rho_s)} In(1 + \alpha_r \frac{\rho_w - \rho_s}{\rho_s})]$$

$$m_{dc} = \sqrt{\frac{2g\rho_w \overline{\alpha_v} A_{dc} V_r (\rho_w - \rho_s)}{k}}$$

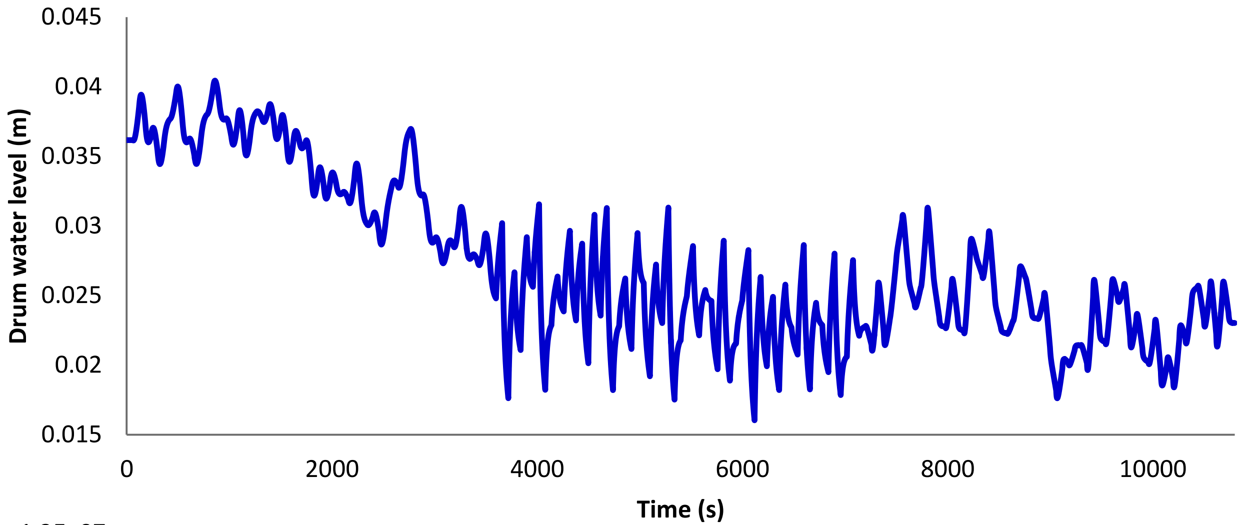
Boiler Drum Data

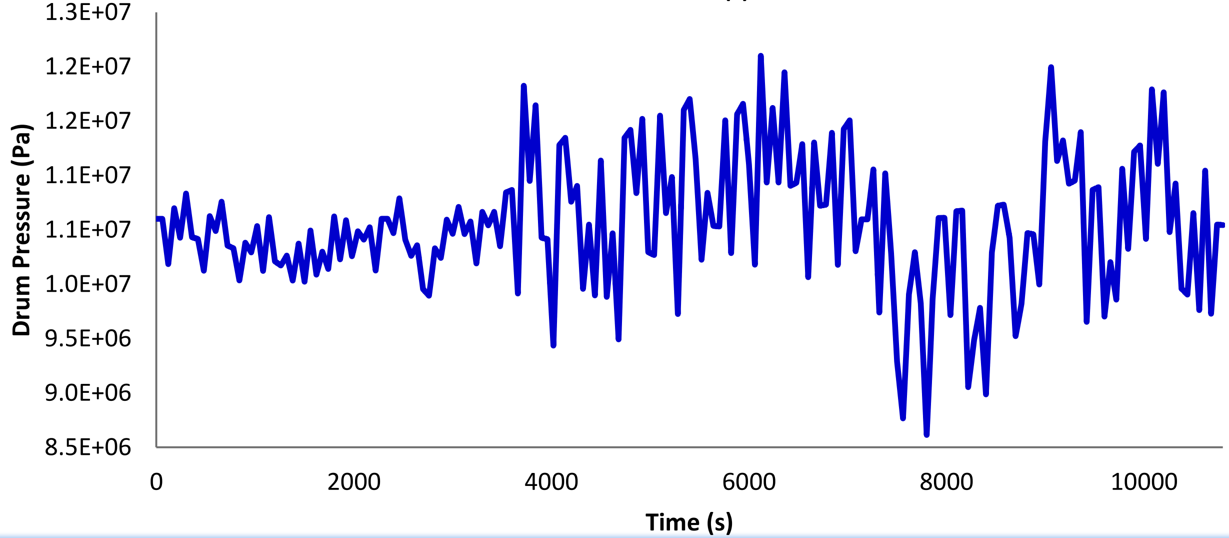
- Data obtained at open loop conditions using the developed model
- The system is excited by perturbing the inputs in succession with a series of step changes in no particular order
- Perturbation in each input is sustained for an hour resulting to a total test period of 3 hours (10800 seconds).
- Other inputs are maintained at their equilibrium value while perturbing the other.

Boiler Drum Data



Boiler Drum Data





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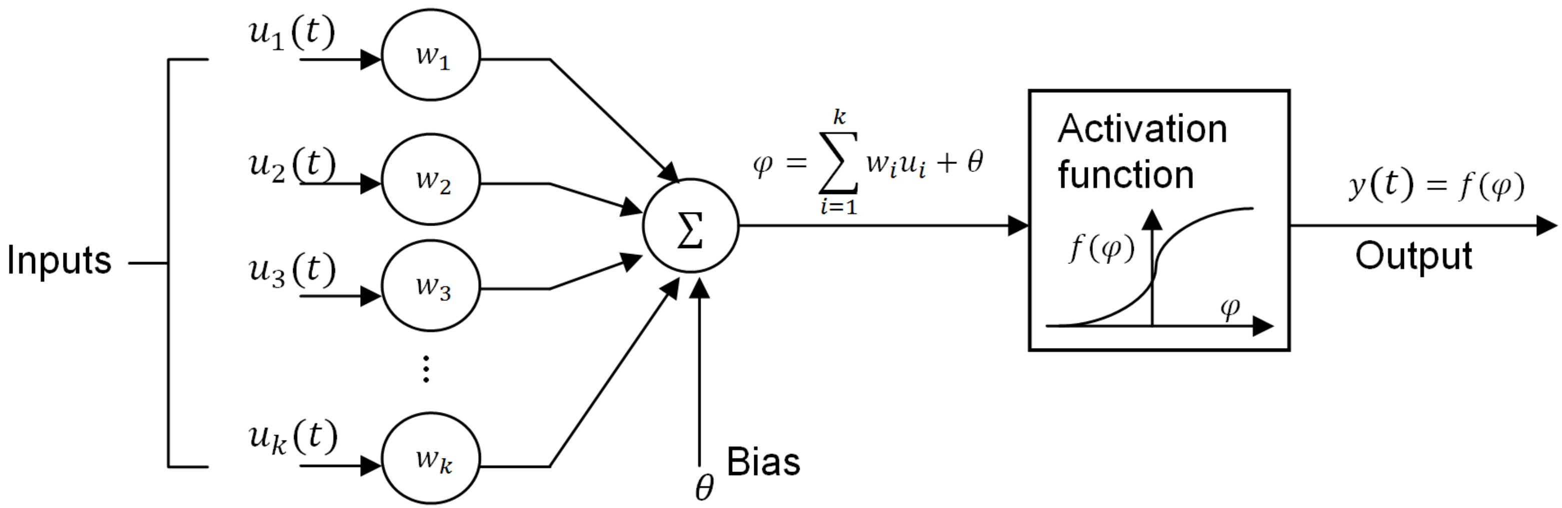
Neural Networks (NNs)

- Computational paradigm inspired from the structure of biological neural networks and their way of encoding and solving problems.

- Able to identify underlying highly complex relationships based on input-output data only.



Neural Networks (NNs)

- NN model capable of reproducing time-dependent (dynamic) data takes into account the time variable by means of a memory process.

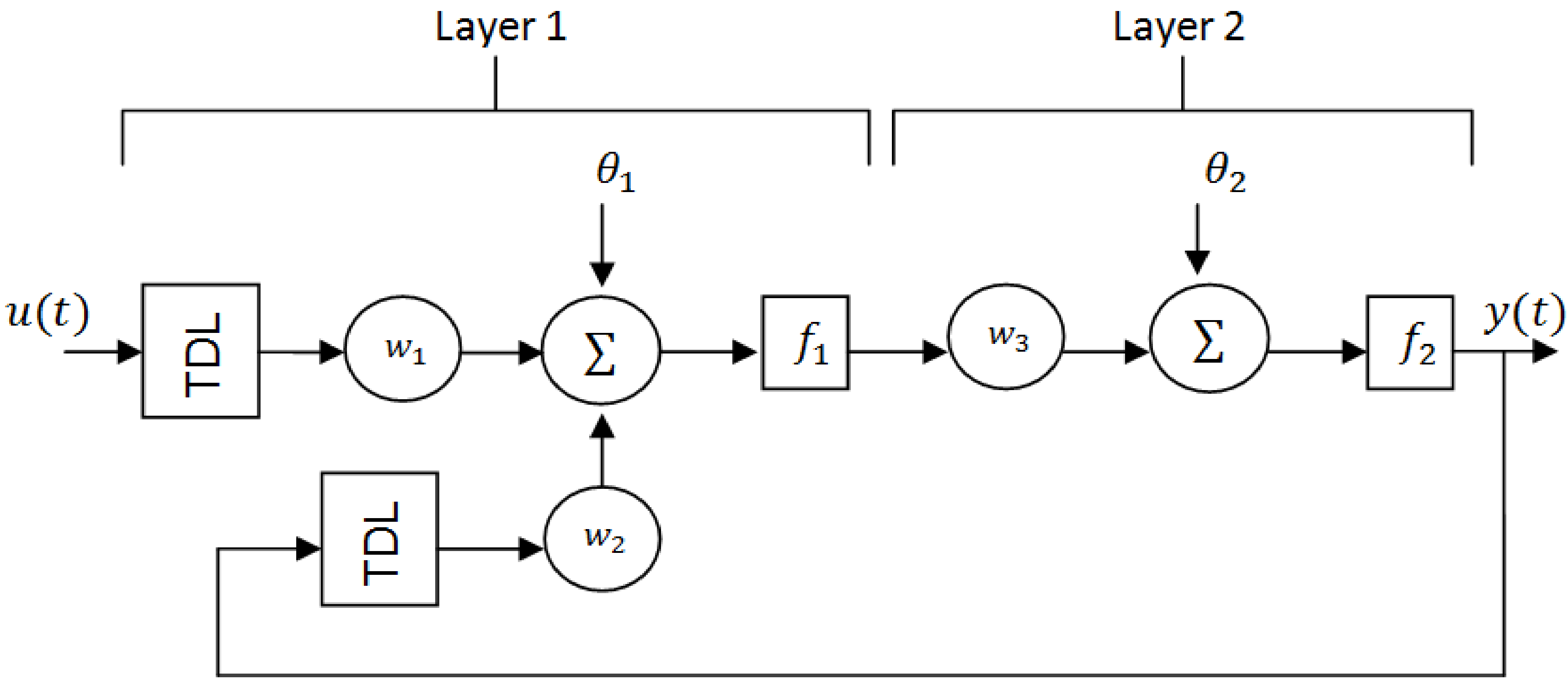
- This is done using NN architectures with feedback connections among neurones and time delay lines (TDL)

- NARX NN is a typical NN with feedback connections enclosing several layers of the network and a TDL.

NARX Model

- NARX Model is defined by the Equation:

$$y(t) = f[y(t-1), y(t-2), \ldots, y(t-n_y), u(t-1), u(t-2), \ldots, u(t-n_u)]$$



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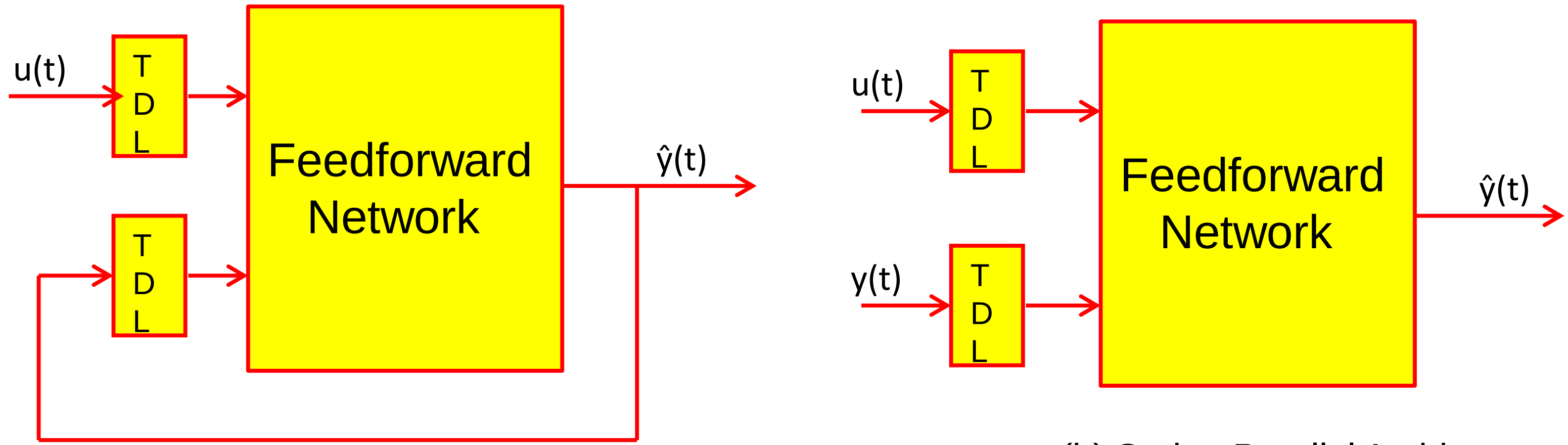
NARX Model Training

- Training complicated due to the feedback loop; ideally dynamic training algorithm which is complex is needed



(a) Parallel Architecture
(Standard NARX Architecture)

(b) Series-Parallel Architecture

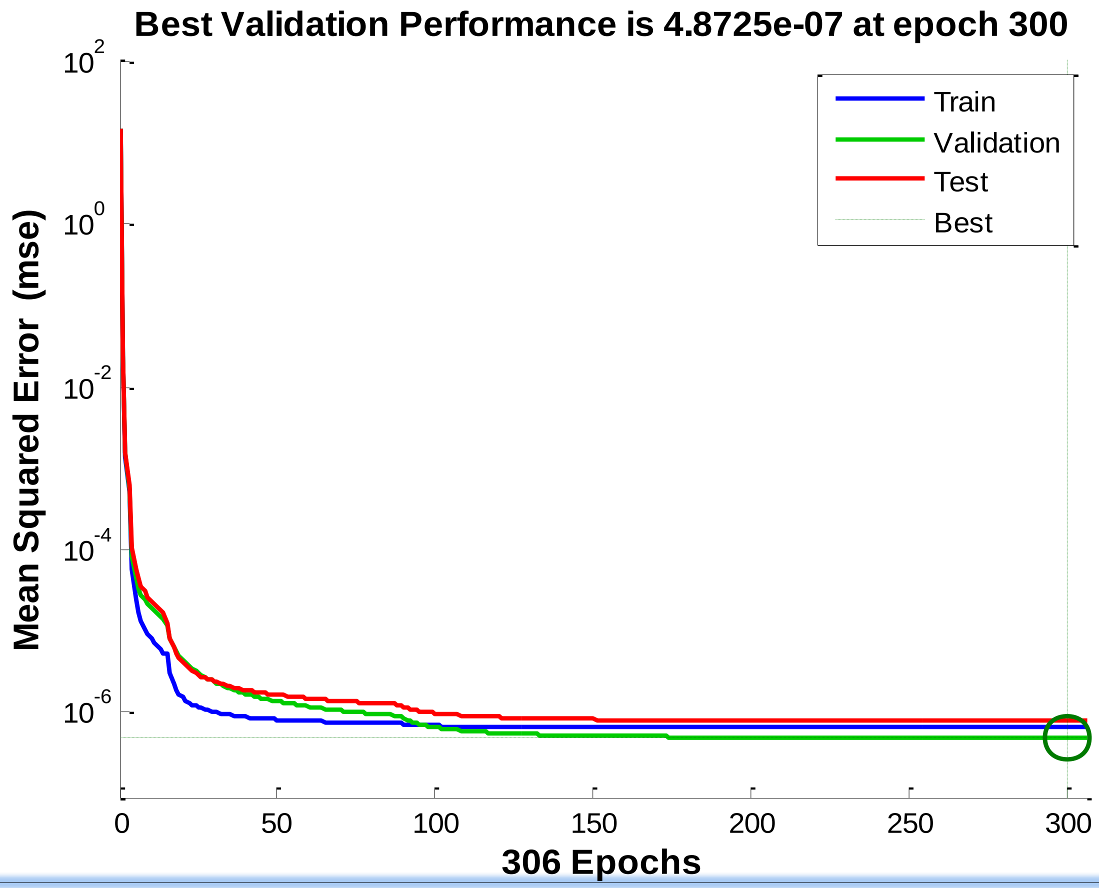
- With (b), less complex static training algorithm is used for training.

NARX Model Training

- Training with simulated data from the detailed physical model.
- Early stopping technique used to avoid overfitting: Data divided into training (70%), validation (15%) and testing (15%) data.
- Levenberg-Marquardt training algorithm used (*trainlm*) with mean squared error (MSE) performance function.
- 100 neurones in the hidden layer each with a sigmoid transfer function

NARX Model Training

$$\mathrm{MSE} = \frac{1}{N}\sum_{i=0}^{N}(z_i - y_i)^2 \rightarrow min$$



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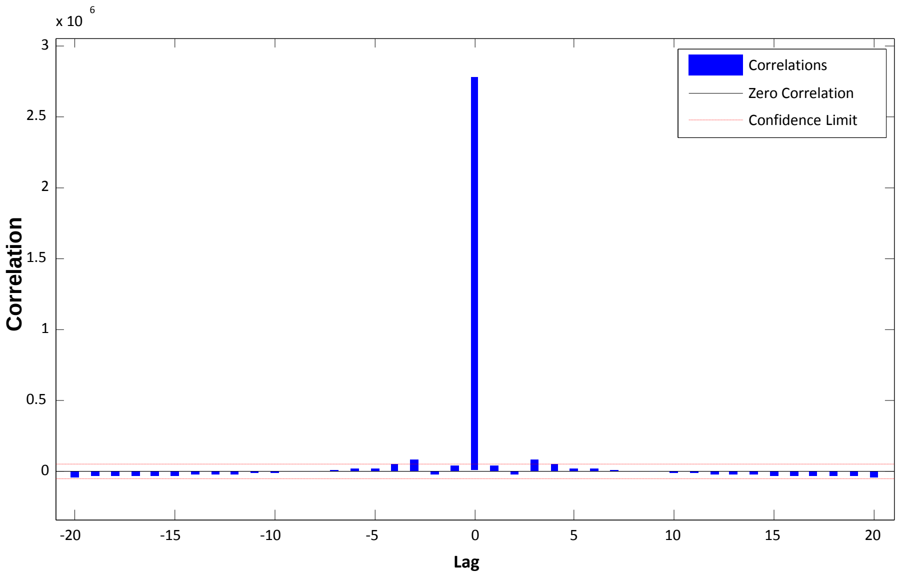
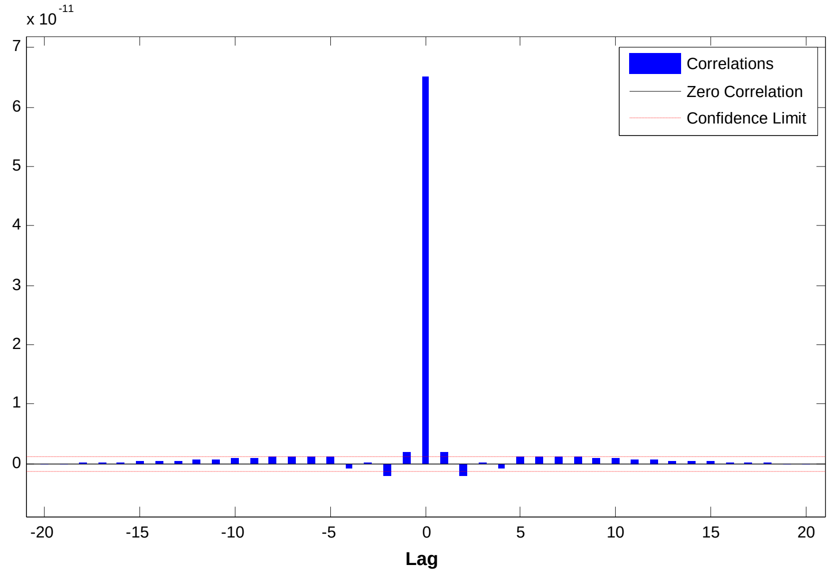
Results

Error Autocorrelation Plot



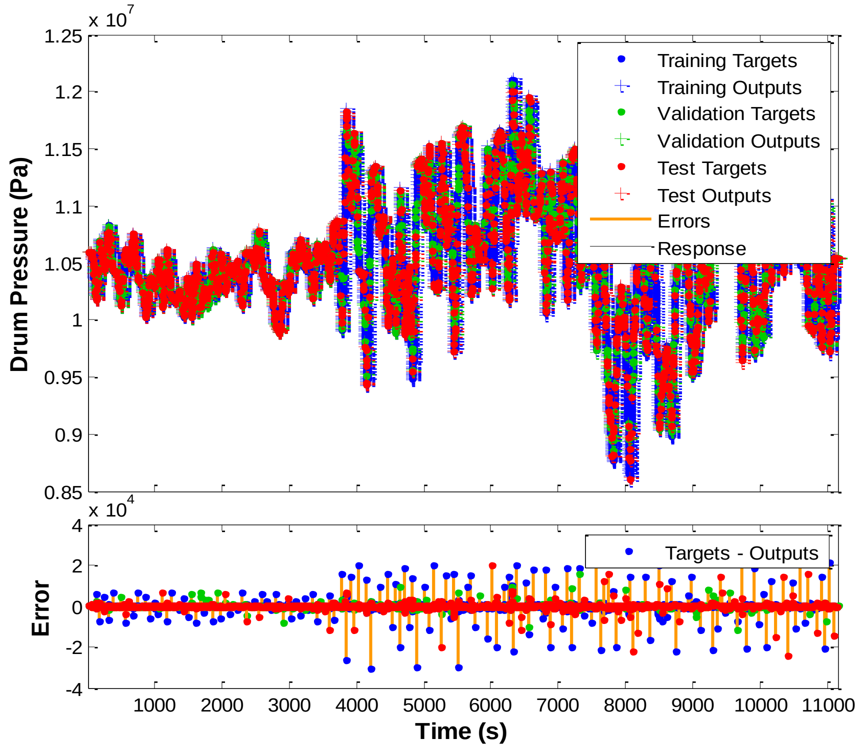
Drum Pressure Prediction Error Autocorrelation Plot



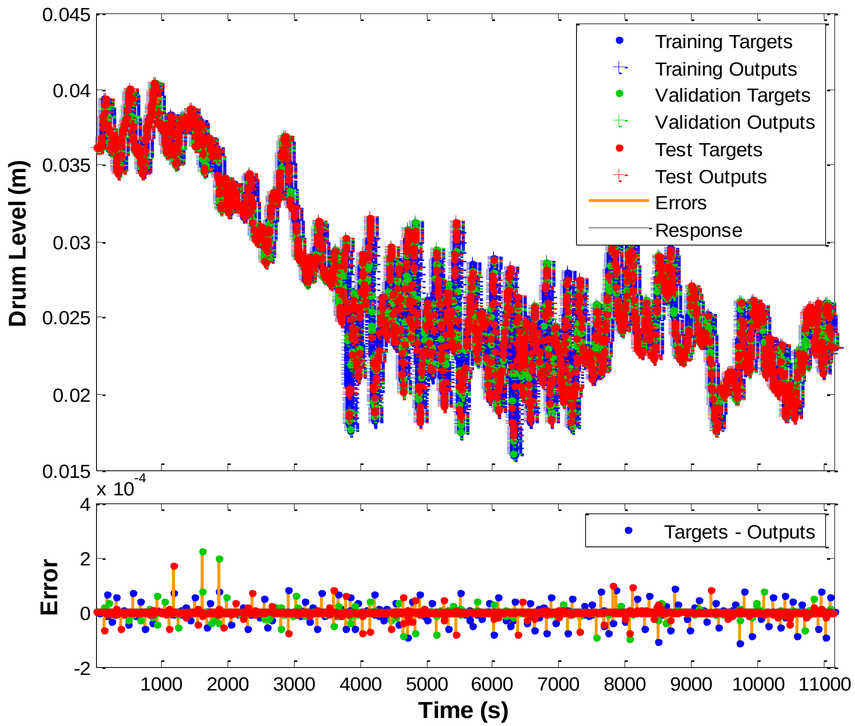
Drum Level Prediction Error Autocorrelation Plot

- The plots show reliable estimate of the network parameters, weights and biases

Results



Output/Target Comparison (Drum Pressure)



Output/Target Comparison (Drum Level)

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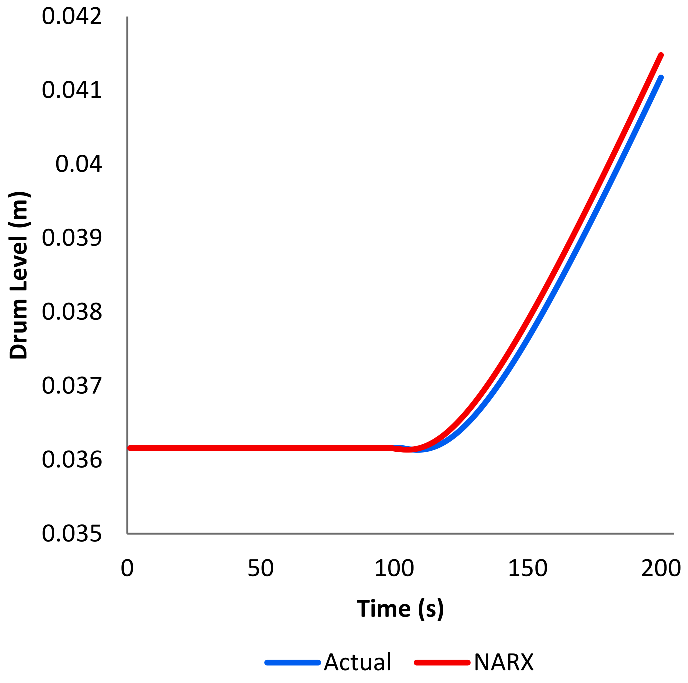
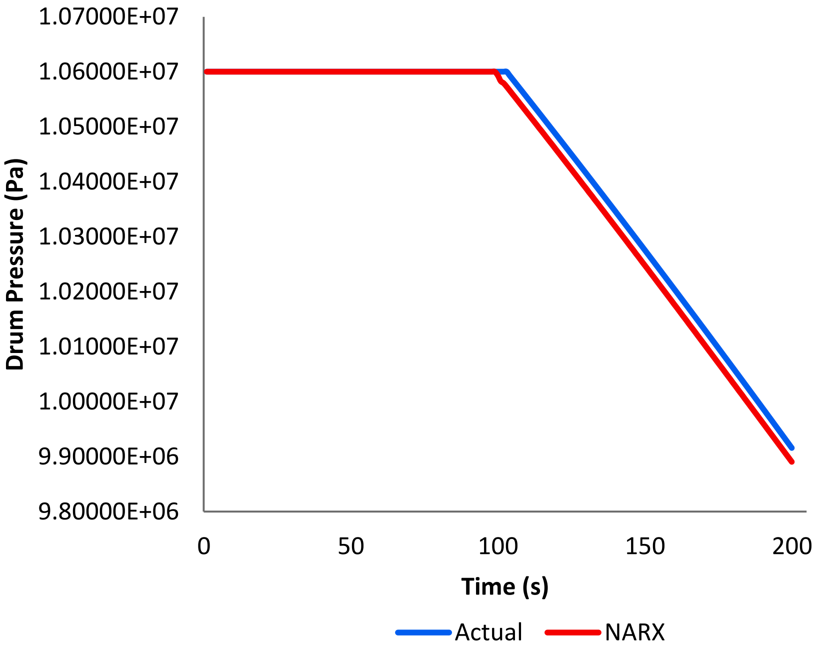
Results

Step Change Test: Performed on one input at a time while other inputs remain unchanged

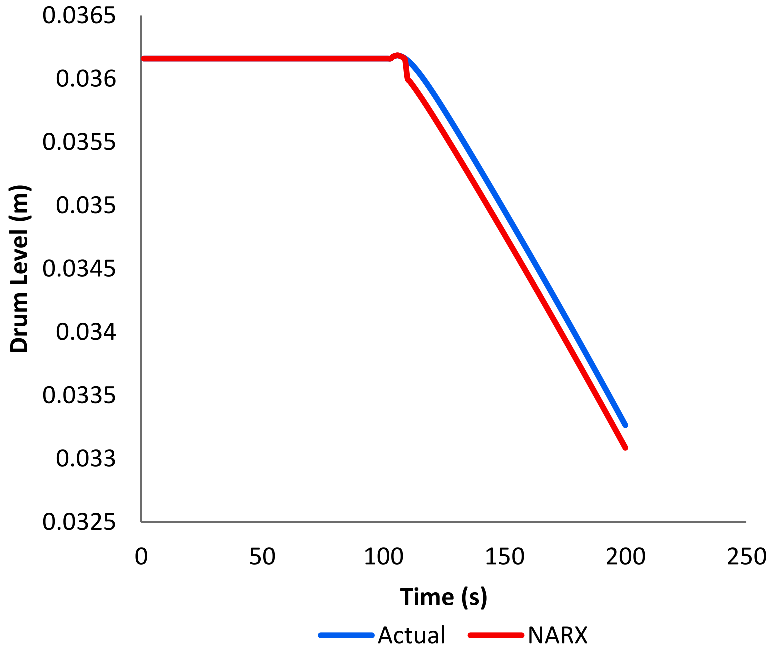
- +30 kg/s step change in feedwater flowrate

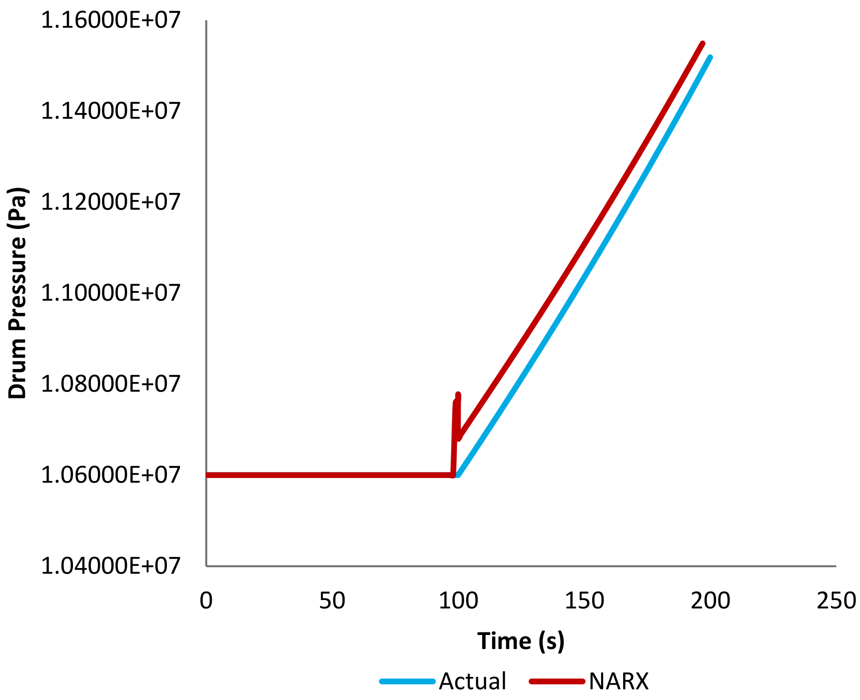




Results

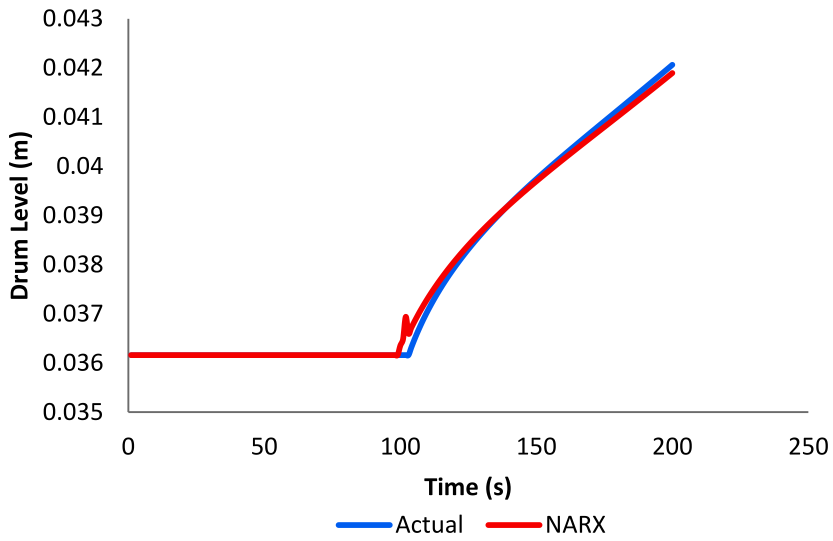
➢+10 MW step change in Heat Input

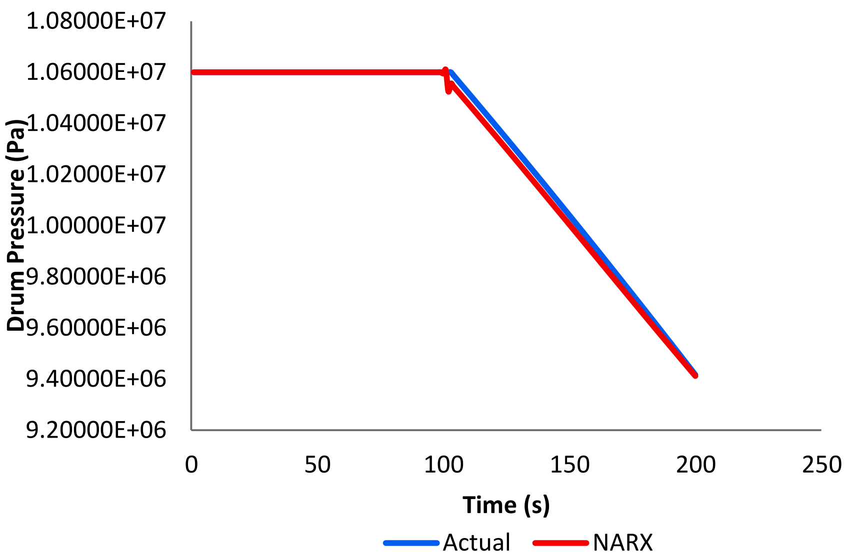




Results

- ➢+10 kg/s step change in Steam Flowrate





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Conclusion and Future Work

- NARX NN can be used to obtain reliable dynamic model of a boiler drum from the plant input-output operating data only.

- Use of NARX NN avoids the rigours of reliable parameter estimation often needed in modelling from first principle.

- As it is the case with all empirical models, NARX NN models are only reliable when they are used within the conditions that they were trained.

- The NARX NN model developed in this study is subject to the inherent deficiencies in Åström and Bell [3] model which was used to obtain the training data.

- Development of model predictive control (MPC) of the boiler drum based on the NARX NN model is on-going.

References

1) Illustrations and text are taken from the Spirax Sarco website 'Steam Engineering Tutorials' at http://www.spiraxsarco.com/resources/steam-engineering-tutorials.asp. Illustrations and text are copyright, remains
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2) Åström, K.J. and Bell, R.D. Drum-boiler dynamics. Automatica 2000; 36: 363-378.

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Multiphase Flow Measurement Research Group,
South East University, Nanjing, China

SOUTHEAST UNIVERSITY

Questions???

Thank you for your Attention!

Contact:
Dr Meihong Wang
Process and Energy Systems Engineering Group,
School of Engineering, University of Hull HU6 7RX
Tel.: +44 1482 466688. E-mail address: Meihong.Wang@hull.ac.uk