Input and State Estimation Tool for Dynamic CFB Models

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Abstract: The present work describes the development and testing of the "HLtool" tool for estimating unknown and uncertain process inputs, parameters and states in a circulating fluidized bed (CFB) boiler model based on output measurements. The model in question was an existing Foster Wheeler dynamic Matlab/Simulink model for the CFB hotloop, which contains the furnace, gas-solid separators (cyclones), the solids circulation system and external INTREX^{TM} heat exchangers. As state estimation is an effective way to integrate models and experimental data, the HLtool software can be used for model validation in the case of inaccurate process inputs, noisy measurements or uncertain model parameters. The tool can also be utilized for interpreting causes for unexpected process outputs and disturbances. The third important application area lies in model synthesis and model parameter estimation, as the tool can be used to alter parameters such as heat transfer coefficients dynamically based on output targets like heat exchanger MW performance requirements. This is especially useful for different load levels in the boiler, as only the 100 % load values for certain parameters might be known to the process designer.

The basic structure of the studied CFB hotloop model was based on ideally mixed 1-D elements with mass and energy balances, a combined energy equation for element temperatures, as well as semi-empirical correlations for hydrodynamics, combustion characteristics and heat transfer. The model could be used for transients and constant inputs and it was applicable for both air and oxy combustion boilers. Because of the large amount of state variables, the model was mainly a simulator for researching dynamics and testing control solutions and should not be applied directly to e.g. model-based control. For the tool, the hotloop model structure was reformulated into an input-output state-space format.

The HLtool state estimation was based on the Bayesian approach and utilized two separate algorithms for non-linear process models: a scaled unscented Kalman filter (UKF) as the primary option and a sampling-importance-resampling (SIR) particle filter as a secondary solution. The UKF approach is a linear Kalman filter extension, in which a specific deterministic sampling algorithm called the unscented transform is used to pick a set of "sigma points" to represent the mean and covariance of the states to be estimated. In the transform, this distribution of points is propagated through the non-linear process model (hotloop model). The mean is calculated as a weighted average and the covariance as a weighted outer product of the transformed points. Compared to the more advanced and more demanding particle filter algorithms, the UKF is computationally efficient, and as all calculations are standard matrix operations, non-linear models can be used directly without linearization. Particle filters are Bayesian filter implementations utilizing sequential Monte Carlo methods. The posterior probability density distribution is approximated as a cloud of random samples, i.e. particles, which are passed through the process model and weighted. In SIR, the likelihoods for observing a set of states given a set of measurements are used as the weighting factors for individual particles and all particles are resampled based on their weights.

In the HLtool development work, the tool was tested with different power plant configurations and state estimation problems to be solved. The estimation tasks included modifying calculated fuel mass flows and air leakage parameters to obtain a better agreement between measured and modelled flue gas compositions, adjusting heat transfer coefficients and fuel moisture contents through furnace temperature and flue gas O_2 measurements, as well as determining heat exchanger heat transfer coefficients on different load levels based on performance requirements. On a whole, the simulations were successful, as reasonable estimates could be obtained in the different cases and as the tool could readily be used with various hotloop model applications. The HLtool software has the potential to effectively assist CFB process and control designers during model synthesis and validation and it also serves as a good platform for further state estimation algorithm studies. The work conducted here is a part of the joint circulating fluidized bed modelling and control research of Foster Wheeler and the University of Oulu.

Keywords: CFB, dynamic models, furnace simulation, Bayesian state estimation, unscented Kalman filter, particle filter.