Hybrid fuzzy-disturbance observer for estimating disturbance in styrene polymerization process

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Abstract. In chemical process systems, disturbances such as heat loss, temperature and flow rate can affect the product yield and production costs. Therefore, observers are used to estimate the disturbance to obtain more stable and precise results. Observer is a computer software algorithm designed to estimate unknown parameters and can be used to replace sensors. This research aims to develop a hybrid observer by combining fuzzy logic and disturbance observer to overcome the limitation of the single observer known as fuzzy-disturbance observer. The hybrid observer will be applied in the styrene polymerization process to estimate the heat loss since it will affect the amount of heat in the reactor and reduced the product yield. The hybrid observer is also compare to a single disturbance observer and a fuzzy logic based observer to prove its effectiveness. The results show the effectiveness of this hybrid observer in estimating disturbance in styrene polymerization process. Further studies can be carried out to combine the hybrid observer with a controller to enhance the overall performances.

Introduction

State variables are naturally considered measurable in chemical process plants although some variables are unmeasurable since they require highly specific estimators or expensive sensors. As an alternative, observers are introduced. Observer, which is an algorithm serves as a tool for estimating those unmeasurable variables developed using software such as MATLAB. Linear observers are the first observer introduced, however it can only be used for linear processes with small disturbances. Therefore, nonlinear observers were later designed to estimate parameters in non-linear processes. These single observers are found to be ineffective with limitations such as inaccurate and unreliable estimations. Thus, the hybrid observer are designed. Hybrid observer is a combination of two or more conventional observers basically to overcome the weaknesses of the single observer (Mazenc, Andrieu, and Malisoff 2015; Gan et al. 2018). There are three combinations to form a hybrid observer. The first combination is a listing between two or more conventional observers to improve the estimator's performance. For example, adaptive observer are combined with sliding mode observers (Gan et al. 2018) and a combination of continuous observers with discrete observers. (Mazenc, Andrieu, and Malisoff 2015). The second combination is a conventional observer with artificial intelligence. Examples of these combinations are fuzzy logic combinations with sliding mode observers (Ali and Hussain 2016) and artificial neural network with disturbance observers (Matassini et al. 2016). The last combination is a merging of two or more AI. Examples of these combinations are fuzzy logic with genetic algorithm forming a fuzzy genetic. (Rafati et al. 2018).

After that, research using Artificial Intelligence (AI) as the estimators has been commenced to align with current 4.0 Industrial & Education revolution policy. AI is defined as an algorithm that able to perform human resource-based tasks (Mohd Ali et al. 2015). Common AI elements used as estimators are fuzzy logic, artificial neural networks, genetic algorithms and expert systems (Mohd et al. 2015). Furthermore, other specific type of observers including disturbance observer is developed aimed at handling the disturbance. Disturbances are expected to happen in a process especially in a nonlinear process. Disturbance observer are used specifically to estimate the disturbance and uncertainties. Disturbance observer was first found in 1983 in a DC motor system. This leads to multiple studies to improve disturbance observer’s performance. The usage and application of disturbance observer is still being studied until now (Saruchi et al. 2017).
In this study, the conventional disturbance observer is combined with fuzzy logic as fuzzy disturbance observer (F-DO). Disturbance observer is used here since the process is nonlinear with various disturbance that required to be estimated (Han et al. 2015). Whereas, fuzzy logic is chosen because it is the simplest AI algorithm compared to other artificial intelligence such as artificial neural networks and genetic algorithms. Besides that, fuzzy logic based observer has simple formulation and can describe imprecise value of parameter accurately especially in a highly arbitrarily nonlinear system (Mohd Ali et al. 2015). Furthermore, it is a straightforward technique and does not require mass data unlike neural network, genetic algorithm and expert system (Kim 2002). The purpose of this hybrid F-DO is to estimate the heat loss, which will disturb the styrene polymerization process. It is worth noting that the proposed F-DO is its first to be applied in chemical process system.

This section is the introduction section followed by methodology in section 2. After modelling the hybrid observer, the result are analysed and discussed in section 3. The final section is conclusion and future work.

Methodology

A hybrid FDO developed in this work is specifically to estimate the heat loss in a styrene polymerization process. The model is based on mechanistic model (Hosen, Hussain, and Mjalli 2011a). Heat loss act as disturbance effecting the final reactor temperature that can affect the production rate. Hence, the hybrid observer is used to estimate them perfectly. The heat loss mention in this study consists of heat loss from the reactor wall, heat loss from heat absorbed or released by the reactant and heat loss by the condenser. The mass balance for the process are given in Eqn. (1), (2) and (3), while Figure 1 depicts the CSTR model of a polymerization of styrene.

\[
\frac{d(I)}{dt} = \dot{V}(I_r - I) - k_d IV, \quad \cdots(1)
\]
\[
\frac{d(M)}{dt} = \dot{V}(M_r - M) - V k_p MP, \quad \cdots(2)
\]
\[
P = \left[\frac{2}{k_e g_e} \left(k_d M^3 + f k_d I\right)\right]^{\frac{1}{2}}, \quad \cdots(3)
\]

The estimated parameter involved is heat loss to verify the effectiveness of this hybrid fuzzy disturbance observer. In a chemical process in the reactor, the value of heat loss is assumed to low and very negligible. However, in this styrene polymerization process, this heat loss rate should be weighted to obtain optimum heat value as well as obtain the best conversion rate. The parameters for polymerization of styrene are tabulated in Table 1 (Hosen, Hussain, and Mjalli 2011b).

| Parameter                                               | Value   | Unit  |
|---------------------------------------------------------|---------|-------|
| Specific heat capacity of reactant (C_p)                | 1.96886 | J/g.K |
### Table

| Parameter                                           | Value          |
|-----------------------------------------------------|----------------|
| Specific heat capacity of coolant \((C_{pc})\)       | 4.29 \(\text{J/g.K}\) |
| Heat of reaction \((H)\)                            | -57766.8 \(\text{J/g.K}\) |
| Flow rate of coolant \((m_c)\)                      | 0.51 \(\text{g/s}\)    |
| Gas constant \((R)\)                                | 8.34 \(\text{J/mol.K}^0\) |
| Coolant inlet temperature \((T_{ji})\)              | 303.14 \(\text{K}\)    |
| Heat transfer coefficient \((U)\)                   | 55.1 \(\text{W/m}^2.\text{K}\) |
| Volume of reactor \((V)\)                           | 1.2 \(\text{L}\)       |
| Volume of jacketed reactor \((V_c)\)                | 1 \(\text{L}\)         |

The observer is then designed based on the styrene polymerization model involving the nonlinear system equation for disturbance observer. Then the error and change of error are obtained from the model. Those values will be the inputs to the fuzzy logic framework to estimate new error.

Styrene polymerization process is a nonlinear process, so a state space equation are given by:

\[
\dot{x} = f(x) + g_1(x)u + g_2(x)d \\
y = h(x)
\]

Where \(x\) is the state variable, \(u\) is the control input, \(d\) is the disturbance and \(y\) is the output.

The observer is then developed based on the state space as follows:

\[
\dot{z} = -l(x)g_2(x)z - l(x)[g_2(x)p(x) + f(x) + g_1(x)u] \\
\dot{d} = z + p(x)
\]

Where \(z\) is the inner state variable, \(p(x)\) is the nonlinear function and \(l(x)\) is the observer gain.

### Results and Discussion

Once the hybrid F-DO has been developed, it will be applied to estimate heat loss in the polystyrene polymerization. The result are illustrated in Figure 2, where the disturbance are being plotted with estimated disturbance to show the effectiveness of observer after fuzzy logic is being designed by inserting the error and change of error of the disturbance to reduce the error. It also showed that the temperature profile is align with the estimation behavior.
Figure 2 Disturbance and estimated disturbance using F-DO

Then, the result are being compared to a single disturbance observer and a fuzzy logic based observer. Figure 3 shows the single disturbance observer in estimating the disturbance. The result shows that estimated disturbance value is too small and negligible, showing that disturbance observer is not effective for this task.

Conclusion
A hybrid fuzzy disturbance observer (F-DO) has been developed here to estimate the heat loss, which is considered as one of the disturbances in a styrene polymerization process. Results from studies show the satisfactory performance of hybrid fuzzy disturbance observer. The hybrid observer is also being compared to a conventional disturbance observer and fuzzy logic to show the effectiveness of the observer. For future work, this hybrid observer can be used in chemical process systems to estimate...
disturbance effectively. It will also be used to estimate other parameters in styrene polymerization process.

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