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Wiener Model Based Real-Time Identification and Control of Heat Exchanger Process

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The control of heat exchanger is complex due to its nonlinear dynamics, particularly the variable steady-state gain and the time constant of the process fluid. In this paper, two Relay Feedback Test (RFT) methods for the Wiener model are discussed to implement in a real-time heat exchanger process. Wiener model consists of linear subsystem followed by static nonlinearity. In the first method, symmetric and asymmetric RFT data are used to identify Wiener process. The identification procedure consists of two steps discussed as follows: First, the symmetric RFT output data is used to obtain the static nonlinearity. An objective function that aims to change the asymmetry to symmetry, in the system output is formulated. A standard optimization procedure is used to minimize this objective function by adjusting the polynomial parameters that is used to represent the nonlinear gain of the Wiener model. In the Second step, asymmetric RFT output is used to obtain a linear subsystem as First Order Plus Dead Time (FOPDT). By way of this approach, the identifications of linear and nonlinear subsystem in the Wiener model are fully separated. In the second method, an on-line procedure is used to obtain the static nonlinearity. The linear subsystem is identified as FOPDT. Different degrees of systems are illustrated to facilitate the understandings of these two RFT methods. The performance of the Wiener model based control strategy is evaluated in real time and the results are compared with those of a conventional PI controller.

Keywords: Wiener, Relay Feedback, Static Nonlinearity, Heat Exchanger.

1. INTRODUCTION

Transfer function models are used to design a control system for mildly nonlinear systems. However, for systems with high nonlinearity, the controller design based on the linear model will not be adequate, due to the significant changes in the steady state gain and time constant of the process. The linear model based controller will not give a satisfactory performance for these types of process. To overcome this difficulty, a suitable nonlinear model representation of the process will be desirable. The dynamics of industrial chemical process like heat exchangers, distillation column and pH neutralization etc. can be easily modeled with the Hammerstein or the Wiener model. These two type of models, comprises a nonlinear static element followed or preceded by a linear dynamic element and are usually given in a block-oriented form. An estimation of the process parameters varies with the structure of the model being identified in terms of the nonlinearity and the differences in model structures.

Relay feedback has wide applications in engineering world and has been studied for centuries. Huang *et al.,* [1] proposed a method to identify Wiener model using Relay Feedback Test (RFT). A new on-line method for identifying block oriented models of Hammerstein or Wiener model using RFT is presented by M.W. Lee *et al.* [2]. Billings and Voon [3] have introduced a criterion that uses statistical correlation to discriminate nonlinear systems from linear systems. It was in the 1980’s that Astrom and Hagglund [4]

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successfully applied the relay feedback method to auto-tune PID controllers for process control and triggered a resurgence of interest from both academics and industry to investigate relay feedback systems, which is still far from complete.

Haber and Unbehauen [5] have summarized different structure selection methods, based on step and impulse tests, frequency response measurements, correlation analysis, repeated reproducible tests. Menold *et al.,* [6] have also studied structure identification methods, which have different complexities in computations and emphasize the use of statistical methods. Kalafatis *et al.*, [7] have identified a pH process based on the Wiener model. Luyben and Eskinat [8] used consecutive RFT to identify the model structures and they suggested that the relay is to be displaced vertically or horizontally, to identify the Wiener or the Hammerstein type. Su Whan Sung [9] discussed the modified relay test to identify a nonlinear system as the Wiener type process. Huang *et al.,* [10] proposed a consecutive relay test to select the block-oriented models and a criterion has been included to choose the model structure feasible for the nonlinear system.

Ho Cheol Park *et al.*, [11] and Sung [12] have studied new methodology for the identification of Hammerstein model using RFT. Srinivasan and Lakshmi [13] have proposed a new method to identify and control Wiener-type process using RFT. A systematic approach to identifying Hammerstein and Wiener models, including the model structure and parameters, for nonlinear process is presented by Jyh-Cheng Jeng *et al.,* [14]. Yu-Der Lin *et al.,* [15] have discussed the reactive distillation column and proved that the high-frequency information can be obtained with the RFT. Ping Wang *et al.,* [16] introduced the concept of phase deviation to compensate for the span between the critical point and the oscillation point, so that the ultimate gain and ultimate frequency can be accurately obtained using only a single RFT.

In this paper, the control of the heat exchanger process is implemented in real-time using two RFT methods. Real-time heat exchanger process is described in section 2. In sections 3 static nonlinearity identification for the heat exchanger is discussed. Section 4 identification of linear subsystem is explained for the process. A symmetric and asymmetric stage of RFT is used to obtain the Wiener model parameters. The performance of the Wiener model based control is implemented in real-time and the results are compared with those of a conventional PI controller. In sections 5 and 6, the real-time heat exchanger process is identified as Wiener model using the online RFT method. The key term of the identification procedure is to estimate the invertible function of the static nonlinear subsystem. A linear dynamic subsystem is identified as FOPDT from the shape of the curve. Five different degrees of complexities are given to facilitate understandings of these two RFT methods.

2. REAL-TIME HEAT EXCHANGER PROCESS

A real-time heat exchanger shown in Figure. 1 is used to transfer heat energy from the hotter side to the colder side. Control of the heat exchanger is complex due to its nonlinear dynamics and particularly the variable steady state gain and time constant of the process fluid. The process fluid and the cooling fluid are chosen as water. This fluid-fluid heat exchanger is operated on a counter-flow mode which contains the process liquid and the cooling liquid flow in the opposite direction. The process liquid is heated using the heater and allowed to enter the heat exchanger. The cooling fluid is allowed to flow in the opposite direction through the heat exchanger. By varying the flow rate of the inlet cooling fluid (u), the outlet temperature of the process fluid (y) is controlled. The process fluid temperature is measured using the temperature sensor and converted into the current signal 4-20mA. A Personal Computer (PC) is used as a controller that generates the control signal by reading the current values through the Analog to Digital Converter (ADC). This signal is converted back into 4-20mA by the Digital to Analog Converter (DAC) and in turn drives the current to pressure (I/P) converter and thereby the pneumatic valve. The main aim is to produce the control signal in order to obtain the desired outlet process fluid temperature in an optimal way. The real time implementation is done through the data acquisition modules and MATLAB.

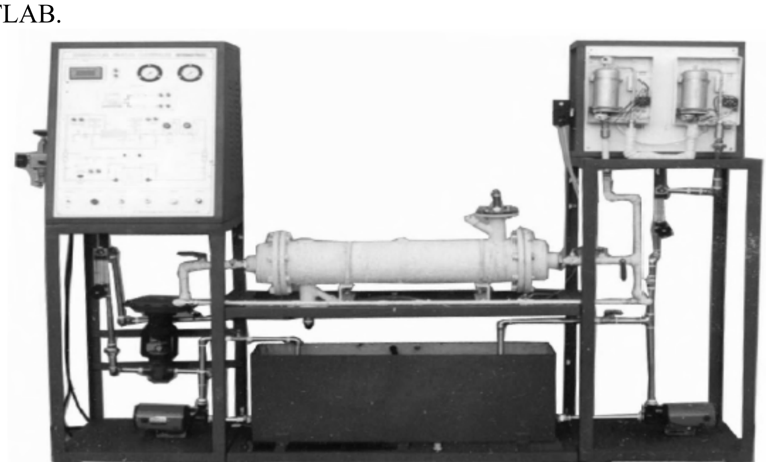


Figure. 1: Heat exchanger process experimental setup.

3. IDENTIFICATION OF STATIC NONLINEARITY

In this section, the Huang et al [1] method is summarized for the identification of the static nonlinear subsystem. Symmetric RFT is conducted for the heat exchanger process and the output data is used at this current stage. For each cycle, the time period of positive and negative output (y) is designated as T_+ and T_-. If both the outputs are equal, then the nonlinear process is structured as the Wiener type. Otherwise, it is of the Hammerstein type. The static nonlinearity is usually expressed as a nonlinear algebraic function. The nonlinear function $f(\nu;\theta)$ in the operating range can be approximated by a given function with parameter, θ, which is to be determined. An approximate inverse of this function is constructed as follows.

Using the nonlinear function $f(v;\theta)$ and discretizing variable v into a sequence of points $\{v_i, i = 1,2...,m\}$, a set of data pairs are prepared and grouped as *S*.

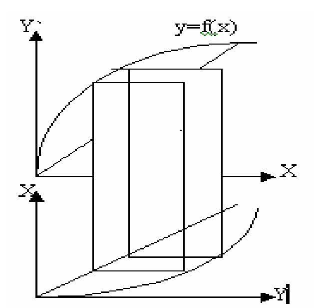


Figure. 2: Construction of the inverse of static nonlinearity.

Then, a sequence for the inverse of $f(\nu)$ is prepared and denoted as S^{-1}. From the sequence of points of S^{-1}, a piecewise linear function curve is constructed ($g(y;\theta)$). The above manipulation is implemented to construct an approximate inverse and is shown in Figure. 2.

$$S = \{[x_i = v_i, y_i = f(v_i;q)],\ i = 1,2,\ldots,m\} \tag{1}$$

$$S^{-1} = \{[x'_i = f(v_i;\theta), y'_i = v_i],\ i = 1,2,\ldots,m\} \tag{2}$$

To generate the instrumental output corresponding to an assumed static nonlinearity, it can be computed as the inverse of output at each sampling instant. In other words, for each assigned parameter θ, a set of instrumental output is computed, i.e. $\hat{v}(\theta)$.

$$\hat{v}(\theta) = \{\hat{v}_i = g(y_i;\theta),\ i = 1,2,\ldots.,m\} \tag{3}$$

Let $A_a(k)$ and $h_a(k)$ are the area and the positive peak of the instrumental output in the period of T_+ which starts from t_k. Where t_k is the starting time of constant cycle after two or three cycles from the RFT output y. Similarly, $A_b(k)$ and $h_b(k)$ designates those of T_- which starts from the same t_k.

$$A_a(k) = \int_{t_k}^{t_k+T_+} \hat{v}\left[t;\theta\right] dt; \mathrm{sgn}\left[\hat{v}\right] \geq 0 \tag{4}$$

$$A_b(k) = \int_{t_k+T_+}^{t_k+T_++T_-} \hat{v}\left[t;\theta\right] dt; \mathrm{sgn}\left[\hat{v}\right] \geq 0 \tag{5}$$

$$h_a(k) = \max_{t\in\left[t_k,\, t_k+T_k\right]} \left\{\hat{v}\left[t;\theta\right]\right\} \tag{6}$$

$$h_b(k) = \max_{t\in\left[t_k+T_+,\, t_k+T_++T_-\right]} \left\{\hat{v}\left[t;\theta\right]\right\} \tag{7}$$

$$\theta = \min_{\theta} \sum_{k=1}^{N} \left[\left(\frac{A_a\left(k;\theta\right)}{A_b\left(k;\theta\right)} - 1 \right)^2 + \omega \left(\frac{h_a\left(k;\theta\right)}{h_a\left(k;\theta\right)} - 1 \right)^2 \right] \tag{8}$$

If the inverse of $f(\nu)$ is exists, then the instrumental output would be the same as ν which would have the same peak and area for both T_+ and T_-. The identification for static nonlinearity is formulated as an optimization problem given in Eq. 8, which makes the instrumental output to have, $A_a = A_b, h_a = h_b$. Where ù is the weighting factor and considered as unity. Many standard searching algorithms can be used to find the optimal parameter θ.

3.1 System study and result

Steady state curve of physical heat exchanger is shown in Figure.3. to know the dynamics of the process. RFT is conducted at the operating point of 42°C and their input and output response of four positive (T_+) and negative (T_-) durations are shown in Figure. 4.(a) and (b). Small amount of disturbance exists during the operation of the process at the inflow.

The second duration of T_+ and T_- are 280 sec and 355 sec respectively. The heat exchanger is assumed as wiener model by the theory of structure identification [10] and the proposed method is suggested. The static nonlinear subsystem is estimated in the form of second order polynomial. Five constant cycles of sample are used to estimate the unknown parameters and is given in Eq.(9). MATLAB searching algorithm is used to solve the optimization problem, given in Eq.(8)

$$y = 35v + 8.9v^2 \tag{9}$$

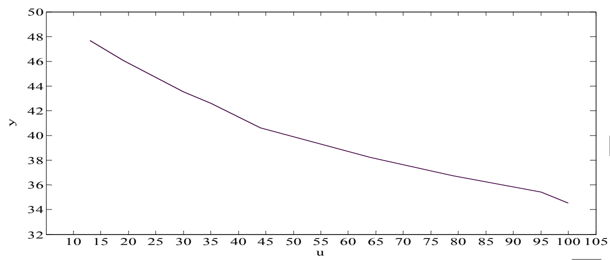
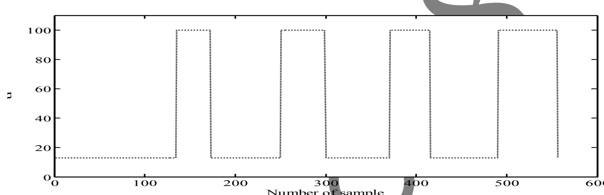
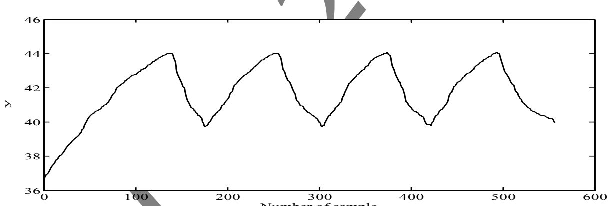


Figure. 3: Steady state curve of real-time heat exchanger process.



(a)



(b)

Figure. 4: (a) Input output responses of the real-time heat exchanger process under RFT. (b) Output [u- Cold water flow rate in liter per hour, y- Hot water temperature in degree Celsius, h_1 =44°C, h_2=40°C; Room temperature=34.5°C; Sampling time=5 seconds].

4. IDENTIFICATION OF THE LINEAR SUBSYSTEM

Identification of the linear subsystem in a Wiener model is the same as those of a linear system [8]. The data from the asymmetric relay test is used to identify the parameters of the linear subsystem. The linear subsystem is given Eq.(10), where L and τ are the dead time and time constant of the linear model. The typical FOPDT output response under RFT is shown in Figure. 5. Dead time can be found in two methods. First method is the time required to reach the peak amplitude from the initial condition and is applicable only for the FOPDT process, i.e., L_a or L_b. Second method is in terms of mean values of positive and negative duration and is given in Eq.(11).

$$G(s) = \frac{k_p e^{-Ls}}{\tau s + 1} \qquad (10)$$

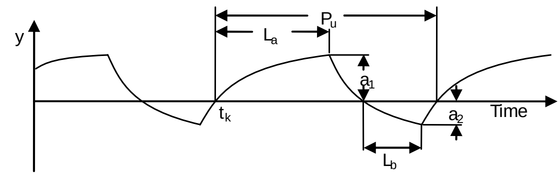


Figure. 5: Relay-feedback response of a typical linear *FOPDT* process.

$$\hat{L} = \frac{1}{2}(\hat{L}_a + \hat{L}_b) \qquad (11)$$

where,

$$\hat{L}_a = \frac{1}{N}\sum_{i=1}^{N} L_{ai} \text{ and } \hat{L}_b = \frac{1}{N}\sum_{i=1}^{N} L_{bi} \qquad (12)$$

Similarly to estimate time constant, a method is given in Eq. (14) in terms of mean value

$$\hat{\tau} = \frac{\hat{\tau}_a + \hat{\tau}_b}{2} \qquad (13)$$

where,

$$\hat{\tau}_a = \frac{\hat{L}_a}{\ln(1 - \hat{a}_1 / h_1)}, \hat{\tau}_b = \frac{\hat{L}_b}{\ln(1 - \hat{a}_2 / h_2)}, \hat{a}_1 = \frac{1}{N}\sum_{i=1}^{N} a_{1i} \text{ and } \hat{a}_2 = \frac{1}{N}\sum_{i=1}^{N} a_{2i} \qquad (14)$$

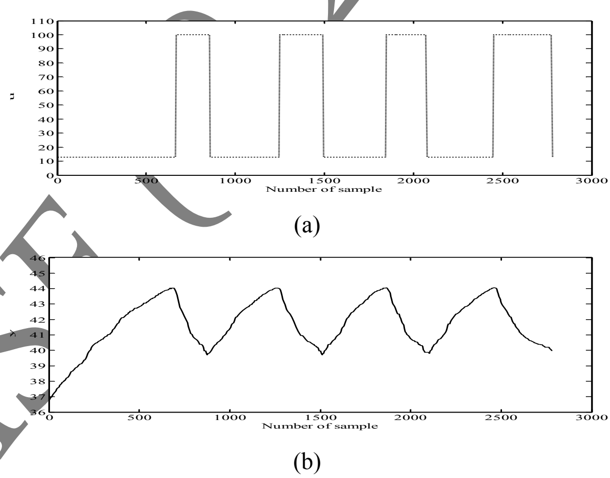


Figure. 6: (a) Input response of the real-time heat exchanger process under RFT. (b) Output [u- Cold water flow rate in liter per hour, y-Hot water temperature in degree Celsius, h_1 =44.2°C, h_2=40°C; Room temperature=34.5°C; Sampling time=5 second].

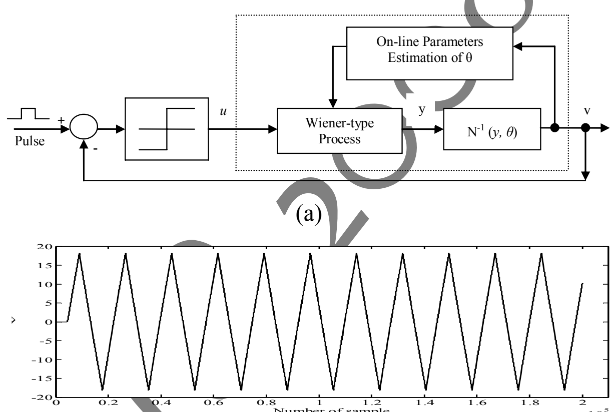
An asymmetrical RFT is conducted for heat exchanger around the operating point of 42°C and their input and output responses are shown in Figure. 6. (a) and (b). Five constant cycles of data are taken to identify FOPDT model and is given in Eq.(15).

$$G(s) = \frac{e^{-28s}}{836s + 1} \tag{15}$$

The linear subsystem steady state gain (K) is assumed to be unity because the overall gain can be accommodated in the nonlinear static subsystem.

5. ON-LINE IDENTIFICATION OF STATIC NONLINEARITY

In this section, the parameters of the nonlinear function are determined via a simple optimization procedure which aims to obtain a symmetric cycling instrumental output. The key term of the identification procedure is to estimate the inverse function of the static nonlinear block. Therefore, the loop can be made approximately linear. Figure. 7(a) shows the structure of the Wiener type system to estimate the static nonlinear subsystem. This subsystem is estimated in the form second order polynomial. The unknown parameters, c_1 and c_2 are determined by the optimization technique. Many standard-searching algorithms can be used to find an optimal parameter θ of Eq. (8). The MATLAB subroutine (fminsearch) is used to obtain the converged polynomial parameters c_1=35.84 and c_2= 7 from the initial values of c_1=1.9 and c_2=0.39. Finding the initial values is an iterative procedure in this method. Uniform positive and negative duration of instrumental variable is shown in Figure. 7(b).



(a)

(b)

Figure. 7: The parameter estimation of the inverse static nonlinear function (a) Wiener model (b) Instrumental Variable (v).

5.1 Identification of the linear subsystem

In general, if the nonlinearity that follows the linear element is monotonic, it does not cause the duration of the positive and negative pulses to be unequal. The period of oscillations in a Wiener model is decided by the linear element and the presence of non-linearity affects only the amplitude of the oscillations. So the linear subsystem parameters can be identified as those of the linear system. FOPDT can be chosen as a linear subsystem and its transfer function is given in Eq.(10). The linear subsystem steady state gain K is assumed to be unity because the overall gain of the nonlinear system can be accommodated in the nonlinear static subsystem. Dead time L can be found in two ways. First, is from the initial stage of the RFT i.e., output starts to increase after the dead time. Second, is the steady state value to a maximum value [17]. Ren-Chiou Chang [18] have estimated time constant (τ) which is given in Eq.(16)

$$\tau = \frac{\pi}{\omega_u \ln\left|2\exp(L/\tau)-1\right|} \tag{16}$$

where $\omega_u = 2\pi / p_u$, p_u is ultimate frequency.

5.2 System Study and results

Table 1: Comprehensive simulation results of methods discussed in section 3, 4, 5, and 6.

Case	Linear subsystem / Static Nonlinearity: $y=2(1-e^{-0.693v})$	Nonlinear static function obtained by section 3.	Linear subsystem identified by section 4.	Nonlinear static function obtained by section 5.	Linear subsystem identified by section 6.
1	$\frac{e^{-s}}{5s+1}$	$1.8457v-0.8027v^2$	$\frac{e^{-0.9935s}}{3.975s+1}$	$1.5653v+0.3887v^2$	$\frac{e^{-s}}{4.1s+1}$
2	$\frac{e^{-s}}{(5s+1)(s+1)}$	$1.8461v-0.8017v^2$	$\frac{e^{-1.4755s}}{5.5859s+1}$	$1.5609v+0.3868v^2$	$\frac{e^{-1.5s}}{6.1s+1}$
3	$\frac{e^{-s}}{(3s+1)(s+1)^2}$	$1.8508v - 0.7911v^2$	$\frac{e^{-2.08s}}{3.762s+1}$	$1.5757v+0.3823v^2$	$\frac{e^{-2s}}{3.9s+1}$
4	$\frac{e^{-s}}{(s+1)^2(2s+1)^2}$	$1.8563v-0.7796v^2$	$\frac{e^{-3.17s}}{3.6s+1}$	$1.7942v+0.0844v^2$	$\frac{e^{-3s}}{4s+1}$
5	$\frac{e^{-s}}{(s+1)^2(2s+1)^3}$	$1.86v-0.7719v^2$	$\frac{e^{-4.3s}}{4.268s+1}$	$1.7984v+0.0846v^2$	$\frac{e^{-4.5s}}{4.8s+1}$

Five types of Wiener model are given in Table 1, to test the effectiveness of the identification procedure. Data of four constant cycles in each stage are sampled for identification. Both the methods have precisely identified the parameters of the linear and static nonlinearity subsystems. The second method is an on-line procedure and is not easy to implement in real-time process. Whereas the first method is easy to implement in real-time but the linear system is identified by the asymmetrical RFT. Normally 90% of the controller in control loops is PID and on-off, the collection of asymmetrical RFT is not possible. All five systems results in slight deviation to estimate c_1, c_2, τ and L. The method discussed in section 3 and 6 will be more suitable for the identification of Wiener-type system in real-time implementation.

6. REAL-TIME IMPLEMENTATION AND CONTROL

The Wiener model based control system given in Figure.8 nullifies the presence of nonlinearity and produces a linear system with unity gain. This resulting linearised system will provide a symmetric oscillation under RFT. Section 3 and 4 has to be revaluated, if there is a considerable change in the operating point. The values of Proportional gain (K_c) is $(1.2\tau)/(KL)$, the Integral time (T_I) is $2.L$ and the Derivative time (T_d) is $0.5L$ are obtained by Zeigler-Nichols (Z-N) method. Servo response of the real-time process are shown in Figure. 9(a) and (b) for K_c=35.82 and T_I= 56. In Fig 9(a) the disturbance is eliminated by the Wiener model based PI controller than the conventional PI controller.

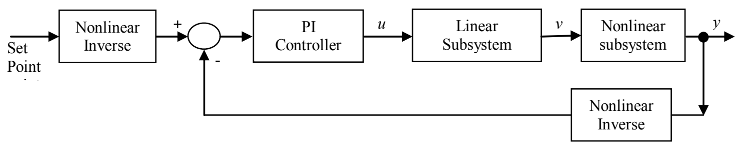
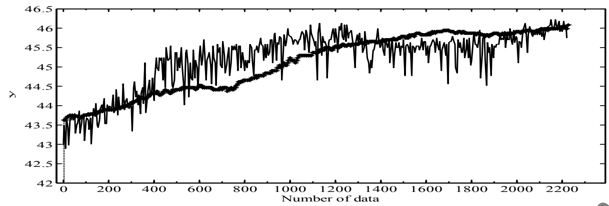
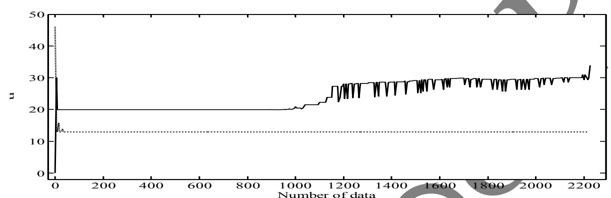


Figure. 8: The Wiener model based control system.



(a)



(b)

Figure. 9: Servo response for real time heat exchanger form 43.5 to 46 degree Celsius for the method discussed in section 3 and 4. (a) Positive step change in hot water temperature (b) Cold water flow rate in liters per hour.

7. CONCLUSION

A real-time heat exchanger is modeled using two types of RFT. Symmetric and asymmetric RFT are conducted for the heat exchanger process. The identification is categorized into two aspects. In the first case, symmetric RFT data is used to determine the parameters of the nonlinear static subsystem via a simple optimization procedure. Whereas in the second case, the transfer function is identified as the FOPDT model using the asymmetric RFT data. Identification of the linear and nonlinear parts is fully decoupled by this approach. The advantage of using the Wiener type model is that it can be easily adapted to use existing linear methods for a closed loop control.

There are many advantages of using RFT. An ideal ON-OFF controller is used to identify the Wiener model. The Wiener based nonlinear control strategy can be easily implemented with any of the computer based controller and also it is a closed loop test, therefore the process will not drift away from the nominal operating point. Processes with larger time constant, it is more time efficient method than the conventional a step or a pulse testing. Finally, it identifies the process information around the important ultimate frequency (p_u). Wiener model identification and control can be effectively implemented in real-time using RFT than the conventional methods. Results of this work prove the effectiveness of disturbance elimination during identification and control. The Wiener model based controller is compared with that of the linear PI controller in real-time. It is proved that the real-time heat exchanger can be modeled and controlled by the RFT method.

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