Type-2 Fuzzy System and Observer Based Controller for Non-Linear System

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Abstract: ***This paper presents the nonlinear system with time delay. For such nonlinear system, robust control problem is designed. Takagi-Sugeno (T-S) fuzzy models can give a proper analysis of nonlinear systems with time delay. The Type-2 T-S fuzzy model approach is extended to achieve temperature control in continuous time nonlinear systems with time delay. Also disturbance tracking response is checked by using Type-2 Fuzzy DOB technique under internal as well as external disturbances.***

Keywords: Type-2 Fuzzy system approach, DOB, Fuzzy DOB

1. Introduction

Time delay is present in many systems such as chemical processes, pneumatic processes and hydraulic systems etc. Because of Time delay source has a problem of instability. Stability issue of time delay systems have been studied in past three decades [1-2]. During last few years, fuzzy logic technique has been successfully used for nonlinear system modeling, especiallywith incomplete plant knowledge for systems [3]. Fuzzy logic system is universal approximators. Takagi-Sugeno (T-S) fuzzy model is used for such approximations [4]. This model used the fuzzy rules to describe a nonlinear system in terms of a set of linear models which is based on fuzzy membership functions. For controller design of complex nonlinear system, T–S fuzzy model based control is used.

Stability analysis and synthesis are very important. A local linearization approach is used for the analysis and synthesis of nonlinear system with time delay. Particularly, some delay-independent stability approach has been proposed for this linear delay [3]. Thus the local model is good for a certain range of desired conditions and so these results can only provide the local stability of nonlinear systems with time delay.

Uncertainties may bring a nonlinear system in complex way. The uncertainty may consist modeling error, parameter perturbations, approximation (fuzzy) errors, and external disturbances. In some cases, existence of external disturbances might not work well [11]. Generally we say that the variable structure control (VSC) is an important approach for such system. Here in this paper, we study the nonlinear systems with time delay. From above design procedure, a given nonlinear system is represented by the TS model with time delay. SuchT-S fuzzy modeling method is simple. By using fuzzy "blending" of the linear delay model, fuzzy model is obtained [11]. In this paper we study a nonlinear system with time-delay model with external disturbances. Section II gives the nonlinear time delay system. Then presentation of Fuzzy time delay model with uncertainty and time varying delay is carried out. Also controller for the above fuzzy time-delay systems shown nonlinear time delay system

Mostly physical systems are nonlinear in nature. Thus, all control systems are nonlinear.Nonlinear differential equationsshow the nonlinear control systems. Consider if the operating range of a control system is small and the exited nonlinearities are smooth, then the control system may be considered by a linearized system, whose dynamics is expanded by a set of linear differential equations. Time delays have been considered unsuitable in control system, because of its tendency to instability of the system. A nonlinear system can be studied well by using the T–S fuzzy model. However, nonlinear systems with time-delay could be represented by a T–S fuzzy time-delay model [2]. Here in this paper, with $r$plant rules we considered a nonlinear time-delay system this could be expanded by the following T–S fuzzy time-delay model.

IF $\theta_1(t)$ is μ_{i1} and ... and $\theta_p(t)$ is μ_{ip} $THEN$

$$\begin{aligned} \dot{x}(t) &= A_{1i}x(t) + A_{2i}x\big(t - r(t)\big) + B_i u(t) \\ y(t) &= C_{1i}x(t) + C_{2i}x\big(t - r(t)\big) \\ x(t) &= \psi(t), t \in [-\tau_0, 0],\ i = 1, \dots, r \end{aligned} \quad (1)$$

Where μ_{ij} is the fuzzy set, $x(t) \in \mathbb{R}^n$ is the state vector, $u(t) \in \mathbb{R}^m$ is the input vector, where$y(t) \in \mathbb{R}^q$ is the output vector, and $A_{1i}, A_{2i}, B_i, C_{1i},\ and\ C_{2i}$ are constant matrices, r is the number of IF-THEN rules, where$\theta(t) = \big[\theta_1(t)\theta_2(t) \dots \theta_p(t)\big]$are the premise variables. It is considered that the there is no dependency of premise variables on the input variables. $r(t) \le \tau_0$is the bounded time-varying delay in the state and it is assumed that

$$\dot{r}(t) \le \beta < 1 \quad (2)$$

i.e., the time-varying delay functionswith derivative, which is a natural supplementary condition. $\psi(t) \in C_{n,\tau_0}$is a vector-valued initial continuous function.

Given a pair of$\big(x(t), u(t)\big)$, which are the final outputs of the fuzzy Systems are inferred as follow

$$\dot{x}(t) = \frac{\sum_{i=0}^{r} w_i(\theta(t))[A_{1i}x(t) + A_{2i}x(t-r(t)) + B_i u(t)]}{\sum_{i=1}^{r} w_i(\theta(t))} \quad (3)$$

$$y(t) = \frac{\sum_{i=0}^{r} w_i(\theta(t))[C_{1i}x(t) + C_{2i}x(t-r(t))]}{\sum_{i=1}^{r} w_i(\theta(t))} \quad (4)$$

2. Fuzzy with consideration time delay model of uncertaity

Consider the following nonlinear time-delay system:

$$\dot{x}(t)=F\left(x(t),x(t-d(t))\right)+\Delta F\left(x(t),x(t-d(t))\right)+G(x(t))u \quad (5)$$

$$x(t)=\varphi(t), t\in\left[-\bar{d},0\right] \quad (6)$$

Where,$x(t)\in\mathbb{R}^n$ which is a state vector, $u(t)\in\mathbb{R}^m$ is the input vector and $d(t)$ is the delay time of the system state with$d(t)\le\bar{d}$, $F(.),G(.)$ are nonlinear functions, and $\Delta F(.)$ is an uncertain nonlinear function. $\varphi(t)\in C_{n,\bar{d}}$isa vector-valued initial continuous function. A fuzzy model is developed [9] to understand input/output relations of nonlinear systems. A TS fuzzy time-delay model is expanded by r plant rules that can be represented as follows [8].

IF θ_1 *is* μ_{i1} *and ... and* θ_p *is* μ_{ip}

Then

$$\dot{x}(t)=A_i x(t)+A_{di}x(t-d(t))+B_i u(t)+\Delta f_i\left(x(t),x(t-d(t))\right) \quad (7)$$

Where μ_{ij} the fuzzy is set, and A_i, A_{di}, B_i are some constant matrices,r is the number of IF-THEN rules, and $\theta_j(t)=\left[\theta_1(t)\theta_2(t)\ldots\theta_p(t)\right]$ are the premise variables. The premise variablesthat do not depend on the input variables. Considering fuzzy model which is achieved by fuzzy blending of each individual rule as follows:

$$\dot{x}(t)=\sum_{i=1}^{r}h_i(\theta)\Big(A_i x(t)+A_{di}x(t-d(t))+B_i u(t)+\Delta f_i\left(x(t),x(t-d(t))\right)\Big) \quad (8)$$

Where $h_i(\theta)=\mu_i(\theta)/\sum_{i=1}^{r}\mu_i(\theta)$

$$\Delta f_i=\begin{bmatrix}\delta_i\left(x(t),x(t-d(t))\right)\\ v_i\left(x(t),x(t-d(t))\right)\end{bmatrix} \quad (9)$$

With $\|\delta_i\|\le 0.1\left(\|x(t)\|+\|x(t-d(t))\|\right)$

$$v_i\left(x(t),x(t-d(t))\right)=a\sin(t)\,\|x(t)\|^2+b\cos(t)\,\|x(t)-d(t)\|^2 \quad (10)$$

3. CSTR

3.1 Experimental Setup

CSTR plays important role in various chemical processes. In this first order exothermic reaction A→B takes place in which a fluid stream is continuously fed to the reactor [4]. Since the fluid is perfectly mixed, the temperature and concentration of the exit stream is same as the reactor fluid. The jacket surrounding the reactor which also has feed and exit streams as well. The jacket which is assumed to have a uniform lower temperature than the reactor. From thereactor into the jacket then energy then passes through the reactor walls removing the heat generated byreaction and tries to maintain the temperature at desired value. There are many examples of this type of reactors used in industries. When we consider the industrial reactors which are typically more complicated kinetics, but the characteristic behaviour is similar.

For highly nonlinear tank, the real time experimental setup is constructed. DAC is used to interface CSTR with the Personal Computer (PC). It consists of a tank, a water reservoir, pump, rotameter, RTD, an electro pneumatic converter, a pneumatic control valve, an interfacing DAC module and a Personal Computer (PC). The interfacing of differential pressure transmitter output is with computer using DAC module in the RS-232 port of the PC. Figure 4 shows the real time experimental setup of a CSTR tank interfaced with MATLAB.

The pneumatic control valve use air as an input and adjusts the flow of the water pumped from the water reservoir to the CSTR tank. The temperature of the liquid inside the tank is measured with the help of RTD and is transmitted in the form of current signaland interfaced DAC module to the Personal Computer.

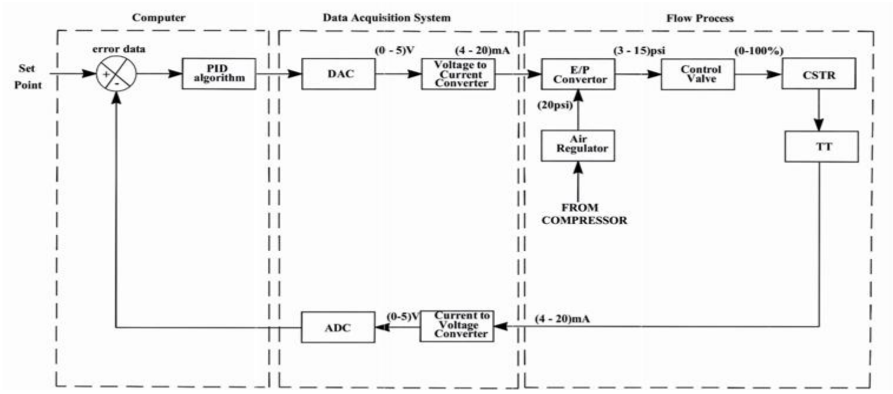

Figure 1: Block diagram of CSTR

By using pade's approximation the second order transfer function is calculated as

$$G(s)=\frac{-0.12s+0.12}{3s^2+4s+1} \quad (11)$$

The state space matrices are given as

$$A=\begin{bmatrix}-1.33 & -0.667\\ 0.5 & 0\end{bmatrix}$$

$$B=\begin{bmatrix}0.25\\ 0\end{bmatrix}$$

$$C=\begin{bmatrix}-0.16 & 0.32\end{bmatrix}\quad D=[0] \quad (12)$$

4. Robustness of Type-2 Fuzzy Controller

1) Interval Type-2 Fuzzy Controller:

During the past decades, various control methods are used in a process control industry [1]. Type-1 (T1) Fuzzy Logic controllers (FLCs) have been widely used as alternatives to conventional controllers. The majority of research work on T1-FLCs focuses on the two-input structures, it has been shown in various works that Single input T1-FLC (ST1-FLCs) provides greater flexibility and better functional properties. Recently, the main research focus is on Interval Type-2 (IT2) FLCs.In a Type-2 fuzzy set we also have uncertainty about the membership function. Type-1 fuzzy sets has crisp membership function and hence not able to directly model the uncertainties. Whereas type-2 fuzzy sets (T2FS) which are able to modeling the uncertainties because their membership function is themselves fuzzy [7,8]. The respective two dimensional fuzzy sets membership function of type-1 (T1FS) and membership function of type-2 fuzzy sets are three dimensional. The robustness is provided by extra third dimension of type-2 fuzzy sets.

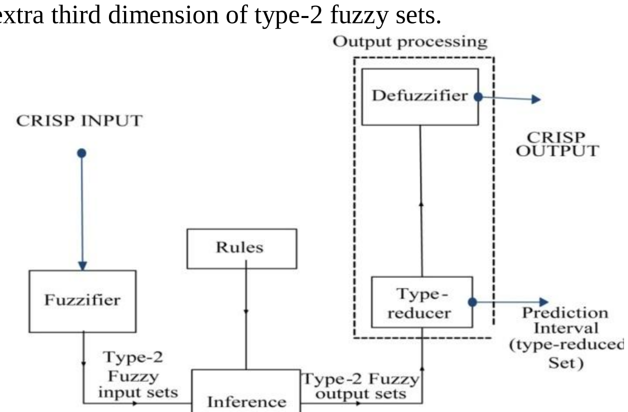

Figure 2: Block diagram of Type-2 Fuzzy

The IT2-FLC with internal structure which is similar to that of Type-1 Fuzzy logic system. Here the major difference is in the extra Type Reduction (TR) procedure required in IT2-FSs .The type-2 Fuzzy Yet, IT2-FLCs designed based on an evolutionary algorithms such that to generate a desired FM (i.e. control surface) .The main problem with the use of this approach is due to the improper understanding of how the Foot print Of Uncertainty parameters affect the system performance. Thus, developing the analytical structure of an IT2-FLC can be an efficient way to supervise the IT2-FLC in the design of the nonlinear control theory .Here, Wu examined that around the steady state IT2-FLCs are potentially more robust since they provide smoother control surfaces as compared to T1 controllers. Recently, stability tests and control design methods for IT2 Takagi–Sugeno–Kang system (Fuzzy logic) systems have been also proposed [9]. Yet, the systematic design and robustness analysis of the IT2-FLC are still challenging problems as it requires good knowledge.Type-2 fuzzy logic controllers consist of following 5 parts: rules, fuzzifier, inferences engine, the type reducer, and defuzzifier. These are connected as shown in Fig. as well.

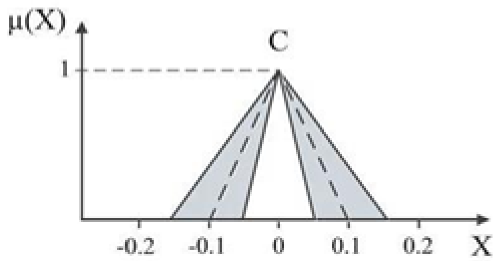

Figure 3: Fuzzy membership function

In many applications a DOB has been used which was proposed by ohnishi.The estimation of system uncertainties as well as external disturbances, and also robustness related to system is achieved by estimating the disturbances in feedback loop[12]. Developing disturbance estimation techniques would be good preferences alleviate the restrictions which are always faced by feed forward control. By nominal plant model achievement of performance goals, an outer-loop controller is designed nonlinear disturbance observer [13]. Disturbance observer-based controls (DOBC) approach for nonlinear systems under disturbances, that is, nonlinearDOBCorNDOBC.Within the NDOBC framework, instead of considering the control problem fora nonlinear system with disturbances as a single one, it is divided into two sub problems, eachwith its own design objectives.

The first sub problem is the same as the control problem for a nonlinear system without disturbances and its objective is to stabilize the nonlinear plant and obtain desired tracking and/or regulation performance specifications. The second sub problem is disturbance attenuation. A nonlinear disturbance observer is designed to estimate external disturbances and then the estimated value is employed to compensate for the influence of disturbances. DOBC for linear systems has been developed and employed in engineering over three decades. Ohishi et al. pioneered the development of DOBC for motion control systems. After that, DOBC has been employed in many mechatronic systems including disk drivers, machining centres, dc/ac motors, and manipulators .Most of the work on DOBC is engineering-oriented and lacks sound theoretic justification. When an attempt is made to extend DOBC from linear systems to nonlinear systems, this results in a composite controller consisting of a nonlinear controller and a nonlinear disturbance observer.

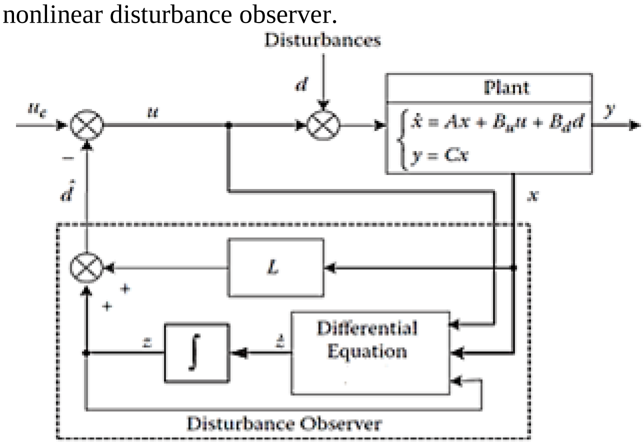

Figure 4: DOB block diagram

The high-order time varying disturbance case, this implies that the disturbance can be expressed in time series expansion. The output design of the nonlinear disturbance observer, which implies that only the output but not the state information, is employed. The method is inspired by the ideas of extended state observer and high-gain observer methods [12]. Time-domain disturbance observer with the above designed parameters has achieved quite fine disturbance estimation performances. Note that the time-domain DO here can be used for both minimum and nonminimum phase MIMO linear systems. However, it requires allthe state information for observer design, while the frequency-domain DO only use the output and input information.

$$\hat{d} = z + L * x \quad (13)$$

$$\dot{e_d} = \hat{d} - d \quad (14)$$

$$\dot{e_d} = -L * B_u * u + B_d * d \quad (15)$$

$$\dot{x} = A * x + B_u * u + B_{d*} d \quad (16)$$

$$y = C * x \quad (17)$$

Where, L=Disturbance compensation gain
z=internal parameter vector
$\hat{d}$ =Estimated disturbance
$\dot{e_d}$=Disturbance estimation error

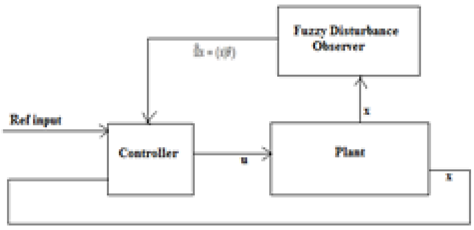

Figure 5: Block diagram of Fuzzy Disturbance Observer

The fuzzy logic system uses the configuration such as fuzzy inference engine, some IF-THEN rules with fuzzy and defuzzifier as well. Here the fuzzy IF-THEN rules are performing in the inference engine to mapping input to output. The output of fuzzy logic system expressed as,

$$y(x) = \frac{\sum_{i=1}^{r} y^i\left(\prod_{j=1}^{n} \mu_{A_j^i}(x_j)\right)}{\sum_{i=1}^{r}\left(\prod_{j=1}^{n} \mu_{A_j^i}(x_j)\right)} = \hat{\theta}^T * \xi(x) \quad (18)$$

Where,$\mu_{A_j^i}(x_j)$ =Fuzzy memebership function

$\hat{\theta}^T = (y^1, y^2, \dots\dots y^r)$ =Adjustable parameter vector
r=Number of fuzzy rules
$x = (x_1, x_2, \dots\dots x_n)^T$ =Input linguistic vector (19)
$\xi^T = (\xi^1, \xi^2, \dots\dots \xi^T)$(20)
$\xi^i = (\prod_{j=1}^{n} \mu_{A_j^i}(x_j)))/\sum_{i=1}^{r}(\prod_{j=1}^{n} \mu_{A_j^i}(x_j))$, are the fuzzy basis functions

2) Simulink Results

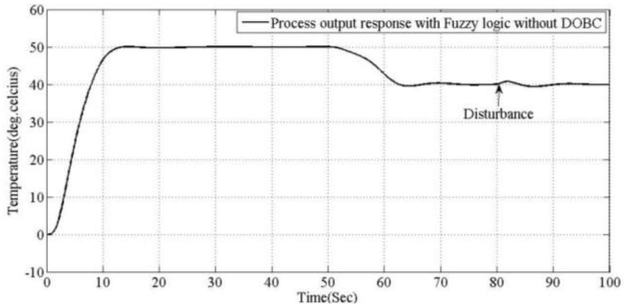

Figure 6: Response of CSTR with IT2 fuzzy controller

Here, the initial temperature is given to CSTR as 50 degree and set point is given as 40 degree. The control signal via such Type- 2 Fuzzy logic systems given to plant at 30 second. Such Simulink response of control action to achieve set point is shown in fig.6.With PI, Fuzzy and TYPE -2 Fuzzy Simulink results are also shown in fig.7.as well.

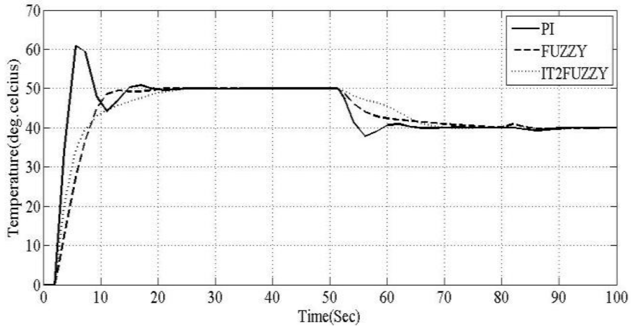

Figure 7: Response with all controllers

The structure of the type 2 fuzzy logic controller is same as that of structure of the type 1 fuzzy logic controller. The differences between types-2 and 1 are associated only with the nature of the membership function [10].The rules are a main component of the fuzzy logic system. These rules may be defined by a man (expert) or calculated analytically.

$\tilde{A} = \{((x,u), \mu_{\tilde{A}}(x,u))\}$which is also defined as
$\tilde{A} = \int_{x\in X}\int_{u\in Jx} \mu_{\tilde{A}}(x,u)/(x,u)$with$x \in X$
$\mu_{\tilde{A}}(x,u) \in [0,1]$
is a type-2 fuzzy membership function and secondary grad.

Jx is called as primary membership function of x whereas secondary membership function takes as [0, 1] in generalized T2FLSs.The fuzzification which has structure of Type-2 which coincides with type-1 fuzzy rule. By considering M rules, the first rule of rule base has form as following.

The fuzzy rules of the fuzzy dynamic model have the form
$IF \quad R^l: IF\ z_1\ is\ F_1^l\ and\ \dots z_v\ is\ F_v^l$

Then
$x(t+1) = A_l x(t) + B_l u(t) + a_l : y(t) = C_l\, x(t)$(13)

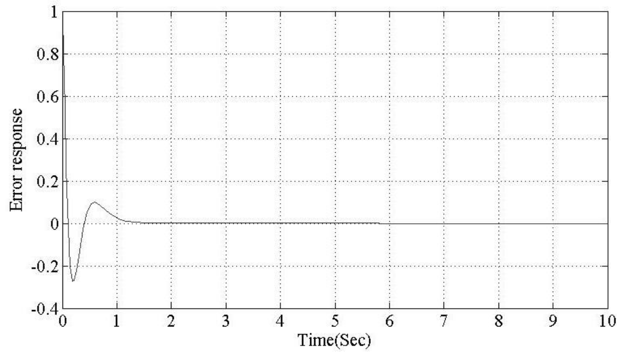

Figure 8: Response of disturbance estimation error

The assumption is considered as disturbance observation error should converge to zero. The objective is to drive x to zero in the presence of uncertainty$\Delta\alpha(x)$ *and* $\Delta\beta(.)$.Also to track the disturbance which is coming in the system d [10]. The uncertainty and disturbance are added together and given as following,

$$\dot{x_n} = [\alpha(x) + \Delta\beta(x)]u + \pi_x(x,u) \quad (21)$$

Consider nonlinear system which is described as,

$$\dot{x_n} = [\alpha(x) + \Delta\alpha(x)] + [\beta(x) + \Delta\beta(x)]u + d \quad (22)$$

$$\begin{aligned} \dot{x_1} &= x_2 \\ &\vdots \\ x_{n-1}^{\cdot} &= x_n \end{aligned} \quad (23)$$

$\alpha(.)$ *and* $\beta(.)$are the nominal functions $\Delta\alpha(x)$*and* $\Delta\beta(.)$ are the uncertainty ,and d is the disturbance
The dynamic system is expressed as,

$$\dot{\mu} = \alpha(x) + \beta(x)u + \widehat{\Omega}x(x,u|\hat{\theta}) + \sigma(x_n - \mu) \quad (24)$$

The disturbance estimation error which shown in fig.8, is given as,

$$\xi = x_n - \mu \quad (25)$$

The disturbance estimation error should goes to zero and perfect matching condition occurs when there is no disturbance which may be external or internal. The condition for perfect matching is given as,

$$\hat{\theta} = 0.$$

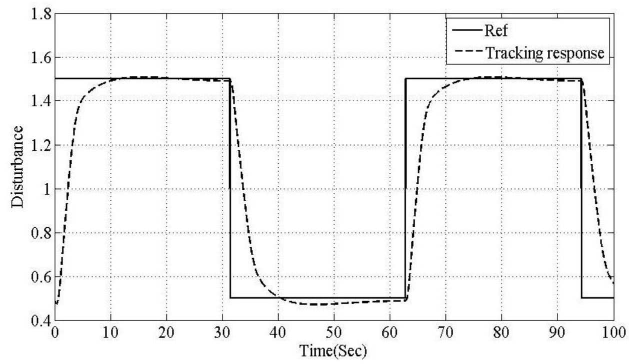

Figure 9: Type-2 Fuzzy DOB disturbance tracking response

Using parameter error $\tilde{\theta} = \theta - \hat{\theta}$ yields,

$$\dot{\xi} = -\sigma\xi + \tilde{\theta}\xi^T(x,u) + \varepsilon(x,u) \quad (26)$$

Fuzzy tuning rules are selected as,

$$\dot{\hat{\theta}} = \gamma\xi\ \xi(x,u) \quad (27)$$

Assuming Lyapunov candidate function with equation (28) which gives,

$$\dot{V} = \xi\dot{\xi} + \frac{1}{\gamma}\widetilde{\theta^T}\left\{\xi\xi(x,u) + \frac{1}{\gamma}\dot{\hat{\theta}}\right\} + \zeta\varepsilon(x,u) \quad (28)$$

$\dot{V} = -\sigma\zeta^2 + \zeta\varepsilon(x,u) = \frac{\sigma}{2}\zeta^2 + \frac{1}{2\sigma}\varepsilon^2(x,u) - \left(\sqrt{\frac{\sigma}{2}}\zeta -\right.$

12σεx,u2≤ −σ2ξ2+12σε2(x,u {29)

Under consideration of Type-2 Fuzzy DOB gives arbitrary closeness to nonlinear function as to monitor unexpectedly occurringdisturbances. As V is negative for $|\xi| \geq (\frac{\bar{\varepsilon}}{\sigma})$ then assumption considered as $\hat{\theta}$ is bounded, that is disturbance observer error is uniformly ultimately bounded [10, 13].

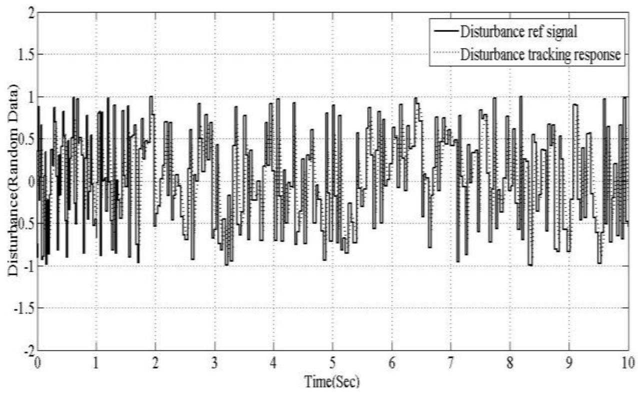

Figure 10: Type-2 Fuzzy DOB disturbance tracking response

The designed FDO $\widehat{\Omega}(x,u|\hat{\theta})$ is tuned in such way that it approaches unknown disturbance in the system. Such tuning parameter θ is adjusted with consideration of fuzzy basis function with respect to disturbance estimation error which is shown in equation (29) and such tracking response and for random data tracking response is shown in fig.9and fig.10respectively in above diagrams.

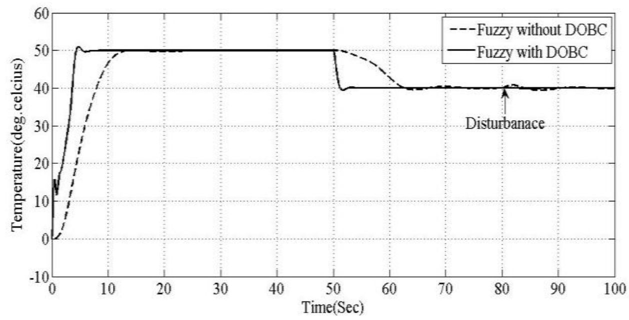

Figure 11: Tracking response (With Fuzzy+ DOBC)

All the simulation results shows the effectiveness of type-2 FLC in achieving a very high control performance and allowing a faster and more precise control of the process, both for set point tracking and disturbance rejection with less amount overshoot compared to type-1 controller. The rise time and settling time in both simulation and real time study reduces in interval type-2 fuzzy logic controller and considering DOB techniques as well.

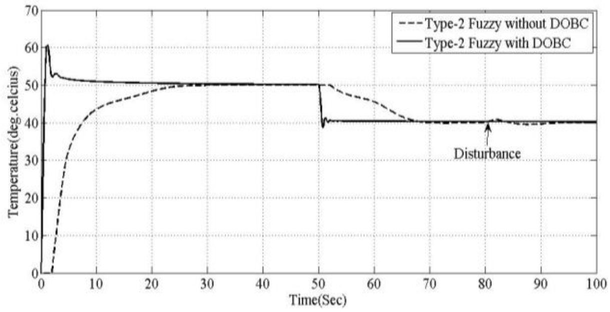

Figure 12: Tracking response (With Fuzzy+ DOBC)

This observer shows a much faster convergence rate than other types of disturbance observers. The observer gain is selected such that $-L * B_d$ is Hurwitz.The eigenvalues of matrix $-L * Bd$are calculated as $\lambda_1 = -101.3836$ and λ_2 =−30.6164, which implies that matrix, $-L * Bd$ is Hurwitz and satisfies the design. In this system the step disturbance is added to the system and tracking response is observed, which is shown in fig.9.

$$\dot{z} = -L * B_d(z + L * x) - L(A * x + B_u * u)(30)$$

Sr no.	Controller	Tr (Rise time)	Ts (Settling Time)
1	With only Fuzzy controller	8	18
2	With Fuzzy +DOBC controller	2	8
3	With Type-2 fuzzy controller	5	13
4	With Type-2 Fuzzy+DOBC controller	1.5	5

5. Conclusion

In this paper, T-S Fuzzy technique is used to study the control problem of nonlinear time-delay system. In the presence of parameter perturbations and external disturbances stabilization problem for uncertain T–S fuzzy time-delay systems are studied. Various control methods are used to achieve the disturbance tracking responses. In this paper two different methods are studied ,where Type -2 Fuzzy system applied for achieving the temperature control in CSTR and disturbance tracking in the system is achieved by using DOB,Type-2 Fuzzy DOB as well and compared their results. Also an internal and external disturbance which determinates the system performance can also be brought nearer to perfect matching condition with disturbance observer control scheme as well. For this, CSTR example is used to validate the results and effectiveness with the help of MATLAB Simulink model.

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