Eng. & Tech. Journal, Vol.30 , No. 8, 2012

Design of Type-2 Fuzzy Logic Controller for a Simple Furnace System

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Received on: 11/10/2011 & Accepted on: 2/2/2012

ABSTRACT

Model uncertainty and robustness have been a central theme in the field of automatic control. Many control techniques are used to reduce the effects of uncertainty which may appear in different forms as disturbances, dynamic delays or as other imperfections in the models used.

In this paper a comparison between conventional type -1 fuzzy logic controller and type -2 fuzzy logic controller has done in simulation conditions of a simple temperature control of a furnace system to show the great effect of the new generation of fuzzy logic controllers to improve the performance of a system with high level of uncertainty.

Keywords: Type-2 Fuzzy, Fuzzy Logic Controller, Furnace system, Type-1 Fuzzy

تصميم مسيطر مُضبب من النوع الثاني لنظام فرن بسيط

الخلاصة

عدم تأكيدية و قوة النموذج الرياضي كانت موضوع أساسي في مجال السيطرة ألأوتوماتيكية. الكثير من تقنيات السيطرة استخدمت لتقليل تأثير عدم التأكيدية و التي يمكن أن تظهر بأشكال مختلفة كالضوضاء أو التأخيرات الديناميكية أو أي عيوب أخرى في النماذج المستخدمة.

في هذا البحث تم إجراء مقارنه بين استجابة النظام بوجود متحكم المنطق المُضبب من النوع الاول او التقليدي مع متحكم المنطق المضبب من النوع الثاني ضمن بيئة محاكاة لنموذج بسيط للتحكم بدرجة حرارة نظام فرن لإظهار التأثير الكبير لمتحكمات الجيل الجديد للمنطق المضبب في تحسين خصائص نظام بوجود مقادير كبيرة من عدم التأكيدية.

INTRODUCTION

The use of fuzzy logic in process control has motivated many researchers in automatic control. The majority of their studies aimed to compare this kind of control with the classical ones like PID. Generally, for classical regulation PID remains widely used, but performances of PID cannot face up to increasing complexity of modern systems, the later needs the use of non-conventional control systems, in order to perform efficient control. One elegant way to solve this problem is the use of fuzzy logic. This method takes into account both good knowledge of the process and the performance requirements, this strategy of process control showed significant advantages when compared with classical PID control, especially in transient regimes [1].

To date type-1 (traditional) Fuzzy Logic Controllers (FLCs) have been applied with great success to many different real world applications. The traditional type-1 FLC cannot handle high levels of uncertainties appropriately, while it has been shown that type-2 FLC that uses type-2 Fuzzy sets can handle such uncertainties better and thus produce better performance. Type-2 FLCs are considered to have the potential to overcome the limitations of type-1 FLCs and produce a new generation of FLCs with improved performance for many applications which require handling high levels of uncertainty [2].

In this paper a comparison between the two types of FLCs, i.e., Type-1 and type-2 have done to show the great effect of the new type of FLCs to improve the performance of a system with high level of uncertainty.

TYPE-2 FUZZY LOGIC SYSTEMS

The concept of type-2 fuzzy sets was introduced by Zadeh as an extension of the concept of ordinary fuzzy sets (type-1 Fuzzy sets). A fuzzy relation of high type (e.g. type-2) has been regarded as one way to increase the fuzziness in a description and this means increased ability to handle inexact information in a logically correct manner. Type-2 sets can be used to cover the uncertainties in membership functions of type-1 sets, due to the dependence of the membership functions on available linguistic and numerical information. Linguistic information (e.g., rules from expert), in general doesn't give any information about the shapes of the membership functions. When the membership functions are determined or tuned based on numerical data, the uncertainty in the numerical data e.g., noise translated into uncertainty in the membership functions. In all such cases information about the linguistic / numerical uncertainty can be incorporated in the type-2 frame work [3].

Type-2 fuzzy set like type-1 fuzzy set contains elements that belong to a degree. In type-2 fuzzy the degree of belonging of an element (*x* which is belongs to the domain X) is expressed as type-1 fuzzy number with in [0, 1]. This means the degree to which an element belongs to the set is uncertain; a type-2 fuzzy set $\breve{F}$ over domain X is given by [4]:

$$\mu\breve{F}(x): X \rightarrow [0,1] * [0,1] \qquad (1)$$

This is called the primary membership function. In order to distinguish between a type-1 fuzzy set and type-2 fuzzy set, a tiled symbol is putted over the symbol of type-2 fuzzy set.

Primary membership grade are the type-1 fuzzy numbers within [0, 1]. The secondary membership function is given in equation (2) where the grades are values between zero to one [4, 5].

$$\mu\breve{F}\left(x, \mu\breve{F}\right): X * [0,1] \rightarrow [0,1] \qquad (2)$$

The membership function of general type-2 fuzzy set $\breve{F}$ is three dimensional as shown in Figure (1)

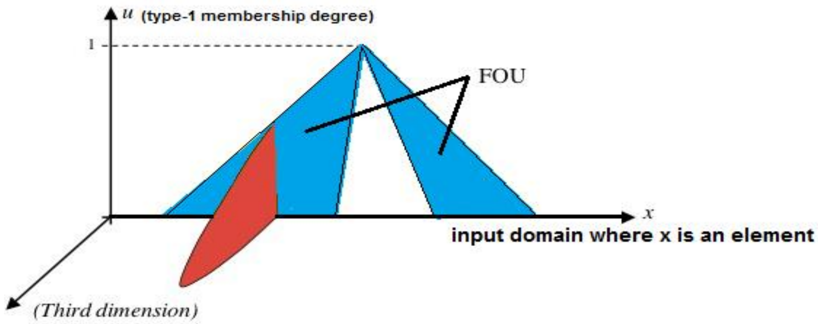


Figure (1) type-2 fuzzy set representation

Where the third dimension is the value of the membership function at each point on its two dimensional domain that is called its Footprint of Uncertainty (FOU). For an Interval type-2 fuzzy set that third dimension value is the same everywhere, which means no new information, is contained in the third dimension of an Interval Type-2 (IT2) Fuzzy Set [4]. A block diagram of a type-2 fuzzy logic system is depicted in Figure (2) below:

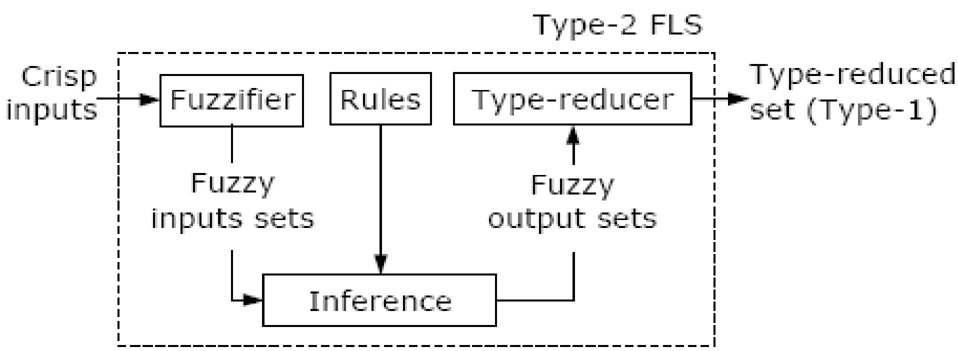


Figure (2) block diagram of a type-2 fuzzy logic system

Measured (crisp) inputs are first transformed into fuzzy sets by the Fuzzification process that activate the rules which are described in terms of fuzzy sets and not numbers. After measurements are fuzzified, the resulting input fuzzy sets are mapped into fuzzy output sets by the Inference process. This is accomplished by first quantifying each rule using fuzzy set theory, and then by using the mathematics of fuzzy sets to establish the output of each rule, with the help of an inference mechanism. Rules, that are either provided by subject experts or are extracted from numerical data, are expressed as a collection of IF-THEN statements, e.g., , the fired-rule output fuzzy sets have to be converted into a number, and this is done in Figure(2) using output processing block. To go from an interval type-2 fuzzy set to a number (usually) requires two steps. The first step, called type-reduction, is where an interval type-2 fuzzy set is reduced to an interval-valued type-1 fuzzy set. The second step of Output Processing, which occurs after type-reduction, is still called defuzzification. Because a type-reduced set of an interval type-2 fuzzy set is always a finite interval of numbers, the defuzzified value is just the average of the two end-points of this interval. For detailed information about IT2FLC see the references [5, 6].

SYSTEM MODEL

The above described methods i.e., Type-1 FLC and Type-2 FLC will be applied to a simple furnace system which can be described in the following transfer function [1]:

$$G(s) = \frac{ke^{-T_d s}}{(1+T_p s)^2} \qquad (3)$$

Where:
k=0.87 static gain
Td=10 sec (system time delay)
Tp=200 sec (system time constant)

Design of Type-1 Fuzzy Logic Controller

In this section, a **Type-1** Fuzzy Logic Controller **(T1FLC)** is developed to impose the plant (furnace system model) to track a reference signal (step input) to study its performance. The T1FLC is designed using Mamdani type it has two inputs; error (e(k)) and change of error (Δe(k)) signals, and one output (control action). The inputs are defined as follows:

$$e(k) = r(k) - y(k) \qquad (4)$$

$$\Delta e(k) = e(k) - e(k-1) \qquad (5)$$

If only two Gaussian membership functions are used then this results in 4 rules where the selection of these rules based on the knowledge of the behavior of the system response:

– If e(k) is positive and Δe(k) is positive, then Δu(k) is positive
– If e(k) is positive and Δe(k) is negative, then Δu(k) is zero
– If e(k) is negative and Δe(k) is positive, then Δu(k) is zero
– If e(k) is negative and Δe(k) is negative, then Δu(k) is negative

Where the index (k) represents the present sampling instant. Reducing the number of rules in a fuzzy controller makes the implementation of the fuzzy controller possible with limited processor throughput [7].

The closed loop structure with T1FLC simulated in Matlab/Simulink environment (R2010a) and shown in Figure (4) below:

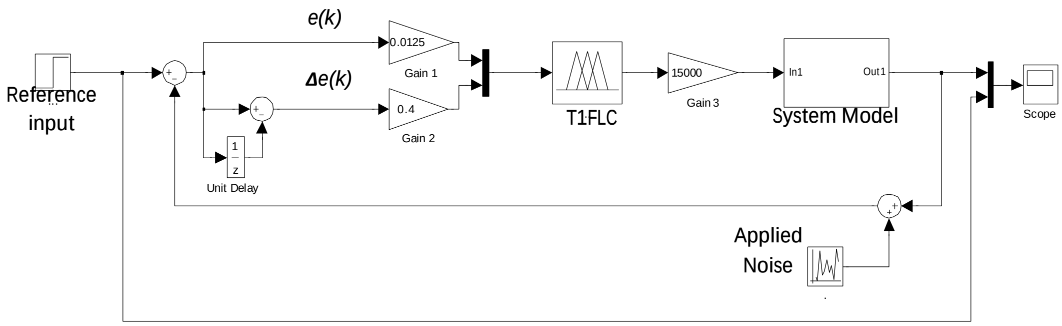


Figure (3) Closed loop structure with T1FLC.

All the membership functions of the FLC inputs and outputs are defined on the common normalized domain [-1, 1] as shown in Figure (4) and Figure (5). The characters N, Z and P are the linguistic variables of the inputs and output fuzzy sets.

The letters N, P, Z represent Negative, Positive and Zero respectively. μ is the certainty of the membership function.

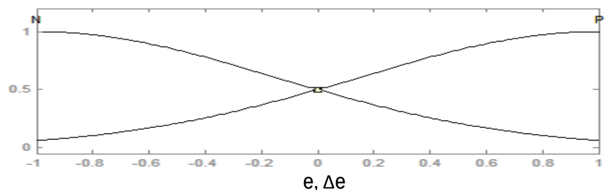


Figure (4) Membership functions for input variables.

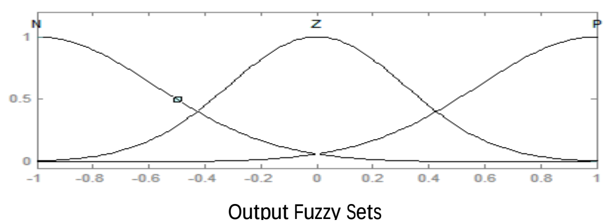


Figure (5) Membership functions for output variable.

The successful design of a FLC depends on the right selection of the input and output scaling factors, and in many cases this task is done through trial and error or based on some training data [8]. In this paper, the FLC scaling factors are tuned manually.

DESIGN OF TYPE-2 FUZZY LOGIC CONTROLLER (T2FLC)

In this section type-2 fuzzy logic controller is designed, the system developed here is identical to that developed in the previous section in order to remove the effect of any other factor within the developed controller on the control action and thus on the plant response and make the comparison is restricted to the impact of the third dimension added to fuzzy sets in the system of type-2. This means the designed controller is of Mamdani type used the same rules, same number of Gaussian fuzzy sets and same inputs and in the following figure **μ is the certainty of the membership function,** the inputs and output fuzzy sets defined on the common normalized domain [-1, 1] is shown:

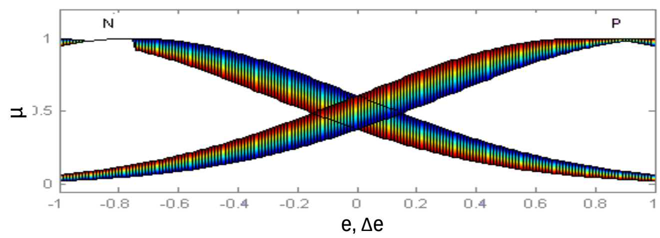


Figure (6) Type-2 fuzzy sets for the input variables.

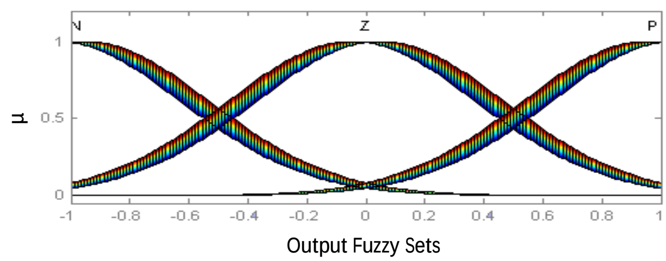


Figure (7) Type-2 fuzzy sets for the output variable.

The closed loop structure with T2FLC simulated in Matlab/Simulink environment and shown in Figure (8) below:

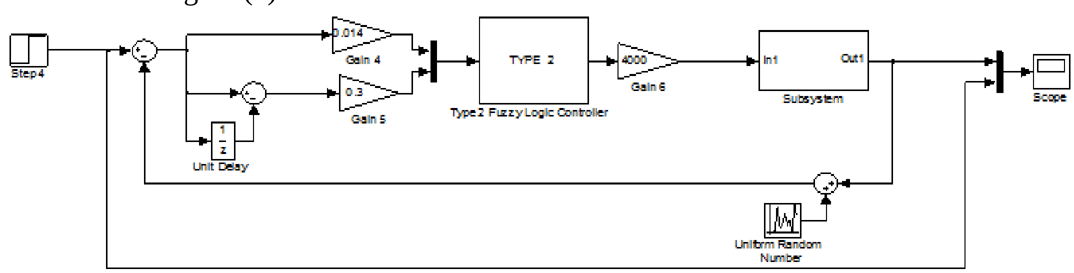


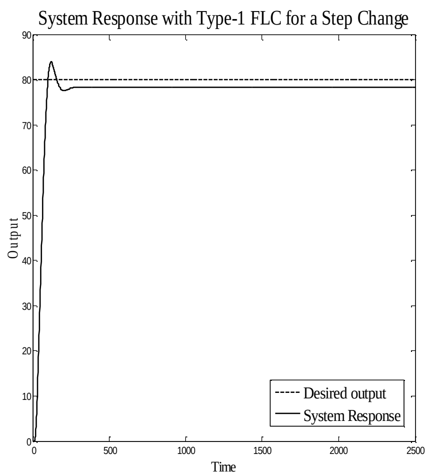
Figure (8) Closed loop structure with T2FLC.

SIMULATION RESULTS

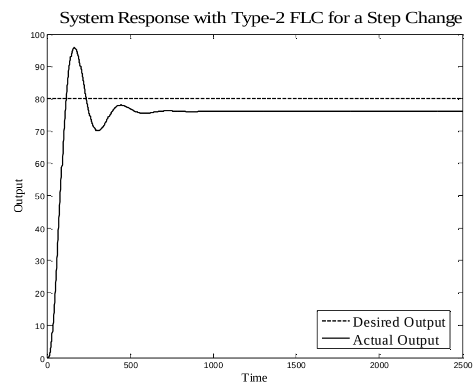
The main goal of this study is to investigate whether a T2FLC can achieve better control performance and better system response than its type-1especially with respect to the parameters that affect system stability.

The performance of the proposed T2FLC is compared with the corresponding T1FLC in terms of **Peak Overshoot (P.O)** and **steady state error (ess)** whose affect system stability. By examining the results shown in in Figure (9) we can notice that both controllers type-1 and type-2 have achieved good tracking ability for both types of entry; i.e., hanging with fixed step input as in Figure (9, a & b) or multi-levels of step

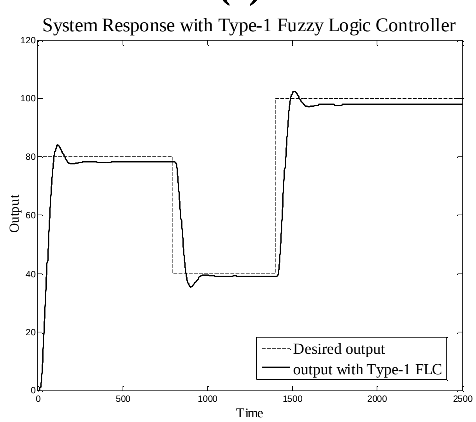
input as in Figure (9, c & d), but type-1 was better in getting less P.O and less ess as shown clearly from the Figure (10, b).



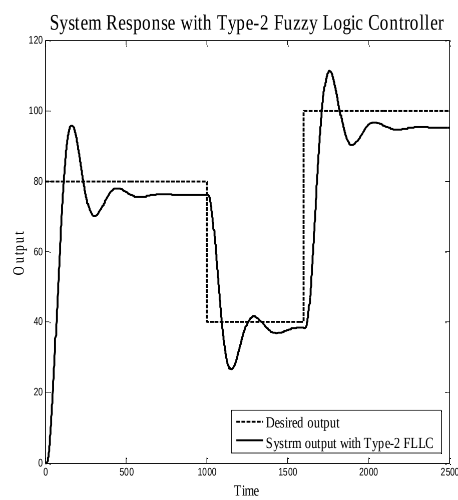
(a)



(b)

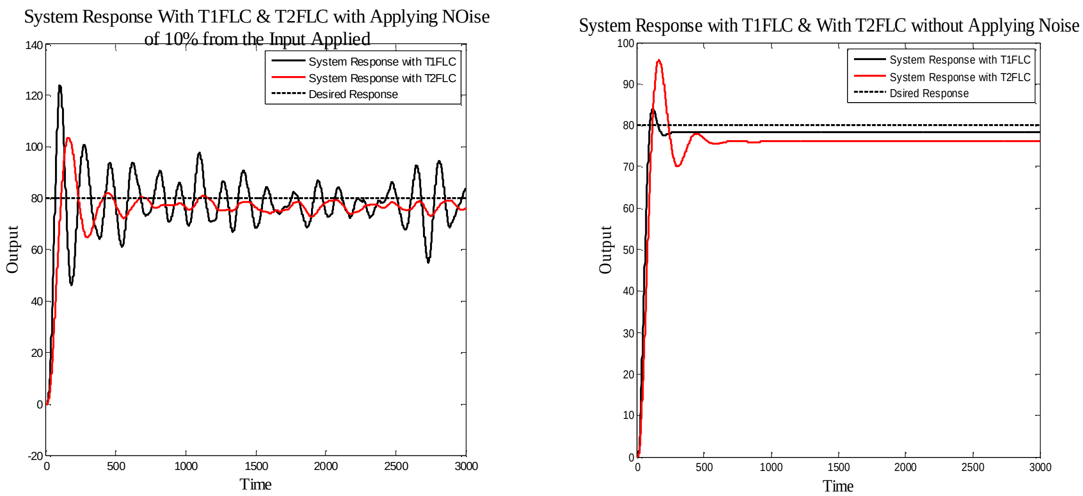


(c)



(d)

Figure (9): Closed loop systems responses without applying Noise



(a) (b)

Figure (10): Comparative plot of the closed loop systems responses with and without applying noise

To test the controllers ability to produce more complex input-output mapping and by exposing the closed loop systems to a different levels of noise to test the controllers ability to handle plants in noisy environment, we found that the system controlled by T2FLC was best in dealing with noise as shown clearly in the Figure (11), while the T1FLC fails completely in control the system response when exposed to a noise of 10% of the input signal by producing completely oscillated response, while the system with T2FLC was more stable has smoother response and provide satisfactory control in spite of noise presence with less rate of ess as shown clearly in Figure (10, a).
To test the FLCs ability to handle un-modeled dynamics, a transport delay was introduced into the feedback loop.
First, a transport delay equal to 10 second (10 sampling period) was added to the nominal system. The step response is shown in Figure (12)(a&b) where both controllers oscillated for a period of time then they settled at a cceptedess.

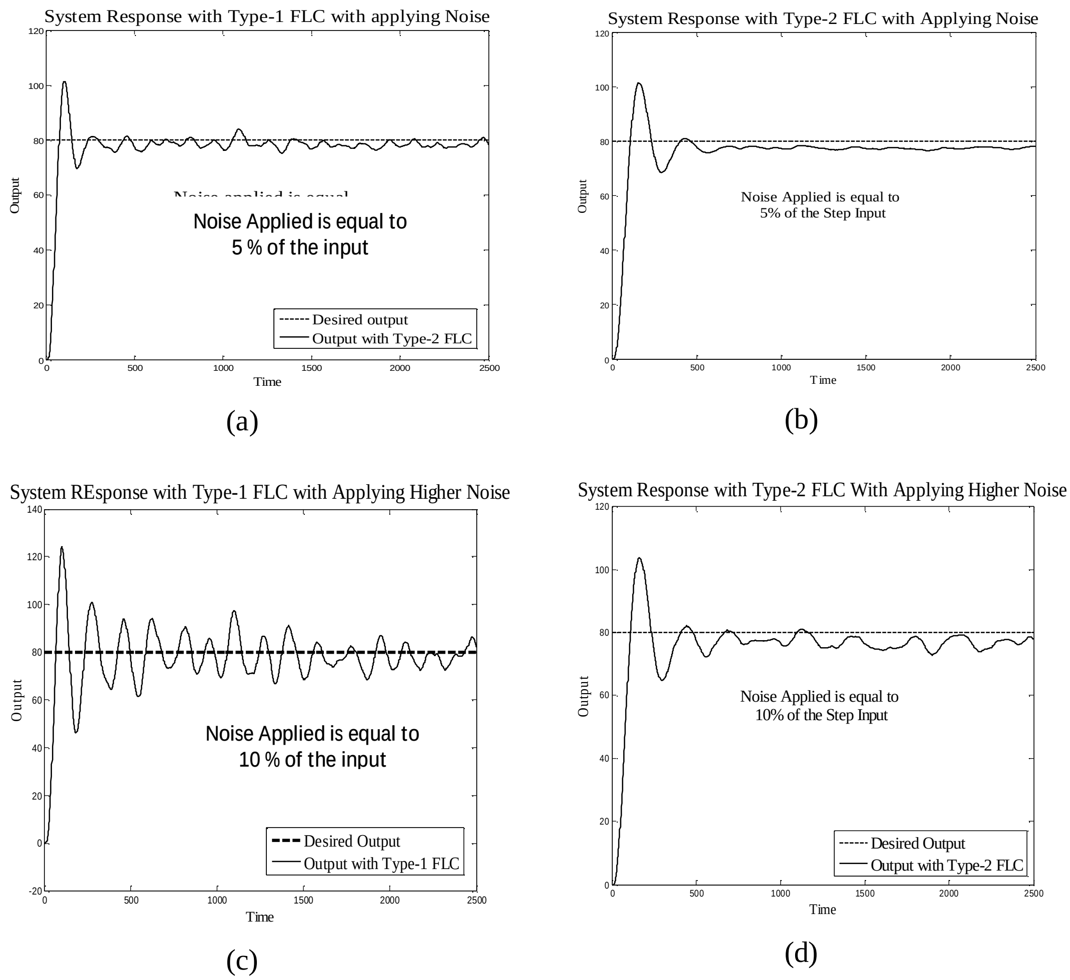
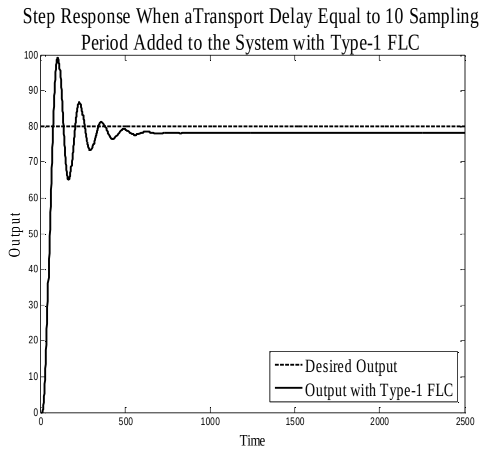


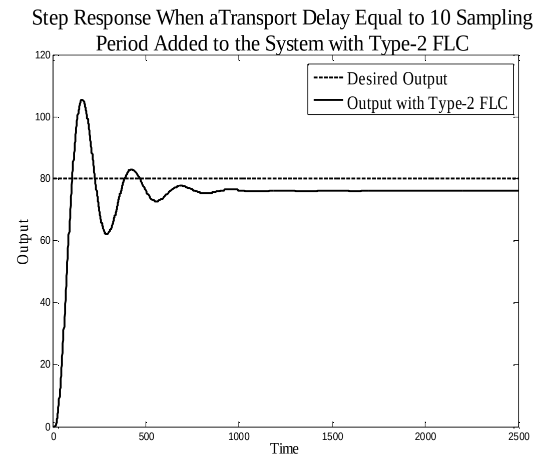
Figure (11): Closed loop systems responses with applying multi levels of Noise

But When a 15 sampling periods transport delay was added to the system, the corresponding step responses is shown in Figure (12, c & d), and finally When a 20 sampling periods transport delay was added to the system, the corresponding step responses is shown in Figure (12, e & f) it's clear from the figures that the system with T1FLC was unable to track the desired step signal applied and the system goes into a sustained oscillation with high peak levels exceeding the maximum value of the step input while with T2FLC the oscillation is eliminated and we got better tracking performance. For better view see Figure (13)

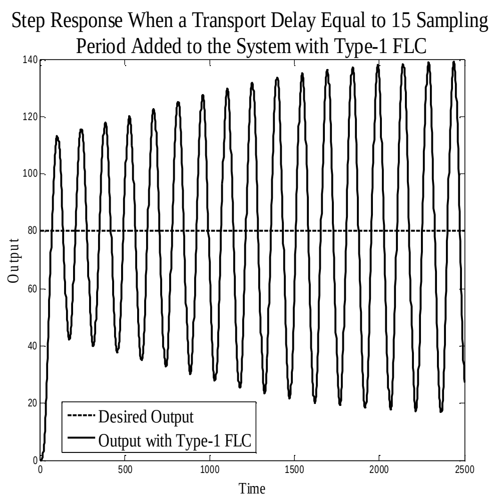
The better performance of T2FLC arises from the extra degree of freedom provided by the FOU made this controller better and able to eliminate persistent oscillations than their T1FLC counterpart. Unlike T1FLCs which utilize certain membership functions, the output of a T2FLC may be obtained via different embedded type-1 sets as the input vector varies.



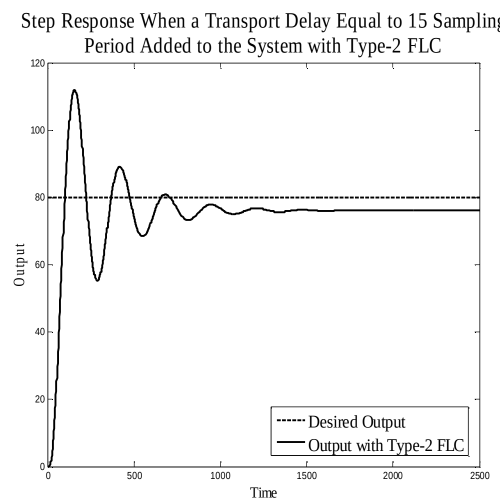
(a)



(b)



(c)



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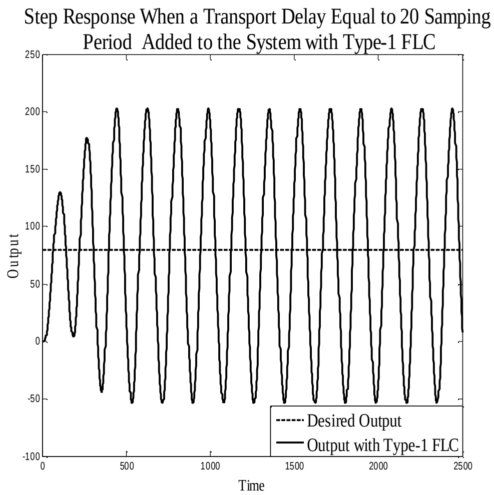
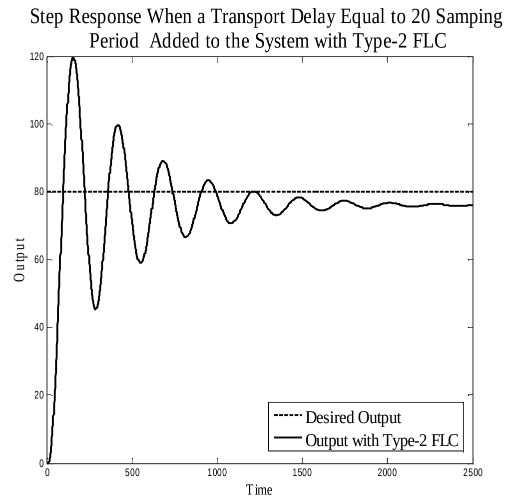
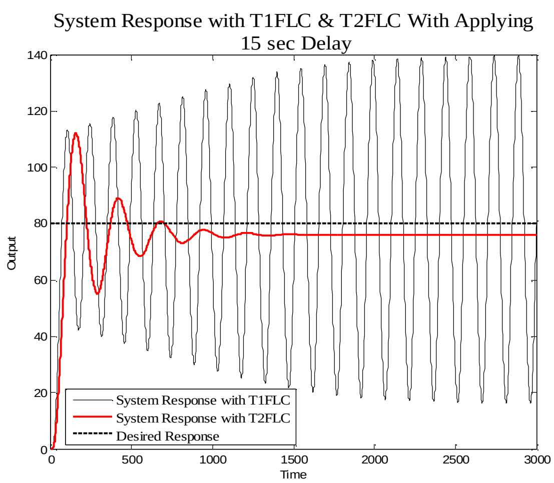


(e)

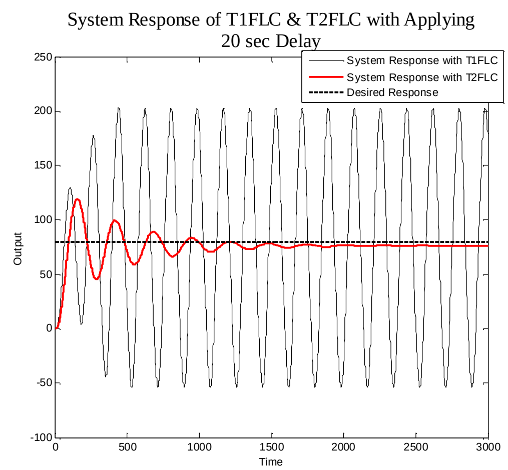


(f)

Figure (12): Closed loop systems responses with applying different periods of time delay



(a)



(b)

Figure (13) Comparative plot of the closed loop systems responses with applying different periods of time delay

CONCLUSIONS

In this paper, wide simulations were led to study the properties of Type-2 FLCs. From the results presented in the previous section, it can be concluded that Type-2 FLC may be able to achieve better control response than Type-1 FLCs did and the ability of Type-2 FLCs to handle modeling uncertainties is superior. Thus, a Type-2 FLC is more appealing than its Type-1 counter-part with regards to accuracy and interpretability. The main advantage of a Type-2 FLC appears to be its ability to eliminate apparent oscillations, especially when un-modeled dynamics were introduced like time delays or noise. This ability to handle model uncertainties is particularly useful when FLCs are tuned off-line and a model has an impact of un-modeled dynamics.

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