PERFORMANCE ANALYSIS OF FUZZY LOGIC CONTROLLER CONFIGURATIONS

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ABSTRACT

Fuzzy logic is a branch of Artificial Intelligence. It is widely used in Engineering, Biological and statistical non linear models where exact mathematical expressions for the given models cannot be written. In this paper the application of fuzzy logic technique is presented for control of a general model of a second order system. The response of the system is studied for four configurations of fuzzy model i.e. Pure fuzzy control, Parallel fuzzy control, Fuzzy logic-refined control, Fuzzy logic-tuned control. The simulations are carried out by Matlab programming.

Keywords: Fuzzy logic, Fuzzy controller, Matlab.

1. INTRODUCTION

The aim of a control system is to obtain a desired response for a given system. This can be done with an open-loop control system, where the controller determines the input signal to the process on the basis of the reference signal only, or with a closed-loop control system, where the controller determines the input signal to the process by using also the measurement of the output. PID control is used to control and maintain processes. This technique is widely used in today’s process industry to achieve control under different process conditions. Applying a PID control law consists of applying properly the sum of three types of control actions: a proportional action, an integral action and a derivative one. PID is simply an equation that the controller used to evaluate the controlled variables [1]. To achieve the desired performance in the necessary scenarios some manual tuning to the controller is mandatory which is also auto tuned.

During these last years, a specific interest for fuzzy techniques in control has emerged. They allow generating numerical data from approximate reasoning based on linguistic knowledge. The use of such techniques is principally relevant in the following cases [2]. Firstly, if the process model is known; fuzzy techniques can be used to improve the closed-loop performances for linear or non-linear plants. When fuzzy controllers are used, the ability to generate non-linear control laws with the various degrees of freedom is interesting [3]. Although it is not always straightforward to tune their numerous parameters, their rule-based nature relies on a new approach introducing a convenient way of designing and understanding the controller [4]. Secondly, if the process model is unknown, fuzzy techniques are useful for modeling human operator knowledge [4, 3, 5, 6]. The major leeway in the existing methods of fuzzy logic controller design in tuning number of parameters. Within this mind, only the parameters are considered for FLC which enable high performance for the system in closed loop operation.

2. FUZZY CONTROLLER

A classical set A is collection of elements or objects. But a Fuzzy set is a set of elements or objects characterized by truth values in the [0, 1] interval rather than crisp 0 or 1 as in the classical set. Fuzzy logic is a branch of artificial intelligence that deals with reasoning algorithms used to emulate human thinking and decision making in machines. These algorithms are used in applications where process data cannot be represented in binary form. Unlike conventional control, which is based on mathematical model of a plant, a FLC usually embeds the intuition and experience of a human operator and sometimes those of designers and researchers. While controlling a plant, a skilled human operator manipulates the process output (i.e., controller output) based on e and Δe with a view to minimizing the error within the shortest possible time. Fuzzy logic control is a knowledge-based system. By analogy with the human operator, the output parameters should be considered a very important parameter of the FLC since its function is similar to that of the controller gain. Moreover, it is directly related to the stability of the control system. So the output parameters should be determined very carefully for the successful implementation of a FLC.

2.1 SYSTEM DESIGN WITH FUZZY LOGIC CONTROLLER

First of all, a quantization module discretizes and normalizes the universes of discourse of the various manipulated variables. Then, a numerical fuzzy converter maps crisp data to fuzzy numbers characterized by a fuzzy set and a linguistic label. These two first modules can be combined in one numerical-symbolic interface. During the next step, the inference engine applies the compositional rule of inference to the rule base in order to
derive fuzzy values of the control signal from the input facts of the controller. Finally, a fuzzy-numerical
converter and a dequantization module, forming a symbolic-numerical interface, provide a numerical value of
the control signal or of the control increment [2].

The parameters of the inference module are, respectively, Mamdani implication function, the \textit{Sup min}
compositional rule of inference, the discretized center of gravity defuzzification method, the interpretation of the
And and Or connectors with the operators \textit{Minimum} and \textit{Maximum}. The overall block diagram of the fuzzy
system is shown in the Fig.1.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Structure of fuzzy logic controller (FLC)}
\end{figure}

\subsection{2.1.1 Fuzzy Membership Functions}

In this paper the inputs are error (e), change in the error (Δe) and the outputs are proportional gain constant (K_p),
derivative gain constant (K_d), integral gain (K_i) constant respectively. A combination of membership
functions is considered for inputs and outputs i.e. triangular and Gaussian membership functions. The range of
the membership function is considered from (-3, 3). It is shown in the Fig.2

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Membership function for the fuzzy controller}
\end{figure}

It comprises of 7 states NB, NM, NS, Z, PS, PM, PB. Their respective membership functions and ranges are
shown in Table-1

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
S.no & State & Membership function & Range* \\
\hline
1 & Negative Big(NB) & Gaussian & (-0.7, -3) \\
2 & Negative Middle(NM) & Triangular & (-3, -2, 0) \\
3 & Negative Small(NS) & Triangular & (-3, -1, 1) \\
4 & Zero(Z) & Triangular & (-2, 0, 2) \\
5 & Positive Small(PS) & Triangular & (-1, 1, 3) \\
6 & Positive Middle(PM) & Triangular & (0, 2, 3) \\
7 & Positive Big & Gaussian & (0.7, 3) \\
\hline
\end{tabular}
\caption{Membership functions and respective Ranges.}
\end{table}

*The range of the membership functions of various states mentioned is calculated using standard fuzzy
design theory.

\subsection{2.1.2 Fuzzy Rulebases}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Structure of fuzzy logic controller (FLC)}
\end{figure}
The set of linguistic rules is the essential part of a fuzzy controller. In many cases it’s easy to translate an expert’s experience into these rules and any number of such rules can be created to define the actions of the controller. In the designed fuzzy system, conventional fuzzy conditions and relations such as: “If $e$ is A and $\Delta e$ is B, then $K_p$ is C, $K_d$ is D and $K_i$ is E.” are used to create the fuzzy rulebase (7 x 7).

### Table-2 Fuzzy Rulebase for $K_p$

<table>
<thead>
<tr>
<th>$e/\Delta e$</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>Z</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
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<td>NB</td>
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<tr>
<td>NS</td>
<td>PM</td>
<td>PM</td>
<td>PS</td>
<td>PS</td>
<td>Z</td>
<td>NS</td>
<td>NS</td>
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<tr>
<td>Z</td>
<td>PM</td>
<td>PM</td>
<td>PS</td>
<td>Z</td>
<td>NS</td>
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### Table-3 Fuzzy Rule base for $K_d$

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### Table-4 Fuzzy Rule base for $K_i$

<table>
<thead>
<tr>
<th>$e/\Delta e$</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
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<td>PS</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
<td>PB</td>
</tr>
</tbody>
</table>

In this paper the DC motor is considered as an application of second order system which uses the PID controller with fuzzy logic. Various configurations of the controllers are considered and analyzed. The general transfer function of the motor is considered i.e.

$$G(s) = \frac{\frac{W(s)}{W(0)}}{s^2(\frac{1}{L_d}) + s(\frac{B_l L_d}{L_d} + R_d) + \frac{1}{J} + \frac{R_a + R_b}{L_d}}$$

where

- $K_b = \text{induced emf constant}$
- $L_d = \text{self inductance}$
- $J = \text{moment of inertia}$
- $B_l = \text{friction coefficient}$
- $R_a = \text{armature resistance}$

considering the parameters $K_p = 0.8$, $L_d = 0.003H$, $J = 0.0167 \text{kg-m}^2$, $B_l = 0.01$, $V = 220v$

### 2.2 FUZZY CONTROLLER CONFIGURATIONS.

The input conditions to the fuzzy controller must be able to trigger conditional rules, meaning that they specify one or more output conditions. Inputs should be selected according to the process situations they describe. In other words, if two inputs are selected that have little to do with each other, the outcomes that they generate will not be as precise or intuitive as the outcomes generated by inputs that deal with the same process element. So various configurations are considered with choice of inputs and outputs.

#### 2.2.1 Pure fuzzy control configuration.

In this configuration the fuzzy controller is directly connected to the process of the system and the feedback signal is sent to the fuzzy controller directly. The system block diagram is shown in the figure-3.
Upon simulation with Matlab for the considered second order system for the above configuration the response is shown in the figure-4.

![Fig-3 Pure fuzzy control configuration](image)

The obtained system time domain specifications are delay time is 0.104sec, Rise time is 0.106 sec, Settling time is 0.149 sec, Maximum peak overshoot is 0.59%, Nature of transient behavior is oscillatory and steady state error is 0.24%.

2.2.2 Parallel fuzzy control configuration.
In this configuration the fuzzy controller is connected parallel to the process of the system. The output of conventional controller and the fuzzy controller is feedback to the system process directly. The system block diagram is shown in the figure-4.

![Fig-4 Parallel fuzzy control configuration](image)

Upon simulation with Matlab for the considered second order system for the above configuration the response is shown in the figure-5.

![Fig-5 System response of Parallel fuzzy control configuration](image)

The obtained system time domain specifications are delay time is 0.101sec, Settling time is 0.19 sec, Maximum peak overshoot is -1.03%, Nature of transient behavior is Smooth and steady state error is 1.52%.

2.2.3 Fuzzy logic Refined control (Modified with fuzzy logic)
In this configuration the fuzzy controller is connected parallel to the process of the system. The output of conventional controller and the feedback signal of the system process are the inputs of the fuzzy logic controller.
The output of the FLC and conventional controller is fed back to the system process directly. The system block diagram is shown in the figure-6.

Fig-6 Fuzzy logic Refined control (Modified with fuzzy logic)

Upon simulation with Matlab for the considered second order system for the above configuration the response is shown in the figure-7.

Fig-7 System response of Fuzzy logic Refined control (Modified with fuzzy logic)

The obtained system time domain specifications are delay time is 0.101sec, Settling time is 0.19 sec, Maximum peak overshoot is -1.03%, Nature of transient behavior is Smooth and steady state error is 1.52%

2.2.4 Fuzzy logic-Tuned control

In this configuration the fuzzy controller is connected parallel to the process of the system. The output of conventional controller and the feedback signal of the system process are the inputs of the fuzzy logic controller. The output of the FLC is tuned is sent to the conventional controller. The output of the conventional controller is fed back to the system process directly. The system block diagram is shown in the figure-8.

Fig-8 Fuzzy logic-Tuned control

Upon simulation with Matlab for the considered second order system for the above configuration the response is shown in the figure-9.

Fig-9 System response of Fuzzy logic-Tuned control
The obtained system time domain specifications are delay time is 0.105 sec, Rise time is 0.109 sec, Settling time is 0.14 sec, Maximum peak overshoot is 0.142%, Nature of transient behavior is oscillatory and steady state error is 0.38%. The simulink model with all this configurations is shown in figure 10.

![Simulink Model](image)

Figure 10 The fuzzy-PID simulation model in MATLAB

3. SIMULATION RESULTS

Upon simulation with Matlab for the considered second order system for the above configurations the response is shown in the figure-11.

Red dashed: Pure fuzzy control configuration; Red: Parallel fuzzy control configuration; Blue dashed: Fuzzy logic Refined control (Modified with fuzzy logic); Pink: Fuzzy logic Tuned control; Black: Normal response. Parallel fuzzy control configuration and Fuzzy logic Refined control (Modified with fuzzy logic) responses are overlapped.

![System Responses](image)

Figure 4 system responses for different configurations

The performance time domain specifications are now calculated and compared as shown in the Table -6.

<table>
<thead>
<tr>
<th>S.no</th>
<th>Configuration used</th>
<th>Time Domain Performance Parameters</th>
<th>% Steady state Error (ESS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Delay Time (Td) in Sec</td>
<td>Rise Time (Tr) in Sec</td>
</tr>
<tr>
<td>1</td>
<td>Normal Response</td>
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<td>0.118</td>
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<td>2</td>
<td>Configuration 1</td>
<td>0.104</td>
<td>0.106</td>
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<tr>
<td>3</td>
<td>Configuration 2</td>
<td>0.101</td>
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</tr>
<tr>
<td>4</td>
<td>Configuration 3</td>
<td>0.101</td>
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<td>5</td>
<td>Configuration 4</td>
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</table>
CONCLUSIONS

The response of the second order system is analyzed for different fuzzy controllers and their responses are compared in terms of their performances indices i.e. Delay time ($t_d$), Rise time ($t_r$), Settling time ($t_s$), Maximum peak overshoot ($M_p$). Nature of transient behavior is oscillatory and steady state error ($e_{ss}$). It is observe that the response of the system with Fuzzy logic-Tuned control configuration is superior compared to other configurations.

REFERENCES