Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 5 (5): 887-891, 2005
ISSN 1812-5654

Non-singleton Fuzzy Logic Control of a DC Motor

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Abstract: In this study, a new control scheme was described for the robust speed control of a DC motor under parameter variations and external disturbances. Non-singleton fuzzification were used in the proposed fuzzy control scheme. The control performance is tested under inertial and frictional variations and an external load torque. In order to show the effectiveness of the proposed control approach, simulation results of the singleton and non-singleton fuzzy control systems are presented together.

Key words: Non-singleton fuzzy logic, drive control, robust control, speed control

INTRODUCTION

Electrical drives are widely used in many industrial systems. Speed or position of electric motors are usually controlled to hold the speed/position under unknown disturbances or to change the speed according to a reference profile. The output of a speed controller is a torque demand and electric drives are called upon to have good torque control performance. The speed control performance obtained using a PI/PID controller is sensitive to the uncertainties such as plant parameter variations, external load disturbances and, unmodelled and non-linear dynamics of the plant. Therefore, a robust controller would be attractive in most industrial applications. A controller is said to be robust if it gives satisfactory dynamic responses in the presence of parameter variations, external disturbances and unmodelled or non-linear dynamics of the plant. The problem of designing robust controllers is thus called robust control.

For the robust control of motor drives, a variety of approaches (e.g., sliding mode, fuzzy, two-degree-of-freedom, torque feed-forward and adaptive control methods) have been investigated by many researchers[1-4]. Although singleton fuzzy logic systems are the most widely used fuzzy logic systems in applications because of their simplicity and lower computational cost, non-singleton fuzzy logic systems are much more useful for incorporating uncertainties[5,6]. Non-singleton fuzzification has been used in some control applications[5] but, to date and to our best knowledge, it has not been used for the robust speed control of an electrical drive system. A short summary of the existing literature on non-singleton fuzzification can be found[5,6].

In this study, a new non-singleton fuzzy logic robust control system was proposed for the speed control of a DC electrical motor drive system. The effectiveness of the proposed control scheme under parameter variations and external disturbances were illustrated by simulation results. The performance comparisons of the singleton fuzzy logic controller and the proposed non-singleton fuzzy controller are provided in the study.

FUZZY LOGIC CONTROL AND NON-SINGLETON FUZZIFICATION

Fuzzy theory was first introduced by Zadeh[7]. During the last two decades, Fuzzy logic control has emerged as one of the most attractive and fruitful areas for research in the application of the fuzzy theory to the real engineering problems. Fuzzy logic control is actually a practical alternative to the conventional control methods for a variety of control applications since it provides a convenient method for implementing linear and non-linear controllers via the use of both heuristic and mathematical information.

A fuzzy controller basically consists of four main components as shown in Fig. 1. These are the fuzzifier, the rule-base, the inference mechanism (also called the inference engine) and the defuzzifier.

The fuzzifier converts the crisp values of input variables into information which can be easily used in the inference mechanism. After the fuzzification process, each input value is represented by a membership degree for

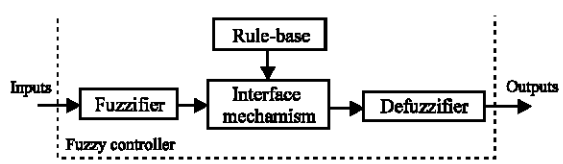

Fig. 1: Basic structure of a fuzzy controller

each fuzzy set defined for the corresponding input variable.

The fuzzification method explained above is known as singleton fuzzification which is the most widely used fuzzification method in the control applications, mainly because of its simplicity and lower computational requirements. However, this kind of fuzzifier may not always be adequate, especially in the cases of uncertainties[5]. The non-singleton fuzzification, that is more effective as far as the uncertainties are concerned, produces a fuzzy set instead of a membership degree.

A fuzzy set F in X may be represented as a set of ordered pairs of a generic element x and its grade of membership functions, $\mu_F(x)$, i.e.,

$$F = \{(x, \mu_F(x)) \mid \forall x \in X\} \tag{1}$$

In non-singleton fuzzification, measurement $x_i = x_i'$ is mapped into a fuzzy number; i.e., the inputs are modelled as fuzzy numbers and membership functions are associated with them. In other words, a non-singleton fuzzifier is one for which $\mu_{X_i}(x_i') = 1$ $(i = 1, \ldots, p)$ and $\mu_{X_i}(x_i)$ decreases from unity as x_i moves away from x_i'[6].

In the rule-base, IF-THEN rules are generally used, which has the form of (the lth rule)

$$\begin{aligned} &R^l: \text{IF } x_1 \text{ is } F_1^l \text{ and } \ldots\ldots\text{and } x_p \text{ is } F_p^l, \\ &\text{Then y is } G^l \qquad l = 1, \ldots\ldots\ldots, M \end{aligned} \tag{2}$$

Where, x_is are inputs (i = 1,….., p), F_i^ls are antecedent sets, G^ls are consequent sets and y is the output. The inference engine of a fuzzy controller provides a mapping from input fuzzy sets to output fuzzy sets by using all rules. The antecedents in a rule are connected by t-norm which corresponds to intersection of the fuzzy sets. By using the sup-star composition, the membership grades in the input fuzzy sets are combined with those in the output fuzzy sets and then, all the rules may be combined by t-conorm operation (union of fuzzy sets) or by defuzzfication using the weighted summation. A crisp output is produced by the defuzzifier from the output of the inference engine, which is actually a fuzzy set[6].

In the existing literature on Fuzzy Logic Systems (FLSs), the two most popular FLSs are the Mamdani and Takagi-Sugeno-Kang (TSK) systems. Up to this point, even though it is not referred to them as such, the described FLS is the Mamdani type FLS. The Mamdani and TSK FLSs are both characterised by IF-THEN rules and have the same antecedent structures, however, they differ in the structure of the consequent parts. The consequent of a TSK rule is a linear or nonlinear function of input variables, whereas the consequent of a Mamdani rule is a fuzzy set. In a Mamdani FLS, the output of the inference engine is a fuzzy set and defuzzification is used to obtain a crisp output (type-0 set). On the other hand, the output of a TSK FLS is a crisp value and defuzzification is not required. TSK FLSs have been widely used in control applications due to their computational effectiveness compared to the Mamdani FLSs.

THE SPEED CONTROL OF A DC MOTOR

Figure 2 shows a block diagram for the closed loop digital speed control of an electrical drive system.

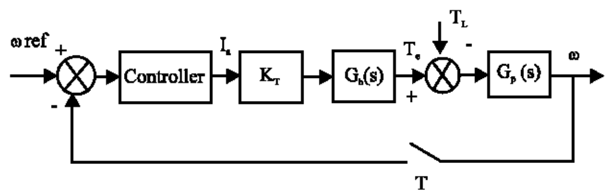

Fig. 2: The closed loop digital speed control system

The output of a speed controller is a torque demand and electric drives are called upon to have good torque control performance. This study concerns the area of speed control and is thus applicable to all machine drive types having good torque and flux control properties. It is assumed in this study that we have good torque control properties and therefore, the fast torque current control loop is ignored and is not included in Fig. 4. Thus, the plant to be controlled consists of only the mechanical dynamics of the drive system, which can be expressed by the transfer function (for $T_L = 0$)

$$G_p(s) = \frac{\omega(s)}{T_e(s)} = \frac{1}{Js + B} \tag{3}$$

where, ω is the shaft speed of the electrical machine, T_e is the electrical torque, J is the moment of inertia and B is the viscous friction. In Fig. 4, K_T is the torque constant, I_a is the torque current, T_L is the load torque, T is the sampling period and $G_h(s)$ represents the zero order hold (z.o.h.).

The control problem is now to design a controller to obtain a robust speed control performance under load torque, inertial and frictional variations.

THE PROPOSED NON-SINGLETON TSK FUZZY CONTROLLER

Consider a TSK Fuzzy Logic Controller (FLC) with two inputs $e \in E_e$, $\Delta e \in E_\Delta$ and one output $u \in U$. The i^{th} rule of the rule base can be expressed as:

$$R^i : \text{IF } (e \text{ is } E_1^i \text{ and } \Delta e \text{ is } E_2^i)$$
Then
$$\begin{aligned}&(u_L^i = k_1 e_L + k_2 \Delta e_L - a_L^i |e_L| - b_L^i |\Delta e_L| \\ &\text{and } u_R^i = k_1 e_R + k_2 \Delta e_R + a_R^i |e_R| + b_R^i |\Delta e_R|)\end{aligned} \quad (4)$$

where, i = 1,..,4; k_1, k_2, a_L^i, a_R^i, b_L^i and b_R^i are constant controller parameters and E_1^i are E_2^i the input membership functions (fuzzy sets); u_R^i and u_R^i are the output functions of i^{th} rule. Since a non-singleton fuzzification is employed, the inputs e and Δe are taken as interval sets for simplicity of calculations. Note that an interval set can be represented just by its domain interval, that can be expressed in terms of its left and right end-points as [L, R], or by its center and spread as [c-s, c+s], where, c= (L+R)/2 and s = (R-L)/2. It is common to express an interval set just by its domain, namely as [L, R] or [c-s, c+s]. When this notation is used, it is known that the membership grade at each point in the domain equals 1. Thus, $e = [e_L, e_R]$ and $\Delta e = [\Delta e_L, \Delta e_R]$ where, $e_L = e - e_s$, $e_R = e + e_s$ and $\Delta e_L = \Delta e - \Delta e_s$, $\Delta e_R = \Delta e + \Delta e_s$. Note also that e is the error between ω_{ref} and ω, Δe is the change of error, e_s and Δe_s are the spreads of e and Δe, respectively ($e_s = 10$, $\Delta e_s = 20$). Figure 3 shows the input membership functions used in the controller ($E_1^1 \equiv E_1^2$, $E_1^3 \equiv E_1^4$ and $E_2^1 \equiv E_2^3$, $E_2^2 \equiv E_2^4$ where, $M_1 = 300$, $M_2 = 2 \times M_1$).

The consequent of a rule R^i, u^i, is also an interval set; i.e.,

$$u^i = [u_L^i, u_R^i] \quad (5)$$

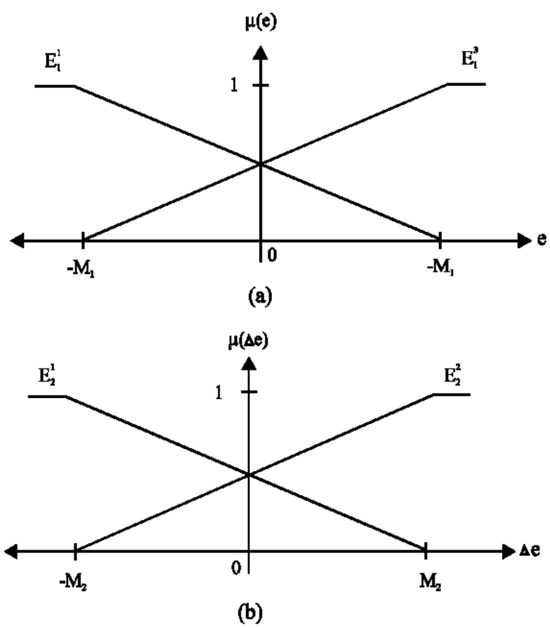

Fig. 3: a) Membership functions for input e, b) Membership functions for input Δe

For a non-singleton TSK FLC, the output is given by:

$$u = \frac{u_L + u_R}{2} \quad (6)$$

where,

$$u_L = \sum_{i=1}^{4} m_L^i u_L^i \quad (7)$$

$$u_R = \sum_{i=1}^{4} m_R^i u_R^i \quad (8)$$

and m_L^i and m_R^i are the normalised certainties of the i^{th} rule for the inputs $[e_L, e_R]$ and $[\Delta e_L, \Delta e_R]$ pairs, respectively. The output of the controller, the torque current I_a, is obtained by integrating the output of the FLC, i.e., in discrete time, the difference equation is given by:

$$I_a(k) = I_a(k-1) + u(k) \quad (9)$$

Thus, the proposed controller becomes a PI-type controller. In order to have a realistic controller, an anti-windup integrator[4] structure is used to stop over-integration and to limit the torque demand.

SIMULATION RESULTS

Some simulation results showing the effectiveness of the proposed controller were given. In these comparative illustrations, the performance of the proposed non-singleton fuzzy controller were compared with the ordinary (singleton) fuzzy controller under external disturbance (the load torque) and parameter variations. It should be noted that the nominal inertia and viscous friction (J_n and B_n) are chosen naturally as the nominal inertia and viscous friction of the drive machine (corresponding to the minimum bounds of the inertia and friction). This is because all drive motors have their own nominal inertia and friction before connecting to a mechanical load.

The constants k_1 and k_2 of Eq. 4 are chosen so that the natural frequency (ω_n) and the damping ratio (ζ) of the closed loop control system becomes 100 rad/s and 0.707, respectively for the nominal inertia and friction coefficient ($J_n = 0.005$ kgm^2 and $B_n = 0.001$ Nms/rad) if a_L^i, a_R^i, b_L^i and b_R^i are set to zero. The controller parameters are found as $k_1 = 0.021$ and $k_2 = 0.119$ for the sampling period T = 2.5 ms. In order to provide a fair comparison, these coefficients are also used and kept constant in the consequent parts of the singleton and the proposed non-singleton fuzzy controllers. The singleton fuzzy controller used in comparison is exactly same with the proposed non-singleton fuzzy controller except that it is a singleton FLC and there is no interval set in the consequent part.

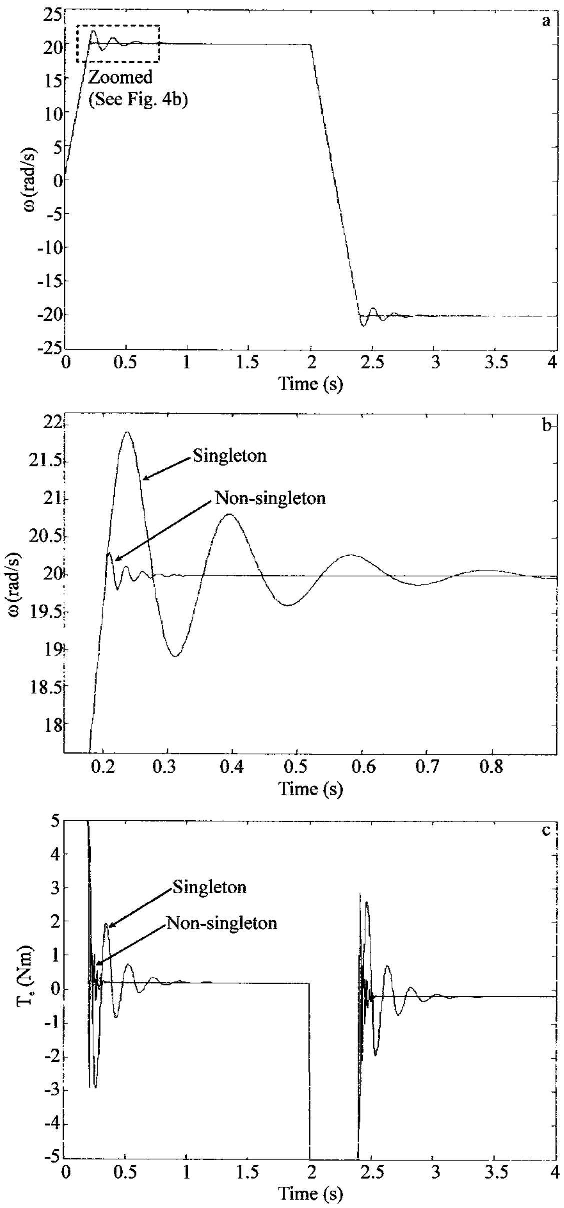

Fig. 4: a) The output responses of the singleton and non-singleton fuzzy control systems to a square-wave reference ($\omega_{ref}(k)$ = +20 rad/s for $0 \le t \le 2$ sec and $\omega_{ref}(k)$ = -20 rad/s for $2 \le t \le 4$ sec) for $J = 10 \times J_n$, $B = 10 \times B_n$, b) Zoomed area of Fig. 4a and c) The outputs of the controllers

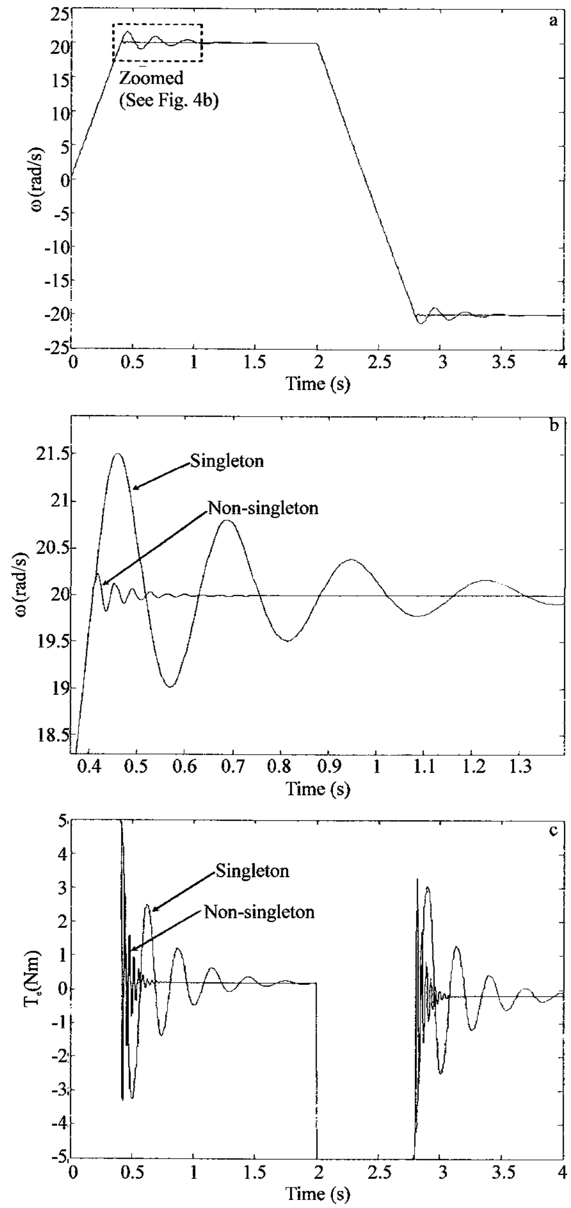

Fig. 5: a) The output responses of the singleton and non-singleton fuzzy control systems to a square-wave reference ($\omega_{ref}(k)$ = +20 rad/s for $0 \le t \le 2$ sec and $\omega_{ref}(k)$ = -20 rad/s for $2 \le t \le 4$ sec) for $J = 20 \times J_n$, $B = 10 \times B_n$, b) Zoomed area of Fig. 5a and c) the outputs of the controllers

It is assumed in this study that the inertia (J) and viscous friction coefficient (B) of the drive system and the load torque (T_L) are not known explicitly but the inertia and friction coefficient may change within the limits given by $J_n \le J \le 20 \times J_n$ and $B_n \le B \le 20 \times B_n$. Therefore, a reference closed loop model using the nominal plant parameters (J_n, B_n) and the controller parameters k_1 and k_2 given above is used in order to determine the unknown control parameters (a^i and b^i for singleton and a^i_L, a^i_R, b^i_L and b^i_R for non-singleton, i = 1,..,4) of the singleton and non-singleton FLCs. Thus, in the first stage of the design, the unknown control parameters are determined using the error between the outputs of the reference model and the plant. Note that the proposed controller is not an adaptive

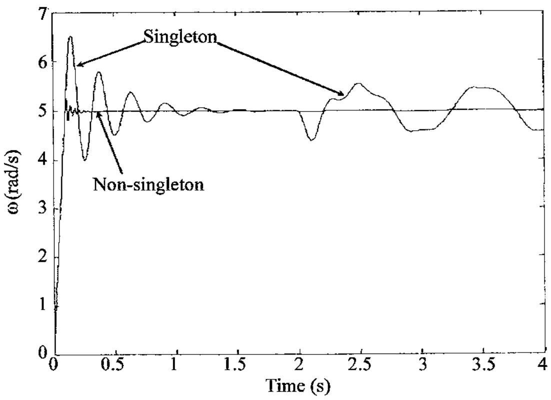

Fig. 6: The speed responses of the systems to a sinusoidal load torque ($T_L(t) = 4\sin(2\pi t)$) applied for t = 2 sec ($\omega_{ref}(k) = 5$ rad/s and $J = 20\times J_n$, $B = 20\times B_n$)

controller and after the training stage (first stage of the design), the control parameters are kept constant for all simulation results presented in the study. The objective function[8] to be minimised then can be defined as:

$$E(k) = \frac{1}{2}e_l(k) = \frac{1}{2}(\omega_m(k) - \omega(k))^2 \qquad (10)$$

where, $\omega_m(k)$ is the output of reference model. Using the gradient descent method, the update rules, for example, for the control parameters can be given as[8]:

$$a_L^i(k+1) = a_L^i(k) - \eta\frac{\partial E(k)}{\partial a_L^i(k)} \qquad (11)$$

where, η (chosen as 0.01) is the learning rate. The derivatives in the above equations can be found using the chain rule, e.g.:

$$\frac{\partial E(k)}{\partial a_L^i(k)} = \frac{\partial E}{\partial e_l}\frac{\partial e_l}{\partial \omega}\frac{\partial \omega}{\partial u}\frac{\partial u}{\partial u_L}\frac{\partial u_L}{\partial a_L^i} \qquad (12)$$

Some simulation results of the singleton and the proposed non-singleton FLCs are now given on the same scale for the comparison purpose. In Fig. 4 and 5, simulation results for $J = 10\times J_n$, $B = 10\times B_n$ and $J = 20\times J_n$, $B = 10\times B_n$ are illustrated to show the robustness of the proposed non-singleton FLC. Results show the output responses of the singleton and non-singleton fuzzy control systems to a square-wave reference ($\omega_{ref}(k) = +20$ rad/s for $0\le t\le 2$ sec and $\omega_{ref}(k) = -20$ rad/s for $2\le t\le 4$ sec). In order to have a better view, some parts of the figures are zoomed and shown in Fig. 4b 5b. Figure 4c and 5c show the outputs of the controllers. The control performance of the proposed non-singleton fuzzy logic control system under the inertial and frictional variations is much better than that of singleton fuzzy logic control system. Note that the outputs of the controllers, torque current demands (I_a), are limited to 1 Ampere (which means that the electrical torque demand T_e is limited to 5 Nm since $K_T = 5$).

Finally, Fig. 6 shows the speed responses of the controllers of the systems to a sinusoidal load torque ($T_L(t) = 4\sin(2\pi t)$) applied for t = 2 sec, where the reference speed is a step demand ($\omega_{ref}(k) = 5$ rad/s) and $J = 20\times J_n$ and $B = 20\times B_n$. The sinusoidal load torque has a very little effect on the speed response of the proposed non-singleton fuzzy logic control system. Once again, the proposed non-singleton fuzzy controller provides much more robust control performance than the singleton fuzzy controller (Fig. 6).

CONCLUSIONS

In this study, a new robust controller based on non-singleton fuzzification was proposed for the speed control of a DC motor under parameter variations and load torque. Non-singleton fuzzification is employed due to its effectiveness on uncertainties. TSK FLC structure was used for the proposed controller because it is more convenient than the Mamdani FLC for control applications. Simulation results showing the robust control performance of the proposed non-singleton fuzzy controller under parameter variations and load torque are given in the study.

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