Adaptive Stick-Slip Friction Compensation Using Dynamic Fuzzy Logic System

Sreekanth Suraneni, I. N. Kar, R. K. P. Bhatt.

Department of Electrical Engineering,
Indian Institute of Technology,
HAUZ K.HAS, NEW DELHI-110016
Email: inkftrix.titd.emui.in

Absiruct-A dynamic fuzzy logic based adaptive algorithm is proposed for reducing the effect of stick slip friction present in 1-DOF (one degree of freedom) mechanical mass system. The control scheme proposed is an online identification and indirect adaptive control, in which the control input is adjusted adaptively to compensate the effect of nonlinearity. Lyapunov stability analysis is used to ensure the boundedness of tracking errors, identification errors etc. The efficacy of the proposed algorithm is verified on a 1-DOF mechanical mass system with stick slip friction.

1. INTRODUCTION

Friction is one of the nonlinearities arising in almost all the mechanical systems. It is unavoidable in high performance motion control systems. In order to achieve high performance, high quality mechanical components are to be used. Friction compensation facilitates us to use cheaper mechanical components.

Stick-slip friction some times known as dry friction, is a natural resistance to relative motion between two contacting bodies. It is commonly modeled as a linear combination of Coulomb friction, stiction, and viscous friction and Stribeck effect.

In the presence of friction the closed-loop systems show steady state tracking errors, oscillations, limit cycles etc. In addition the friction characteristics may change easily due to the environment's changes, for instance, the variation of the load, temperature, and humidity. So the friction compensation is important in high performance motion control systems and it is not an easy problem to solve.

The friction model has been studied by numerous researchers |I|,|2|,|3|. A nonlinear compensation technique which has a nonlinear proportional feedback control force for the regulation of the one degree of freedom (1-DOF) mechanical system is proposed in |4|. A robust adaptive compensation technique for tracking of 1-DOF mechanical system with stick-slip friction is proposed in [5|.

In this paper, we are proposing the adaptive control based on *Dynamic Fuzzy Logic System* (DFLS) for the control of systems with friction. The DFLS is used for both identification and control. Although so many methods such as model reference adaptive control, self tuning regulators etc are there, however, it is also known that these kinds of approaches generally suffer such weaknesses as the requirement for explicit *a priori* knowledge of model structure, and ineffectiveness in dealing with intrinsic system nonlinearities. Another class of identification techniques that has recently emerged is those with universal nonlinear approximation capabilities, such as Fuzzy Logic Systems and Artificial Neural Networks (ANN). This class of approaches neither requires *a priori* knowledge of system structure, nor is impaired by the presence of nonlinearities and unknown internal dynamics. The ANN is characterized by massive parallelism and learning ability, but its parameters generally lack explicit physical meaning, while the FLS provides an effective framework for incorporation of human linguistic descriptions of unknown systems, and its parameters have clear physical interpretations.

Motivated by the fact that the physical systems of interest are generally dynamic, a so called DFLS has been developed. It incorporates dynamical elements into ordinary fuzzy logic systems and hence would itself be more naturally integrated into dynamic systems. It can take the advantage of intrinsic dynamics and can provide new tools in identification and control |10|. It is a soft computing method and it can take care of more nonlinearities which will arise in the system being more general method. Also it provides an effective framework of analyzing the stability of DFLS based on Lyapunov stability theory.

In this paper, we are proposing the DFLS based adaptive control scheme for the control of systems with friction. Attempt has been made to develope a control algorithm based on DFLS for compensating the friction. This algorithm is successfully applied on a 1-DOF mechanical system with friction.

2 1-DOF mass system with friction

In this section a 1-DOF mechanical mass system with friction is described.

The 1-DOF mechanical system under investigation is a mass constrained to move in one; dimension with stick-slip friction present between the mass and the supporting surface as shown in Figure (2.1).

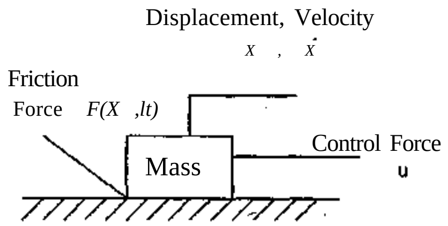

Figure 2.1 :The l-DOF mass system

The equation for this model is described as follows |4|:

$m\ddot{x}+F\{X,u) + v(t) = u(t)$. . . . .(2.1)

Where m is a mass, $x(t\ )$ is a relative displacement, $F(X,lt)$ is a friction force.$X= \backslash\_X,\dot{x}\backslash^{T}$ is state vector, »(/) is the input force and v(0 is a bounded external disturbance which represents the equivalent total disturbance due to the measurement noise and noises in the power source etc. The external disturbance is assumed to be bounded within the unknown upper bound $£_d$ as follows:

$|v(0|<£_{(/}$ for all $t>0$. . . . .(2.2)

The stick-slip friction force $F(X,u)$ is assumed to be modeled as follows :

$F\{X,u) = F_{slip}(\dot{x})[\lambda(\dot{x})] + F_{,llct}(u)[l\ \ -\lambda(\dot{x})]$

…….**(2.3)**

Where

$$X(\dot{x}) = \begin{cases} l & |\dot{x}| > \alpha, \quad a>0 \\ 0 & |\dot{x}| \le \alpha \end{cases}$$

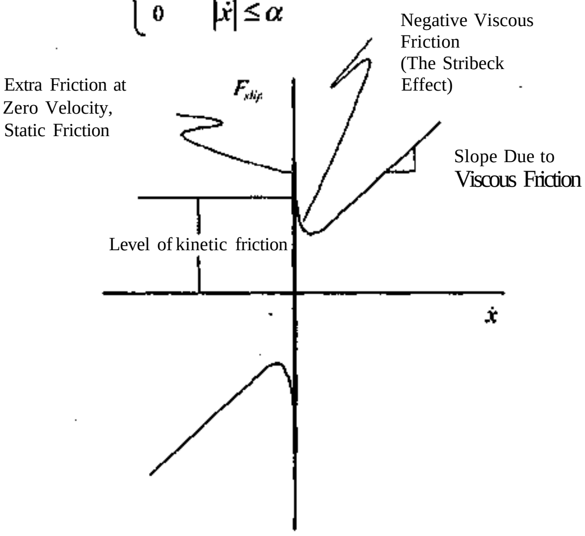

Figure 2.2: Slipping friction

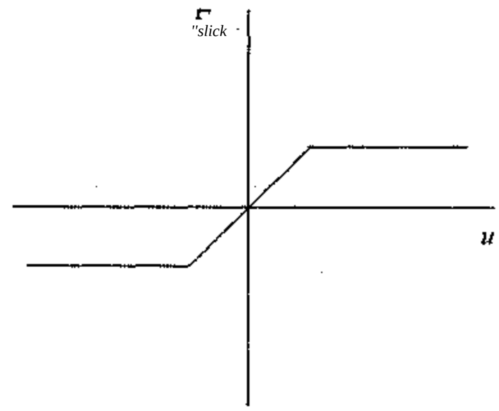

Figure 2.3: Sticking friction

The graphical representation of the terms $F_{sli/l}(\dot{x})$ (slip friction) and $F_{slick}(n)$ (stick friction) are given in figure (2.2) and (2.3). Here the problem is to design *a* control input $u(t)$ such that the position $x(t)$ will track a pre-specified trajectory.

The slip friction force is modeled as a summation of the Coulomb friction, viscous friction and the Stribeck effect |4|.

3 Dynamic Fuzzy Logic System

Here, the introduction of dynamic element in the fuzzy logic system and the so obtained Dynamic Fuzzy Logic System (DFLS) |9| is described. The DFLS is as shown in Figure (3.2). It consists of a static fuzzy logic system (FLS) shown in Figure (3.1). It's output >>, is followed with a combination of a dynamic element-the integrator- and a positive coefficient feedback a.

3.1 The Static Fuzzy Logic System

The basic structure of the fuzzy logic system considered is shown in Figure (3.1).

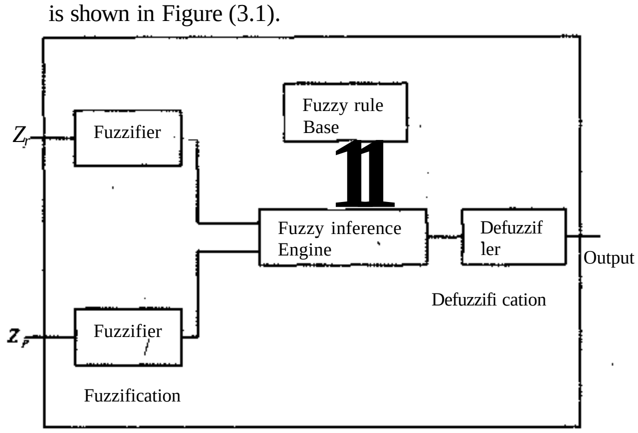

Figure 3.1: Static fuzzy logic system

It is composed of four major components, namely, *a fuzzy interface, a fuzzy rule base, a fuzzy inference engine* and *a clefuzzification interface.* Because multi-input, multi-output (MIMO) system can often be decomposed into group of multi-input, single-output (MISO) systems, only MISO fuzzy logic systems will-be considered in this work.

By using some particular rules (refer [6|^]^nd^ |9| for complete details and expressions) the output of the static fuzzy logic system obtained as product of two vector as shown below.

$$y_F = \sum_{i=1}^{l} \bar{y}_i \Phi_i(Z) = \Phi^T \bar{Y} \quad \ldots\ldots(3.1)$$

$\bar{Y} = \{\bar{y}_1, \ldots, \bar{y}_l\}^T$ (called parameter vector) and $\Phi = \{\Phi_1, \ldots, \Phi_l\}^T$. Eq. (3.4) shows that Φ is characterized by the number of input fuzzy sets, $\{U_1^1, U_1^2, \ldots, U_1^{p_1}, U_2^1, U_2^2, \ldots, U_n^{p_n}\}$, as well as the position and shape of the membership function for each input fuzzy set. If we fix these parameters and leave only, $\bar{y}_i$ $i=1, \ldots, l$, as adjustable parameters, it makes the above expression linear in it's parameters.

3.2 Dynamic Fuzzy Logic System

The fuzzy logic system characterized by Eq. (3.1) is capable of approximating any real continuous functions on a compact, set to arbitrary accuracy, i.e., it can be viewed as a versatile and accurate static non-linear mapping. However, as mentioned in the Introduction, the physical systems in identification and control applications are generally dynamic, so that advantage can be taken of the intrinsic dynamics by incorporating some sort of dynamics into fuzzy logic systems. This motivation led to the investigation of *dynamic fuzzy logic system* (DFLS).

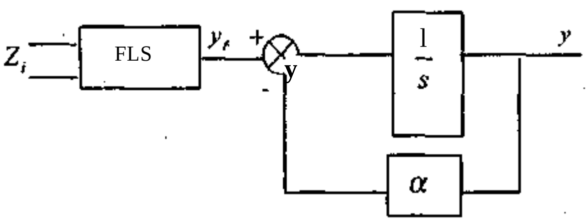

Figure 3.2: Dynamic fuzzy logic system

Consider the Dynamic Fuzzy Logic System (DFLS) illustrated in Figure 3.2. It can be represented by the following differential equation of the form

$$\dot{y} = -ay + \Phi^T(Z)\bar{Y} \quad \ldots\ldots (3.2)$$

where y is a scalar variable, and a is a positive constant. The second term on the right hand side of the above equation is the fuzzy logic system defined in Eq. (3.1).

The DFLS described here is chosen to poses the universal approximation property (refer [9| for statement and proof)-

4.1 DFLS Based Adaptive control

Now, an indirect control algorithm for the class of nonlinear systems expressed in the companion form is described.

A general class of non linear systems can be represented as

$$x^{(n)} = f(X) + bu, \quad \ldots\ldots (4.1)$$

Above equation can be rewritten in the state space representation as

$$\dot{x}_N = f(X) + bu \quad \ldots\ldots (4.2)$$

The above system is identified and controlled simultaneously by a parameter updating law (obtained from Lyapunov stability analysis) and a control law which are given below.(refer [10| for more detailed explanation)

Parameter Updating Law:

$$\dot{\bar{Y}} = -H[\Phi(X,u)h\tilde{x} - \Phi(X,0)(B^T Pe)] - S[\,]H\bar{Y} \quad \ldots\ldots(4.3)$$

where H is a constant positive definite symmetric matrix, h is a positive constant that weighs the identification error, P is a positive definite symmetric matrix that satisfies Lyapunov equation, e is the tracking error matrix, S and β are switches and ε is the identification error.

Control Law:

$$u = \frac{1}{b}\left[\dot{q}_N + \alpha q_N - \Phi^T(X,0)\bar{Y} - \sum_{k=1}^{N-1}\alpha_k e_k\right] \quad \ldots\ldots(4.4)$$

q_N and $\dot{q}_N$ here are the desired states. α_k are weights for tracking errors. It can be shown that the control law (4.4) along with the updation law (4.3) guarantee the stability of the closed loop system.

4.3 Stability Properties of DFLS based adaptive control

The described DFLS based indirect adaptive control scheme ensures the parameter vector $\bar{Y}$, tracking error,identification error parameter estimation error and modeling error are all bounded (refer |10| for proof)-

5 Adaptive stick-slip friction compensation

The state equations for 1-DOF mass systems can be represented in the form of Eq. (4.2) as follows.

$$\dot{x}_x = x_2$$
$$\dot{x}_2 = u(t) - F(X,u) - v(t) \quad \textbf{(5.1)}$$

where $F(X,u)$ is given in Eq.(2.3).

The adaptive law for $\bar{Y}$ from Eq. (4.3) is

$$\dot{\bar{Y}} = -H[\Phi(X,u)h\xi - \Phi(X,0)(B^T Pe)] - SI3H\bar{Y} \quad (5.2)$$

From Eq. (4.4) for a second order system the control law becomes

$$u = \frac{1}{b}[\dot{q}_2 + aq_2 - \Phi(X,0)\mathbf{F} - a,<?, -cc_2 e_2] \quad (5.3)$$

For Typical values taken for different variables in friction model refer [5].

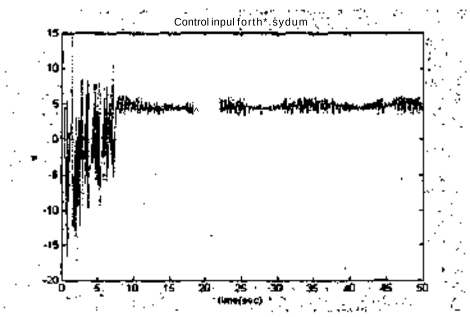

Figure 5.1: Control input u for the system

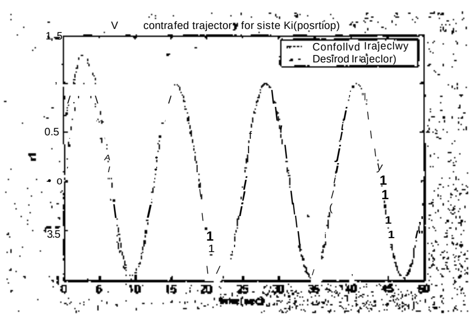

Figure 5.2: Position tracking

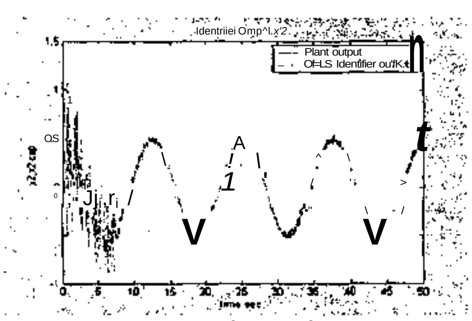

Figure 5.3: Identification for state x_2

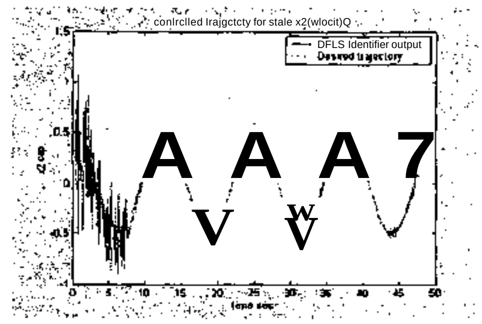

Figure 5.4: Velocity tracking

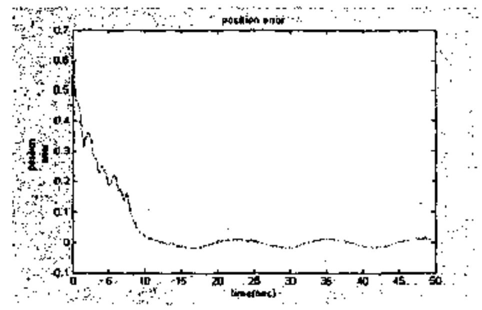

Figure 5.5: position error

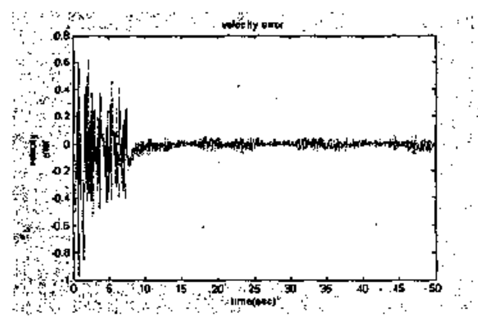

Figure 5.6: Velocity error

The adaptive control algorithm based on DFLS is applied on a 1-DOF mechanical system with stick-slip friction. The desired trajectory for position is selected as $qi = sin(0.5t)$. Typical system parameters are taken from [5] for the purpose of simulations. Position and velocity tracking results are shown in figure (5.2) and (5.4) respectively. Corresponding tracking errors are shown in figures (5.5) and (5.6) which proves the satisfactory tracking results. The control input is given in figure (5.1) which contains both low and high frequency signals. The high frequency signal can be compared with the conventional dither signal.

The only problem associated with this method is the design of off-line parameters. So many offrline design parameters such as OC, h, H, coefficients CC_k, scaling factors for the inputs of DFLS and the number of primary fuzzy sets etc should be selected off-line. Thus far, *ad hoc* analysis based on physical intuition is required for selecting these values. After off-line design, the parameter vector $\overline{Y}$ is adjusted on-line with the adaptive law given in Eq. (4.3). If satisfactory results are not obtained by adjusting $\overline{Y}$, one must return to the off-line design process to modify the parameters and repeat the entire procedure. Future scope of work lies in this area.

Conclusion

In this paper, the development of an adaptive tracking control scheme to compensate stick-slip friction present in 1-DOF mass system using DFLS was presented. The 1-DOF mass system with friction is identified as well as controlled simultaneously. The stability of overall system is established in the Lyapunov sense. Finally simulation results have verified the effectiveness of the control scheme. Use of this type of algorithm is advantageous as it can take care of more number of nonlinearities present inherently in the system being a more generalized method. Further it can be seen that the control signal generated here contains high frequency signal resembling the conventional dither based approach for friction compensation.

REFERENCES

[1] B.Armstrong-Helouvry."Stick slip and control in low speed motion." *IEEE Trans, on Automatic Control,* vol 38,oct.l993.

[2] C. Canudas, H. olsson, K. J. Astrom, and P.Lischinsky," Dynamic Friction models and control design." in *Proceedings of American Control Conference,* June, 1993 pp. 10-12.

[3] B. Armstrong-Helouvry, P. Dupont and C. C. De Wit. "A Survey of models, analysis tools and compensation methods for the control of machines with friction." *Automatica.* vol30,No.7, pp. 1083-1138, 1994.

[4] S. C. Southward, C. J. Radcliffe and. C. R. MacClur," Robust nonlinear stick-slip friction compensation," *ASME journal of dynamic system measurement and control,* vol. 113, pp. 639-645, Dec. 1991.

[5] Seon-Woo Lee, Jong-Hwan Kim," Robust adaptive stick-slip friction compensation." *IEEE Trans. On Industrial Electronics,* vol. 42,No. 5, pp. 474-479, Oct. 1995.

[6] C. C. Lee , "Fuzzy logic in control systems, Fuzzy logic controller -part I and part II," *IEEE Trans Systems Man Cybernetics,* 20,404-435, 1990.

[7] L. A. Zadeh, "Outline of a new approach to analysis of complex systems and decision processes.", *IEEE Trans. System, Man. Cybernetics, 3,* 28-44. 1973.

[8] L. X. Wang and J. M. Mendel, "Fuzzy basis functions, universal approximation and orthogonal least squares learning," *IEEE Trans. Neural Networks,* 3, 807-814, 1992.

[9] Lee J. X and G. Vukovich, "The Dynamic fuzzy logic system: Nonlinear system identification and application to robotic manipulators", *Journal of Robotic Systems,* **14(6),** 1997,391-405.

[10] Lee J. X and G. Vukovich, "Stable identification and Adaptive control-A dynamic fuzzy logic system approach", in W. Pedrycz (ed), *Fuzzy Evolutionary Computation* , 223-248, Kluwer , Boston, London, Dordrecht, 1997 .

[1 1] Slotine J. J. E. and Li, W., *Applied Nonlinear Control.* Englewood Cliffs, NJ: Prentice Hall, 1991.

[12] G. C. Goodwin and D. 0- Mayne, "A parameter estimation perspective of continous time model reference adaptive control", *Automatica.* 23, 57-70, 1987.

[13] P. A. loannou and A. Datta. "Robust adaptive control: Design, analysis and robustness bounds," in *Foundations of Adaptive Control,* P. V. Kokotovic, Ed., Springer, Berlin, 71-152, 1991.

[14] M. M.. Pe'ycarpou and P. A. loannou, "Stable Nonlinear System Identification using neural network models", in *Neural Networks in Robotics,* O. Bekey and K. Gold-berg, Eds., Kluwer, Norwell, MA, 147-164, 1993.

[15] Narendra, K;S. and Annaswamy, A. M., "Stable adaptive systems" Etwood Cliffs, N.J: Prentice Hall, 1989.