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# A Hybrid Fuzzy – PID Controller for Tabletting Machine with Force Control

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***Abstract***

In this paper, the dynamics modeling applied to force control of tabletting machines with electro - hydraulic and a hybrid of Fuzzy – PID controller is presented. This system includes a hydraulic cylinder/piston, an electronic servo valve, a force sensor and a controller. Flow rate that flows through the valve is a function of voltage signal and a square root of pressure drop across the valve. Therefore, linearization technique is employed to solve this nonlinear function. The transfer function that relates directly between output force and input reference voltage signal can be developed. The controller is a PC computer that sends a control signal through Data Acquisition Card (DAQ) to the servo valve. The feedback control signal is directly measured by the force sensor that is installed upper the tabletting block. The control law is a hybrid Fuzzy – PID controller. Fuzzy controller is used to control force far away from the target force. PID controller is applied when the force is near the desired force reference. The control results in both computer simulation and actual hardware system are shown. The controller that is designed in this paper is able to control the magnitude of the force as desired. In conclusion, the performance of the control system is satisfactory.

***Keywords**:* Tabletting Machine with force control, Electro – hydraulic, Servo valve, Hybrid of Fuzzy - PID.

## 1. Introduction

Many tabletting machines used of experiment with pressing process the tablet in some Pharmacy Department of Thailand are imported from foreign countries. The conventional machine cannot control a pressing force that may cause directly to the quality of the tablet, for example, the solubility, hardness, rough of surface, etc. In this project, the tabletting machine which can control the pressing force will be developed and used to analyze the effect of controller–parameter onto the quality of the tablet.

Due to their high force to weight ratio, small size, flexible, ease of setting speed, force and torques, and high precision control etc., [1,2] electro – hydraulic system is for use in mainly system of the tabletting machine. The accurate design and high performance of the control system have importance as requirement, so the mathematic model of hydraulic system firstly will be developed. They are the highly nonlinear phenomena such as fluid compressibility, the flow/pressure relationship and the many uncertainties of hydraulic system due to linearization. Therefore, it seems to be quite difficult to perform a high precision control by using linear control method.

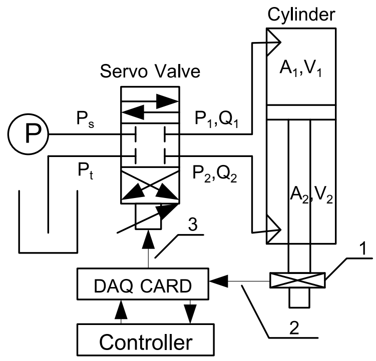
Classical PID controller that can improve both the transient response and steady error of the system at the same time has parameters containing $K_P$, $K_I$, $K_D$ that are usually fixed during operation. Consequently, a controller is inefficient for control a system while the system is disturbed by unknown facts, or the surrounding environment of the system is changed.

Fuzzy controller that has a short rise time and a small overshoot has been successfully used in the complex ill-defined process with better performance than a PID controller. It is robust to the system with variation of system dynamics and the system of model free or the system which precise information is required. One of the important problems involved with the design of fuzzy logic controller is the complexity of fuzzy controller that increases exponentially when the number of input variable increases. The hybrid of Fuzzy – PID controller takes advances of the nonlinear characteristics of the Fuzzy controller and the accuracy near a set point which is guaranteed by the classical PID controller [3].

## 2. Mathematic model of Electro-hydraulic force control system

The specification of the Tabletting machine is depicted in Fig.1 that is shown a diagram of the system. The force control of the tabletting machine procedure is described as follows: Upon the intended initial and force from the end of piston are given, the computer receives the feedback signal though DAQ card (A/D) from force sensor, realizes various control algorithm and transmits a control signal though DAQ card (D/A) and amplifier card to servo valve. The force from the end of piston is proportional to the input signal.

In order to provide mathematic basic for choosing control strategy, the mathematic model of electro-hydraulic force control system was built and analyzed.




1. Load sensor 2. Force Signal 3. Control Signal

Figure 1: Diagram of Tabletting Machine and Electro-hydraulic force control system.

In the Fig. 1, $P_S$ is the supply pressure, $P_t$ is the reservoir pressure, $P_1$ and $P_2$ are pressure in side 1 and 2 of the cylinder, $Q_1$ and $Q_2$ are fluid flow, $A_1$ and $A_2$ are the piston area of side 1 and 2, $V_1$ and $V_2$ are the cylinder volume of side 1 and 2, and $U$ is the control signal.

While the mathematic model is obtained, hydraulic pipe and valve dynamics are neglected and it is considered that there is no leakage between the piston and the cylinder. Besides, it is assumed that the supply pressure is constant and reservoir pressure is zero. The orifice equation simplify to [4]

$$Q_1 = \begin{cases} +C_d U\sqrt{|P_s - P_1|}, & U \geq 0 \\ -C_d U\sqrt{|P_s - P_2|}, & U < 0 \end{cases} \quad (1)$$

$$Q_2 = \begin{cases} +C_d U\sqrt{P_2}, & U \geq 0 \\ -C_d U\sqrt{P_1}, & U < 0 \end{cases} \quad (2)$$

So only the supply or the return orifice is open at the given time.

The signs which are in the right-hand of equations assign by the control signal, can be rewritten as in [5]

$$Q_1 = C_d U\sqrt{P_S - P_1} = f_1(U, P_1) \quad (3)$$

$$Q_2 = C_d U\sqrt{P_2} = f_2(U, P_2) \quad (4)$$

Eq. (3) and (4) are lineraized by using Taylor's expansion theory. The first differentials are more dominance than the other terms.

$$\delta Q_1 = \left.\frac{\partial Q_1}{\partial U}\right|_{P_{1(0)}} \delta U + \left.\frac{\partial Q_1}{\partial P_1}\right|_{\substack{U_{(0)} \\ P_{1(0)}}} \delta P_1 \quad (5)$$

$$\delta Q_2 = \left.\frac{\partial Q_2}{\partial U}\right|_{P_{2(0)}} \delta U + \left.\frac{\partial Q_2}{\partial P_2}\right|_{\substack{U_{(0)} \\ P_{2(0)}}} \delta P_2 \quad (6)$$

In this project, the servo valve which is symmetry, is designed, and relationship directly between flow-rate and control signal are variation [6]. With their assumes are

$$\left.\frac{\partial Q_1}{\partial U}\right| = \left.\frac{\partial Q_1}{\partial P_1}\right| = K$$

$$\left.\frac{\partial Q_1}{\partial P_1}\right|_{\substack{U_{(0)} \\ P_{1(0)}}} \delta P_1 \quad and \quad \left.\frac{\partial Q_2}{\partial P_2}\right|_{\substack{U_{(0)} \\ P_{2(0)}}} \delta P_2 \quad \approx \quad 0$$

Finally, the linear equation of servo valve can be rewritten as in

$$Q_1 = Q_2 = KU \quad (7)$$

Where $K$ is the flow constant of servo valve, it is obtained from the manufacturer's data.

Using Newton's law, the piston force balance result in differential equation is as in (8). Applying the continuity equation to both side of cylinder, the following (9) and (10) can be derived [6,7].

$$\ddot{z} = (P_1 A_1 - P_2 A_2 - c\dot{z} - F_s)/M \quad (8)$$

$$\dot{P}_1 = \frac{\beta}{V_1}(Q_1 - A_1\dot{z}) \quad (9)$$

$$\dot{P}_2 = \frac{\beta}{V_2}(-Q_2 + A_2\dot{z}) \quad (10)$$

It is assumed that the initial total volume is

$$V_1 = V_{01} + A_1 z \quad (11)$$

$$V_2 = V_{02} - A_2 z \quad (12)$$

When $\beta$ is the bulk modulus of the fluid, it is obtained from the manufacturer's datasheet.

Substituting of Eq. (7), (9), (10), (11), (12) and $F_s = k_s z$ into Eq. (8), we have

$$\dddot{F} = \Big(\frac{\beta KUA_1 k_s}{k_s V_{01} + A_1 F} - \frac{\beta A_1^2 \dot{F}}{k_s V_{01} + A_1 F} - \frac{\beta A_2^2 \dot{F}}{k_s V_{02} + A_2 F} + \frac{\beta KUA_2 k_s}{k_s V_{02} + A_2 F} - \frac{c\ddot{F}}{k_s} - \dot{F}\Big)\frac{k_s}{M} \quad (13)$$

So that is the non-linear equation of electro-hydraulic force control system.

It is considered that the piston works at the center of cylinder. Therefore, the displacement of motion of piston controlling the pressing force is ultrashot. The volumes of the both sides of the cylinder are changed very little. From Eq. (11) and (12), we obtain

$$V_1 = V_{01} \quad and \quad V_2 = V_{02} \quad (14)$$

Thus, substituting of Eq. (7), (9), (10) and (14) into Eq. (8), and rearranging, we have

$$\frac{M\dddot{F}}{k_s}=\frac{\beta KUA_1}{V_1}-\frac{\beta A_1^2\dot{F}}{k_sV_1}-\frac{\beta A_2^2\dot{F}}{k_sV_2}+\frac{\beta KUA_2}{V_2}-\frac{c\ddot{F}}{k_s}-\dot{F} \qquad (15)$$

Consequently, using the Laplace transformation, we have the transfer function

$$\frac{F(s)}{U(s)}=\frac{\frac{\beta Kk_s}{M}(\frac{A_1}{V_1}+\frac{A_2}{V_2})}{s^3+\frac{c}{M}s^2+(\frac{\beta A_1^2}{MV_1}+\frac{\beta A_2^2}{MV_2}+\frac{k_s}{M})s} \qquad (16)$$

Substituting of $\beta$ =1.5x10$^9$ $N/m^2$, $K$ = 5x10$^{-5}$, $A_1$= 3.117x10$^{-3}$ $m^2$, $A_2$=5.726x10$^{-4}$ m$^2$, $V_1$= 2.182x10$^{-3}$ $m^3$, $V_2$= 1.718x10$^{-4}$ $m^3$, $M$ is the mass of piston = 5 $kg$, $c$ is the viscous friction coefficient = 3x10$^4$ N/ms$^{-1}$, $k_s$ is spring coefficient = 1.489x10$^9$ N/m into Eq. (16), we obtain

$$P(s)=\frac{F(s)}{U(s)}=\frac{1.063\times10^{15}}{s^3+6000s^2+1.458\times10^{10}s} \qquad (17)$$

We can get the electro-hydraulic force servo control system open loop bode figure as Fig. 2 from Eq. (17) and related parameter simulation. We can know from Fig. 2 that the amplitude margin and phase margin of the system are not adequacy, and they cannot satisfy the system steady condition, the open loop gain of the system is no steady, and we must design controller to proofread the system.

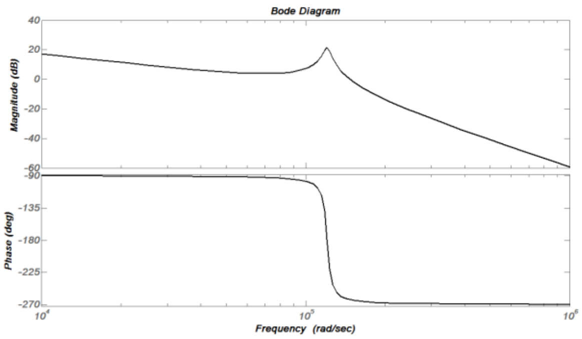



Figure 2: The open loop figure of electro-hydraulic force servo control system

**3. Control system design.**

There are various types of control system used in classical control, modern control and intelligent control systems. Each has been study and implement in many industrial applications. Every control system method has its advantage and disadvantages. Consequently, the trend is to implement hybrid system consisting of more than one type of control technique. The hybrid of Fuzzy – PID controller is presented. Fuzzy controller is used to control force far away from the target force. PID controller is applied when the force is near the desired force reference.

**3.1 PID controller design.**

The PID control method has been widely used in industry during last several decades because of its simplicity. The implementation of PID control logic, as shown in Eq. (18), requires finding suitable values for the gain parameters $K_P$, $K_I$ and $K_D$.

$$U(s)=K_P+\frac{K_I}{s}+K_Ds \qquad (18)$$

Rearranging Eq. (18), we obtain

$$U(s)=\frac{K_C(s^2+as+b)}{s} \qquad (19)$$

$$U(s)=\frac{K_C(s+z_1)(s+z_2)}{s} \qquad (20)$$

When $K_C=K_D$, $a=K_P/K_D$ *and* $b=K_I/K_D$ .

The PID controller is designed by root locus method. The performances of system as requires are no overshoot and less than 3 second of setting time. Designed and simulated in the computer by Matlab program. In the PID controller, the two zero that the first zero is 0.005 and the second zero is 4.5 are added in the PID. In the root locus plot, we have $K_C=0.00001$. Thu, the PID controller is

$$U(s) = \frac{0.00001(s+0.005)(s+4.5)}{s} \quad (21)$$

Comparing Eq. (21) with Eq. (19), we have $K_D = 0.00001, K_I = 4.505 \times 10^{-5}$ *and* $K_P = 2 \times 10^{-7}$

We can know from Fig.5 that the amplitude margin and phase margin of the system are adequacy, and the system is steady, and the low frequency gain of the system is increased, but we can find the slop of the frequency response curve of the system crossing 0 decibel line is bigger than 20dB, when the elastic load rise to definite extent. The phase margin of the system is decrease very rapid. So PID control cannot provide very good control performance. Aiming at this reason, fuzzy control algorithm is designed and adopted in the controller design process.

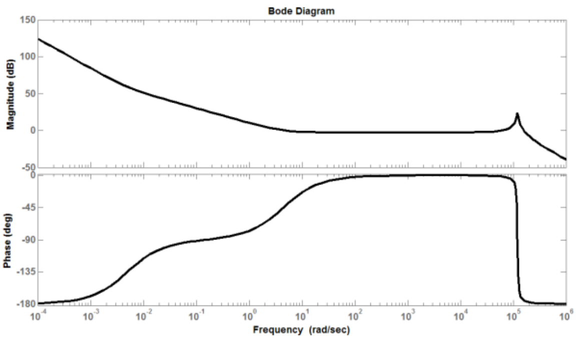



Figure 3: The open loop figure of electro-hydraulic force servo control system corrected by PID – controller

**3.2 Fuzzy controller design.**

Fuzzy control is a kind of expert control and the control rule of it fully reflect person's intelligent activity. It can control difficult process by simulating person's fuzzy controller, input and output port, actuator, controlling object and sensor, etc usually. The basic of fuzzy control principle is shown as Fig.4. The part including in the dotted line in Fig.4 is fuzzy controller, we can also find from Fig.4 that the main part of fuzzy controller is fuzzification process, knowledge base, fuzzy reasoning decision and exactness.

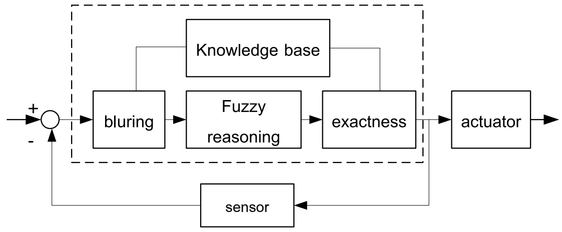



Figure 4: The basic structure of fuzzy control

In this project, input of model is the derivation $e$ and it change rate $\dot{e}$ of output force and their fuzzy subset are (1, 2, 3) and their linguistic value and universe division grade receptivity is *{negative, zero, positive}* and *{negative big, negative middle, negative small, zero, positive small, positive middle, positive big}*
= {NB, NM, NS, Z, PS, PM, PB}
= {-3, -2, -1, 0, 1, 2, 3}.

Let linguistic variable of output control variable *u* is *U,* and its fuzzy subset is (1,2,…,5) and its linguistic value respectively and universe division grade receptivity is

{quick close, slow close, no move, slow open, quick open} and *{negative big, negative middle, negative small, zero, positive small, positive middle, positive big}*
= {NB, NM, NS, Z, PS, PM, PB}
= {-3, -2, -1, 0, 1, 2, 3}

Fuzzy set is described by membership function, and common membership function in fuzzy system is gaussmf style membership function. The curve shape of gaussmf is normal distribution curve, and expression of it is

$$\mu(x) = \exp[-((x-c)/\sigma)^2] \quad (22)$$

The membership functions of three variable of fuzzy controller design in this paper are all gaussmf style membership function, in both parameter $\sigma$ and $c$, the numerical value of $\sigma$ directly influence the shape of the membership function curve, and the parameter $c$ is the center of the membership function curve.

Table 1. The parameter value of membership function of $e$ and $\dot{e}$

| Parameter valve | | name | | |
|---|---|---|---|---|
| | | negative | zero | positive |
| variable | $e$ | [1.4,-3] | [1.4,0] | [1.4,3] |
| | $\dot{e}$ | [1.4,-3] | [1.4,0] | [1.4,3] |

Table 2. The parameter values of membership function of $U$

| Parameter value | | name | | | | |
|---|---|---|---|---|---|---|
| | | Quick close | Slow close | No move | Slow open | Quick open |
| variable | $U$ | [0.13, -2.5] | [0.13, -1.5] | [0.13, 0] | [0.13, 1.5] | [0.13, 2.5] |

Table 3. Fuzzy control rule table

| $U$ | | $\dot{e}$ | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | NB | NM | NS | Z | PS | PM | PB |
| $e$ | NB | PB | PB | PB | PB | PM | Z | z |
| | NM | PB | PB | PB | PB | PM | Z | Z |
| | NS | PM | PM | PM | PM | Z | NS | NS |
| | Z | PM | PM | PS | Z | NS | NM | NM |
| | PS | PS | PS | Z | NM | NM | NM | NM |
| | PM | Z | Z | NM | NB | NB | NB | NB |
| | PB | Z | Z | NM | NB | NB | NB | NB |

The parameter values of the membership function adopted in this paper are shown as table 1 and table 2. According to expert experiment, we can get fuzzy control rule, and the fuzzy control rule table are shown as table 3.

Mamdani reasoning method is adopted during fuzzy reasoning designed. Mamdani reasoning method is introduced briefly as follow. Let error gotten after a certain time sampling is $e$, the variety of error is $\dot{e}$. $e$ is belong to fuzzy sets $A_1$ and $A_2$, and the membership degree of $A_1$ and $A_2$ respectively is $\mu_{A_1}(e)$ and $\mu_{A_2}(e)$. $\dot{e}$ is belong to fuzzy sets $B_1$ and $B_2$, and the membership degree of $B_1$ and $B_2$ respectively is $\mu_{B_1}(\dot{e})$ and $\mu_{B_2}(\dot{e})$.

If hypothesis of two reasoning rules following is tenable

IF $e = A_1$ and $\dot{e} = B_1$, then $U = C_1$

IF $e = A_2$ and $\dot{e} = B_2$, then $U = C_2$

Then according to Mamdani reasoning method we can get fuzzy set of $U$ is

$$n_1 \vee n_2 \qquad (23)$$

Where

$$n_1 = [m_1 \wedge \mu_{C_1}(U)], \quad n_2 = [m_2 \wedge \mu_{C_2}(U)]$$

$$m_1 = \mu_{A_1}(e) \wedge \mu_{B_1}(\dot{e}), \quad m_2 = \mu_{A_2}(e) \wedge \mu_{B_2}(\dot{e})$$

The production of membership function degree, fuzzy rule and fuzzy reasoning can be realized by Matlab tool box.

**3.3 A hybrid Fuzzy – PID controller design.**

While convention PID controllers are sensitive to variation in the system parameter, fuzzy controllers do not need precise information about the system variable in order to be effective. However, PID controllers are better able to control and minimize the steady state error of the system. Hence, a hybrid system, shown as Fig.3, was developed to utilize the advantages of both PID controller and fuzzy controller.

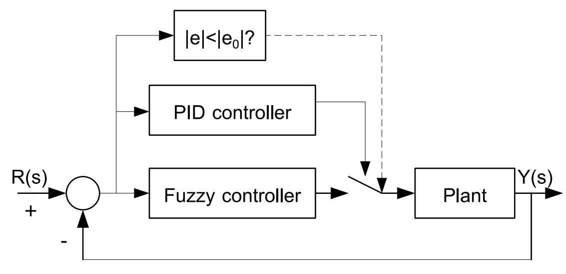



Figure 5: Diagram of a hybrid Fuzzy PID controller

Fig. 5 shows a switch between the fuzzy controller and PID controller, where the force of the switch depends on the error between the actual value and set point value.

If the error in force reaches a value higher than that of the threshold $e_0$, the hybrid system applies the fuzzy controller, which has fast rise time and small amount overshoot, to the system in order to correct the force with respect to the set point. When the force is below the threshold $e_0$ or close to the set point, the hybrid system shifts control to the PID, which has better accuracy near the set force.

## 4. Results

In order to verify the effectiveness PID controller and hybrid Fuzzy – PID controller, and compare analyzing the three controllers; the simulation of system is done. Simulink module of Matlab is adopted in the simulation. The unit step responses simulation curve is shown as Fig.7. The simulation results show that adjusting time is longer when PID controller is adopted and rising time is shorter than PID controller when fuzzy controller is adopted. The rapidity performance of system controlled by fuzzy controller is greatly improved, but oscillation of system is relatively violent, and stability performance is not better, the stability value is 0.962. Therefore, The hybrid Fuzzy – PID controller is improved. There are short rising time that is characteristics of fuzzy controller and the good stability performance. In this project, the stability value is 1.001.

In order to validate the validity PID controller and hybrid Fuzzy – PID controller in fact use and compare practical controlling effects of two controllers, experiment study is done on the tabletting machine shown as Fig. 6.

Figure 6: Tabletting Machine

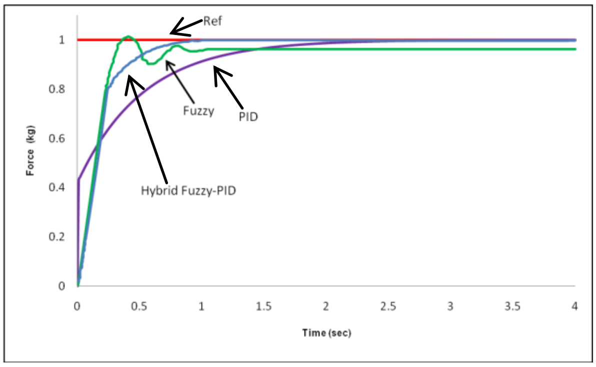



Figure 7: Simulation curve of unit step response

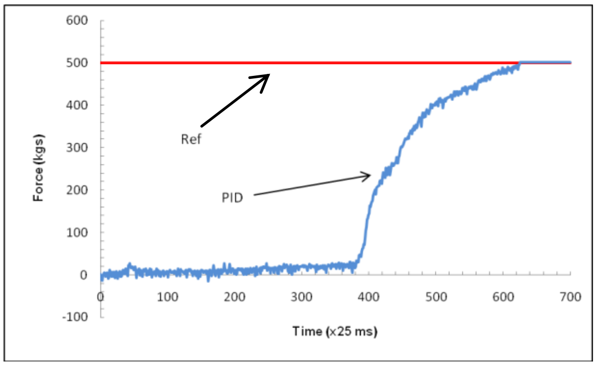



Figure 8: Unit step response experimental curve of PID controller

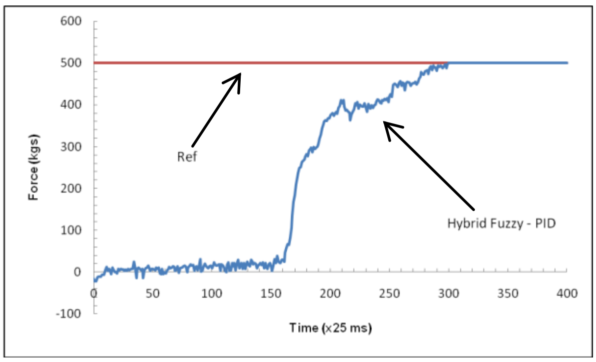



Figure 9: Unit step response experimental curve of Hybrid Fuzzy - PID controller

Fig. 8 is unit step response experimental curve of the tabletting machine controller by PID controller. There are 5.5 sec of rising time, 6.75 sec of setting time and 2 kgs of error.

Fig. 9 is unit step response experimental curve of the tabletting machine controller by hybrid Fuzzy - PID controller. There are 2.5 sec of rising time, 3 sec of setting time and 1 kg of error.

## 5. Conclusions

Aiming at the characteristics of electro-hydraulic force servo control itself, building model and simulation are done. We find the problem that the open loop gain of system is less and frequency width of system is low and easy to be unsteadily. The object of the project was to develop a control scheme for the tabletting machine. First, a PID controller was individually applied to the tabletting machine. The PID controller accurately controller the steady – state error but did not robustly handle parameter variation in the system while the fuzzy controller provided a fast rise time and low overshoot of the dynamic response output of the system. Then, the hybrid Fuzzy – PID controller proposed in this project was tested experimental and the results were compared with that of individually applied PID and hybrid Fuzzy – PID controllers. The experimental results show that the proposed controller has superior performance compared to individual PID controller. Hence, it can be concluded that the hybrid fuzzy – PID controller is suited for the tabletting machine.

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