Design and Implementation of Adaptive PID Controller for Speed Control of DC Motor

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***Abstract*— This paper describes the design and implementation of adaptive PID control strategy for controlling the angular velocity of the DC motor. Adaptive PID controller is designed to calculate the control parameters which are tuned adaptively to give desired control performance even if parameters of DC Motor are changed. The controller's parameters are online tuned when the motor is running using a Recursive Least Squares (RLS) method. The controller is able to change the value of the controller's constants to maintain motor performance as it is desired when parameters of DC motor are changed. Initially a Pseudo Random Binary Sequence (PRBS) signal is given to the system for 0.07 seconds to get the estimated transfer function of the plant system (DC motor) using the RLS algorithm. From coefficients of the estimated system's transfer function, the poles of a desired characteristic equation can be obtained for the system that has the appropriate output. Thus, the proportional, integral and derivative constants of controller can be obtained by using online pole placement method. Here, an online identification system is used to determine the new control parameters. The effectiveness of this adaptive PID controller is verified by experimental results using a microcontroller STM32F446.**

Keywords*— *adaptive controller, DC motor, PID controller, recursive least square, STM32F446

I. INTRODUCTION

The application of DC (direct current) motor has a quite considerable number in the industrial world. To achieve effective performance in matching the output speed with the input speed, proportional, integral and derivative (PID) controller is commonly used for DC motor speed control. The determination of PID constants depends on the characteristics of the DC motor that are being used, which is different in each motor and sometimes change throughout the time. Most people use the method of trial and error to find the optimal PID constants which certainly requires a lot of time.

Previously, several researches have been done on adaptive DC motor control, such as adaptive DC motor using minimum variance to estimate controller parameters in linear control [1], adaptive DC motor using artificial neural network to estimate the Ki and Kp parameters of the PI controller [2], adaptive DC motor with RLS to estimate the parameters of the system [3], Fuzzy Model Reference Adaptive Control (RMFAC) [4], and the Model Reference Adaptive Control (MRAC).

This paper will discuss a system that is able to find the PID constants based on the characteristics of DC motor and also able to change the PID constants in case of parameter changes.

This paper is organized as follows; section II presents the DC motor description which contains the modelling of dynamic system and state space model for DC motor speed. Section III presents estimation using RLS method. Section IV presents the controller method. Section V presents the result of the simulation. Section VI presents the result of experiment using STM32F663NR microcontroller, and the last section presents the conclusion based on the purpose of this paper.

II. DC MOTOR

Direct current motor is an electric machine that converts electrical DC power into mechanical power in the form of rotation of the rotor.

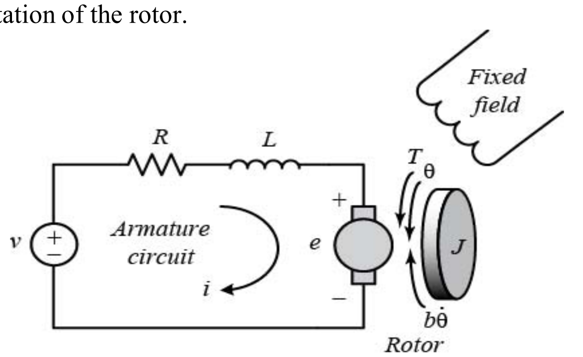

Fig. 1. Electrical scheme of DC motor.

The speed of the DC motor is proportional to the voltage applied. Meanwhile, the motor torque is proportional to the current. Speed control can be controlled by varying the supply voltage, resistance or electronic control. A simple DC motor model is shown in figure 1. Armature circuit consisting of a resistor (R_a) connected in series with the inductor (La) and a voltage source (e_b) that represents the reverse voltage (back electromotive force) that induced during the rotation of the DC motor.

The motor torque (T_m) related to the armature current () and torque constants (Ki):

$$T_m = K_t i_a \tag{1}$$

The reverse voltage (e_b) due to the back electromotive force is proportional to the angular velocity (w_m) and reverse voltage constant (K_b):

$$e_b = K_b w_m \qquad (2)$$

From figure (1) we can write the following equations based on Newton's law combined with Kirchhoff's law:

$$v = i_a R_a + L_a \frac{di_a}{dt} + e_a \qquad (3)$$

$$L_a \frac{di_a}{dt} + i_a R_a = v - K_b \frac{d\theta}{dt} \qquad (4)$$

$$J_m \frac{d\theta}{dt} + B_m \frac{d\theta}{dt} = K_t i_a \qquad (5)$$

Differential equations above can be rewritten into state space form as below:

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du \qquad (6)$$

Considering eq. (2) to (5):

$$\frac{d}{dt}\begin{bmatrix} \dot{\theta} \\ i_a \end{bmatrix} = \begin{bmatrix} -\frac{B_m}{J} & -\frac{K_t}{J}_s \\ -\frac{K_t}{J} & -\frac{R_i}{J}_s \end{bmatrix} \begin{bmatrix} \dot{\theta} \\ i_a \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L_a} \end{bmatrix} v \qquad (7)$$

$$y = [1 \quad 0] \begin{bmatrix} \dot{\theta} \\ i_a \end{bmatrix} \qquad (8)$$

III. RECURSIVE LEAST SQUARE

Estimator is used to tune the value of the polynomial coefficients A and B in the transfer function of the plant:

$$y(t) = \frac{B}{A} u(t) = \frac{b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}} u(t) \qquad (9)$$

In order for the estimator to be used in the adaptive control system, the equation must be converted into an iterative equation, so that the model's parameters can be updated every sampling period in each new data acquisition. Therefore, RLS (recursive least squares) is used.

The reason of using RLS algorithm instead of ordinary least squares is its advantage in computational speed. Because in ordinary least squares, the calculation is based on the overall data acquired from the beginning of the acquisition time, making it unsuitable when used in online identification, whereas the RLS parameters calculation depends only on the current sampling time.

The basic idea of RLS algorithm is to compute the new parameters estimation at time instant *k* by adding some correction vector to the previous parameters estimation at time instant *k-1*.

The algorithm of RLS is given as below:

1. Give an initial value for parameter matrix

   $$\theta(t) = \begin{bmatrix} -a_1 \\ -a_2 \\ b_1 \\ b_2 \end{bmatrix} \qquad (10)$$

   And also initial value for covarian matrix

   $$P(t) = \alpha I \qquad (11)$$

   with α is a value that determines learning rate.

2. Get the input and output of plant at every time sampling. Then set up the data into data matrix x(t):

   $$x(t) = [y(t-1) \quad y(t-2) \quad u(t-1) \quad u(t-2)] \qquad (12)$$

3. Calculate the error of the estimator using the formula:

   $$\varepsilon(t) = y(t) - x(t)^T . \theta(t) \qquad (13)$$

4. Update the value of the covariance matrix *P(t)* using the formula:

   $$P(t) = P(t-1)[I - \frac{x(t)x(t)^T P(t-1)}{x(t)^T P(t-1) x(t)}] \qquad (14)$$

5. Update parameter matrix as given below:

   $$\theta(t) = \theta(t-1) + P(t)x(t)\varepsilon(t) \qquad (15)$$

   And then repeat step 2 - 5 in the next sampling sequence.

IV. CONTROLLER

A controller based on pole placement method in a closed loop feedback control is designed to stabilize the closed-loop system based on equality predetermined characteristics. Digital PID controller can be expressed in the form of discrete transfer function.

$$u(t) = \frac{w(t)(f_0 + f_1 + f_2) - (f_0 + f_1 z^{-1} + f_2 z^{-2}) y(t)}{1 - z^{-1}} \qquad (16)$$

Coefficients f_0, f_1 and f_2 associated with the constants of proportional, derivative, and integral can be determined by the equation:

$$K_P = -f_1 - 2f_2$$
$$K_I = f_0 + f_1 + f_2 \qquad (17)$$
$$K_D = f_2$$

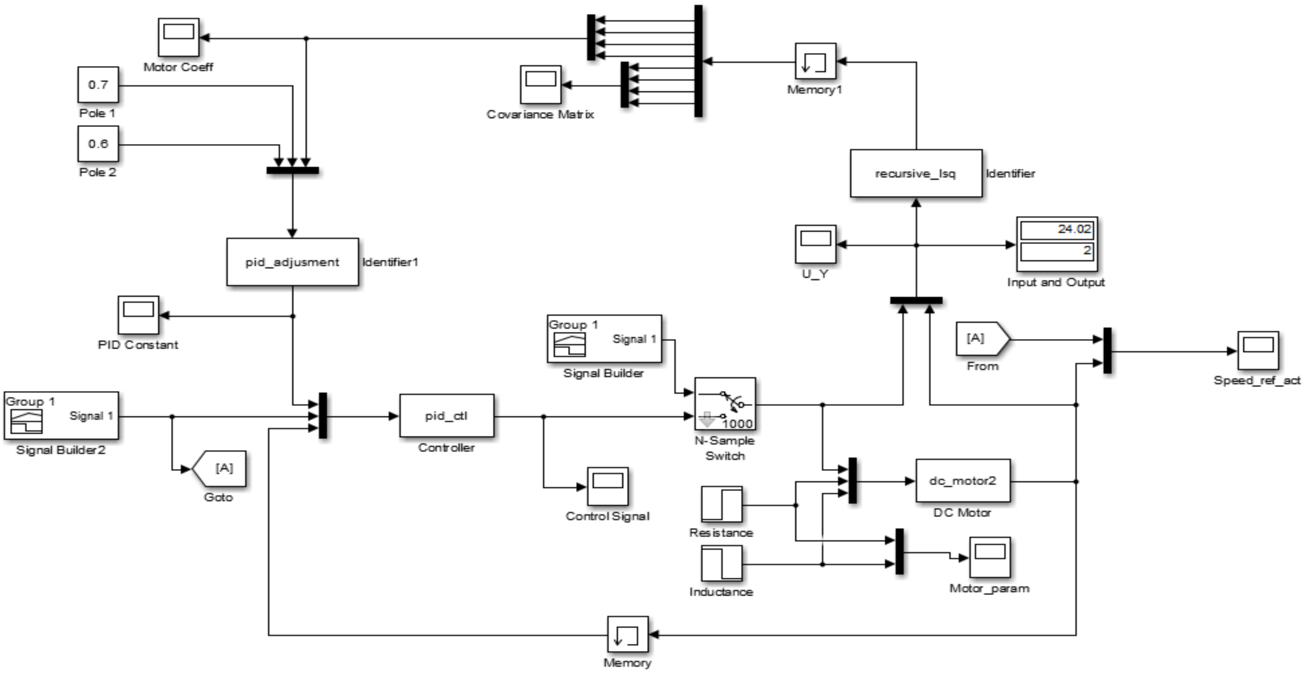

Fig. 2. Block diagram of system used in MATLAB Simulink.

To realize the design, we have to assume that the system which we want to control has the following structure:

$$y(t)=\frac{b_1z^{-1}+b_2z^{-2}}{1+a_1z^{-1}+a_2z^{-2}}u(t) \tag{18}$$

Design process begins by combining the system model given by eq. (18) with a controller in eq. (16) to achieve the closed-loop equation as follow:

$$y(t)=\frac{(b_1z^{-1}+b_2z^{-2})(f_0+f_1+f_2)}{(1-z^{-1})(1+a_1z^{-1}+a_2z^{-2})+(b_1z^{-1}+b_2z^{-2})(f_0+f_1z^{-1}+f_2z^{-2})}u(t) \tag{19}$$

The coefficients can be selected to produce a desired output. The objective of this scheme is to find closed-loop system poles in the desired position, which are given by the following polynomial:

$$T=1+t_1z^{-1}+t_2z^{-2} \tag{20}$$

The coefficients of controller can be determined by:

$$\begin{aligned}T&=(1-z^{-1})(1+a_1z^{-1}+a_2z^{-2})\\&+(b_1z^{-1}+b_2z^{-2})(f_0+f_1z^{-1}+f_2z^{-2})\end{aligned} \tag{21}$$

by matching the coefficients of eq. (20) and (21), the coefficients f_0, f_1 *and* f_2 can be calculated by the rule below:

$$\begin{aligned}f_0&=\frac{t_1-(a\ \ -1)}{b_1}\\ f_1&=\frac{t_2-(a_2-a_1-b_2f_0)}{b_1}\\ f_2&=\frac{a_2-b_2f_1}{b_1}\end{aligned} \tag{22}$$

V. Simulation Result

The system model is transformed into C-MEX code and simulated on MATLAB Simulink as shown in Fig. 2. The parameters of DC motor used are $R = 1\Omega$, $L = 0.5H$, $J = 0.01Kgm^2$, $K = 0.01$, and $B = 0.01Nms$, and substituted into the state space model as described in chapter II. In this simulation, the system is initially given Pseudo Random Binary Sequence (PRBS) signal for 0.07 seconds so that the RLS calculation can be done to find the coefficients of the DC motor. The sampling time used in this simulation is 0.01 seconds. Furthermore, the coefficients of DC motor that obtained are used to locate the PID constants based on the location of desired poles. In this simulation, the poles are desired to be located at 0.7 and 0.6. Then the PID constants obtained are used to calculate the incoming control signals to the DC motor in order to follow the speed reference. In the middle of the simulation (at t=80), the value of resistance and inductance in DC motor are modified to *R = 1.2Ω* and *L = 0.4H* (see Fig. 3 (c)) to prove that the system is able to adapt if the DC motor parameters are changed.

Figure 4 (b) shows the changing PID constants as the DC motor parameters are changed at t=80s. It is seen that the output speed of DC motor follows the reference speed and tend to adapt as the DC motor parameters are changed. The rise time of this simulation is around 18 seconds while steady state value is reached in 20 seconds. Based on the figures below, it can be concluded that the system created in this simulation is able to adapt to changes in the parameters of the DC motor.

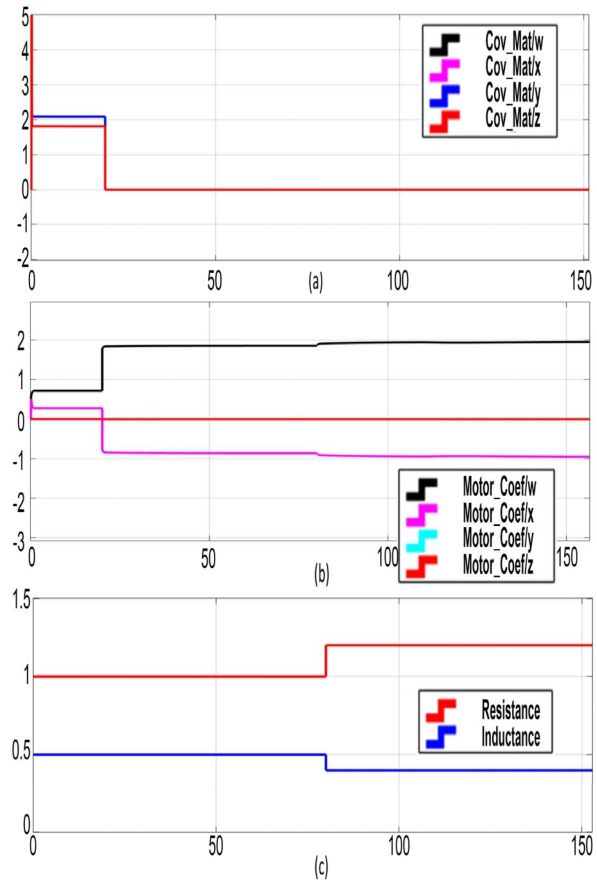

Fig. 3. (a) Covariance matrix. (b) DC motor parameters. (c) Change of resistance and inductance value of DC motor

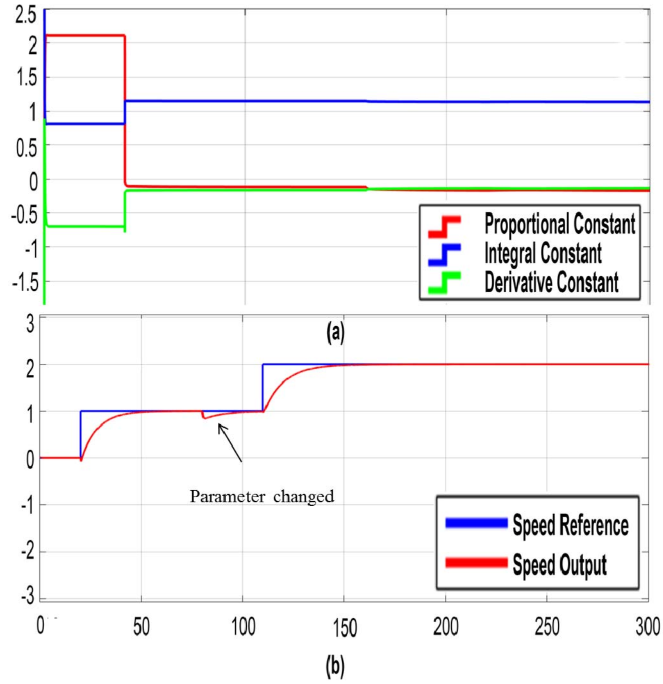

Fig. 4. (a) The change of Controller Constants (Kp, Ki, and Kd) (b) The comparison of motor speed and speed reference for adaptive PID controller

VI. Experiment Result

In the experiment, computations needed are done in computer. The computer will calculate control signal to microcontroller, and PWM (Pulse Width Modulation) signal will be sent to motor driver (L293) by microcontroller. Encoder will send the actual speed of DC motor as feedback response to microcontroller. In this experiment, Robotics Operation System is used to compute the algorithm and visualize the graphic result. The sampling time that is used in this experiment is 1 second.

Fig. 5. Experiment device

The use of computer as a computational device is to reduce the computational constraint on microcontroller. The rise time of this experiment is around 7 seconds while steady state value is reached at 20 seconds. In figure 6 (b) seen that the PID constants are changes due to motor parameter changed (see

Fig. 7 (a)). Based on the figures above, it can be concluded that DC motor is able to adapt and automatically tune the controller constants.

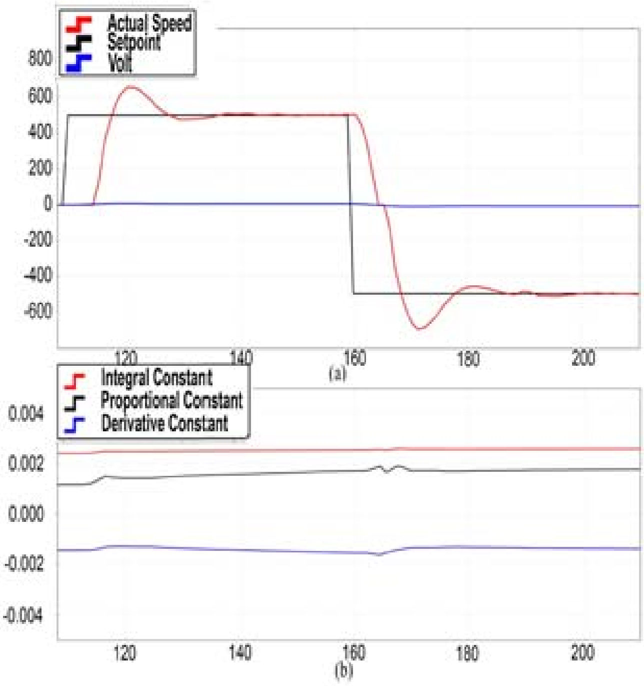

Fig. 6. (a) The comparison of motor speed and speed reference; (b) The change of controller constants (*Kp, Ki, and K*d)

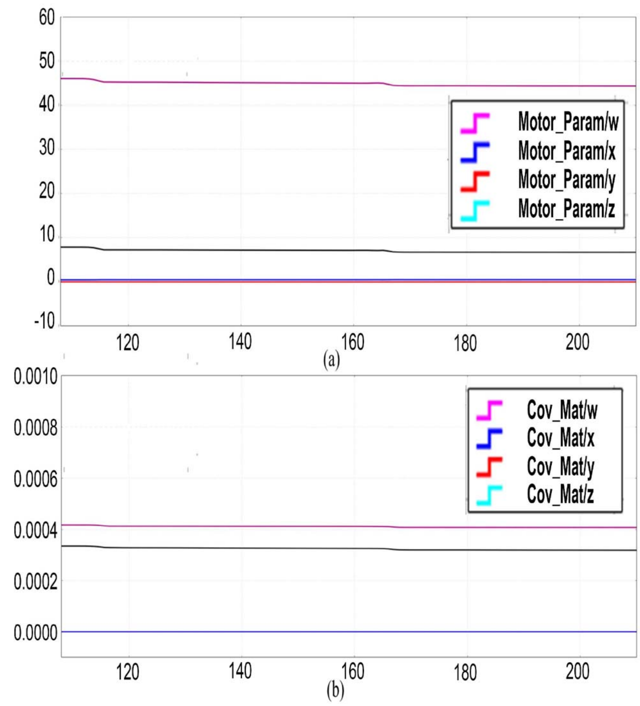

Fig. 7. (a) DC motor parameters; (b) Covariance matrix.

VII. Conclusion

DC motors are widely used as actuating elements in industrial applications for their advantages of easy speed and position control and wide adjustability range. This paper basically explains advantage of model reference adaptive control. The validity of the proposed algorithm has been demonstrated by simulation and experiment. In the simulation result, controller constants can be adjusted automatically while the parameters of DC motor changed and send control signal to the DC motor. The experiment also proves the same result as in simulation. The algorithm can adjust DC motor parameters and update the controller constants.

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