Adaptive-Fuzzy-PID Controller Based Disturbance Observer for DC Motor Speed Control

Zulfatman Has, Ahzen Habibidin Muslim, Nur Alif Mardiyah
Department of Electrical Engineering
University of Muhammadiyah Malang
Malang, Indonesia, 65144
Email: zulfatman@umm.ac.id

***Abstract*—DC motors are one of the most widely used actuators in industry applications. In its use, the reliability of DC motor performance becomes an important prerequisite that must be met. Therefore, a control scheme is required to meet the above performance demands, especially in the transient, steady state, and system stability aspects. The main problems in DC motor control system, especially in terms of speed control, are the occurrence of changes in system parameters and the presence of disturbances such as load changes. This study offers an Adaptive-Fuzzy-PID (AFPID) control scheme equipped with Disturbance Observer (DOb). AFPID scheme plays a role in handling the change of system parameters, while DOb serves to estimate the occurrence of disturbance. The AFPID control scheme was verified experimentally on a DC motor test-rig that was subjected to load-bearing disturbance. The results of the experiments show that the AFPID control scheme with DOb has a better transient response performance than AFPID without DOb, as well as in the ability to compensate the load changes. The combination of AFPID with DOb offers a more stable performance to DC motor has and is more insensitive to disturbance.**

Keywords—DC motor; adaptive control; fuzzy-PID; disturbance observer; various load

I. INTRODUCTION

DC motors are one of actuators that have been widely used in various industrial applications. The advantages of DC motors are low cost, high reliability, easy maintenance, and simple control technique can be applied for speed and position [1-2]. Control of DC motors speed is generally done by adjusting the input voltage on DC motors. In order to control speed of DC motors, various control techniques have been designed and applied in previous studies [3-9]. From literatures, the most widely used control technique for DC motors speed control is Proportional Integral Derivative (PID) technique. However, the PID control technique is only appropriately applied when DC motors are assumed to be linear since they operated for a shorter time in an ideal environment, and do not require higher precision and accuracy.

The problems that often arise in DC motors control are the occurrence of parameter changes when the DC motors are run in a relatively long span of time and worse operating condition and environment. The problems may cause the DC motors system to change to become nonlinear and contains uncertainty elements [10-11]. In addition, there are also appear various internal and external disturbances, such as friction on the rotor and load changes, respectively. These conditions potentially affected the output performance and stability of DC motor systems. Under such system conditions, PID control techniques cannot be fully relied upon, especially for applications that require a high precision and accuracy.

One of the most common solutions offered for the systems that experience parameter changes, contain uncertainty elements, and receive disturbances, is by developing adaptive control schemes [12-13]. The adaptive control scheme that has been widely used is a reference adaptive control (MRAC) or a standalone control scheme like PID, Sliding Mode Control (SMC), and Backstepping that are modified their algorithms to become adaptive [14-16]. Such that, the parameters of the control scheme can change and adapt to the changes that occur in DC motors. In order to estimate magnitude of the changes, observers and estimators have been used widely. However, in the previous studies the problems were generally solved by developing optimization techniques on tuning process of a standalone control parameters, without being fully adaptive [17]. In the Fuzzy-PID scheme, for example, tuning process of the PID control parameters is optimized by using the fuzzy logic method [18], and also can be tuning by GA and PSO for GA-PID and PSO-PID schemes.

Therefore, this study proposed a fully adaptive control scheme which were combining the tuning optimization method and the estimation method to compensate the changes in the system. The new scheme incorporates the Adaptive-Fuzzy-PID (AFPID) control technique with the Disturbance Observer (DOb). The combined scheme was prepared to guarantee the DC motor becomes more robust to the parameter changes and the presence of disturbances. Thus, the DC motor has better performance and can be used in applications that require high precision and accuracy.

II. METHODOLOGY

A. DC Motor Modelling

DC motor modeling is done by using system identification method based on a set of input and output data from DC motor, by utilizing system identification toolbox in Matlab. The obtained model describes the characteristics of DC motor

978-1-5386-0549-3/17/$31.00 ©2017 IEEE

system, in the form of output transient response, steady state error and system stability. The characteristics of the obtained model become the basis for the design of the control algorithm to be applied, either as a standalone control technique or as an observer.

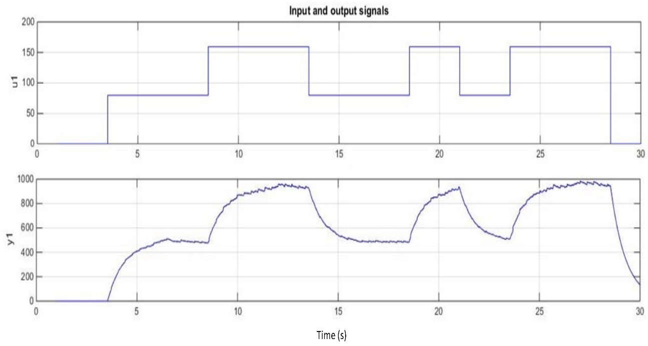

Fig. 1. A set data input and output of modelling

In general, the steps of DC motor modelling include data collection, selection of modeling structures, estimation process and model validation. In the data retrieval step, data is taken from the input and output of DC motor when DC motor is running in closed loop form. The input data is reference signal data given on the DC motor, while the output data is taken from the data of the speed reading on the sensor. A set input and output data used in the modelling are shown in Fig. 1.

The modeling structure chosen in this study is ARX 221, which indicates that the model produced is 2^{nd} order model. Then it is followed by the steps to estimate the model from the prepared data, and validate the estimated model with the measurement data. From the validation process obtained that the estimated model has an accuracy of 95.16%, as illustrated by the curve in Fig. 2. The modelling accuracy of 95.16% indicates that the modeling is acceptable, because it passes the minimum limit of estimation accuracy, which is 90%.

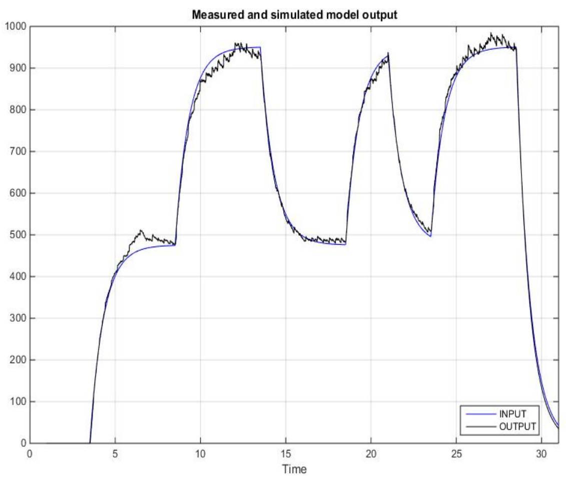

Fig. 2. Validation curve of the estimated model output on the measured data

From the system identification, also obtained equations of the system model in the form of discrete polynomial ARX 221.

$$A(z)y(t) = B(z)u(t) + e(t) \quad (1)$$

$$A(z) = 1 - 1.075\, z^{-1} + 0.08611\ z^{-2} \quad (2)$$

$$B(z) = 0.01239\, z^{-1} + 0.0551\ z^{-2} \quad (3)$$

From polynomial equations in (1) to (3), transfer function of the DC motor can be obtained in continuous form as follow

$$TFc = \frac{0.2706\, s + 4814}{s^2 + 248.2\, s + 298.8} \quad (4)$$

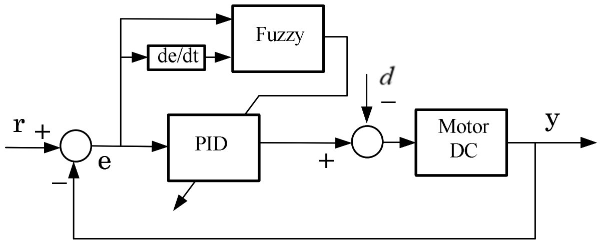

Fig. 3. Adaptive-Fuzzy-PID (AFPID) control scheme

B. Control Design

Structure of the Adaptive-Fuzzy-PID (AFPID) control scheme is shown in Fig. 3. Fuzzy logic plays a role to enhance capability of the PID controller to be more sensitive on the changes of the DC motor parameters and the existence of uncertainty. Initial parameters Kp, Kd, and Ki of the PID controller are obtained by using Ziegler-Nichols tuning method by assuming no change in the system parameters and no uncertainty exist. While, the fuzzy system design is arranged under the condition the system parameters changes, and the disturbance exist, due to obtain the maximum range of the system output error *e* and the change of the error *de*.

Based on structure of the control scheme in Fig. 3, outputs of the fuzzy system are influenced by two variable inputs: the system output errors *e* and the change of the errors *de*. Fig. 4 shows more detail relation inputs and outputs of the fuzzy system. Mamdani inference is employed as the fuzzy method in this study. Output of the fuzzy system is set to be $K'p$, $K'd$, and $K'i$. The range of parameters Kp, Kd, and Ki of the AFPID control scheme are $[Kp\ min, Kp\ max]$, $[Ki\ min, Ki\ max]$, $[Kd\ min, Kd\ max]$.Through several preliminary tests on the system, parameters Kp, Kd, and Ki of the AFPID control scheme are set in the ranges: $Kp \in [1, 26]$, $Ki \in [1.45, 26.45]$, and $Kd \in [0.001, 0.901]$. These ranges specify the minimum and maximum ranges of the AFPID parameters that can be enhanced by fuzzy system.

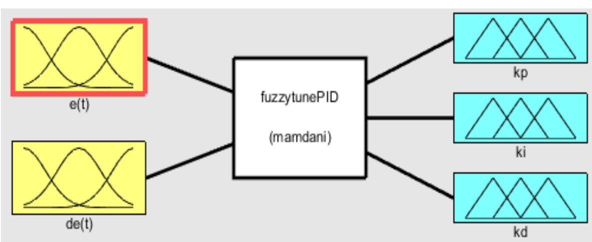

Fig. 4. Fuzzy logic system inference

Such that, outputs of the fuzzy system can be defined as follow:

$$K'_p = \frac{K_p - K_{p\,min}}{K_{p\,max} - K_{p\,min}} \quad (5)$$

$$K'_i = \frac{K_i - K_{i\,min}}{K_{i\,max} - K_{i\,min}} \quad (6)$$

$$K'_d = \frac{K_d - K_{d\,min}}{K_{d\,max} - K_{d\,min}} \quad (7)$$

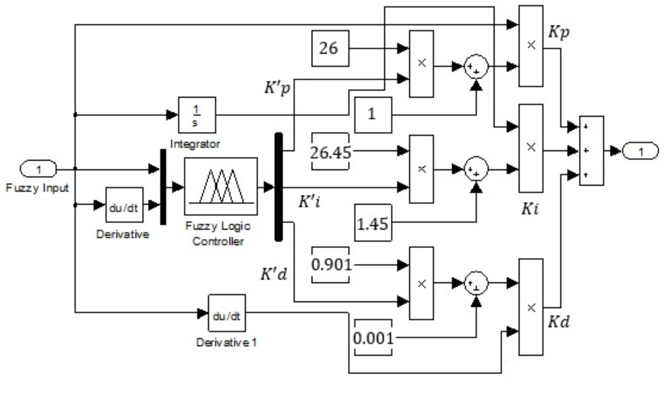

Fig. 5. Simulink block of AFPID control scheme

Based on Equations (5) to (7) and the ranges mentioned above, the final values for each parameter of the AFPID control scheme can be calculated by formula: $K_p = 25K'_p + 1$, $K_i = 25K'_i + 1.45$ and $K_p = 0.9K'_d + 0.001$. These formulas are expressed clearly by Simulink block of the AFPID control scheme in Fig. 5.

More detail in fuzzy system design, membership function of inputs and outputs of the fuzzy system are expressed in five levels of linguistic variables and built in triangular functions. Linguistic variables for the inputs *e* and *de* are defined as Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB), in range 0-1000 and 0-100, respectively. While the outputs $K'p$, $K'd$, and $K'i$ are described as Small (S), Medium Small (MS), Medium (M), Medium Big (MB), and Big (B), in range 0 to 2. Relations of inputs and outputs of the fuzzy system are described by the following matrix.

TABLE I. MATRIX OF FUZZY INFERENCE

de/e	NB	NS	ZE	PS	PB
NB	S	S	MS	MS	M
NS	S	MS	MS	M	MB
ZE	MS	MS	M	MB	MB
PS	MS	M	MB	MB	B
PB	M	MB	MB	B	B

Relation of inputs and output of the fuzzy in the matrix expressed in Fig, 6 are expressed for the three fuzzy outputs by using the following rule:

If *e* is E_i and *de* is dE_i then $K'_p = A_i$ and $K'_i = B_i$ and $K'_d = C_i$.

where *i* is levels of linguistic variable from lower to higher.

Since the initial control scheme has not been prepared for the presence of disturbance in the system, the initial scheme can be enhanced by Disturbance Observer (DOb). A complete structure for the new control scheme as illustrated in Fig. 6 below.

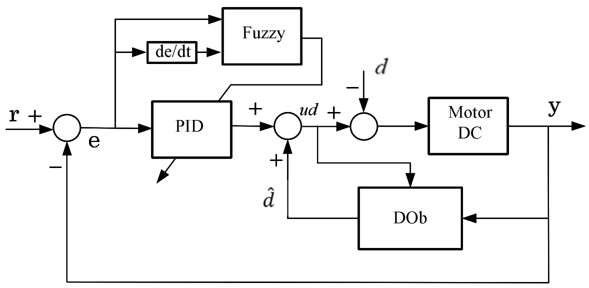

Fig. 6. AFPID with DOb control scheme

The DOb is added to the control scheme to improve capability of the control scheme in compensating the presence of disturbance. Control signal of the new control scheme is expressed as

$$u_d = u_{AFPID} + \hat{d} \quad (8)$$

where u_d is total control signal, u_{AFPID} is control signal of the AFPID control, and $\hat{d}$ is estimated value from the observer.

The DOb design as added in Fig. 6, consists of a low-pass filter *Q(s)* and a nominal model of the system, $P_n(s)$. The nominal model is derived from initial model of the system that has been modelled in the previous step. DOb makes the system behavior between the control signal and the output signal of the plant not affected by interference. Detail of block diagram of the DOb as shown in Fig. 7.

The filter used in this study is a first order filter to have a simple computation. The equation of the filter is expressed as the following equation

$$Q(s) = \frac{1}{0.0097s + 1} \quad (9)$$

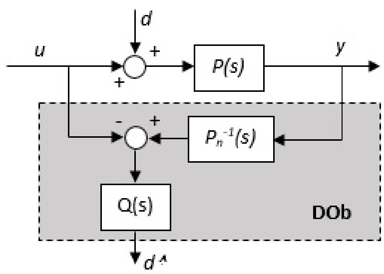

Fig. 7. Simulink block of Disturbance Observer

Stability of the AFPID control law can be guanteed by employing the Lyapunov candidate function *V* under consideration on the dyanmics error of the system and the estimation error of the observer for $V > 0$.

C. Experimental Setup

In order to verify the proposed control scheme, a series of experimental works are prepared in real-time on the test-rig of DC motor. The test-rig contains a DC motor, rotary encoder, interface, and motor driver. The DC motor and the rotary-encoder connected and communicated in closed loop form with the proposed control scheme in Matlab Simulink via Arduino Mega 2560, which is employed as ADC and DAC interface. Complete configuration of the test-rig of DC motor is illustrated by the following figure.

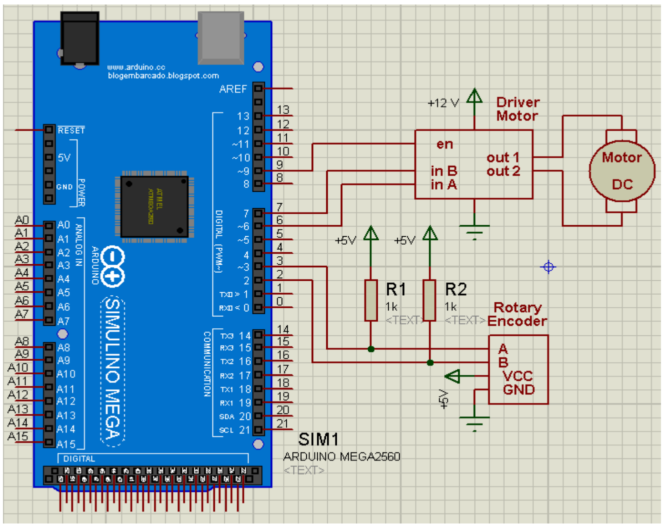

Fig. 8. Configuration of DC motor test-rig

Verification on the proposed control scheme are done in two steps: (1) experiment on the control scheme without DOb, and (2) experiment the control scheme with DOb. The first experiment is used to observe the superiority of the AFPID than the conventional PID controller in terms of transient response and stability aspects. Transient aspects considered in this study are rise time (t_s), overshoot maximum (m_p), and peak time (t_p). Stability aspect is represented by error steady state (e_{ss}). While, the second experiment is done to proof the capability of the AFPID scheme in the addition of DOb in estimating and rejecting the disturbance.

Since the proposed control scheme is prepared to increase the performance of DC motor speed, such that the reference signal for the experimental must be in speed form (rpm). The reference signal is set in step function, with the desired speed in 1000 rpm. In the both experiments, the system suffers from disturbance, which is represented by the change of load.

III. Results and Discussion

Results and discussion of the experimental works separated into two parts:

A. Verification on the AFPID scheme without DOb

Experimental result of the first verification is shown in Fig. 9. The figure compares the DC motor system output response using PID controller and AFPID control scheme. The system output response with the AFPID control scheme performed much better than the PID controller, in the whole aspects that are used as reference in measuring the performance of transient response, and also in the steady state error. In term of rise time for example, the AFPID control scheme produced a response that was almost three times faster than the PID controller. In term of maximum overshoot, peak time aspects, and steady state errors, the AFPID also produced the same pattern.

However, even though the system response with AFPID control scheme seemed slightly better than PID controller, both of the control schemes presented the same weaknesses in ability to compensate the presence of disturbance. It was caused by unavailability of the control schemes to estimate the existence of disturbance. The control schemes have not been equipped with estimator or observer for the disturbance. The control scheme without disturbance observer takes longer time to return to its stable condition.

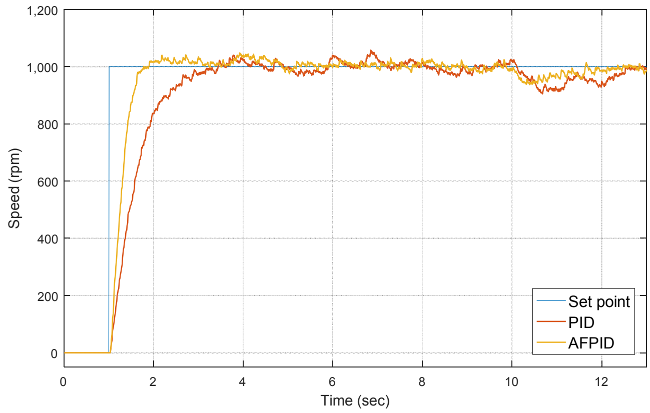

Fig. 9. Output responses of the system with PID controller and AFPID control scheme.

The conclusion taken from the discussion above that specified for the output responses in Fig. 9 is supported statistically by transient response and stability data as presented in the following table.

TABLE II. Transient Response and Stability

Parameters	PID	AFPID
RiseTime	1.1153	0.4533
Overshoot	6.2889	5.4491
Peak Time	6.84	3.91
Error SS	4.2%	2.3%

B. Verification on the AFPID scheme with DOb

Fig. 10 shows the experimental result of the second verification, which compares the output response of the system using the AFPID scheme without DOb and the AFPID scheme with DOb. From the figure, it is clearly shown that the inclusion of the DOb into the AFPID control scheme gave a significant improvement in the capability of the AFPID control scheme in compensating the presence of disturbance, when the system was operated in certain time. Moreover, even though the DOb is not prepared for transient response and error steady state performance improvement, the addition of the estimated value of the disturbance into the total control signal of the control scheme caused the output response had a bit faster rise time and higher overshoot. The control scheme with disturbance observer can return faster to its steady state than the control scheme without disturbance observer. In another word, the disturbance observer helps the control scheme to be more insensitive on the presence of disturbance.

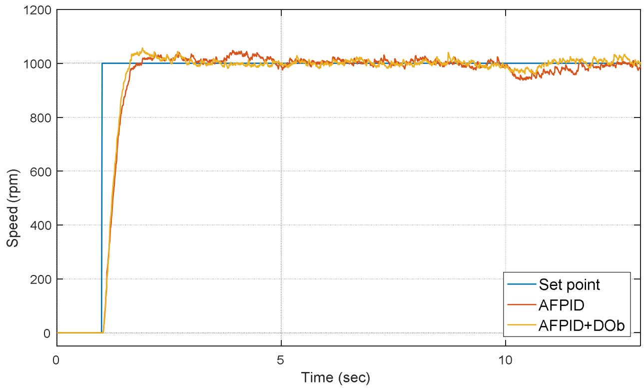

Fig. 10. Output responses of the system with AFPID control without and with DOb

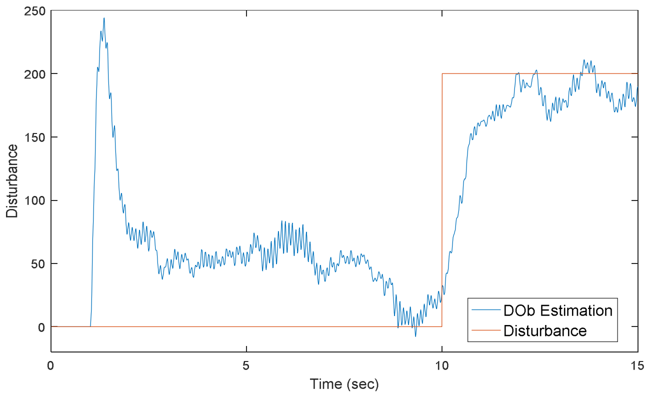

Fig. 11. DOb estimation on the presence of disturbance

A statistical data from the experiment was presented to support the conclusion taken from the discussion on Fig. 10 as follow.

TABLE III. TRANSIENT RESPONSE AND STABILITY

Parameters	AFPID	AFPID-DOb
RiseTime	0.4533	0.3717
Overshoot	5.4491	7.2326
Peak Time	3.91	1.90
Error SS	2.4%	1.27%

Capability of the DOb in estimating the disturbance is shown in Fig. 11. From the figure, it can be seen that the estimated value was trying to track the disturbance precisely. Then, the estimated value of the disturbance was summed with the control signal produced by the initial control scheme that were calculated as the total control signal of the whole control scheme.

IV. CONCLUSION

A control scheme that had capabilities in improving the performance of transient response and error steady state of the system, and also available to estimate and compensate disturbance had been successfully developed and verified experimentally. A fuzzy system can be developed to optimize the PID controller parameters to be more flexible on the change of the system parameters and successfully improved the performance of transient response and steady state of the DC motor output response. Moreover, the inclusion of DOb into the control scheme significantly enhanced its capability in compensating the presence of disturbance in the DC motor. Thus, this combined scheme can guarantee the DC motor to have a better performance and available for the applications that require a high precision and accuracy.

ACKNOWLEDGMENT

This study is fully supported by Direktorat Penelitian dan Pengabdian kepada Masyarakat (DPPM), University of Muhammadiyah Malang (UMM) through Internal Research Grant Scheme (PKID-SI) 2017. Authors are grateful to DPPM UMM in supporting the present work.

REFERENCES

[1] N. Matsui, "Sensorless PM brushless DC motor drives," IEEE Trans. on Industrial Electronics, vol. 43, no, 2, pp. 300-308, 1996.

[2] J.S. Ko, J.H. Lee, S.K. Chung and M.J. Yeon, "A robust digital position control of brushless DC motor with dead beat load torque observer," IEEE Trans. on Industrial Electronics, vol. 40, no, 5, pp. 512-520, 1993.

[3] E.E. El-Samahy, "Speed control of DC motor using adaptive variable structure control, " *Annual 31st Power Electronics Specialist Conference,* Irland, 2010.

[4] C.U. Maheswararao, Y.S.K. Babu, K. Amaresh, "Sliding Mode Speed Control of a DC Motor*", International Conference on Communication Systems and Network Technologies (CSNT),* India, 2011.

[5] R.G. Kanojiya and P.M. Meshram, "Optimal tuning of PI controller for speed control of DC motor drive using particle swarm optimization*", International Conference on Advanced in Power Conversion and Energy Technologies (APCET),* India, 2-4 August, 2012.

[6] W.M. Elsrogy, M.A. Fkirin, M.A.M. Hassan, "Speed control of DC motor using PID controller based on artificial intelligence techniques," International Conference on *Control, Decision and Information Technology* (CoDIT), Tunisia, 6-8 May, 2013.

[7] M. Kamal, L. Mathew and S. Chatterji" Speed Control of Brushless DC Motor Using Intelligent Controllers. " IEEE Engineering and Systems (SCES), 2014 Students Conference, 28-30 May, 2014,

[8] A.T. El-Deen, A.A.H. Mahmoud, A.R. El-Sawi, "Optimal PID Tuning for DC Motor Speed Controller Based on Genetic Algorithm", Int. Review of Automatic Control (IREACO), vol. 8 no. 1, 2015.

[9] Hasanjani Reza Akbari, Javadi Shahram dan Nadooshan Reza Sabbagi, "DC Motor Speed Control by Self-Tuning Fuzzy PID Algorithm", Islamic Azad University, Teheran, Iran, 2014.

[10] T. Kara and I. Eker, "Nonlinear modeling and identification of a DC motor for bidirectional operation with real time experiments," Energy Conversion and Management, vo. 45, no. 7-8, pp. 1087-1106, 2004.

[11] S. Bucchner, V. Schreiber, A. Amthor, C. Ament and M. Eichhorn, "Nonlinear modeling and identification of a dc-motor with friction and

cogging," *39th Annual Conf. of the IEEE Industrial Electronics Society (IECON)*, Vienna, 10-13 Nov., 2013.

[12] C-Y. Su and Y. Stepanenko, "Adaptive control of a class of nonlinear systems with fuzzy logic," IEEE Trans. on Fuzzy Systems, vol. 2, no. 4, pp. 285-294, 1994.

[13] D.H. Kim, H.O. Wang and H-W. Yang, "Robust Adaptive Control of Nonlinear Output Feedback Systems Under Disturbances With Unknown Bounds," J. Dyn. Sys., Meas., Control, vol. 126, n0. 1, pp. 229-235, 2004.

[14] M. Kanamori and M. Tomizuka, "Model reference adaptive control of linear systems with input saturation," *IEEE Int. Conf. on Control Applications,* Model reference adaptive control of linear systems with input saturation Taipei, 2-4 Sept. 2004.

[15] Z. Has, M. F. Rahmat, A. R Husain and M. N. Ahmad, "Robust position control of an electro-hydraulic actuator system based on disturbance observer," Int. J. of Precision Eng. and Manu., vol. 16, no. 8, pp. 1753-1760, 2015.

[16] S.M. Rozali, M.F. Rahmat, A.R. Husain and M.N. Kamarudin, "Robust controller design for position tracking of nonlinear system using backstepping-GSA approach", ARPN J. of Eng. and Applied Sciences, vol. 11, no. 6, pp. 3783-3788, 2016.

[17] A. Fatoni, J. Pramudijanto, dan A. Yonatan, "Perancangan dan Implementasi Disturbance Observer untuk Pengaturan Kontur pada Simulator Mesin Freis", Thesis ITS Surabaya, 2009.

[18] Cai dan Wang,"A Fuzzy-PI Hybrid Controller Based on a Disturbance Observer", *9th International Conference on Natural Computation (ICNC)*, 2013.

[19] Zulfatman and M. F. Rahmat, "Application of Self-Tunning Fuzzy PID Controller on Iindustrial Hydraulic Actuator Using System Identification Approach", UTM Skudai, Malaysia, 2009.