Fuzzy-based PID with Iterative Learning Active Force Controller for An Anti-lock Brake System

Mohammed Al-Mola, Musa Mailah, Abdul Halim Muhaimin and Mohd Yunus Abdullah
Department of Applied Mechanics and Design
Faculty of Mechanical Engineering, Universiti Teknologi Malaysia
81310 UTM Johor Bahru, Johor, MALAYSIA
daadmaster@gmail.com, musa@fkm.utm.my

Pakharuddin Mohd Samin
Department of Aeronautics, Automotive and Ocean Engineering
Faculty of Mechanical Engineering, Universiti Teknologi Malaysia
81310 UTM Johor Bahru, Johor, MALAYSIA
kjauto@fkm.utm.my

Abstract — **Anti-lock braking systems (ABS) are safety and control devices implemented in ground vehicles that prevent the wheel lock-up during panic braking. The existing ABS controls have the ability to regulate the level of pressure to optimally maintain the wheel slip within the vehicle stability range. However, the ABS shows strong nonlinear characteristics in which the vehicles equipped with the existing controllers can still have a tendency to oversteer and become unstable. In this paper, a new intelligent robust control method based on an active force control (AFC) strategy is proposed via a rigorous simulation study. It is designed and implemented in a hybrid form by having the AFC loop associated with an iterative learning (IL) algorithm cascaded in series with a self-tuning fuzzy logic (FL)-based proportional-integral-derivative (PID) control for the effective overall performance of the proposed ABS. Both the IL and FL techniques are for the appropriate acquisition and computation of the important parameters in the controller. From the results, it is evident that the FL-PID with ILAFC scheme shows faster and better response compared to the FL-PID and FL-PID+AFC controllers in the wake of the given load and operating conditions. The incorporation of the AFC-based scheme into the ABS serves to provide an enhanced and robust performance that has the potentials to be implemented in a practical and real-time system.**

Keywords - anti-lock brake system, AFC strategy, fuzzy logic, PID controller, iterative learning algorithm

I. INTRODUCTION

Today's passenger cars are increasingly equipped with antilock brake systems (ABS) with the advent and availability of low cost sensors and microcomputers. ABS is a safety device for an automotive vehicle that prevents the wheels from being totally locked in the event of an emergency braking or braking on slippery road surfaces. It is essentially comprised of an electronic control unit, a brake force actuator and wheel speed sensors. It is the objective of an ABS to achieve shorter stopping distance and maintain a good steering stability during braking. As a mechanical system, the first ABS was developed for airplanes in 1947 [1]. It was considered too expensive to design and develop an ABS for use in the automotive industry at that time. In 1954 the first trial for automotive using ABS was on a limited number of vehicles which were fitted with ABS from a French aircraft. In the late 60's, Ford, Chrysler, and Cadillac offered ABS on a very few models. These very first systems used analogue computers and vacuum-actuated modulators [2]. At that time, it was not commercially successful [3]. The development of ABS for serious automotive use was actually started in the 1970s. Mercedes and BMW started to introduce electronically-controlled ABS systems and that was in the late 70's. By 1985, Bosch ABS has been employed in Audi, and BMW cars [2]. The unknown parameters of the environment associating with the vehicle and the nonlinearity characteristics in its performance, made this mechanism as a typical nonlinear system. Many researchers used various control strategies to facilitate the ABS phenomenon and one of them is through the implementation of a fuzzy logic control (FLC). The other more advanced control approach applied to the ABS is a fuzzy logic PID control (FLPID) design method which is also known as a hybrid control strategy based on the combination of fuzzy control and conventional PID control methods. The main advantage of the FLPID control scheme is that is that it uses fewer fuzzy rules than the initial FLC [4]. Yet another robust control scheme known as an active force control (AFC) has emerged and has been shown to be far superior compared to the conventional PID control method in controlling various dynamical systems [5-10]. This technique has been implemented successfully in the active suspension system [11-13]. This strategy used in ABS by [14] to control the optimum wheel slip value in order to prevent the wheel from being totally locked under nonlinearities, parametric uncertainties and disturbance conditions. This strategy has also been implemented by [15] on two degrees of freedom of a spacecraft pitch attitude control enhanced with PD controller and, by [16] on two degrees of freedom new brake model with PID controller. Recently, hybrid controller using this technique has been applied to ABS and other control methods [17]. This conventional PID control method has a non-learning capability when the controller parameters are tuned. Therefore, the controller cannot adapt itself in the

DOI 10.5013/IJSSST.a.13.3A.05 TISSN: 1473-804x online, 1473-8031 print

system has changed in the conditions. There are a number of techniques that can be found in literature which is largely based on adaptation methods involving various algorithms. One of them is the iterative learning control (ILC) method that was introduced and actively researched by Arimoto and co-workers in middle of 80s [18]. In general, there are three types of basic ILC algorithms which have been applied to dynamical systems [19-22]. An extension to this iterative learning technique to avoid the system's instability when the robot is operated for a longer period of time has been done in [23]. In the automotive field, [24] used the method in hybrid electric vehicles (HEVs) and electric vehicle (EV) propulsion systems to achieve the antilock braking performance without a conventional (ABS). The system can be easily achieved using this technique for various road conditions to keep the tire slip ratio corresponding to the peak traction coefficient during braking.

The principal objective of this study is to propose a hybrid controller, comprising a fuzzy logic with PID controller and a new robust active force controller with ILC applied to an ABS. The response of the ABS with the classic PID controller only is deemed not ideal and sufficient, because when the vehicle tries to follow or track the slip ratio, it takes a longer time to reach the reference input slip. To overcome this problem, a fuzzy logic controller is designed specifically for tuning the PID gains. This configuration together with the AFC strategy with ILC provides a means of robust control so that the overall performance in an emergency braking maneuver is considerably improved.

II. SYSTEM DYNAMIC

Figs. 1 and 2 show the road condition and the free body diagram for a single wheel model, respectively. Based on this diagram, a simplified longitudinal vehicle model considering the rotational dynamics of the wheel and the linear vehicle dynamic can be derived.

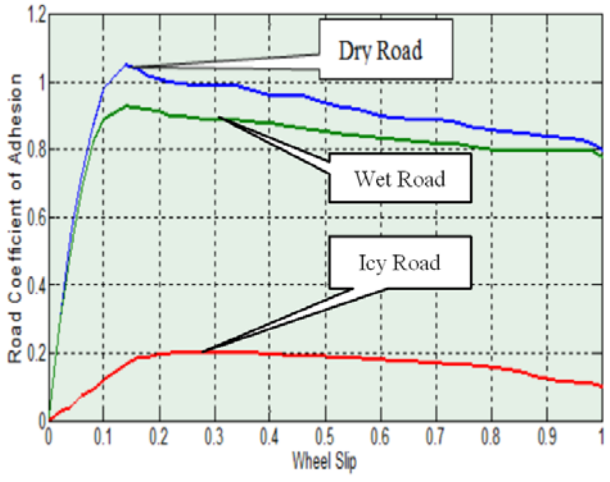

Figure 1. The road conditions [25]

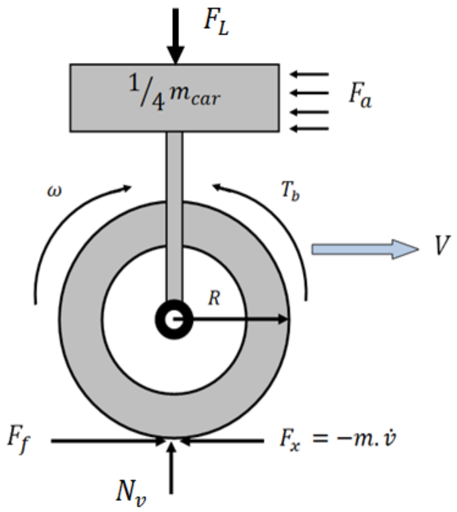

Figure 2. Dynamic model for the single wheel

A. Linear Dynamic of the Wheel

The linear dynamics of the wheel are derived from the standard Newtonian equation of motion and is formulated as follows:

$$\dot{V} = \frac{-N_w F_x - F_a + F_f}{M_v} \quad (1)$$

$$F_x = N_V \mu(\lambda) \quad (2)$$

$$N_v = m_t g + F_L \quad (3)$$

$$F_L = \frac{M_v h_{cg}}{L} \dot{V} \quad (4)$$

$$F_a = (\frac{\rho}{2} C_d A_f V^2) \quad (5)$$

$$F_f = f_o + 3.24 f_s (K_{mph} V)^{2.5} \quad (6)$$

B. Rotational Dynamic of the Wheel

The rotational dynamics of the wheel are modelled by the following equation:

$$J_w \dot{\omega} = -T_b + R_w F_x - R_w F_f \quad (7)$$

To simplify the model, the relationship between caliper pressure P and the braking torque T_b is assumed to be linear:

$$T_b = K_b P \quad (8)$$

All the variables and parameters used in equations (1)-(8) are described as follows:

M_v: the total mass of vehicle (kg), m_t: the single tire mass of vehicle (kg), N_v: Normal load of the tire (N), □: wheel angular speed (rad/s), V: vehicle linear speed (m/s), F_a : Aerodynamic drag force (N), F_x : Friction force (N), F_f: Rolling resistance force (N), F_L: Longitudinal weight transfer load due to braking (N), T_b: Brake torque (N/m), R_w: radius of the wheel, J_w : Moment of inertia of wheel (kgm^2), L: wheel base (m), ρ: Air density (kg/m^3), h_{cg}: Center of gravity height (m), C_d: Aerodynamic drag coefficient, λ_i: The desired slip, A_f: Frontal area of the vehicle (m^2), K_b: Specific torque constant, P: Output hydraulic pressure (kPa), f_0: basic coefficient, f_s: speed effect coefficient, k_{mph}: scale factor between (m/s) and (mph), ($k_{mph} = 2.237$).

III. CONTROL DESIGN

In this section, the design of the fuzzy-self tuning PID and AFC used to develop the scheme are presented.

A. *Fuzzy Self-Tuning PID Control*

In this section, the proposed scheme is introduced. It does not rely on Ziegler-Nichols or trial-and-error methods. It uses first order Takagi-Sugeno (T-S) fuzzy systems as the tuning-tool for each of the PID control modules. In this way, the proposed scheme can be devised for any linear or nonlinear system in a straightforward manner [4]. Three decoupled fuzzy systems constitute the proposed self-tuning system; each of the corresponding parameter in the PID controller:

$$u(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{de(t)}{dt} \qquad (9)$$

The error and change in error are used as a behavior-recognizers of the closed-loop performance. They are available signals in the closed loop system of the ABS and do not require extra hardware. The self-tuner can be expressed as:

$$\begin{aligned} K_P &= FS\left[e(t),\dot{e}(t)\right], \\ K_I &= FS\left[e(t),\dot{e}(t)\right], \\ K_D &= FS\left[e(t),\dot{e}(t)\right] \end{aligned} \qquad (10)$$

Where the fuzzy module is connected in parallel to the actual PID elements to generate the resultant controller signal as shown in Fig. 3 where the fuzzy module is trying to recognize when the corresponding parameter is not properly tuned and then seeks to adjust it to obtain the improved performance.

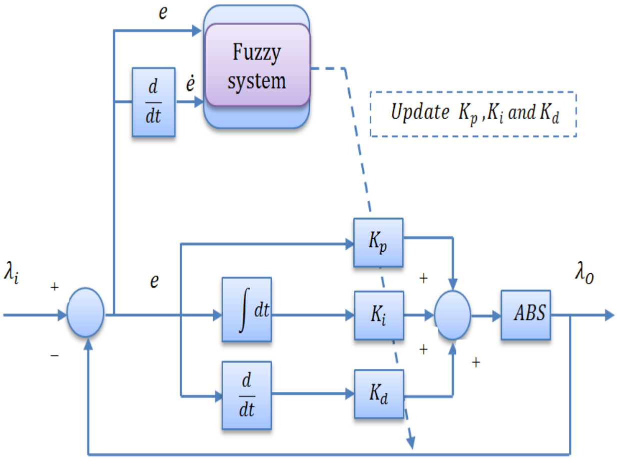

Figure 3. Self-tuning fuzzy PID controller

A T-S type fuzzy system is used to synthesize each module. A typical rule has the following form:

IF x1 IS A AND x2 IS B THEN z1 = f (x1, x2), z2 = f (x1, x2) and z3 = f (x1, x2)

Where A and B are fuzzy sets in the antecedent, while z1=f (x1, x2), z2=f (x1, x2) and z3=f (x1, x2) are crisp functionally in the consequent. With this form, the fuzzy system can be characterized as two input three output fuzzy systems. In the proposed self-tuner, the inputs, i.e., e and ė are normalized using three Gaussian membership functions; negative N, zero ZE, positive P, negative big NB, negative small NS, positive big PB, positive medium PM, and positive small PS; so that the four rules constitute the rule base for each module as illustrated in Table 1. In this controller, there are two inputs and three outputs. Fuzzy rules have been developed as follows:

1. If (e is PB) and (de/dt is ZE) THEN (KP is PB)(KI is PS)(KD is PS)
2. If (e is ZE) and (de/dt is NB) THEN (KP is NS)(KI is PS)(KD is PM)
3. If (e is NB) and (de/dt is ZE) THEN (KP is NB)(KI is PS)(KD is PS)
4. If (e is ZE) and (de/dt is PB) THEN (KP is PS)(KI is PM)(KD is PM)

TABLE 1: THE LINGUISTIC OUTPUT VALUES FOR THE LINGUISTIC VARIABLES K_P, K_I AND K_D

de/dt	**NB**			**ZE**			**PB**		
e	K_P	K_I	K_D	K_P	K_I	K_D	K_P	K_I	K_D
NB				NB	PS	PS			
ZE	NS	PS	PM				PS	PM	PM
PB				PB	PS	PS			

B. *Active Force Control*

Hewit and Burdess proposed the idea of AFC which is derived from the Newton's second law of motion such as for a rotating mass, we have [5]:

$$\sum T = J\alpha \tag{11}$$

Where T is the sum of all torques acting on the body, J is the moment of inertia, and α is the angular acceleration. The objective of this control scheme is to control the dynamic system in order to ensure the system will remain stable and robust in the presence of known and unknown disturbances. For the ABS that will be embedded with the AFC scheme, the equation of motion becomes:

$$-T_b + R_w F_x - R_w F_f + Q = J_w \dot{\omega} \tag{12}$$

Where T_b is the brake torque, Q is the disturbance torque, F_t is the road friction torque, R_w is the wheel radius, J_w is the moment of inertia of the wheel. Fig. 3 illustrates the principle of the AFC applied to the ABS.

The physical quantities directly need to be measured from the system are the actuating force and the vehicle acceleration which should be done by some sensing elements. The estimated disturbance torque Q' can be computed by the equation:

$$Q' = \frac{T_b}{R} - E_m \dot{V} \tag{13}$$

Where E_m is the estimated mass which can be tuned using an intelligent method as proposed in this study, □. is the vehicle acceleration, R represents the radius of the single wheel.

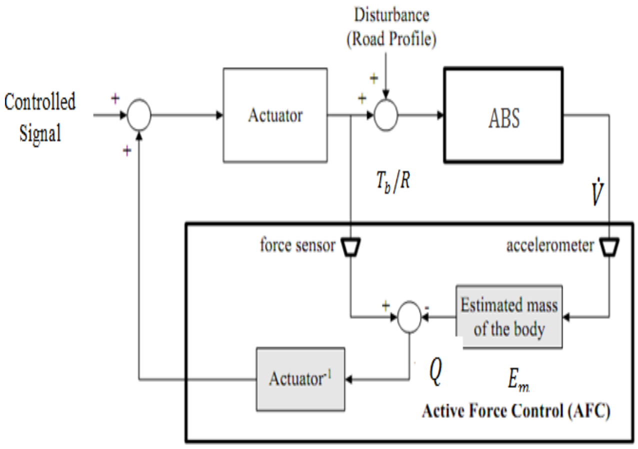

Figure 4. AFC concept applied to an ABS

The brake torque is a function of the brake pressure that is generated by the non-linear hydraulic actuator. The aim of this control scheme is to control the dynamic system in order to ensure the system will remain stable and robust in the presence of known and unknown disturbances. In this work, AFC method was applied to the ABS in simulation and comparison was made to the other closed-loop controllers for benchmarking the proposed system performance.

C. *Iterative Learning Control*

The control of ABS using AFC can be considerably improved if a method is found to provide good estimates of the mass of the ABS. ILAFC scheme uses the iterative learning as the inertial parameter estimator with the self-tuning fuzzy PID. The P type of iterative learning is attached to the active force control loop to estimate the required parameter. The learning parameter Φ has to be selected suitably that affects the speed of iteration [22]. Several trials are performed to determine the appropriate values for this constant and the results suggested that the assumed value is acceptable, i.e., IL-P which has the P-type gain, Φ =1.2. The proportional (P) type as explained in [22-23] is expressed as follows:

$$u_{k+1}(t) = u_k(t) + \{\Phi\}(\lambda_i(t) - \lambda_o(t)) \tag{14}$$

Fig. 5 shows the basic simulation structure of ABS control enhanced by ILAFC.

IV. SIMULATION STUDY

The parameters used in the simulation study are as follows:

(1) For the PID controller gains:
  - Proportional gain, $K_p = 21$
  - Integral gain, $K_i = 0.08$
  - Derivative gain, $K_d = 0.6250$.

(2) The main simulation parameters:
  - Simulation time start: 0,
  - Simulation time stop 10 s
  - Minimum step size: auto
  - Maximum step size: auto.

(3) The single wheel parameters used in the simulation study are selected as shown in Table 2.

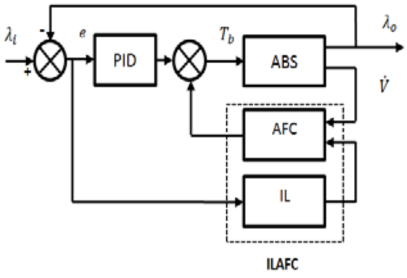

Figure 5. Structure of ILAFC

TABLE 2: VEHICLE PARAMETERS

Symbol	Value
¼ m_{car}	375 kg
R_w	0.326 m
J_w	1.7 kgm^2
L	0.5 m
ρ	1.23 kg/m^3
h_{cg}	0.5 m
C_d	0.539
A_f	2.04 m^2
g	9.81 m/s^2
λ_i	0.2
f_0	0.01
f_s	0.005
k_{mph}	2.237

The performance of the proposed AFC-based controller was investigated and the results are compared between the proposed hybrid controller and self-tuning fuzzy PID controller. It is assumed that the vehicle is moving in a straight-line at 60 km/h. All tests are run for a 1ms sampling period and the maximum braking torque is limited to 2050 Nm. In a first step, the fuzzy self-tuning PID was simulated and its efficiency compared to the classic PID controller in terms of the vehicle speed, stopping distance, wheel slip ratio and braking torque. The road surface in this study considers a dry road condition. Fig. 6 shows the vehicle and wheel speed during the braking under self-tuning fuzzy PID. The braking torque behaviour for various controllers is shown in Fig. 7

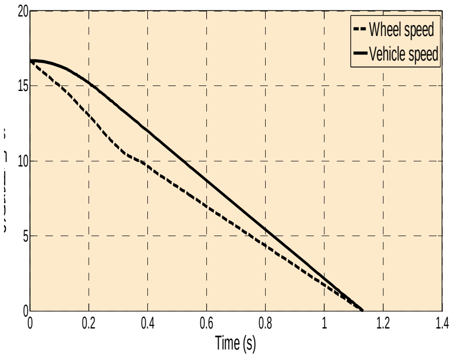

Figure 6. Vehicle and wheel speed during the braking in dry road condition

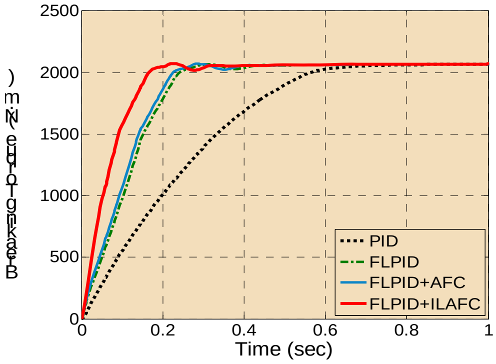

Figure 7. Braking torque during the braking on dry road condition

It can be observed that the time response of the torque was best under the AFC-based strategies with the ILC method outperforms the rest. For the wheel slip ratio, the proposed hybrid FLPID-ILAFC controller has a very good response to track the desired slip ratio which leads to good stability and steerability of the vehicle considering a straight line motion as depicted in Fig. 8. It is also shown that the wheel tends to approach the desired slip after starting the braking process for all the PID-based controllers after a short period of time but in the case of the self-tuning PID and the proposed hybrid AFC-based controllers, they produce a much faster response to reach the slip reference with good rising time compared to the conventional PID (PID). Using the iterative learning technique with the proposed AFC (FLPID+ILAFC), the rising time has significantly improved under the same conditions. Fig. 9 shows the stopping distance curves for all the controllers considered. It is obvious that the minimum stopping distance is achieved by FLPID-ILAFC, having reached a distance of 9.775 m with duration of 1.095s, thereby implying that it is the best ABS controller compared to the rest of the control schemes.

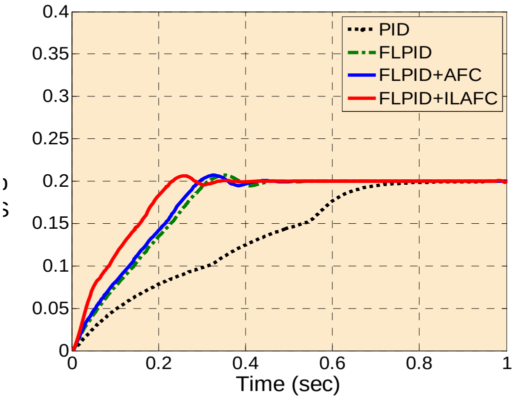

Figure 8. Wheel slip during braking case

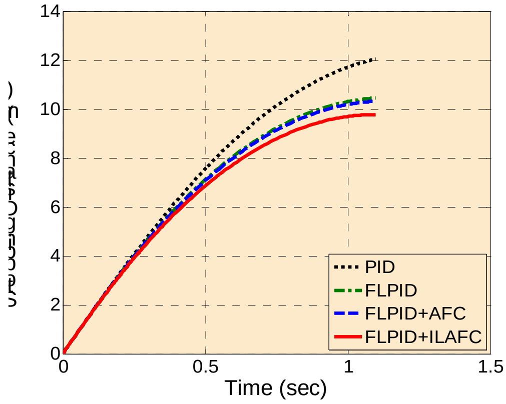

Figure 9. Stopping distance during the breaking on dry road condition

Table 3 shows the results of the stopping distances considering a number of different control schemes.

TABLE 3: STOPPING DISTANCES

	Dry road condition for (60 km/h)	
ABS controller	**Distance (m)**	**Time (sec)**
PID	12.12	1.75
FLPID	10.46	1.64
FLPID+AFC	10.34	1.131
FLPID+ILAFC	9.775	1.095

V. CONCLUSION

Simulation was carried out on an anti-lock brake system with slip ratio 0.2 as the reference input. A self-tuning PID controller has been designed and is implemented to the ABS via three different schemes. Firstly, a self-tuning PID controller for ABS under dry road condition has been considered. In this scheme, the PID gains have been appropriately tuned using the fuzzy rules. In the second scheme, a novel hybrid AFC controller has been proposed. In the third scheme, the proposed self-tuning PID and AFC controllers has been enhanced by iterative learning algorithm. To perform an acceptable result, it was applied to estimate the best value of estimated mass. The performances of the PID controller with fuzzy logic and proposed controllers are compared through a rigorous simulation study. In contrast, iterative learning with fuzzy logic scheme demonstrates more improved performance than the conventional controller including the fuzzy self-tuning PID method. In brief, the stability, robustness, and accuracy of the system is greatly enhanced, thereby implying that the vehicle has adequate lateral stability and good steerability in dry road conditions. Other loading and operating environments could be experimented in future works. The validation of the proposed algorithms via a practical system is currently undergoing.

ACKNOWLEDGMENT

The authors gratefully acknowledge the Universiti Teknologi Malaysia for their full support of this research through a fundamental research university grant scheme (Vote No.: 013J38).

REFERENCES

[1] C. Altrock, "Fuzzy logic technologies in automotive engineering", Wescon 94, Idea/Microelectronics Conference Record, September. 27-29, 1994.

[2] I. Petersen, Wheel slip control in ABS brakes using gain scheduled optimal control with constraints, Norwegian University of Science and Technology, Ph.D. Thesis, 2003.

[3] P. E Wellstead and N. Pettit, "Analysis and redesign of an antilock brake system controller", *IEE Proc. of Control Theory Application*. IEE, 1997, pp. 413- 426.

[4] A. B. Sharkawy, "Genetic fuzzy self-tuning PID controllers for antilock braking systems", Engineering Applications of Artificial Intelligence, vol. 23, no. 7, 2010, pp. 1041-1052.

[5] J. R. Hewit, J. S. Burdess, "Fast dynamic decoupled control for robotics using active force control", Mechanism and Machine Theory, vol. 16, no. 5, 1981, pp. 535 - 542.

[6] M. Mailah, "A Simulation Study on the Intelligent Active Force Control of Robot Arm Using Neural Network", Jurnal Teknologi, vol. 30, 1999, pp. 55 – 78.

[7] S. B. Hussein, H. Jamaluddin, M. Mailah, "A hybrid intelligent active force controller for robot arms using evolutionary neural networks", IEEE Intl. Conf. on Intelligent Systems and Technologies (TENCON 2000), September 2000, Kuala Lumpur.

[8] G. Priyandoko, M. Mailah, "Controller design for an active suspension of a quarter car model using fuzzy logic active force control", Proc. of the 2nd Intl. Conf. on Mechatronics. May 2005, Kuala Lumpur, pp. 693-700.

[9] R. Varatharajoo, C. T. Wooi, M. Mailah, "Two degree-of-freedom spacecraft attitude controller", Advances in Space Research, vol. 47, no. 4, 2011, pp. 685-689.

[10] M. H. A. Al-Mola, Robust intelligent active force controller for a Wagner brake model, Universiti Teknologi Malaysia, Faculty of Mechanical Engineering, 2009, Master thesis.

[11] Z. Omar, Modelling and simulation of an active suspension system using active force control strategy, Universiti Teknologi Malaysia, 2002, Master Thesis.

[12] K. Hudha, H. Jamaluddin, M. P. Samin, and R. A. Rahman, "Active roll control suspension system (ARCS) using active force control strategy on a new modified half car model", Society of Automotive Engineers, Warrendale PA, 2003.

[13] G. Priyandoko and M. Mailah, "Controller design for an active suspension of a quarter car model using fuzzy logic active force control", Proc. of the 2nd Intl. Conf. on Mechatronics, May 2005, Kuala Lumpur, pp. 693-700.

[14] W. Lutfi, "Modelling and control of intelligent antilock brake system", Universiti Teknologi Malaysia, Desember. 2005, Malaysia: Master Thesis.

[15] R. Varatharajoo, C. T. Wooi, and M. Mailah, "Two degree-of-freedom spacecraft attitude controller", Advances in Space Research, 2011, vol., no. 4, p. 685-689.

[16] M. H. Al-Mola, M. Mailah, S. Kazi, A. H. Muhaimin, and M. Y. Abdullah, "Robust active force controller for an automotive brake system", 3rd Intl. Conf. on Intelligent Systems Modelling and Simulation (ISMS 2012), 2012, pp. 467-472.

[17] M. H. Al-Mola, M. Mailah, A. H. Muhaimin, and M. Y. Abdullah, "Intelligent active force controller for an anti-lock brake system application", 1st Intl. Conf. on Systems, Control, Power, Robotics in Singapore (SCOPORO 2012), 2012.

[18] S. Arimoto, "Robustness of learning control for robot manipulators", Proc. of the IEEE Intl. Conf. on Robotics and Automation, Cincinnati, Ohio, U.S.A., 1990, pp. 1528-1533.

[19] S. Arimoto, T. Naniwa, and H. Suzuki, "Robustness of P-type learning control with a forgetting factor for robotic motions", Proc. of the IEEE 29th Conf. on Decision and Control, Honolulu, Hawaii, U.S.A., 1990, pp. 2640-2645.

[20] K. Hamamoto and T. Sugie, "Iterative learning control for robot manipulators using the finite dimensional input subspace", IEEE Trans. Robot. Automat., 2002, 18(4). 632-635.

[21] M. Norrlöf, "An adaptive iterative learning control algorithm with experiments on an industrial robot", IEEE Trans. Robot. Automat. 2002, 18: 245–251.

[22] A. R. Tavakolpour, M. Mailah, and I. Z. Mat Darus, "Self-learning active vibration control of a flexible plate structure with piezoelectric actuator", S*imulation, Modelling Practice and Theory*, 2010, vol. 18, no. 5, pp. 516-532.

[23] M. Mailah and J. Chong, "Control of a robot arm using iterative learning control with a stopping criterion", *Jurnal Teknologi,* 2002, vol. 37, pp. 55-72.

[24] S. Chunting Mi, L. Hui, and Y. Zhang, “Iterative learning control of antilock braking of electric and hybrid vehicles”, IEEE Trans. on Vehicular Technology, 2005, vol. 54, no. 2.

[25] F. Tianku, Modeling and performance analysis of ABS systems with nonlinear control, Montreal, Canada, Concordia University, 2000: Master Thesis.