112 The Study of ABS control system with different control methods

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In this paper, an ABS control system is studied by considering the design of a practical controller and its implementation with four kinds of control methods, conventional threshold, fuzzy logic, variable structure sliding mode and PID. The control accuracy and robustness are analyzed considering the non-linear tire characteristic and hydraulic actuation system. These ABS control methods are then simulated, and the results are evaluated.

Keywords/ ABS, Control algorithm, Nonlinear system , Simulation, Wheel slip.

1. INTRODUCTION

ABS control systems have been extensively applied in all kinds of vehicles. The technology of ABS is widely regarded as a mature one. However, the control methods for practical ABS system are mostly based on thresholds of deceleration and wheel reference slip. These methods are simple and reliable, but require much experimentation for implementation and for matching correct technology to different vehicles. Furthermore, the process of control always results in some oscillation of the wheel slip around its optimal point, which degrades for both the feeling of the system and its braking performance. Recently, slip control has appeared in the literature and has been implemented in prototype vehicles. Many systems of slip control try to get better performance than conventional ABS. On the other hand, slip control ABS is easy to be combined with other vehicle dynamic control system, such as IVD. The method of slip control is the ideal method in theory. It relies on keeping the real slip rate at an optimal target slip using continuous control during braking, resulting in optimal braking performance. However, the difficulty for this kind of control system is that the optimal slip point must be selected properly, and the velocity of vehicle must be estimated or measured in a low cost and reliable way in order to develop this method into a practical product.

Considering the ABS control based on slip, the important thing is the robustness of the control system due to various vehicles and surface conditions, and various disturbances which affect control performance. The accuracy becomes less important than robustness. Therefore, developing robust control system for ABS becomes more and more important. Recent years a large amount of literature appears in this area[1][2][3] studying each method separately and mainly focusing on aspects of theory of control. There is little research into the practical aspects of implementation and little comparison with different systems. Therefore, in this paper, we study four different control methods: traditional deceleration threshold, PI control with gain scheduling, variable structure sliding mode and fuzzy logic control. The threshold control is regarded as a comparison. The other three are usually regarded as robust control systems that are popular for use in automobile control systems. The purpose is to find a good control method for practical application.

2. THE BRIEF DESCRIPTION OF MODEL FOR VEHICLE DYNAMICS SYSTEM

The vehicle model is described by seven degrees of freedom which include rotational dynamics of four wheels, and longitudinal, lateral and yaw motion of the vehicle body. The tire model uses a "Magic Formula"[4]. According to physical principles, the equations that describe these dynamics are built and solved by a digital differential method using C or FORTRAN programming. Those programs, which are taken as users programs and embedded in the Xmath environment, combine input and output interfaces and the control system to form the whole simulation system. The system can be developed into a real time system using hardware such as ISI's AC100.

In addition to a good vehicle model, it is important to model properly the hydraulic braking system which is key to understanding controller in simulation and easily validating hardware. The physical equation for build and damp valve flow is described as:

$$Q = PWM \cdot A_s \cdot C_D \cdot \sqrt{\frac{2 \cdot |\Delta P|}{\rho}}$$

The caliper volume is calculated by integrating the difference between build and dump valve flows. The pressure in the clipper is calculated using a third order algebraic equation obtained from experimental data. In order to achieve good control effectiveness in a continuos system, the ideal method is to use a proportional pressure valve or servo pressure valve as the actuating system. However, this is too expensive to develop into a practical ABS system. A suitable method is to use high speed on/off valves to realize the continuous control by PWM. The relationship of PWM signal and flow which can be regarded as an effective coefficient of area can be determined by experiment.

In the following control system, two types of hydraulic systems are required: flow control and pressure control. Flow control requires a linear relationship between PWM signal and flow. Pressure control requires linear relationship between PWM signal and pressure. From equation(1), it can be found that this system is non-linear system which will result in many problems. This system can be linearized in some way. However, it is more difficult to linearize the pressure and PWM because the pressure has a relation with time history of flow which can be represented by a third order algebraic equation of caliper volume.

3. The design of control system

Both classic and modern control theory are mainly established on the basis of linear systems while there is not a universal method to deal with non-linear systems. The control method now implemented in most of controllers in vehicle use looking-up table methods. ABS control in products uses this method which requires a lot of experiment to calibrate the controllers. Modern control theory based on system models can be difficult to apply to automobile control systems which have strong non-linear factors that are difficult to model, requiring many measurements and much matrix calculation. The common method for dealing with non-linearity is to linearize the non-linear system at several working points. Digital PID is a practical method which can be applied to both linear and nonlinear systems, and many improvements such as anti wind up and gain scheduling can be found in practical applications and can be easily implemented in a controller. Variable structure sliding mode and fuzzy control are kinds of robust system which are suitable to nonlinear systems and can be easily implemented in hardware. So, from the practical point of view, these control methods are candidates for ABS control.

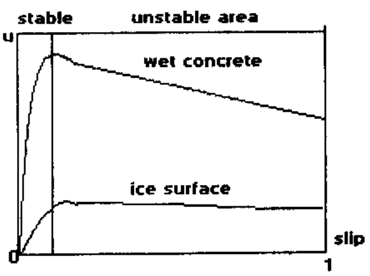

Fig 1 The tire characteristics

The dynamic system of a vehicle is a high non-linear primarily due to tire properties. Fig.1 shows typical tire characteristics under two different road surfaces. It can be found that on each surface there exists a peak between 5%-20%. When slipping below this peak, the friction coefficient increases with slip. This can be called the "stable area" referring to a open loop vehicle dynamic system. When slipping above this peak, the friction coefficient decreases with slip. This can be called the "unstable area" Here, a small force will result in large change of slip. The tire can be modeled with a bilinear model to represent the stable and unstable regions. This is difficult to realize in vehicle because it requires identifying the tire characteristics to determine the stable and unstable areas and sometimes the magnitude of the peak value of friction. Secondly, the control energy in the unstable area often requires large decrease which is beyond the ability of hydraulic system that can provide. Another method is to consider only the stable area and regard the unstable area as the disturbance of stable area. It can be easily found in Fig.2 that the disturbance is small in low (and large in high (which have a negative slope. The literature [1] has proven that the vehicle dynamics with negative slope of tire characteristics is unstable physical system referring to open loop system.

Additionally, the non-linear nature of the hydraulic actuation system also brings difficulty to the design of controller. Controlling the slip rate directly by flow requires a good linear relationship between flow and PWM control signal which represents the orifice opening of the PWM valve. From equation (1), it can be seen that the flow depends on not only the orifice opening but also the square root of the pressure difference upstream and downstream of the valve. In practice, this should be accounted for when controlling the valves. Even more important is to cancel the valve "dead band" which dictates the control duty circle needed to open the flow valve. In order to realize the pressure control with flow, we should form a cascade control system using caliper pressure control as the inner loop and slip rate control system as the outer loop. The cascade control system requires faster dynamic response in the inner loop than in the outer loop to obtain stable control. When operating on high which requires high pressure, the pressure difference across the build valve reduces, reducing the flow given the same orifice opening resulting in a slower dynamic response. When ABS functions in the unstable tire curve area (which has fast wheel dynamics), stable ABS control become difficult task due to the above reasons.

The following four kinds of control methods are briefly introduced:

3.1 Threshold Control

This is a conventional control method which has already been applied widely in ABS products. There are a lot of many publications reporting the research on this subject. In this paper, a simple description can be given:

$Ka = C_s \times S_{ref} + C_a \times A$ (2)

Where Ka is the synthesized deceleration and acceleration threshold, Cs, Ca are the weighing factors of reference slip rate and deceleration threshold respectively, Sref is the reference slip rate, A is the deceleration of the controlled wheel.

The control law can be expressed as:

$Ka < -a_1$	pressure decrease	
$Ka > +a_2$	pressure hold	(3)
$Ka > -a_3$	pressure increase	

Where a_1, a_2, a_3 are the threshold of acceleration and deceleration.

3.2 PID Control

The general Proportional, Integral and Derivative control (PID) has been adapted widely to industry, which is suitable to both linear and non-linear dynamic system. Many different methods and variations of PID have been developed, such as anti-wind up to tune the PID parameters properly. In order to realize the slip rate control, an inner loop control for pressure may be added, (see Fig. 2) to form a cascade system in which the inner

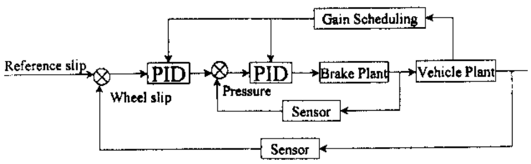

Fig. 2 PID Control for Pressure and Wheel Slip

loop is pressure control and outer loop is slip control. The incremental algorithm is adapted for a PI controller with different gains in different range of error and gain scheduling for different road surface.

$P^i = P^{i-1} + \Delta P$

$\Delta P = K_{i1} \times E^i + K_{p1} \times (E^i - E^{i-1})$ $|E^i| > |error|$ (4)

$\Delta P = K_{i2} \times E^i + K_{p2} \times (E^i - E^{i-1})$ $|E^i| < |error|$

Where P^i, P^{i-1} are the control value in two consecutive time steps, K_i, K_p are the proportional and integral parameters, and E^i is the control error.

3.3 Variable Structure Sliding Mode Control

Variable structure sliding mode control should be divided into two parts. The first part is sliding mode control in which the phase track is kept on the sliding surface. This is a kind of continuous control based on the system model. The second part is the variable structure section in which the phase track approaches the sliding surface. This part has no relationship with the system model as long as it satisfies the sliding mode condition. This is the advantage for variable structure control, it is robust. During ABS control process, it is difficult to control on the sliding surface due to its non-linearity and uncertainty. In this paper, two kinds of variable structure are designed in which when the phase track is far away from the designated sliding surface, the large control energy is adapted. When the phase track approaches the sliding surface, the small control energy is adapted. In this way, the magnitude of chatter on the sliding surface can be reduced and at the same time, the fast response of dynamic system can be obtained. The designed sliding surface is :

$$S = E' + \lambda \times E \quad (5)$$

The sliding condition is: $S \times S' < 0$ which should be satisfied for researching sliding surface. The control law is as follows:

$S > S_1 > 0$	Q_{large-}	
$S < -S_1 < 0$	Q_{large+}	(6)
$0 < S < S_1$	Q_{small-}	
$-S_1 < S < 0$	Q_{small+}	

Where λ is a weighing factor, S_1 is the designated sliding error range, E is slip rate error, and Q is flow command, the symbol "+","-" represent input and output flow to and from calipers, "large" and "small" represent large and small flow.

3.4 Fuzzy Logic Control

Fuzzy logic control is based on experience rules produced by human being. It has no direct relation with the system model, and has good robustness and feasibility for non-linear system. However, there exists a problem in calibration due to its lack of theory. The control laws are made by method of trade-off. Nevertheless, most of fixed target control systems have similar pattern which can be easily summarized from a control rule set table into a simple formula which is similar to PD control (self-organizing fuzzy control method):

$U = \alpha \times E + (1-\alpha) \times DE$ (7)

Where α is a weighing factor, E,DE are linguistics variables for the error of slip rate and its derivative, and U is linguistics variable for control flow.

Through defuzzization of U, the real control value can be obtained (PWM signal). Under a large error, E has a large effect. While weighing a large factor on E, the control energy mainly functions to reduce the error. Under a small error, the control system mainly functions to reduce the change of error in order to achieve stable target tracking, which can be attained by a large weighing factor on DE. In this paper, variable weighing factors are adopted according to error range and vehicle speed.

4. ANALYSIS OF SIMULATION RESULTS

In order to implement ABS and add it to IVD system easily in a vehicle, only front wheels are braked with ABS functions, and rear wheel are free , from which a vehicle velocity as well as front wheel slip can be obtained.

The simulation conditions are straight braking on ice (μ=0.1) and wet concrete surfaces(μ=0.6). The initial velocity of the vehicle is 20m/s. The type of vehicle is a Taurus SHO. In order to compare the performance of the control algorithms, two typical conditions are designated: even friction road and friction coefficient transition from high μ to low μ. On an even μ surface, two kinds of targets of slip rate are selected: one locates in stable area of tire, another locates in the unstable area of tire, which means that there is a large disturbance to the linear dynamic system, especially on the high μ surface. On the low μ surface, the targets of slip rate are 0.2 and 0.4, while on high μ surface the targets of slip rate are 0.05 and 0.2. The threshold control doesn't have this problem, since it has no targets. The reason for selecting different targets is to examine the robustness of the control algorithm under real conditions, since during the braking it is very difficult for the vehicle control system in real time to determine the position of slip peak for the tire and its magnitude. Therefore, it is difficult to determine a proper slip target which is in the stable area and approaches the peak value of the friction coefficient. This requires a robust control system. This means that under any condition, the system can achieve stable control. Since some parameters of controllers are designed according to road surface (gain scheduling), the condition of road surface jump from high μ to low μ is imposed to examine the fast adaptation of the control system. The slip target is 0.1 under those two kinds of road surface.

The evaluation of performance index for the simulation results are braking distance and the square sum of error in order to evaluate the robustness and accuracy of control system. The square sum of errors can be expressed as $\sum (S - S_0)^2 \cdot \Delta t$. The simulation results on the ice surface are shown in figure 3 for four kinds of

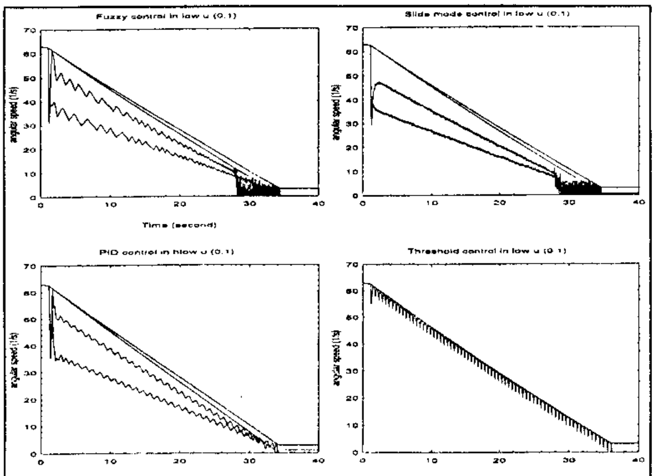

Fig. 3 Simulation results for low μ with slip targets 0.2 and 0.4

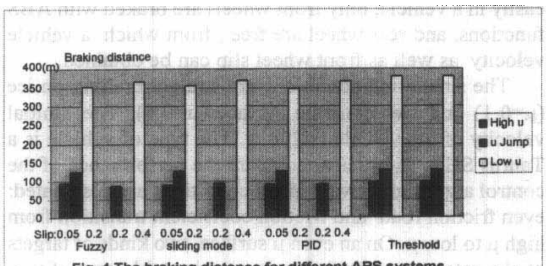

Fig. 4 The braking distance for different ABS systems

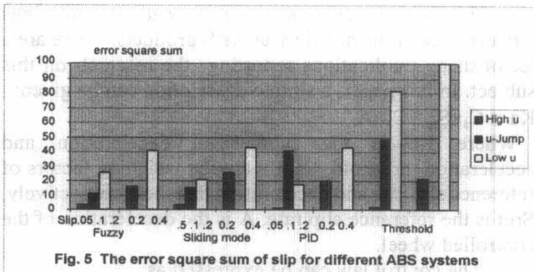

Fig. 5 The error square sum of slip for different ABS systems

control algorithms. Two slip targets are set by using the same control parameters to examine the performance and robustness of the controllers. With the exception of the conventional threshold ABS control, the three slip controller all can follow the slip target and maintain stable control. However, each system produces a unique response with unique square errors and braking distances. It can be seen in figure 4 that the threshold controller produces a relatively long braking distance, while the other three slip controller produce almost the same braking distance. This is due to the special characteristic of threshold control in which it cannot maintain the maximum friction coefficient during the ABS control process. From figure 5, it can be seen that PID control has the smallest error at the 0.2 slip target, while fuzzy control has a slight error at 0.4 slip target. However, when the wheel speed is more than approximately 10 rad/s, the variable structure controller has the smallest error and oscillation of wheel speed. The threshold control has the largest oscillation of wheel speed and the largest error because its control logic has this kind of oscillation essentially. Fuzzy logic and variable structure control produce oscillations of wheel speed at low vehicle speed. This is because the type of control that they adopt is on-off which controls the flow by finitely switching PWM. The accuracy of control is limited by this kind of discrete control method. Otherwise, the switching quantity must increase greatly to get control accuracy . This is difficult to implement in a controller. At the same time, in the range of small flow which is required at low speed . The relationship between the opening of the valve orifice and the hydraulic flow is highly non-linear, which makes control difficult. At low wheel speed, the required hydraulic flow is very sensitive to wheel speed. In this case, proper control requires a large weighing factor on the change of error and a decreased weighing factor on error. This may limit the change of error, resulting in a longer braking distance. We need to calibrate the control parameters carefully in this area. The advantage of the variable structure is that it has only one sliding surface on which the control energy switches. As long as there is a sufficient supply of fast energy for the controller, good control performance can be achieved. This control requires a reliable valve due to its high speed switching. Fuzzy control uses the magnitude of error and its derivative to obtain the control effect with finite classifying of the control range . If the control classes are further divided, the control accuracy is improved, but the implementation of the controller becomes more difficult. In the implementation of a fuzzy controller for this report, a class of control ranges is given such that the control accuracy does not appears to be good. This situation can be improved as long as the parameters are calibrated carefully.

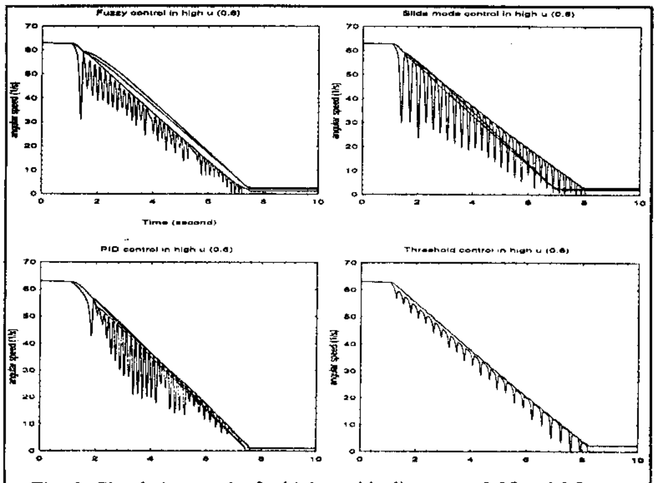

Fig. 6 Simulation results for high μ with slip targets 0.05 and 0.2

It is difficult for an ABS system to get good control results on a highμ surface as the above mentioned reasons explained. To demonstrate this, two slip rate targets are set in the stable and unstable tire curve areas respectively. Fig 6 shows the simulation results. As on low μ, threshold control has a long stopping distance as compared to the other three slip controllers which show little difference in braking distance. As seen in figure 4 to 6, PID control has the smallest error , while and fuzzy and variable structure control have slightly larger errors when the slip target is set in the stable area. When the slip target is set in the unstable area, the three slip control algorithms produce different levels of oscillation of wheel speed. Fuzzy control has slightly smaller errors which means that it is a robust controller, while variable structure control produces large error. It is difficult to use the same control parameters for different slip rate targets. It is obvious that it needs large gain for proportional coefficient or large weighing factor for slip error due to the large slope of the tire characteristic so that the controller can cancel the error quickly and get short braking distances. While in the unstable area of slip, the braking torque is very sensitive to tire slip due to the small negative slope of tire characteristic. It requires small gain for the proportional coefficient or large weighing for the change of error so that the oscillation of the wheel speed can be limited resulting in stable control. However, it is difficult for a practical controller to implement a real time algorithm to identify tire characteristics such as the position and magnitude of friction the coefficient. There is no mature technology to do so at present. Therefore, the controller should compromise those two situations and select one set of parameters for the controller to be suitable for slip control in both the stable and unstable area, although calibrating control parameters separately in different areas will result in better control.

In order to examine the robustness of the controllers and its fast adaptation , a μ transition test is used. Assuming that the control system could roughly identify the surface condition such as high μ or low μ which can be realized by present technology μ we have applied it successfully in traction control system) , a 0.1 slip target is set for both high μ and low μ surface, which implies that on high μ, the slip target is in unstable area and on low μ the slip target is in stable area. Of course the optimal condition is to take the slip of peak friction coefficient as the slip target, but this is difficult to realize in a practical control system as explained above . Since the surface condition can be known roughly , the control system can use different control parameters on different surfaces to obtain optimum braking control results. From the figure 7

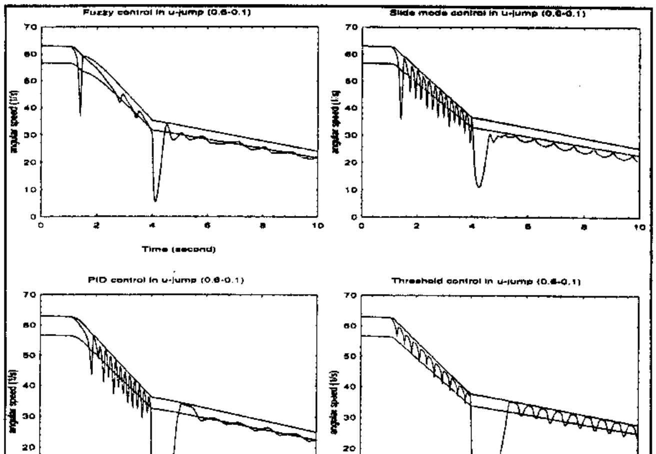

Fig. 7 Simulation results for μ transition with slip targets 0.1

simulation results it can been seen that fuzzy control produces results in braking performance and control error (see figure4,5) while threshold control has slightly poorer performance. From the point of view of adaptation, fuzzy and variable structure control all can get quick recovery of braking torque increase from the μ transition, while PID control has a slow recovery of braking torque increase since it is producing an initially large braking torque before the transition of μ, which needs a period of time to reduce the braking torque. This means that the control command according to the PID algorithm has a relationship with the time history, while the control command according to fuzzy and variable structure control only has a relationship with present error and its derivative value so that it is easy for control system to adapt to this abrupt change.

It should be pointed out that the above simulation results are not the optimal effect for each controller. Some controllers could get better control results through calibrating control parameters carefully, but it may not change greatly the conclusion for evaluating each control algorithm. Furthermore, the same effect is made to calibrate the parameters of controller. From the calibrating process, fuzzy control is the easiest to implement in a control algorithm, while PID and threshold control need to spend some time and human efforts to calibrate its control parameters carefully. It is difficult to find a large range of stable parameters for PID control . This means that control stability is very sensitive to PID parameters which make PID difficult to implement in a real controller. Variable structure control need to satisfy the sliding condition which is slightly complicated. From the point of view of the implementation of a controller, conventional threshold is so easy that it only needs input signal of wheel speed, but its software is complicated. Next, fuzzy control and variable structure are easy , which need input of wheel speed and vehicle speed. PID control is complicated to implement, in which a inner loop for pressure control is required, which needs the measurement of pressure, wheel speed and vehicle speed.

Each of the control algorithms has unique characteristics. A combination of them may produce an effective control method, for example, slide mode+ fuzzy, fuzzy+PID, slide mode + PID etc., as long as proper switch conditions for the two kinds of control systems are established. In this way each advantage of control can be developed, and the disadvantage of each can be limited. The control frame for each control system is summarized in figure 8.

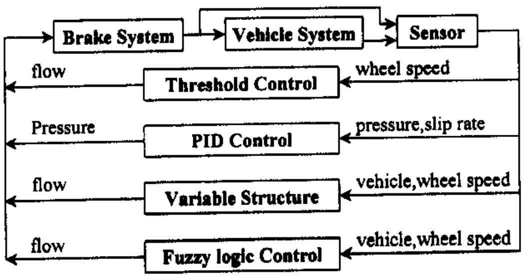

Fig. 8 The Control Frame for four kinds of ABS Systems

5. CONCLUSION

In this report, four kinds of control methods are studied. From the above study, it can be concluded that it is difficult to for one control system to get optimal control accuracy and robustness under all kinds of braking conditions. At the same time, the level of complication and cost for each controller is also different. Fuzzy control is robust and easy to implement but is not good in performance index. Variable structure control is similar to fuzzy control and has slightly better control accuracy but it requires high reliability for actuation system due to the high speed switch near the sliding surface. PID control is simple with good accuracy but poor robustness and requires pressure seniors in implementation. Conventional threshold has a complicated algorithm in software but low cost in hardware. Therefore, it is better to integrate different control system to offset the defect each other so as to get good control performance. For example, PID+Fuzzy combination can take advantage of the robust of fuzzy control and the accuracy of PID control. Since there exists some defects in hydraulic control system, the relationship between the PWM signal and flow is strongly non-linear, especially in the range of small flow which is very sensitive to the control accuracy. Care should be taken to focus on the study of linearization of flow and PWM by changing the period of PWM or by conversion of the valve flow equation. On the other hand, the pressure proportional valve of PWM or pressure servo can be used as control actuation system instead of flow valve of PWM, which can result in fast linear hydraulic system to improve the control system. Also, the design and calibration of controllers in this report are mainly based on trade off methods, which lack the foundation of control theory and analysis. Those problems should be resolved in a future study. Also the field test should be carried out to validate the various control algorithms.

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REFERENCE

[1] W.C.Lin etal, "Design and analysis of an antilock brake control system with electric brake actuator," Int. J. of Vehicle Design, Vol.14 No.1 1993 p13-43.

[2] Marjan Voit etal, "Methodology for the design of a new strategy in vehicle braking: simulation and comparison of algorithms," Proc. of AVEC'94, 1994, pp. 485-491.

[3] Georg F. Mauer etal, "Fuzzy logic continuous and quantizing control of an ABS braking system," SAE paper 1994 No. 940830.

[4] Bakker,E.,H.B. Pacejka, and L. Lidner (1989)"A New Tire Model with an application in Vehicle Dynamics Studies,"SAE Paper 890087.