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Design of Antilock Brake System for a BAJA Vehicle

Nikhil A. Bhilare[1] and Satyajit R. Patil[2]

[1]*S.Y.M. Tech. Student, Automobile Engineering Department, Rajarambapu Institute of Technology, Sakharale, Dist. Sangli, Maharashtra, India*
[2]*Mechanical Engineering Department, Rajarambapu Institute of Technology, Sakharale, Dist. Sangli, Maharashtra, India*
E-mail: [1]bhilarenikhil29@gmail.com, [2]satyajit.patil@ritindia.edu

Abstract—*In recent years, the functionality of vehicle braking systems has been improved by electronic controls. This use of electronics has led to the development of wheel-slip control systems such as Antilock braking system. To improve the vehicle safety, antilock brake system is one of the most important systems. It is well known that wheels will slip and lockup during severe braking or when braking on a slippery road surface. This usually causes a long stopping distance and sometimes the vehicle will lose steerability. In BAJA competition the vehicle must have to face the situation like severe braking which may lead to longer stopping distance and loss of steerability. However present BAJA vehicle at RIT is not equipped with ABS. In order to provide the design characteristics necessary to improve stability against skidding or locking of wheel, it is essential to have an anti lock braking system to BAJA vehicle. This work is concerned with the design methodology used and its selection for various components of antilock brake system like master cylinder, wheel cylinders, sensors, controller etc. of antilock brake system for a BAJA vehicle.*

1. INTRODUCTION

The antilock brake system (ABS) is one of the most important and commonly used active safety system used in present passenger cars. ABS is recognized as an important contribution to road safety as it is designed to keep a vehicle steerable and stable during heavy braking moments by preventing wheel lock. It is well known that wheels will slip and lockup during severe braking or when braking on a slippery road surface. This usually causes a long stopping distance and sometimes the vehicle will lose steering stability. Baja SAE is an intercollegiate design competition run by the Society of Automotive engineers where students have to design and build small off-road cars. RIT is also part of this competition. Students of automobile and mechanical engineering department have successfully participated in this competition and obtained good ranks in various testing. In BAJA competition the vehicle must have to face the situation like severe braking which may leads to longer stopping distance and loss of steerability. However present BAJA vehicle at RIT is not equipped with ABS. So to provide the design characteristics necessary to improve stability against skidding or locking of wheel, it is essential to have an anti lock braking system to BAJA vehicle.

When a driver applies the brakes, the shoes/pads cause the rotating wheel to slow down relative to the ground. This generates slipping between the road and the tire, and this slip generates the braking forces on the vehicle. As the driver increases brake pressure, the slip increases and generates higher braking forces. This process is limited by the static coefficient of friction between the road and the tire. Beyond that point, the slip increases uncontrollably, and at 100% slip the wheel is locked.

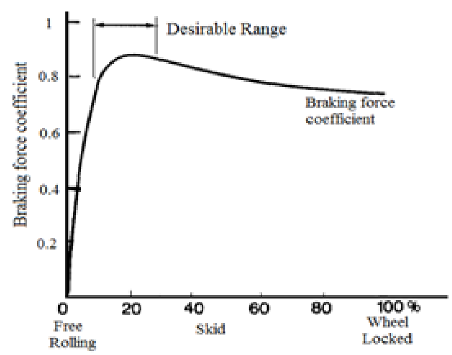

Fig. 1: Desired range of slip ratio.

Many theories and design methods for antilock brake system have been proposed by several literatures for different types of vehicle. Huang et al. [2] have proposed an ABS system to motor cycle. Researchers have mainly focused on controller design and considered a slip ratio as a controlling parameter. Duksun et al. [3] have used a sliding mode controller for ABS and carried out test for various types of road condition. Naderi et al. [4] have combined sliding mode controller with fuzzy logic controller to improve performance of ABS. N. Raesian et al. [5] have proposed a PID controller for ABS. Many researchers have presented mathematical models of ABS.

Cheli et al. [6] have prepared a simplified numerical model. But detail designing of different components used in ABS has not been taken in to consideration. Also there is no any literature available on designing of ABS for BAJA vehicle. So this paper presents the design methodology used for components of ABS in detail. This work will provide roadmap for designing antilock braking system for BAJA vehicle.

2. PRINCIPLE OF ANTILOCK BRAKE SYSTEM

Typical antilock brake system shown in Fig. 2 consists of master cylinder, solenoid valve, electronic control unit, accumulator and pump. Force applied by brake pedal pressurizes the fluid in master cylinder used to apply brake force on the wheel. Wheel speed sensor attached to wheel senses the speed and gives signal to the electronic control unit (ECU). Then ECU sends the signal to the solenoid valve to reduce the brake pressure if one or more wheels get locked. After receiving the commands solenoid valve allows the brake fluid to flow from brake caliper cylinder to the accumulator. The stored fluid in accumulator is pressurized by pump and sends back to the master cylinder.

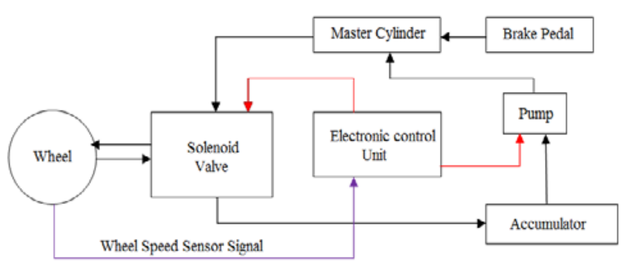

Fig. 2: Line diagram of Antilock Brake System.

3. DESIGN OF ANTILOCK BRAKE SYSTEM

Designing of antilock brake system consist of designing of master cylinder, accumulator, pump and selection of component like wheel speed sensor, solenoid valve etc. The dimension of BAJA vehicle to which antilock brake system is designed is as shown in table 1.

Table 1: Dimension of BAJA vehicle.

Total weight	280 kg
Wheel base	1500 mm
Wheel track at front	1346 mm
Wheel track at rear	1295 mm
Tyre radius at front	286 mm
Tyre radius at rear	686 mm

3.1 Design of master cylinder

At first from above measured parameter the center of gravity of the vehicle is determined. As we know that, after braking total kinetic energy of the vehicle will be equal to work done in bringing the vehicle to rest [7]. So average braking force required by the vehicle for complete stop is given by

$$\therefore F = \frac{mv^2}{2\times s} \quad (1)$$

In above equation F is the average braking force, m is the mass of the vehicle, V is the maximum velocity of the vehicle. S is the stopping distance of a BAJA vehicle which is determined by using motions of equations. After braking there will be transfer of weight from rear axle to front axle. So to calculate actual braking torque, the dynamic weight transfer during braking has to be considered while designing [8]. So this dynamic weight transfer is given by

$$w_d = \left(\frac{h}{l} \times \frac{W}{g} \times D_x\right) \quad (2)$$

Where h is the height of center of gravity from ground, W is the total weight of vehicle, D_x is the deceleration of the vehicle during braking. In normal practices the braking torque required is calculated by multiplying the total weight on the respective axle and wheel radius. So for perfect braking the produced torque should be equal to required torque T. The torque produced by fixed type of brake caliper is given by

$$T = 2\mu PAR_e \quad (3)$$

In above equation P is the pressure required to be produced by the master cylinder, A is the area of brake caliper cylinder, R_e is the effective radius of rotor disc and μ is the coefficient friction between disc and brake pad. Most of the high performance car benefits from the largest possible rotor that will fit. Maximum rotor diameter is about 75 mm smaller than wheel diameter. So the pressure required is calculated by using above equation. Now from the brake fluid volume analysis of a hydraulic brake system it follows that the fluid displaced by the master cylinder equals the fluid absorbed by the individual wheel cylinders due to their piston travel to press the brake pad against the rotor [9].

$$\text{So } V_{mc} = V_{wc}\left(\frac{\pi}{4} {d_{mc}}^2\right) \times l_{mc} = \left(\frac{\pi}{4} d_{wc}^2\right) \times l_{wc} \quad (4)$$

Where V_{mc}, d_{mc}, l_{mc} is the volume, diameter and piston displacement of master cylinder respectively and V_{wc}, d_{wc}, l_{wc} is the volume, diameter and piston displacement of wheel cylinder respectively. In hydraulic disc brake system the displacement of wheel cylinder piston equals twice the coefficient of friction μ between disc and brake pad [9];

$$\therefore l_{wc} = 2\mu$$

As BAJA vehicle has four wheels, the number of wheel cylinder piston is equal to 8. So displacement of master cylinder piston is eight times the wheel cylinder piston. So diameter of master cylinder is calculated by using equation (4). Now consider the master cylinder as pressure vessel. So the thickness of master cylinder is given by,

$$t_{mc} = \frac{P \times d_{mc}}{2 \times \sigma_{all}} \quad (5)$$

Where t_{mc} is the thickness of master cylinder and σ_{all} is the allowable strength of material of master cylinder. So Table 2 shows the designed values of components used in ABS for said BAJA vehicle.

Table 2: Designed Values of Components of ABS.

Overall Braking Force Required	2747 N
Braking Torque Required	672980 N mm
Rotor Diameter	219 mm
Maximum Pressure Required	9.73 N/ mm2
Dia Of Wheel Cylinder	38 mm
Thickness of wheel cylinder	3 mm
Dia Of Master Cylinder	13.43 mm
Thickness of master cylinder	1.2 mm

3.2 Selection of Wheel Speed Sensor and solenoid Valve

The wheel speed sensors signal the wheel speed to the electronic control unit. The signal from a speed sensor is transmitted to the electronic control unit where it is evaluated and angular rotational wheel deceleration is determined. The ECU sends appropriate electronic control impulses to hydraulic pressure modulator valve. A proper response of the modulation valve requires a valid data point within approximately ten milliseconds [9]. To create a valid data point approximately sixty impulses are required. So it requires a specific number of impulses per pulse wheel rotation. So the number of impulses n_i per wheel rotation can be determined as follows,

$$n_i \geq \frac{(2\pi R \times 60)}{0.01\ V} \quad (6)$$

Where R is the wheel radius and V is the minimum vehicle speed after which the ABS will be turned off. So by using number of impulses per wheel rotation we can select the wheel speed sensor.

A solenoid is a magnetic coil operated by the ABS computer used to control the brake fluid. When power is applied to the solenoid, magnetic force opens and closes the valves, controlling the flow of brake fluid. Requirements of a solenoid valve are 1) it should sustain the maximum operating pressure. 2) The material of solenoid valve should be anticorrosive. 3) It should consume less power and should be suitable for high speed cycling. The solenoid valves are selected mainly based on the maximum operating pressure required to control and number of ports required. Generally for antilock brake system, number of ports required is three and equation 3 gives the maximum operating pressure. So we can select solenoid valve required for our system.

3.3 Controller Design

A controller is a small computer on a single integrated circuit containing a processor core, memory, and programmable input/output peripherals. Controllers are designed for embedded applications, in contrast to the microprocessors used in personal computers or other general purpose applications. To attain optimum brake retardation of the vehicle, a small amount of tyre to ground slip is necessary to provide the greatest tyre tread to road surface interaction.

When no slip takes place between the wheel and road surface, the wheel's speed and the vehicle's speed are equal. If, when the brakes are applied, the wheel circumference speed is less than the vehicle speed, the speed difference is the slip between the tyre and road surface. When the relative speeds are the same the wheels are in a state of pure rolling. When the wheels stop rotating with the vehicle continuing to move forward the slip is l00%, that is, the wheel has locked. So as from Fig. 1, the prime function of an antilock brake system is to prevent the wheels from locking, and ideally to keep the skid of the tire within a desired range in 10 to 30 percent. To control this operation 'C' program is written for the controller. A programming flow chart is shown in Figure. 3.

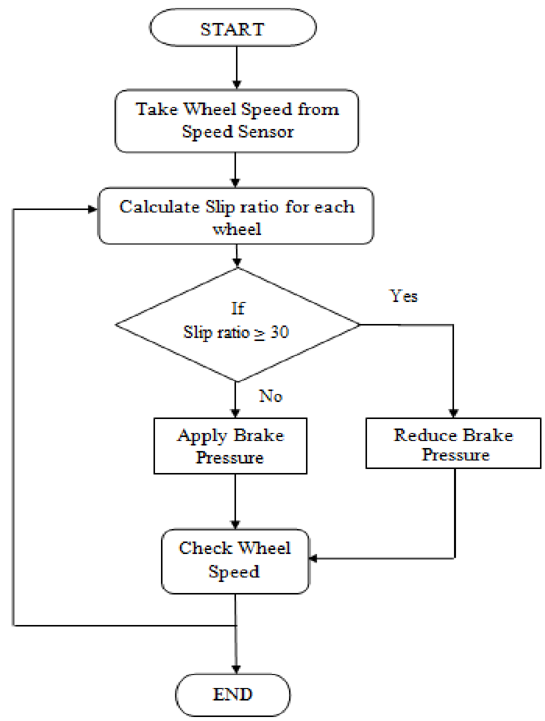

Fig. 3: Programming flow chart.

In this operation wheel speed sensor senses the speed of the each wheel and send signal to the electronic control unit. Electronic control unit calculates the slip ratio for each wheel which is the ratio of difference between vehicle speed and wheel speed to the vehicle speed. Then it checks whether the slip ratio is below 30 percent or not. If the slip ratio is above 30 percent then it will signal to solenoid valve to brake the flow of brake fluid from master cylinder to wheel cylinder so that brake pressure can be reduced and slip ratio will be maintained below 30. The cycle repeat itself until the vehicle is stop.

3.4 Accumulator and Pump Design

A hydraulic accumulator is a device that stores the potential energy of an incompressible fluid held under pressure by an external source against some dynamic force. The external source can be a spring, a raised weight, or a compressed gas. When the solenoid valve closes and stops the brake fluid from master cylinder, simultaneously it opens the valve from another side and allows the brake fluid to move from brake caliper cylinder towards accumulator. As the pressure of brake fluid is high, the accumulators are used to absorb the hydraulic line shocks and used extensively to maintain pressure in a circuit, especially where actuators are used.

Accumulator sizing is based on the pre-charge gas volume. The change in gas volume and pressure determines the amount of liquid that can be added or withdrawn. The exact shape of the accumulator characteristic curve depends on pressure–volume relations. When an accumulator is charged or discharged rapidly, there is not enough time for sufficient heat transfer through the accumulator walls cause adiabatic expansion. So for adiabatic expansion [10].

$$P_0 V_0^n = P_1 V_1^n = P_2 V_2^n \tag{7}$$

In above equation P_0, P_1, P_2 are the precharge gas pressure, minimum operating pressure and maximum operating pressure of gas and V_0 ,V_1 ,V_2 are the volume of gas at that pressure respectively. For practical purposes and to give a safety margin the value of P_0 is 4 to 6 times lesser than maximum operating pressure [9]. The maximum storage of liquid will be obtained when the gas precharge pressure P_0 is as close as possible to the minimum operating pressure P_1. So it is assumed that P_0 is 0.9 times the minimum operating pressure P_1 [9]. The difference between V_2 and V_1 is the maximum amount of fluid stored in accumulator which is equal to brake caliper cylinder volume.

$$\therefore \Delta V = V_1 - V_2 \tag{8}$$

So from equation (7) and (8) we get;

$$V_0 = \frac{\Delta V}{\left(\frac{P_0}{P_1}\right)^{\frac{1}{n}} - \left(\frac{P_0}{P_2}\right)^{\frac{1}{n}}} \tag{9}$$

After getting value of V_0 we can determine the size of accumulator or we can select accumulator from manufactures catalogue.

Pumps are used in antilock brake system to supply brake fluid to the master cylinder. The pump displacement V_g is defined as the volume of liquid delivered by the pump per revolution. Now as the volume of brake fluid moved from brake caliper cylinder to the accumulator, there will be extra fluid available at the accumulator. So this extra fluid should be pumped back to the master cylinder for next cycle. So the pump geometric displacement will be equal to brake caliper cylinder volume. Now ΔP is the pressure difference between pressure at outlet and pressure at the inlet of the pump. As the brake fluid is sucked from the accumulator which is at minimum operating pressure and pumped back to the master cylinder which is at maximum pressure. Hydraulic power required [11] by the pump is given as,

$$P_0 = 2\pi n T = V_g \times n \times \Delta P \tag{10}$$

Where P_0 is the power required to drive the pump, T is the torque required to the pump and n is number of revolution per second. So by rearranging the equation (11) we can calculate torque required to drive the pump.

4. CONCLUSION

In this work an attempt is made to design various components of antilock brake system for BAJA vehicle. In this ABS design, slip ratio is taken as controlling parameter. Various design procedures have been used while designing of different components. This design will be helpful for development of ABS system for BAJA vehicle which will lead to improvement in stability, reduction in stopping distance and prevents skidding of BAJA vehicle.

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