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Development of a Dc Motor Assisted Hydraulic Braking System for Automotive Use

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A B S T R A C T

Deceleration or stopping the vehicle without any diving and lateral acceleration is essential to develop an effective braking system. The hydraulic braking system with intelligent braking called Antilock Braking system (ABS) and Electronic Stability Control (ESC) has been introduced. However, due to the insufficient human effort, the ABS and ESC to some extent, not function well. This has been emphasized to develop a DC motor assist hydraulic braking system with associating the wheel speed and engine fuel flow sensor to stop the vehicle in required braking distance without any diving and lateral movement. This study investigates theoretically by Solid work simulation model and experimentally by product development. The simulation model has shown that a full load passenger car needs 15.7Mpa of braking pressure to stop 50km/h vehicle in 10m. The experimental results of the model show that the pressure develops when the pedal fully applied without and with aids of the DC motor is 910 kPa and 1130 kPa respectively, which contribute to 23.3% of pressure increase.

1. Introduction

Braking is an important safety feature of the vehicle, "as reported in National Transportation Safety Board-Special Investigation Report, 90% vehicle rear-end accidents and 60% frontal collision can be avoided effectively if the vehicle is braking ahead of time 1s"[1]. The conventional hydraulic brake has been used for last few decades and it has been broadly utilized in a variety of vehicles including trucks and buses. The disc brake is a component which slows down the rotation of the wheel by caused of friction. However, the performance of the braking system is not only depending on the friction of the brake disc, material of friction used and the size of brake pad, but it also depends on the force and pressure available in brake fluid line. For a better performance, the brake technology keeps on advancing it features in achieving a higher safety performance [2].

Electronic hydraulic brake system (EHBS) is one of the brake-by-wire system. The EHBS has its own characteristic such as simple structure, compatible with ABS and ESC system, without vacuum booster and used in recycling the braking energy easily [3]. The system that being introduced in this study is another alteration of current hydraulic braking system by means of dc motor assisted the braking system. The earliest proposed electro-hydraulic braking (EHB) system is improved from conventional hydraulic system that still has complex hydraulic hoses. Thus, BOSCH, Delphi and Siemens have all developed their brake-by-wire (BBW) systems and applied for many patents [2] . The BBW system can be applied to different platforms of vehicles. Therefore, it saves a lot of time in designing the

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braking system in different cars [2]. This study has emphasized more to electro-hydraulic braking system (EHBS) with an additional force assisted by means of DC motor. The system that being introduced in this study keeps all the components of ABS, traction control (ASP) and electronic stability program (ASR). The new system has been developed with the components such as, brake pedal mechanism, a push rod, a tandem master brake cylinder, an EHBS actuator, a valve control unit and wheel brakes. The EHBS actuator that is used as an electric power brake booster consists of a current-controlled electric motor. A pinion and rack is a type of linear actuator that engages a pair of gears which convert rotational motion into linear motion [4].

2. MATHEMATICAL MODELLING

Performance characteristics of a road vehicle refer to its capability to accelerate, decelerate and stops. The tractive or braking effort developed by the tires and resisting force acting on the vehicle determine the performance potential of the vehicle. [6] The maximum tractive force can be determined by using the equation of motion along the longitudinal x-axis. Therefore, the tractive force of the vehicle is expressed by:

$$F_t = R_a + R_r + R_d + R_g + \frac{a \cdot W}{g} \quad (1)$$

Where, F_t is total tractive force, R_a aerodynamic resistance, R_r rolling resistance, R_d drawbar load and R_g is grade resistance. There is a phenomenon during braking called as load transfer in which the load is delivered from rear to the front axle. Thus, the normal load on each axle can be determined by using the following equation (J Wong, 2001):

The normal load on the front axle is

$$W_f = \frac{1}{L}[Wl_2 + h(F_b + f_r W)] \quad (2)$$

The normal load on the rear axle is

$$W_r = \frac{1}{L}[Wl_1 - h(F_b + f_r W)] \quad (3)$$

The maximum braking force on each axle can be estimated by using the following equation:

$$F_{bf(\max)} = \mu W_f = \mu\left[\frac{W[l_2 + h(\mu + f_r)]}{L}\right] \quad (4)$$

$$F_{br(\max)} = \mu W_r = \mu\left[\frac{W[l_1 - h(\mu + f_r)]}{L}\right] \quad (5)$$

Where, μ is the coefficient of road adhesion, while W_f and W_r are the load distribution on front and rear axle respectively. For the simulation: the mass of the vehicle is 1793kg, road adhesion coefficient of 0.6, the height of the center of gravity h of 0.553m, vehicle distance L of 2.66m and distance of front axle to the center of gravity of 1.239m. Next, the force applied by the driver is expressed as:

$$F_d = P_h \times \frac{L_2}{L_1} \times A_{mc} \quad (6)$$

Where, P_h is Hydraulic Pressure of Master Cylinder, $L1/L2$ is brake pedal ratio and A_{mc} is Cross-section area of Master Cylinder. Then, the braking effort can be found by multiplying the coefficient of friction of brake pad, μ_b with the actuating force $F_{a(f)}$ as follow:

$$F_{b(f)} = \mu_b \cdot F_{a(f)} \quad (7)$$

During braking, the vehicle may take some distance before it stops. Therefore, the stopping distance can be estimated as:

$$S = \frac{v^2}{2 \times \mu \times 9.81} \quad (8)$$

Next, the torque and power consumption of the motor can be defined as:

$$T = F_m \times r_p \quad (9)$$

$$P = T \times \omega_m \quad (10)$$

Note that, F_m is the force delivered by motor, r_p is pinion radius of the motor and ω_m is the angular speed of the motor. By considering the formula of Power, $P = VI$ and considering the efficiency of the motor, $\eta_m = 90\%$, the current, I required by the motor can be calculated as follow:

$$I = \frac{P \cdot \eta}{V_b} \tag{11}$$

3. ELECTRO-HYDRAULIC BRAKING SYSTEM

The DC motor assisted hydraulic braking system is one of electro-hydraulic brake systems (EHBS). The advantages of this EHBS where the feedback force of the brake pedal to the driver is assisted by an electric power DC motor. In this system, the brake pedal force will be assisted by the DC motor where the overall system will be controlled by the wheel speed sensor, brake controller and proportional valve. As the illustration, Figure 4.1 shows the schematic diagram of this EHBS system:

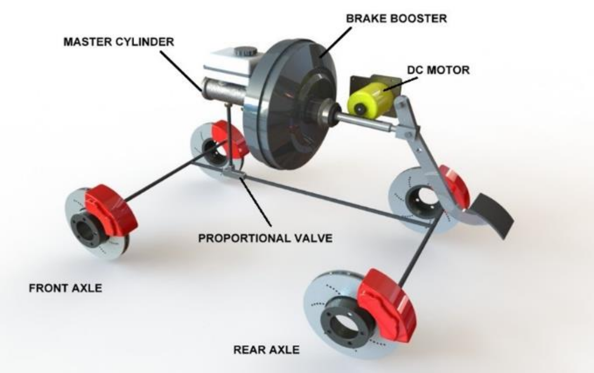


Figure *1:* DC Motor assisted hydraulic braking system

4. PERFORMANCE OF THE SYSTEM

4.1. Theoretically

Braking performance has been conducted theoretically by using Microsoft EXCEL to show the results of stopping distance, braking force and hydraulic pressure in graphical analysis. Some parameters are determined throughout the simulation process. The vehicle mass, m=1793kg, road adhesion, μ_p=0.6, frictional coefficient of brake pad, μ_b=0.46, lever ratio of 8:1 and master cylinder bore of 2.85 cm. Figure 2 shows the braking distance according to the vehicle sped. Result shows that the stopping distance increases as it stops at higher speed.

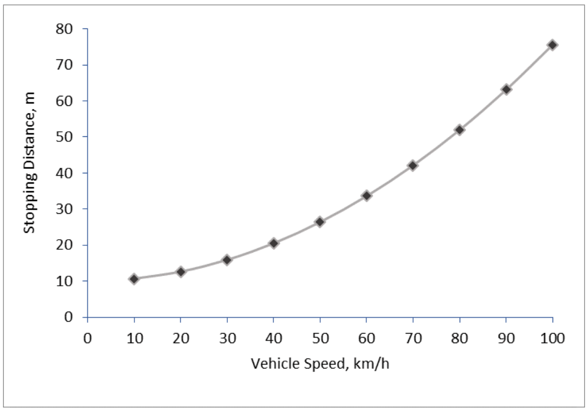


Figure *2:* Stopping distance of the vehicle

Once the stopping distance is known, the braking force, F_b can be found. Furthermore, by having the braking force, the actuating braking force, F_a which is the clamping force on the brake pad can be calculated from Eqn. (7). Thus, the following Figure 3 illustrates F_a and F_b:

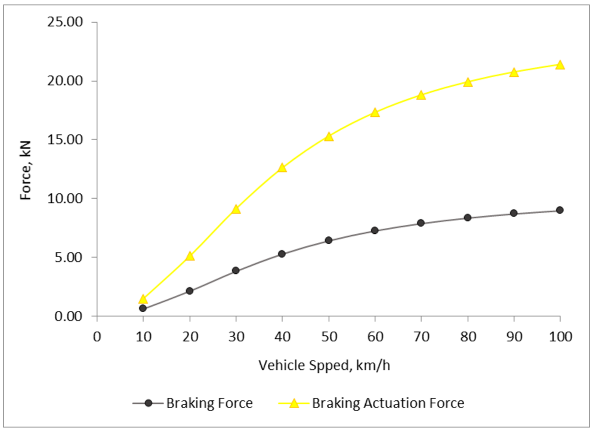


Figure *3:* : braking force and brake actuating force according to vehicle speed

By having F_a and $A_{p(mc)}$ and $F_a/A_{p(mc)}$ gives the hydraulic pressure, P_h in the master cylinder. This pressure is the required pressure needed by the brake system for full stop vehicle. Figure 4 shows the full illustration on pressure required, pressure developed by driver and the pressure developed by DC motor. There are lack of pressure for braking needed by the car starting from 30km/h and above. For example, the figure shows the pressure difference between the required and delivered for the car to stop from $50 km/h$ is $17.2 MPa$ Therefore, the lack of pressure will be assisted by DC motor that will give additional force on the brake pedal:

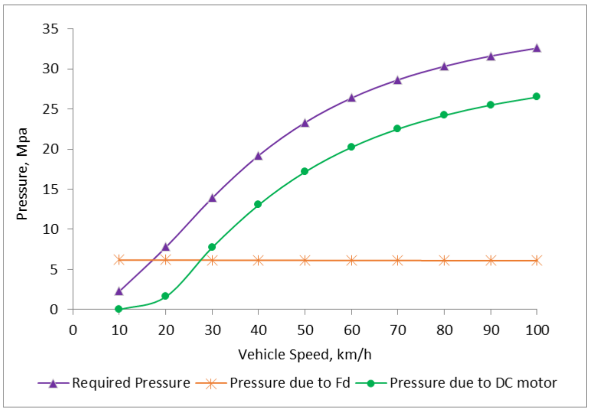


Figure 4: : Hydraulic pressure against vehicle speed

Next figure, Figure 5 illustrates the hydraulic pressure based on load distribution on front axle. Note that the pressure required for braking on front aaxle is higher since the load is transfered to the front. Let's consider the speed of 50km/h, the required pressure (blue line) indicates that the car needs 15.7Mpa while the effort by the driver only satisfy around half of it, which is 6.2Mpa. therefore, the force by the motor will support the remaining required pressure by 9.6Mpa:

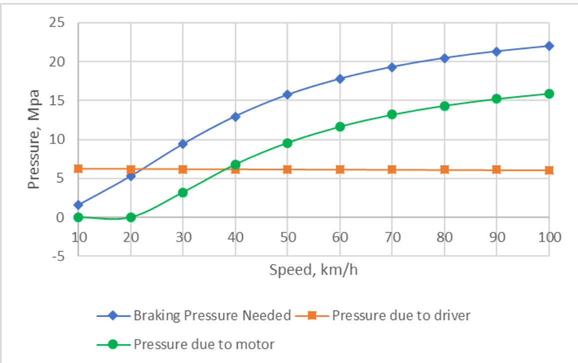


Figure 5: : Braking pressure based on front axle

4.1. Experimentally

In this study, a prototype of the system has been developed in order to show the actual operation of the system. Throughout this chapter, even the system is not built as the whole, but at least we can see how the main component operates which is the DC motor itself. For the prototyping and experiment part, I have used motorcycle braking parts to represent the system that I have studied for my Final Year Project. The system configuration is shown in the following figure:

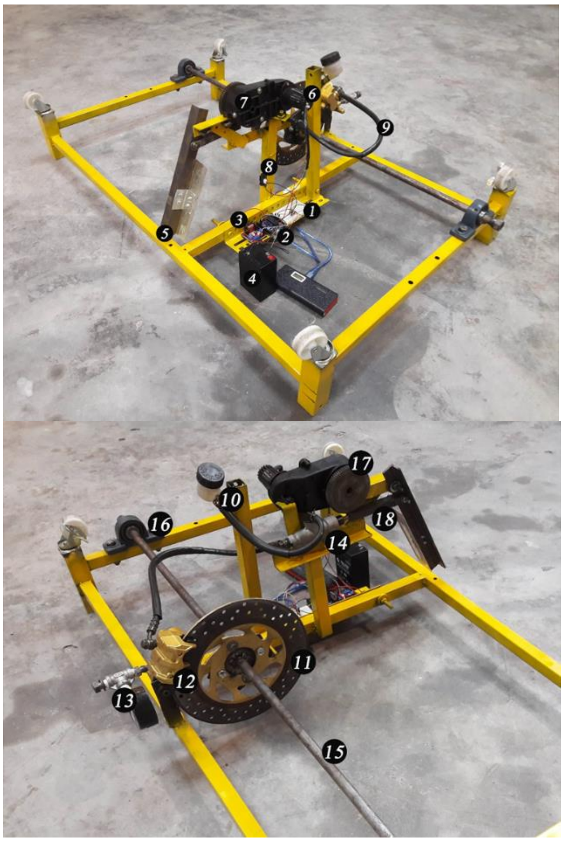
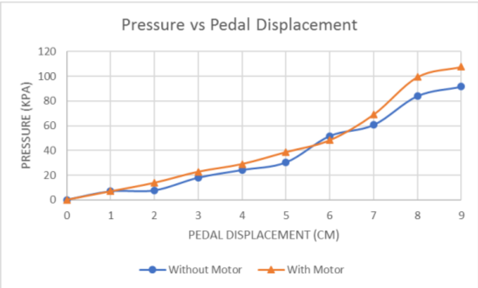


Figure6: : Prototype configuration

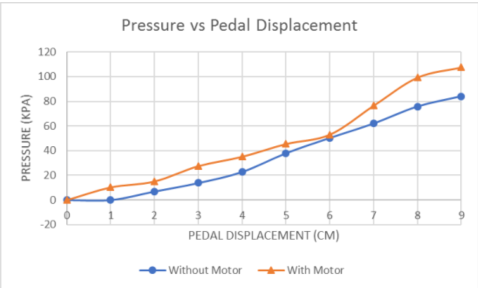
Note that from Figure 6: 1. Circuit Bread Board 2. Arduino Circuit Controller 3. L298N DC Motor Driver 4. 6V Battery 5. Brake Pedal 6. DC Motor 7. Gearbox 8. Distance Sensor 9. Brake Fluid Hose 10. Brake Fluid Reservoir 11. Brake Disc (Rotor) 12. Brake Caliper 13. Hydraulic Pressure 14. Master Pump 15. Rotating Shaft. 16. Bearing Support 17. Pinion 18. Rack. Table 1 below shows the difference of the pressure gauge reading when brake is applied. I have taken three trials for this experiment so that I can have a better average result. Thus, the following Table 1 shows the pressure developed in the brake fluid line for both with and without using the aids of DC Motor in the first trial.

Table 1:Pressure gauge reading with and without the aids of DC motor.

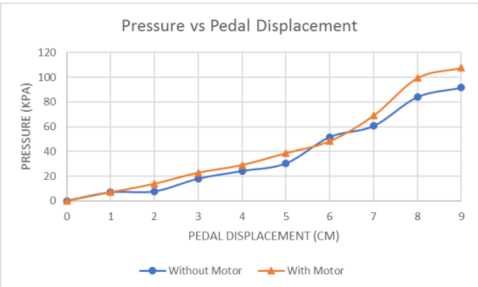
Without Motor Aids		**With Motor Aids**	
Distance between brake pedal and sensor (cm)	Pressure gauge (psi)	Distance between brake pedal and sensor (cm))	Pressure gauge (psi)
22	0	22	0
21	1.0	21	1.0
20	1.1	20	2.0
19	2.6	19	3.3
18	3.5	18	4.2
17	4.4	17	5.6
16	7.5	16	7.0
15	8.8	15	10
14	12.2	14	14.4
13	13.3	13	15.6



a) Trial 1



b) Trial 2



c) Trial 3

The main purpose that I can deliver here is to show how much the DC motor is able to help the driver in braking and stopping the vehicle. The following Figure 8 shows the average value of pressure reading based on the three trials from Figure 7:

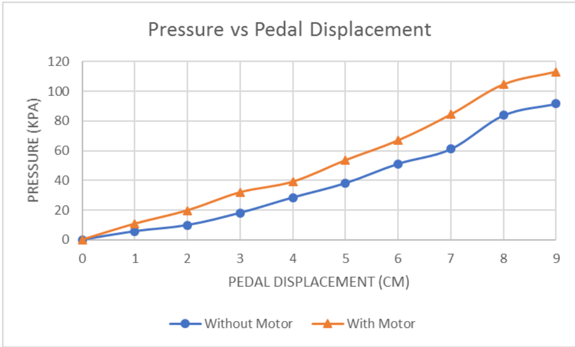


Figure 1: Average presure gauge reading vs pedal displacement

From the figure above, orange line indicates the hydraulic pressure developed when we used the DC motor in assisting the braking. Obviously, we could see that the hydraulic pressure produced is higher compared to the pressure developed without the aids of DC motor. Since the braking system of this experiment is from motorcycle components, let us consider the actual braking parameter of motorcycle. It is said for the motorcycle, the maximum pressure imparted in the braking system may exceed 150 psi which is equal to 1.034 MPa. (Source: https://www.motorcyclistonline.com/motorcycle-brake-system-how-it-works).

As mentioned in the article, we are assuming the speed for 1.034MPa pressure developed was 100km/h. Note that 100km/h is equal to 27.78 m/s while in my experiment, the rotational speed applied on the brake disc or rotational shaft was 200 rpm. We can find the linear velocity of the disc by applying the following formula:

$$V = \omega \cdot r \quad (12)$$

Applying equation 12 yields the disc velocity of 2.6 m/s. Therefore, to validate the experimental value, we can calculate the theoretical maximum pressure required for my prototype which is 99.3 kPa which and it is close to the maximum pressure when the brake pedal is fully applied.

From the average experimental value, let us consider the pressure developed when the pedal is fully pressed. By using the aids of DC Motor, the pressure increased is about 23.3%. So, this amount of additional pressure is useful to avoid road accident whenever sufficient pressure is developed. This is because, a sufficient pressure will help the vehicle to stop within the desired distance.

5. Conclusions

Based on the scope and the contents of the report, the following conclusion has been made. Practically, some drivers are slow in making decision during emergency. Not only that, they also might be panic and not giving the sufficient force for braking to put the car to stop. So, the car will not be able to stop within the shortest distance as it can due to lack of hydraulic pressure for braking. It is also might be some lost during braking which need extra force to develop the sufficient hydraulic pressure in master cylinder.For this project, the mathematical model has been conducted to measure the stopping distance, the hydraulic pressure required for braking based on the vehicle speed and its mass. There is a lack of pressure when the pressure delivered by driver is lower than pressure required. From the pressure difference, I computed the force that the motor should deliver. The characteristic of the DC motor also has been determined. Finally, for experimental part, it seems that the DC motor is able to give an additional force to the master pump as well as boost up the hydraulic pressure.

Therefore, it is believed that the development of this system may enhance the braking performance and efficiency. Lastly, there is a hope that the DC motor assisting hydraulic braking system might be useful in future.

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