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To cite this version:
Saleh Mobasseri, Mohammad Mobasseri. A Comparative Study Between ABS and Disc Brake System Using Finite Element Method. 2017. hal-01624015

HAL Id: hal-01624015
https://hal.archives-ouvertes.fr/hal-01624015
Submitted on 5 Nov 2017

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A Comparative Study between ABS and Disc Braking System Using
Finite Element Method

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ABSTRACT

This paper, refers to the history of the rise of brake system and describe its importance in passenger’s lives. An Anti-lock braking system (ABS), is the safety of vehicle systems to achieve maximum braking and decelerating in terms of increasing the stability and balance of the car and reduces the braking distance is designed. The performance of disc brake system and the ABS controller are also compared with each other by the kinetic analysis of the braking system and evaluate the impact of each parameters are checked on the vehicle stopping distance. In this study, we use Finite Element software Abaqus 6.14 and we found some interesting result, such as the effect of temperature on the performance and braking system efficiency. The Anti-lock braking system (ABS) is one of the most important feature that affect on vehicle safety and for this research much efforts have been made to improve this system. One of the aims of this paper is to compare system performance between disc brake system and ABS with the help of modeling in different conditions (rainy, snowy, etc).

KEYWORDS: Anti-lock braking system (ABS), Car Stability, Finite Element Simulation, Stopping Distance, Tire-Slip.

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1. Introduction
Due to the advancement of technology and increase the number of automobiles, some people prefer to travel by private cars. This approach leads to increase the volume of vehicles traffic in urban and inter the city routes and increase fuel consumption [1,2]. Reducing of stopping distances and increasing the car stability, are the most important factors in the reducing number of accidents. These two factors are depended to coefficient friction between automobile tires and the ground. Due to the advancement of technology and sensors in the 80's, use of these technologies in automobiles are began. The biggest disadvantage of conventional brakes is that the driver can't precisely control the amount of brake torque applied to the wheels. If there is no precise information on road conditions, sudden and excessive pressing the brake pedal will lock the wheels. To counter the risks of collisions and reduce accidents, control the automobile and driving in different weather conditions, reduced stopping distances, increase stability and steering, avoid locking the brakes, development of new system like ABS, VDC, EBD, ESP is necessary, so that up to 40% of accidents can be avoided. Since 80's, the Anti-lock braking system (ABS) in automobiles, increased by using a safety airbag [3]. The ABS, try to keep the maximum longitudinal and lateral tire friction coefficient. Thereby, achieving the minimum distance to stop the vehicle, increasing car's stability. The parameters that influence of the brake process:
The force applied by the driver's foot on the brake pedal, ambient air pressure and air pressure in the tire, tire quality, friction between the tire and the ground, car speed at the beginning of the braking process, orifices discharge coefficient, the external force acting on the vehicle body, how to distribute the weight of the car on wheels, type of pads, road conditions and tire, brake torque exerted on the tire.

2. Types of braking system:
2.1) Disc Brake System: Research, design and manufacture of disc brake system in England began in 1890 and was registered in 1902 in Birmingham by “Frederick William Lanchester” and the modified model was designed in 1949.
The way of disc brakes operation: Power of driver’s foot enters the booster and then, is reinforced the power of driver’s foot by the pressure difference created on both sides of the diaphragm; In fact, the force of the brake pedal and booster, brake circuit, creates hydraulic pressure and the pressure generated by the hydraulic line is transferred to the wheel's cylinder and turns into the braking force and in accordance with the wheel's piston area, a force is exerted to the wheel.
In the time of booster activation, the diaphragm in front of the air and the vacuum motor is attached [4]. The duty of booster is to increase the power of the driver's foot of 4 to 6 times.
2.2) **Kinds of braking modes:**

a) The optimal mode of braking ($\text{Torque}_{\text{brake}} = \text{Torque}_{\text{frictional}}$) When the braking torque is equal to the friction torque.

b) Non-Optimal braking mode:

   The first mode: When the brake of torque is greater than the frictional torque: ($\text{Torque}_{\text{brake}} > \text{Torque}_{\text{frictional}}$)

   In this situation, due to the lack of braking force, stopping distance of the car will be increase.

   The second mode: Torque of brake, is greater than friction torque.
   ($\text{Torque}_{\text{brake}} < \text{Torque}_{\text{frictional}}$)

   In this situation, the wheels are locked and the car will be in a state of imbalance.

   Disc brake components are Brake lent, Caliper, Rotor.

3. **Simulation**

As the simulation results of disc brake system indicate, due to the high friction, the temperature is increased and ultimately, the efficiency of braking system will be reduced.
4. The disadvantages of disc brake system:

1) Low-speed performance when pressing the brake pedal.
2) High brake stopping distance.
3) Slip vehicle on slippery distances.
4) Imbalance in the car.
5) Sensitive to dust and moisture.
6) Reduced brake system efficiency because of the rising temperatures.

5) Anti-lock braking system (ABS): This system is an electronic device when the brake with hydraulic pressure control and associated with disc or drum pads, hold, hang up and rapid. The result of continued rapid and repeat this process is destroying the locking in brakes system. The importance of this kind of brakes will appear more, on wet and slippery surfaces or braking at high speeds. The first time was raised in 1905 in Germany. For the first time was mechanically used in the aircraft in 1930 and at the same time, many changes occurred in the aviation industry through the development of this system [5,6]. In 1969, the first ABS for cars were installed only on the rear wheels, was produced at Ford Motor Company and the modern ABS with electronic control unit was designed and built in 1976 by the "Daimler-Benz" and "Bosch company" [7].

All over the world, researcher in designing field, have done many kind of researches on the ABS system and achieved different results. The most important of them are:

Gerdes et al. have been studying and modeling the brake system [8]. Most of their studies have been modeling the car’s vacuum booster. The main feature of this model is the static model of control boost valve with a dynamic of the air inlet. WU et al. have don modeling the brake system in more detail than previous studies [9]. The important parts of their paper, are designing PWM sliding mode controller and evaluation of controller which was designed in experimental test. Khan et al. have done modeling and simulation the boosters. The method used for modeling and simulation of the booster has Bond Graph [10]. So, in their paper, the governing equations of the system are not available, and modeling of hydraulic of the ABS system has not performed. Hu et al. have done modeling and simulation the features of main cylinder of the brake system in static model [11]. Their study is based on the main cylinder brake system. At first, they extract components of the static model of the main cylinder and their effort was to utilize the friction force between the piston and the cylinder in calculations. Harifi et al. just provided a dynamic model of the vehicle body and tires [12]. In their paper, the modeling of all components of the ABS were
ignored. Kuang et al. modeled the dynamic of hydraulic brake systems about a vehicle for active controller systems of the car [13]. The name of method which used in their paper, is Bond Graph method. Soliman et al. have been created an integrated controller between the active suspension system and the ABS system using Fuzzy-Logic control theories to improve braking performance [14]. The simulation result of their research obtained show that the active and ABS with integrated controlled reduces the braking time and distance in the range from 3% to 5% compared with the same without integrated controller.

Kaldas et al. have been developed a control system that combines suspension and brake system [15]. The simulation result of their work, demonstrates that using Fuzzy-Logic control with controlled suspension systems and the ABS provides a significant improvement in truck ride comfort and braking performance under different driving conditions. Soliman and Kaldas, they have been studied the influence of vehicle initial speed and tire-road friction coefficient is investigated [16]. The result showed that, using Fuzzy-Logic Control in ABS, improved the braking performance than the conventional ABS. Kaldas and Soliman, showed the effect of investigating the influence of the preview control of the active suspension on the vehicle ride and braking performance [17]. The results are generated in the time domain to simulate the vehicle response during braking, while wheels are subjected to vertical road input. Emil Precup et al. in their research, suggest a synergy of Fuzzy-Logic and nature-inspired optimization in terms of the nature-inspired optimal tuning of the input membership functions of a class of Takagi-Sugeno-Kang (TSK) fuzzy models dedicated to ABS [18]. The objective of Qiang Wang et al. is to minimize total impact energy by determining the desired braking force [19].

5.1) Introduction ABS: In this system, the amount of braking force on each wheel can be different. Therefore, the wheel which has less speed than the other wheel, proportionally, the pressure of brake fluid is reduced. The pressure, reduction is across-sectional and continues until wheel’s spin to be equal. The ABS start to control the brake system up to 6 km/h and if for any reason getting problem, the ABS switched off and the brake operate as normal [9,20]. The ABS include electronic controls, a solenoid (for releasing and re-applied brake pressure) and the sensor of speed to the wheel [21]. Modes of the ABS performance: The vehicle’s mainframe with sensors in each wheel, checks the wheel’s speed during braking. If the rotational speed of the wheel’s different than other wheels, the main frame changes the pressure inside the cylinder with a required command to the electronic brake valve that makes change in amount of braking force applied to the wheels and vehicles wheel is getting out of the critical situation. So the possibility of locking the wheel is decrease. The above process, are continuously done with high speed so that the process is repeated in per minute between 15 to 20 times. In ABS, we must know when the wheels are
slipping or locked. Speed sensors which have been installed on each wheel, give us this information. By recognizing slip or locking of the wheels, controller commands the modulator to reduce the braking torque to prevent the wheels from locking.

Slip is [9]:
\[ \lambda = \frac{V - R \omega}{V} \]

\( \lambda \) = The amount of slip between tire and car
V = Vehicle speed
\( \omega \) = Tire rotation speed
R = The radius of the wheel

In this case, the wheels of the car are locked. The below figure shows an example of friction sliding friction coefficient curves for the road conditions [22].

![Coefficient of friction on the slip curve](image)

**Figure 6: Coefficient of friction on the slip curve [22]**

5.2) Types of the Anti-lock braking system (ABS): Generally, the ABS based on the number of channels (number of valves that are separately controlled) and the number of speed sensors, divided to the various categories that the most important of them are mentioned below:

1- The ABS with 4 channel and 3 speed sensor: This case, is extremely functional in trucks and vans with 4 Anti-lock wheels.

2- The ABS with 3 channels and 3 speed sensor: This case, more applications are in the trucks and vans with 4 Anti-lock wheels and on the front wheels, a sensor and the valve is designed; But for the rear wheel, there is only one sensor and the valve which is located on the rear axle. In fact, for each front wheel, is a separate controller so more braking force be applied to the front wheels. One of the disadvantages of this case (three-channel system with three sensor), is the rear-wheel ABS, locked and
therefore, using this system may lock the rear wheels while braking that reduces the effectiveness of the brake and the car balance.

3- The ABS with a channel and sensor: This system exists in vans and trucks which their rear axle is Anti-lock. The control valve for each wheel and speed sensor is located on the rear axle. In this way, it is possible lock the wheels during the braking.

The main part of the Anti-Lock System: In ABS, there are 4 main sections:
1- Sensor of speed: The ABS must know when the car wheel, being locked up. Speed sensors, provide the necessary information for his system.
2- Valves: In the brake pipe, 1 valve is existing.

6. Modeling:

6.1) Modeling and description of some of the components of braking system is as follow:

6.1.1) Modeling of pedal: Brake pedal, is the first component of the brake system, which is reinforced the force of driver’s foot, is supported by the following formula:

\[
F_{\text{pedal}} = \frac{b}{a} F_{\text{in}}
\]

The maximum force is applied to the brake pedal, for women is about 445 Newton and for men is 823 Newton [24].

6.1.2) Booster: As we explained in the disc brake section, the duty of booster is Quadruple Sextuple the force of the driver’s foot [4].

When the booster is activated, the following relation are dominate:

\[
F_{\text{booster}} = F_d + F_{\text{pedal}} - F_{\text{rs}}
\]

\[
F_{\text{booster}} = \text{External power booster}
\]

\[
F_d = \text{The pressure difference between the 2 sides of the diaphragm}
\]
\( F_{rs} = \text{Return spring force booster} \)

Therefore, the amount of \( F_d \) can be calculated as follows:

\[
F_d = (P_a - P_v)A_d
\]

\( P_v = \text{Pressure on the diaphragm} \)

\( P_a = \text{Pressure behind the diaphragm} \)

\( A_d = \text{The effective area} \)

Booster has 3 modes are:

- Apply the force
- Hold Force
- Release the force

So the amount of \( F_d \) is different in each of these modes. Three considered cases can be written as following equation:

\[
F_{\text{pedal}} < F_{\text{release}} \implies \text{Release}
\]

\[
F_{\text{release}} \leq F_{\text{pedal}} \leq F_{\text{apply}} \implies \text{Hold}
\]

\[
F_{\text{apply}} \leq F_{\text{pedal}} \implies \text{Apply}
\]

6.1.3) Hydraulic section: Most important point of Anti-lock braking system is controlling the amount of the pressure of brake hydraulic fluid behind the piston caliper or wheel cylinders.

The section of ABS hydraulic system, begins from the main cylinder and continues to the wheel cylinder.

Vehicle dynamics modeling: The following shape shows a free diagram of the car which is braking.
By using Newton’s second law we have:

\[
a_x = \frac{\sum F_b}{M} = \frac{F_{bf} + F_{br} + D_a + R_{xf} + R_{xr} - W \sin \theta}{M}
\]

- \(F_b\) = The process of brake force in braking
- \(M\) = The mass of vehicle
- \(F_{bf}\) = Brake force rear wheel
- \(D_a\) = Air resistance force
- \(R_{xf}\) = Rolling resistance force of front wheels
- \(R_{xr}\) = Rolling resistance force of the rear wheels
- \(W \sin \theta\) = The slope of the road force

Rolling resistance force is as follows [23]:

\[R_x = R_{xf} + R_{xr} = (W_f + W_R) f_r\]

- \(W_f\) = Vertical force applied to the front tire
- \(W_R\) = Vertical force applied to the rear tire

\(R_w\) = The radius of the wheel

\(f_r\) = The factor of rolling resistance

Vertical force exerted on the front and rear wheels are from the following equation:
\[ W_f = \frac{WH \sin \theta}{2(L_f + L_r)} + \frac{Ma_x + H}{2(L_f + L_r)} + \frac{WL_f \cos \theta}{2(L_f + L_r)} - \frac{D_a H_a}{2(L_f + L_r)} \]

\[ W_r = -\frac{WH \sin \theta}{2(L_f + L_r)} - \frac{Ma_x + H}{2(L_f + L_r)} - \frac{WL_f \cos \theta}{2(L_f + L_r)} + \frac{D_a H_a}{2(L_f + L_r)} \]

H = The height of the center of gravity of the vehicle from the road

a\_x = Longitudinal vehicle acceleration

M = Vehicle mass

L\_f = Distance from the center of front wheel to the center of gravity

L\_r = Distance from the center of front wheel to the center of mass

H\_a = Effective height of the air force

D\_a = Air resistance force

6.2) Tire modeling:
Generally, tire’s models can be divided into 2 categories, static model and dynamic models. Static friction models are used in terms of linear and angular velocities. Dynamic models represent the actual behavior of the tire at the time changing the speed [24]. The quality of the tire and asphalt paving plays an important role in maintaining the car’s balance. An appropriate road for a car is the broadband to control the car in the road. Control of the vehicle on the road depends on the wheel sticking to the ground and the other vehicle characteristics such as a height of the center of the wheel, axle length and mass distribution in the automotive and etc. In simulation and analysis of vehicle, dynamics adhesions is one of the most important parameters that must be considered in the design of the suspension.

The low graphs show the change in the coefficient of friction on the surface of the slide [25]:

\[ (2)(2\cos r_f)^2 \, (2)(2\sin r_f)^2 \]
7) **The analysis of car stop in making brake is divided into 2 categories:**

7.1) **Kinematic analysis:** kinematic situation of the car which can be analyzed at any time by 4 parameters as follows: speed, acceleration, distance and time. We assume the car is moving at a constant speed $V_1$. When the driver sees an obstacle in the path until the brake pedal is pressed, takes as much as “$t$”, which is called as “driver reaction time”. This time is usually between 0.75 to 1.5 seconds [26]. After applying a force on the brake pedal, the linings are about 0.1 to 0.2 seconds connected to the disc with a time lag. After passing “$t$”, decelerating the car begins to increase until it reaches the maximum amount and then remains constant till its full stop. In the range of “$t$”, acceleration is changed and at any moment can be calculated.

7.2) **Kinetic analysis:** The total rolling resistance and static friction, reduce car’s speed when using the brake. When the brakes are locked, the tires slip on the road surface and thus can’t effectively reduce car speed. The maximum braking force occurs when there is about 11% of slip between the wheels and the road. This issue is used to increase the efficiency of ABS [24]. To kinetic analysis of the brake system and
optimization of its perform, the most important parameters are: Vehicle speed, stopping distance, the force on the wheel, the force applied to the brake pedal, the diameter of main cylinder and the cylinder of the wheels, the force on the wheel, the coefficient of friction between the surface in contact like the surface of lining with disc, the car’s holder force.

7.3) The advantages of ABS: Reduce stopping distance, increase vehicle stability and steering, reduce the amount of tire’s vibration, reduce the torsion of tire, and prevent the diversion of car on slippery roads during heavy braking.

7.4) The disadvantages of ABS: This system along with its advantages, has more disadvantages of the brake system, include:

a) Rapid and continuous replication of connecting and disconnecting of the brake way by ABS, causing the loss of the blocking or locking the brakes.

b) In ABS, serve noise is heard during the braking on extremely slippery surfaces.

c) This system on soft surface (such as snow or sand) doesn’t have a good performance. One of the cause of increasing the stopping distance in these situations is that, when the driver of vehicles with conventional braking system (disc brake), presses the brake pedal, because of locking wheels, some of snow or sand are collected in the wheels. The same applies helps to increase braking power.

d) On the surface which is the combination of asphalt and snow, the tire will swerve to asphalt.

e) Given that this ABS in composed by more components than the brake disc, its repair and maintenance cost are higher.

Table 1: Summary of the deceleration values [27]:

<table>
<thead>
<tr>
<th>Road surface</th>
<th>Braking [m/s²]</th>
<th>Acceleration [m/s²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice</td>
<td>3.43</td>
<td>1.96</td>
</tr>
<tr>
<td>Snow</td>
<td>0.88</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Table 2: Summary of braking decoration on the icy surface [28]:

<table>
<thead>
<tr>
<th>Tire type</th>
<th>ABS</th>
<th>Surface temperature [°C]</th>
<th>Ambient temperature [°C]</th>
<th>Braking deceleration [m/s²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>Yes</td>
<td>-5.4</td>
<td>05.9</td>
<td>2.65-1.47</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td></td>
<td></td>
<td>2.06-1.47</td>
</tr>
<tr>
<td>Summer</td>
<td>Yes</td>
<td>-5.2</td>
<td>-3.1</td>
<td>1.96-1.28</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td></td>
<td></td>
<td>1.57-1.47</td>
</tr>
</tbody>
</table>
8. Conclusion

According to the modeling that carried out in this paper and researcher’s studies in the field of the accidents which lead to life and financial casualties, it was determined that serve or uncontrolled vehicles are around the vertical axis is the main cause of these accidents. In the perspective of vehicle dynamic, such intensive rotational motion is caused by the instability of the lateral dynamic of the car. The other important parameters that effect on the process of stopping the vehicle, can refer to the following: The of driver’s feet, the geometry of the pedal. The amount of engine’s vacuum, coefficient of orifices discharge, opening and closing properties of electronic valves, the effective radius of the tire, radius of brake discs, type and quality the tire, the amount of the tire’s tread, road type, the amount of vertical load on the wheels, specification of hydraulic oil of brake, the amount of existence air in the hydraulic oil of the brake. The hydraulics of ABS, with a time lag of about 0.5 seconds from pressing the pedal to start reducing the vehicle’s speed that the above factors are effective in changing this time duration. During pressing the brake pedal, pressure of hydraulic oil reaches about 60 times. Based on the presented entries in the paper and the importance of stopping the car in different situations by keeping the balance, the performance of ABS can be summarized as follows:

1) These systems by preventing the wheels from locking, increasing the car’s steering.
2) In some special circumstances, such as sandy or snowy road, the cars which has the ABS, their distance to stop rises than the vehicles with conventional brakes.
3) The mass of the vehicle does not have any special effect on the stopping distances of the car and it can only effect on the force of brake pedal, so that by increasing the mass of the vehicle, the required force is increasing to lock the wheels.
4) The ABS prevention of temperature rises during this process because the type of designing ABS.

References:


