Assessment and Comparison Performance of the Conventional and an Anti-Lock Braking System

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Abstract - *In this paper, the experimental work was carried out to investigate the effect of Anti-Lock Braking System on the brake performance at different operating parameters such as brake oil pressure, and sliding speed. All experimental tests are conducted in the same conditions 60 seconds of braking. Three brake oil pressures are selected during the tests from 6 bar to 10 bar. Also, three sliding speeds are selected during the tests; these speeds were 100, 200 and 300 r.p.m. The experimental results illustrated that, the brake forces of the conventional brake system and Anti-lock braking system are increased with increasing the brake oil pressure. The increase with Anti-lock braking system is greater than with the conventional brake system. At brake oil pressure of 6, 8 and 10 bar the value of the mean brake force of the anti-lock brake system increases by 12%, 21%, 29% respectively over the value of the mean brake force of the conventional brake system. The increase of the oil pressure causes an increase of the mean friction coefficient of the brake system. Also, the increase of the sliding speed causes a decrease of the mean friction coefficient of the conventional brake system and Anti-lock braking system. At pressure 10 bar and with increasing sliding speed the mean friction coefficient for Anti-lock braking system increases by 14%, 11.8%, 10% respectively over the value of the mean friction coefficient of the conventional brake system.*

Key Words: Disc brake, ABS, coefficient of friction, oil pressure

1.INTRODUCTION

One of the most important components in road vehicle is its braking system. Vehicle brakes are mechanical device for generating the frictional resistance that retards or stops the turning motion of the vehicle. So the brake system converts the kinetic energy of the vehicle into thermal energy by the process of friction, and this heat must be efficiently dissipating to the ambient air by the components of the brake system.

The basic functions of a brake system are to slow the speed of the vehicle, to maintain its speed during downhill operation, and to hold the vehicle stationary after it has come to a complete stop [1]. In vehicles, there are varies types of braking system such as

- Hydraulic braking systems.
- Mechanical braking systems.
- Air braking systems.
- Electrical braking systems (Brake by wire).

The hydraulic braking system is commonly used in the automobiles so; the hydraulic braking system is used in this paper. The principle of Hydraulic brakes works on the principle of Pascal's law which states that "pressure at a point in a fluid is equal in all directions in space". According to this law when pressure is applied on fluid it travels equally in all directions so that uniform braking action is applied on all four wheels. In hydraulic braking systems, the pressure applied at the brake pedal is transmitted to the brake mechanism by a liquid [2]. There are two main types of vehicle brakes namely, drum and disc brakes. The main advantages of the drum brakes are that can apply more stopping power for a given amount of force applied to the brake pedal than disc brake. This is possible because the drum brake design offers a self- energizing action. The disadvantages of the disc brakes are no self- energizing or servo action, brake noise, and poor parking brake performance [3]. The hydraulic system applies the brakes at all four wheels with equalized pressure when pedal is operated. The components of the Hydraulic braking system which consists of the master cylinder, the wheel cylinder, the brake lines and hoses, and the brake fluid [2].

The master cylinder is the primary unit in the brake system that converts the force of the operator's foot into fluid pressure to operate the wheel cylinders. It is normally mounted to the firewall, which allows for easy inspection and service, and is less prone to dirt and water.

The master cylinder has four basic functions:

- It develops pressure, causing the wheel cylinder pistons to move towards the drum or rotor.

- After all of the shoes or pads produce sufficient friction, the master cylinder assists in equalizing the pressure required for braking.

- It keeps the system full of fluid as the brake linings wear.

- It can maintain a slight pressure to keep contaminants (air and water) from entering the system [4].

Friction brakes operate by converting the vehicle kinetic energy into thermal energy (heat). Heat is created due to friction at the interface between a rotor (disc or drum) and stator (pads or shoes). During braking, a large amount of heat can be created and has to be absorbed by the rotor and stator. A sufficient cooling of these components is essential to achieve satisfactory performance of the braking system [5]. It is therefore vital that heat is effectively dissipated for the successful operation of a braking system. Brake performance is improved by increasing the friction coefficient between the rotor and stator, so the friction coefficient plays an important role in the braking process [6].

Nowadays, most passenger cars use the disc brakes as well as in the front of light duty trucks. The main advantages of the disc brake over drum brake are: [5].

•The rubbing surfaces of the disc brake are exposed to atmosphere providing better cooling and reducing brake fade and brake fluid vaporization.

•In drum brakes, expansion of the drum at elevated temperatures well result in longer pedal travel and improper contact between the drum and shoes, whereas in disc brakes elevated temperatures cause an increase in disc thickness, with no adverse effect in braking.

•Disc brake adjustment is achieved automatically whereas drum brakes need to be adjusted as the frictional material wear.

On the other hand, the main advantages of the brakes that is self- energizing.

Drum brakes use the force generated by friction to increase the clamping force (applied force) of the brake shoes. The main disadvantages of the conventional disc brake that is not self-energizing.

In disc brakes, the braking force (friction force) depends mainly on the coefficient of friction between rotor and brake pads and the normal force which affects the brake pads. The coefficient of friction is affected by several parameters such as surface finishing of the rotor, friction material type, temperature, sliding speed, existing water between rotor and pads and the normal force which depends on the brake oil pressure inside the slave cylinder. This leads to the observation that the friction coefficient has no constant value during braking [7].

1.1 Disc brake

The other types of brake used are disc brakes. In these types of brakes, the braking force is generated by piston squeezing frictional material in both sides of the rotor/disc which is attached to the wheel. The U-shaped caliper is supported by stationary vehicle components such as the suspension system [8]. A typical disc brake caliper is shown in figure (1).

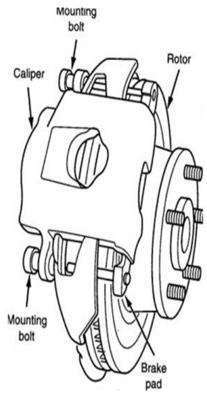
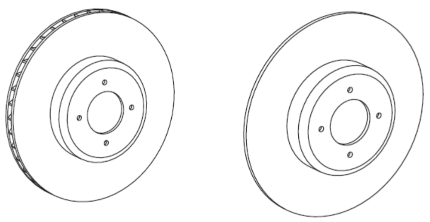


Figure (1) Disc brake system

Brake disc, also called brake rotor, is fixed to the axle, so it rotates with the same speed as the wheel. Braking power of a disc brake is determined by the rate at which kinetic energy is converted into heat due to frictional forces between the pad and the disc. For an efficient brake design, it is also important that heat is dissipated as quickly as possible otherwise the temperature of a disc might rise and affect the performance of a disc brake. So to get an optimum performance in demanding applications, ventilation is introduced in the brake discs which increase the cooling rate. Brake discs could be divided in two categories solid brake discs and ventilated brake discs [9].

A solid brake disc is the simplest form and consists of a single solid disc. In a ventilated disc, vanes or pillars or both separate two annular discs and provide a passage for the air to flow. Ventilated brake discs increase the cooling rate and result in lower surface temperature. This lower temperature reduces the risk of brake fade and also helps in reducing wear of the disc and pad. Both of these designs are constructed with or without a mounting bell. A mounting bell increases the distance from the friction surface to axle and the surface area of the disc which improves cooling [10] and therefore it helps to protect the wheel bearings from the high temperature generated due to braking operation. A schematic description of these two types of discs is given in figure 2. When mounting bell is not a part of the brake disc then this multi-part disc configuration is called hybrid or composite brake disc. In this design, the disc is sometimes called the braking or friction ring. There are different ways to join a mounting bell and a friction ring mainly depending upon the material of the disc. In figure 3, two methods (patented [11, 12]) used for joining a friction ring and a mounting bell by using a connecting element are shown. In figure 3a the connecting element is a special threaded bolt which is screwed to the mounting bell and free to slide in radial direction inside the friction ring. This bolt is usually made of steel which could experience corrosion and heat could conduct quickly to the mounting bell. In figure 3b the connecting element is made of a ceramic material to avoid the corrosion problems and reduce the heat transfer to the bell. The head of the ceramic pin is cast into the mounting bell. In another design (patented [13]), shown in figure 4, several projecting teeth on the inner periphery of friction ring are finely machined and then mounting bell is casted so that these teeth are embedded into the bell material. In this design mounting bell is usually made of a light alloy e.g. aluminium or magnesium [14].



(a) Ventilated disc with bell.

(b) Solid disc with bell.

Figure (2) Schematic representation of different brake discs.

A brake pad consists of a friction material which is attached to a stiff back plate. Figure 3 shows a brake pad attached to a back plate. Sometimes the friction material and back plate together are called a brake pad. A brake pad usually incorporates slots on its face and chamfers at the ends. Figure 4 shows different configurations of pads. A pad can have more than one slot and it could be arranged in different orientations. One purpose to incorporate chamfers and slots is to reduce squeal noise [15]. Relatively higher temperature at the pad surface than the interior will result in convex bending of the pad [16]. A slot will allow the material to bend and help avoid cracks. Furthermore, it facilitates to clean the dust collected between disc and pad surfaces by offering an escape.

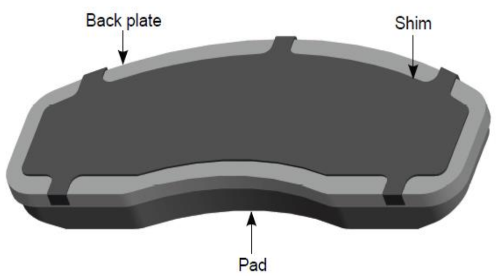
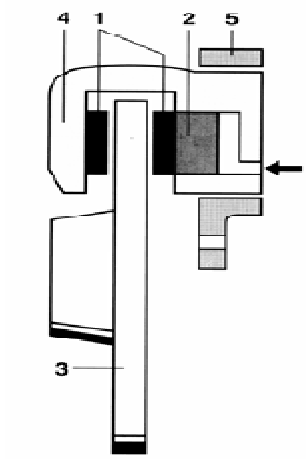


Figure (3) An assembly of pad, back plate and shim.

The disc brake system has many advantages over drum brakes. The rotor of the disc brake systems heats up during the braking action. The major part of the rotor is exposed to air, therefore there is sufficient air flow over brakes to dissipate the heat generated resulting in cooling down of rotor easily. The rotor expands in the direction of the frictional material in disc brake as opposite to drum brakes, in addition to the disc brake systems are self-adjustment. The main disadvantages of disc brake systems are no self-energizing or servo action, brake noise and poor parking brake performance [17]. It should be noted that non-occurrence of the phenomenon self-energizing stills the main disadvantages of disc brakes. Hence, so there were many efforts to modify the disc brakes that could be self – amplified.

The disc brake systems are classified as floating and fixed caliper. A floating caliper type is shown in figure (4). This type of brake uses only a single piston to squeeze the brake pad against the rotor [18]. The reactive force shifts the caliper housing and presses the other brake pad against the rotor. Figure (4) shows the idea of operation of floating type disc brake, the brake fluid pushes the piston to the left when the brake is applied, so the piston pushes the inner pad and presses it against the disk, the sliding caliper housing reacts by shifting towards right pushing the left pad against the disc, in order to generate a frictional torque to slow or stop the rotor (and wheel's rotation).

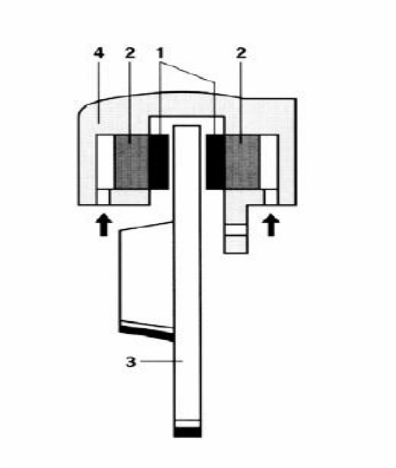


1. Brake pad. 2. Piston 3. Disc (rotor) 4. Caliper

5. Bracket

Figure (4) Floating caliper disc brake

A fixed- caliper type is shown in figure (5). In this type of brake, the caliper body is fixed and uses two or more pistons on each side of the rotor. The pistons are located in each half section of the fixed caliper. Hydraulic pressure is applied during braking to each of the piston. Each piston presses the brake pad towards the rotor, in order to generate a frictional torque to slow or stop the rotor.



1. Brake pad. 2. Piston 3. Disc (rotor) 4. Caliper

Figure (5) Fixed caliper disc brake

Recently, there were many efforts to improve the performance of the conventional disc brake system and making it with self-amplification. The self-amplification action can be acquired for the conventional disc brake by two mechanisms which are: disc brake with self- boosting and the wedge disc brake with self-boosting [7].

1.2 Drum brake

The drum brake has been more widely used than any other automotive brake design. Drum brake continues to have a number of advantages that contribute to its widespread use on the rear axle of most vehicles. The main advantage of the drum brakes is that it can apply more stopping power for a given amount of force applied to the brake pedal than disc brakes. This is possible because the drum brake design offers a self- energizing action that helps force the brake linings tightly against the drum. In addition, some drum brake designs use an effect called servo action that enables one brake shoe to help applying the other for increased stopping power. Another significant advantage that results from the superior banking power of drum brakes at low application forces is that it makes excellent parking brakes. Drum brake disadvantages are: brake fade, brake adjustment. The greatest drawback of drum brakes is that it is susceptible to fade i.e. the loss of stopping power that occurs when excessive heat reduces the friction between the brake shoe linings and the drum [19].

2 Literature review

Blau, [20]. Showed the effect of the normal force (contact pressure) was divided into three zones. At low normal force, the friction coefficient decreases with the increase of the normal force because the friction of metallic material was governed by oxides or tarnish films. At high contact pressure, the friction coefficient raises as a result of film rupture and plowing the subsurface material. At very high contact pressure, the friction coefficient tends to decrease again because the hydrostatic stress field increased produced plasticity. Blau, also, mentioned eight typical forms variations of friction coefficient versus sliding time. It can be illustrated that, the friction coefficient versus sliding time is influenced by several conditions: contamination of contact surfaces, boundary lubricated or unduplicated metals, coatings of materials and cleanliness of the contact materials

Österle et al. [21]. Presented an experimental study, illustrated the variations of the friction coefficient against the time at continuous braking. The initial value of μ is low approximately 0.13, but it increases rapidly up to 0.3 at 50 sec of braking time, however beyond 200 sec a slight fading effect is evident.

Halderman, J.D. [22] Showed, in the disc brakes, the braking force is generated by piston squeezing frictional material in both sides of the rotor/disc which is attached to the wheel. The U-shaped caliper is supported by stationary vehicle components such as the suspension system. A typical disc brake caliper.

Chatterley, T.C et.al. [23] have shown that Brake discs can be manufactured from different materials. The most commonly used brake disc material is grey cast iron. Also, materials such as aluminum metal matrix composites and carbon ceramic composite are used. Stainless steel presently only used for motorcycles. Grey cast iron is a good compromise when considering cost to performance ratio. Carbon ceramic materials can provide an excellent performance, but at high cost and are for this reason only used on racing cars.

Mostafa Makrahy [7] In the majority of automotive disc brakes, the disc is made of gray cast iron. This material is wear resistant and relatively inexpensive. In order to protect the wheel bearings from the high temperatures induced in a braking action at the rotor-pad interface, the rotor is shaped like a top-hat. The hat section increases both the surface area to improve cooling and the length of the path that the heat must travel to affect the bearings.

H.P. Khairnar et.al. [24]. presented a comparative frictional behavior of drum brakes and disc brakes in automobiles has been investigated. The influential factors; contact force and friction radius were modeled for the estimation of the friction coefficient for drum as well as disc brakes. The effect of contact force and friction radius is studied with varying conditions of parameters; longitudinal force, caliper force and torque on piston side as well as non-piston side. The numerical results obtained have been compared with the similar obtained from virtual Matlab/Simulink models for drum and disc brakes. The results evidenced that friction radius predominantly affects brake pressure and thus the friction coefficient, also the increase in contact force resulted with decrease in friction coefficient both for drum and disc brakes. Further it has been found that disc brakes exhibit gradual decrease of friction coefficient due to the equitable distribution of braking effort while drum brake presents sudden variations in friction coefficient. It can be revealed that frictional behavior of disc brake is more consistent than drum brake.

NOUBY M. GHAZALY et.al. [25]. Designed and implemented a brake test rig capable of measuring the performance of a drum brake at different operational and environmental conditions. The effects of dry and humid environment are considered under different applied forces and vehicle sliding speed. The experimental results showed a slight increase in the friction coefficients between drum and brake lining with increasing pressure or speed at dry and wet conditions. that in general the friction coefficient increases with increasing applied load. In addition, in the case of wet braking tests, there is a significant reduction in the friction coefficient to unacceptable levels for frictional brake applications which in a rainy and humid environment is considered as a serious problem as it influences the safety of the vehicle.

V. M. PHALLE. et.al. [26]. presented an effective assessment of the braking system drum–shoe friction coefficient (μ) considering longitudinal forces involved in the braking process using the set of basic equations of classical mechanics with friction. The relationship of influential factors—contact forces (Fl and Ft), actuating force (Wl and Wt) and Coulomb friction forces (μFl, and μFt) with friction coefficient (μ) was used in the estimation algorithm to compute the friction coefficient (μ). According to the simulation results it can be asserted that the Coulomb friction force (μFl and μFt) is dependent on the contact force (Fl and Ft) and brake actuating force (Wl and Wt). Kato [27] has investigated an experimental work aimed to obtain the relation between the sliding speed and the coefficient of friction under extreme loads. His results indicated that the sliding friction greatly increases with the decrease of the sliding velocity. Aviles et al. [28] have experimentally investigated the relation between the coefficient of friction and the sliding speed. They have used five different brakes. The coefficient of friction has no exact trend with sliding speed. Each brake has a trend that differs from the other, however, the coefficient of friction decreased with the sliding speed in all the brakes that were investigated in their study.

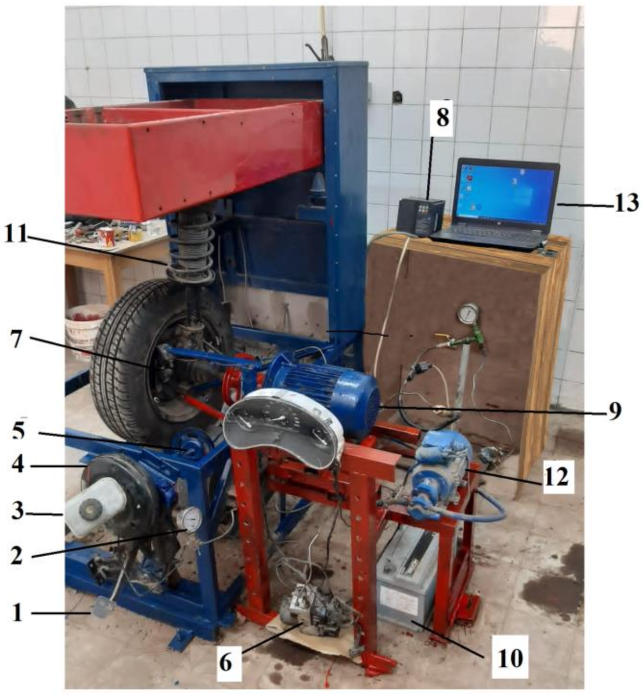
M.A. Chowdhury et al. [29] have investigated experimentally the effect of sliding speed and normal load on the friction and wear property of an aluminum disc sliding against stainless steel pin. To do so, a pin-on-disc apparatus was designed and fabricated. Experiments were carried out under normal load 10-20 N, speed 500-2500r.p.m and relative humidity 70%. Results showed that the friction coefficient decreases with increase of sliding speed and normal load. It also found that the wear rates increase with the increase of the sliding speed and normal load. Mikael Eriksson, [30] studied the effect of different friction-velocity behaviors. Number of different brake pads was evaluated with respect to friction behavior with changing speed. The results showed that there is a negative friction-velocity behavior. Most pads showed a slightly higher coefficient of friction at low sliding speeds. It was also found that at braking with constant speed the effect slightly reduced.

Rhee [31] has carried out an experimental investigation aimed to study the friction properties of a phenolic resin filed with iron and graphite. He investigated the influences of the normal force, sliding speed and drum temperature on the coefficient of friction. His results illustrated that the coefficient of friction ranged from 0.3 to 0.4 and with increase both of the normal force and rotational speed (sliding speed), the coefficient of friction decreased.

Severin et al. [32] have carried out an experimental study aimed to investigate the effect of the temperature on the coefficient of friction as a function of the number of brakes. the variation of the temperature and the coefficient of friction with the number of brakes along individual rings around the friction surface of a drum brake. The results as shown in the figure showed that the increase of the number of brakes increases the friction temperature as well as the coefficient of friction is not maintained at constant value as a result of the friction temperature increase. Also, the results showed that, the coefficient of friction has minimum value when the temperature is at maximum value.

3. Test rig and measurement instruments

The brake test rig has main objectives. The first objective is the ability to measure the generated brake power of the conventional and ABS disc brake at all operating parameters. The second objective of the test rig is to generate the required kinetic energy that could be overcome by the braking system. The test rig is designed and constructed to achieve these requirements. Figure (6) and Figure (7) shows the main components of the test rig which are: conventional and ABS disc brake system assembly, components of generation the kinetic energy and the components of generation the normal force.



1- Brake pedal 2- Pressure gauge 3- Master cylinder

4- Brake booster 5- Circular handle 6- ABS unit

7- Disc brake 8-Invertar 9- A.C motor

10- Battery 11-Suspension system

12- Electric pump 13- Computer

Figure (6) Main components of the test rig.

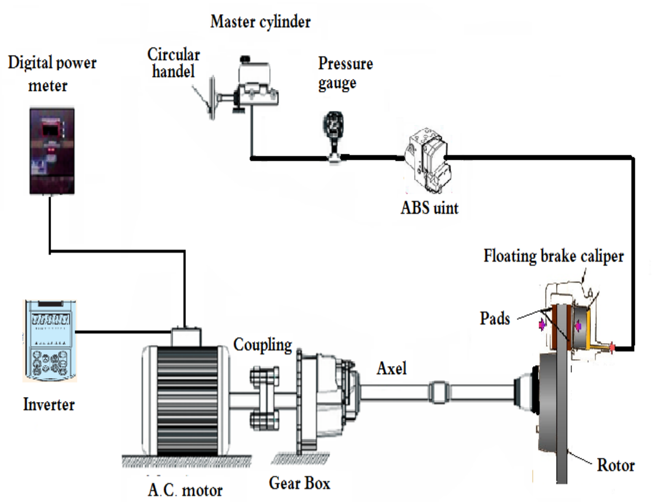


Figure (7) Schematic sketch of the test rig and measurement instrumentation.

A disc brake of passenger car is used in the test rig. This braking system is a floating caliper disc brake. The main components of this system. Are consists of floating caliper with its slave cylinder which contains a hydraulic piston of diameter 4.9 cm, rotor disc, two brake pads, wheel bearing, finger and hub. The hydraulic pipe is connected between the master cylinder and the hydraulic piston. An A.C electric motor is used in the test rig, as shown in Fig. (7). The electric motor is three phase type which has maximum power 5 Hp at 1500 r.p.m. In order to do the experiments at various speeds, Electric motor speed can be controlled by an inventor device to change the speed. The braking force is depending on two main parameters. The first parameter is the normal force affecting the brake pad. The second parameter is the coefficient of friction between the brake pads and the rotor disc. So, the normal force is considered the main factor of generating the brake force. Hence its effect on the braking process has to be taken into consideration. The generated normal force must have constant values during the tests according to the operating conditions. A master cylinder of commercial passenger car model Opel is used to generate the constant normal force. The master cylinder has two outlets of brake lines; each line is for two-wheel slave cylinder. The front hydraulic line allows the hydraulic oil to pass directly to the hydraulic piston of the slave cylinder. The brake pedal and the power booster are replaced by a screw push link with a circular handle to give the required forces. The purpose of this mechanism is to supply oil pressure that squeezes the hydraulic piston of the slave cylinder to generate the normal force that affects the brake pads. The measurement instrumentations system which are used can be divided as following: Pressure measurement and normal force calculation, Speed measurement, Brake torque, brake force and coefficient of friction calculation.

3.1 Normal force calculation

Use oil pressure gauge to measure the value of the oil pressure in the brake system as shown in equations. The pressure gauge is mounted in the hydraulic line between the master cylinder and the slave cylinder of the brake system. The normal force of the disc brake system is calculated as the multiplication of the piston area of the slave cylinder and the magnitude of the oil pressure. Different values of the normal forces of the conventional system are determined according to the values of the oil pressure as shown in the equations below:

$$A_s = \frac{\pi}{4} D_s^2 \qquad (1)$$

$$P = \frac{F_n}{A_s} \qquad (2)$$

$$F_n = P * A_s \qquad (3)$$

Where:

D_s The piston diameter of the slave cylinder equals (0.049 m)

A_s The piston area equals (1.89*10^{-3} m^2)

F_n The normal force of the disc brake system which affects the brake pad.

Four oil pressure values of 2, 4, 6, 8, 10 bar are selected during the tests. According to equation (3) these values of pressure equal normal forces of 378, 756, 1134, 1512, 1890 N respectively for the disc brake system.

3.2 Brake torque calculation

The brake power is measured by using digital power meter as shown in Fig (7). The type of the digital power meter is Schneider PM 1200 which has range from 20 watt to 300 k.watt and has accuracy 1% of reading for power and gives 60 readings per minute. In this study the brake power was determined as follow:

$$T_b = \frac{P_b}{\omega} \qquad (4)$$

$$\omega = \frac{2\pi n}{60} \quad (5)$$

Where:

P_b The brake power (watt)

T_b The braking torque (N.m)

ω The angular speed of the rotating disc (rad/sec.)

n The sliding speed of the rotating disc (r.p.m)

$$T_b = F_b \cdot r_{eff} \quad (6)$$

For a disc brake system there is a pair of brake pads, thus the total brake torque is:

$$T_b = 2\, F_b\, r_{eff} \quad (7)$$

$$r_{eff} = \frac{r_o + r_i}{2} \quad (8)$$

Where:

F_b The brake force generated (N)

r_{eff} The effective radius of the brake pad, equals 0.087 m

r_o The outer radius of the brake pad (m)

r_i The inner radius of the brake pad(m)

From equation (7) the brake force of the conventional system can be calculated as follow:

$$F_b = \frac{T_b}{2\, r_{eff}} \quad (9)$$

Where:

F_b The brake force of the conventional system (N)

However, the braking force is dependent upon the normal force and the friction coefficient, which is derived as below:

$$F_b = \mu\, F_n \quad (10)$$

The generated normal force of the conventional system was determined based on the brake-line pressure (P) as mentioned in equations (3) and (4), then by substituting equations (3) in equation (10), the coefficient of friction of the conventional system can be calculated as follow:

$$F_b = \mu\, P\, A_s \quad (11)$$

$$\mu = \frac{F_b}{P\, A_s} \quad (12)$$

Where:

μ The friction coefficient of the conventional system.

4. Results and Discussion

The experimental work is carried out to investigate the effect of different operating parameters such as brake oil pressure, sliding speed on the brake force and friction coefficient of the conventional disc brake. All experimental tests are conducted in the same conditions 60 seconds of braking. Three initial operating brake oil pressures are selected during the tests of the conventional disc brake and an Anti-Lock Braking System, these values were 2, 4,6,8 and 10 bar. Also, three sliding speeds are selected during the tests, these speeds were 100, 200 and 300 r.p.m. The brake power was measured every second by the digital power meter. The sliding speed, the brake oil pressure and measured during each test for the conventional disc brake. The brake force and friction coefficient of the conventional disc brake and an Anti-Lock Braking System were calculated every second and plotted with the brake time during each test.

The effect of the brake oil pressure on the normal force of the conventional system is presented in figure (8). From the results shown, it can be seen that, the increase of the brake oil pressure causes an increase of the normal force of the conventional system as shown in figure (8). The values of the oil pressure of 2, 4 and 6 bar produce normal forces of values 378, 756, 1134, 1512, 1890 N for the conventional system. The effect of the normal force on the brake force obtain from the relation Fb = µ. Fn.

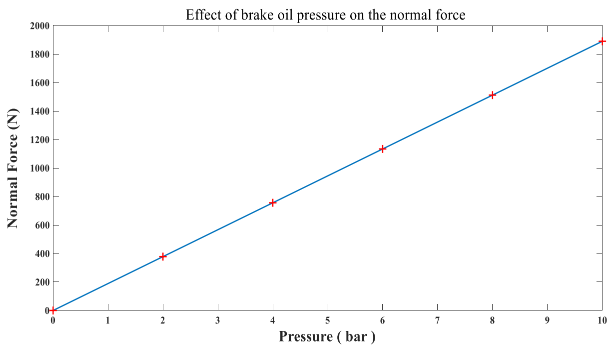


Figure (8) Effect of brake oil pressure on the normal force of conventional system.

In this section, the experimental tests are carried out at different values of the brake oil pressure at constant sliding speed.

The effect of brake oil pressure on the brake force of the brake system at sliding speed 100 r.p.m is presented in Figure (9). The results shown in Figure (9), Figure (10) and Figure (11) explain that, the brake forces of the brake system are increased with increasing the brake oil pressure. The brake forces of the brake system fluctuate with no identical trend at each constant pressure with the brake time. The fluctuation of the brake force is due to the variation of the friction coefficient with the time. Also, Figure (9) shows that, the mean brake force of the brake system at 10 bar is higher than the mean brake force of the brake system at 8 bar, 6 bar, 4 bar and 2 bar.

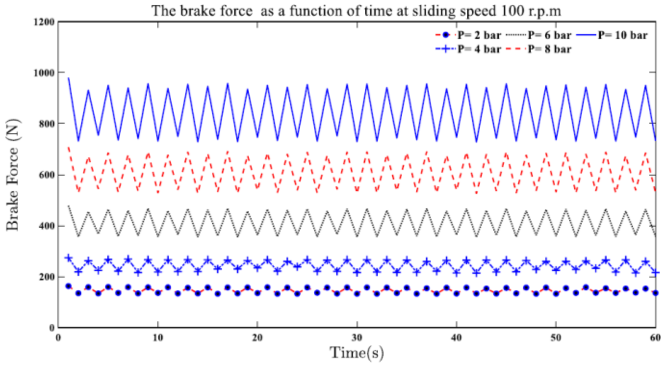


Figure (9) Variation of brake force of the brake system as a function of time at sliding speed 100 r.p.m at different brake oil pressure

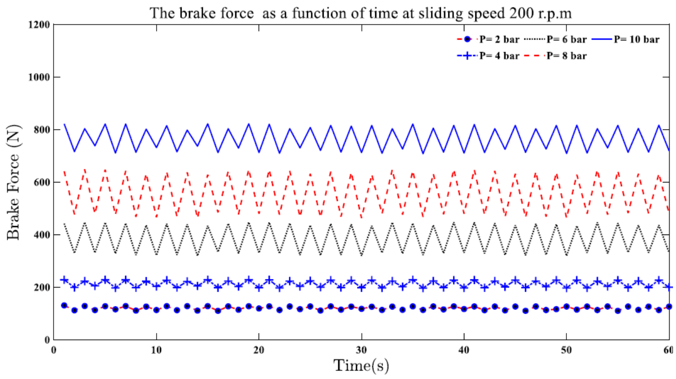


Figure (10) Variation of brake force of the brake system as a function of time at sliding speed 200 r.p.m at different brake oil pressure

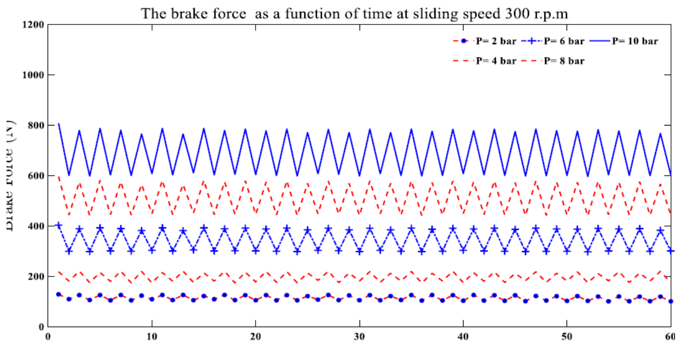


Figure (11) Variation of brake force of the brake system as a function of time at sliding speed 300 r.p.m at different brake oil pressure

Figure (12) shows that, the mean brake force of the brake system at sliding speed 100 r.p.m, 200 r.p.m and 300 r.p.m, at all sliding speeds the mean brake force increases with the increase brake oil pressure. At sliding speed 100 r.p.m, the mean brake forces of the brake system are 145, 242, 411, 608, 842 at brake oil pressure of 2, 4 ,6 ,8 and 10 bar respectively. At increasing brake oil pressure from 2 bar to 4 bar and from 4 bar to 6 bar and from 6 bar to 8 bar and from 8 bar to 10 bar, the value of the mean brake force of the brake system increases by 67%, 65%, 47%, 38% respectively with the increase brake oil pressure. At sliding speed 200 r.p.m, the mean brake forces of the brake system are 120, 212, 383, 556, 764 at brake oil pressure of 2, 4, 6, 8 and 10 bar respectively. At increasing brake oil pressure from 2 bar to 4 bar and from 4 bar to 6 bar and from 6 bar to 8 bar and from 8 bar to 10 bar, the value of the mean brake force of the brake system increases by 76%, 71%, 45%, 37% respectively with the increase brake oil pressure. At sliding speed 300 r.p.m, the mean brake forces of the brake system are 114, 197, 344, 509, 690 at brake oil pressure of 2, 4, 6, 8 and 10 bar respectively. At increasing brake oil pressure from 2 bar to 4 bar and from 4 bar to 6 bar and from 6 bar to 8 bar and from 8 bar to 10 bar, the value of the mean brake force of the brake system increases by 74%, 71%, 47%, 35%, respectively with the increase brake oil pressure.

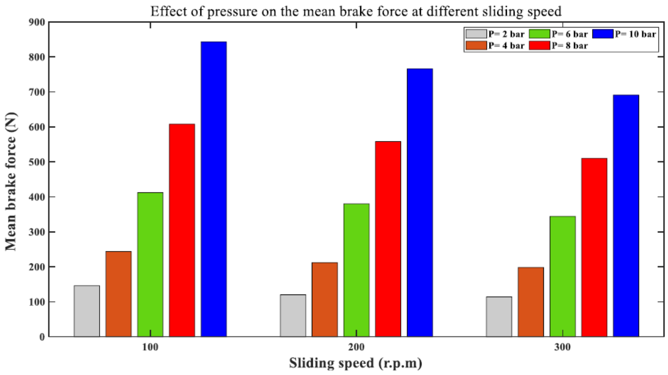


Figure (12) Effect of pressure on the mean brake force of the brake system at different sliding speed.

The presented results in Figure (13) show the effect of the brake oil pressure on the mean friction coefficient of the brake system at different sliding speed. The results indicated that, the increase of the oil pressure cause an increase of the mean friction coefficient of the brake system. Also, Figure (13) shows that, The highest value of the mean friction coefficient of the brake system at 10 bar. Also, the minimum value of the coefficient of friction at 2 bar. This is because the normal force which affects the brake pad of the brake system increases with brake oil pressure. This leads to increase the mean friction coefficient of the brake system at each pressure. At the sliding speed 100 r.p.m the increase of the oil pressure from 2 to 10 bar, the lowest value of the coefficient of friction is 0.3035 at 2 bar and it increases with increasing pressure to reach the highest value of 0.4064 at 10 bar. At the sliding speed 200 r.p.m the increase of the oil pressure from 2 to 10 bar, the lowest value of the coefficient of friction is 0.277 at 2 bar and it increases with increasing pressure to reach the highest value of 0.425 at 10 bar. At the sliding speed 300r.p.m the increase of the oil pressure from 2 to 10 bar, the lowest value of the coefficient of friction is 0.259 at 2 bar and it increases with increasing pressure to reach the highest value of 0.354 at 10 bar.

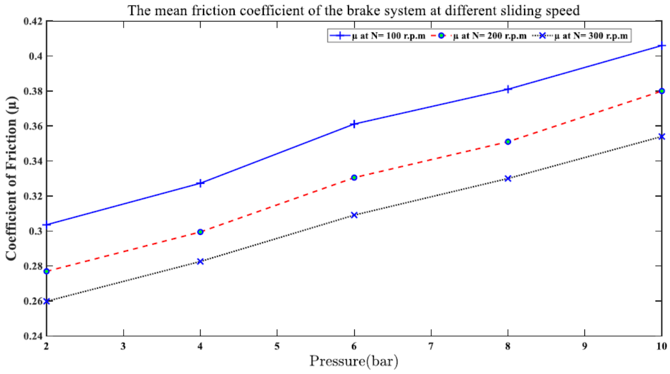


Figure (13) Effect of pressure on the mean friction coefficient of the brake system at different sliding speed.

4.2 Effect of sliding speed

In this section, the experimental tests are carried out at different values of the sliding speeds at constant brake oil pressure. The effect of sliding speed on the brake force of the brake system at brake oil pressure 10 bar is presented in Figure (14). The results shown in Figure (14) explain that, the brake forces of the brake system are decrease with increasing the sliding speed. The brake forces of the brake system fluctuate with no identical trend at each constant sliding speed with the brake time. The fluctuation of the brake force is due to the variation of the friction coefficient with the time. Figure (14) shows that, the mean brake force of the brake system at100 r.p.m is higher than the mean brake force of the brake system at 200 r.p.m and 300 r.p.m.

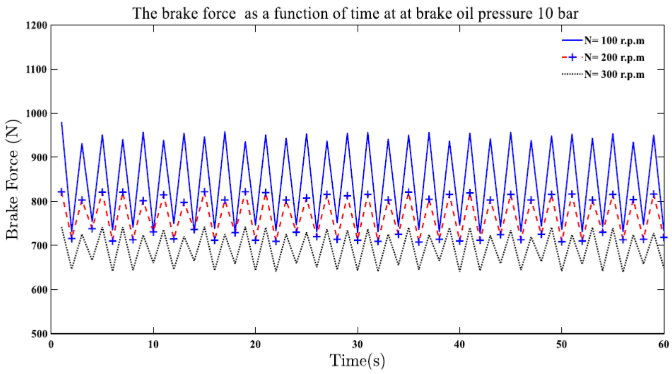


Figure (14) Variation of brake force of the brake system as a function of time at brake oil pressure 10 bar at different sliding speed

Figure (15) shows that, the mean brake force of the brake system at brake oil pressure 2 bar, 4 bar and 6 bar, at all brake oil pressure the mean brake force decreases with the increase sliding speed. At brake oil pressure 10 bar, the mean brake forces of the brake system are 842, 764, 690 at sliding speed of 100, 200 and 300 r.p.m respectively. At increasing sliding speed from 100 r.p.m to 200 r.p.m and from 200 r.p.m to 300 r.p.m, the value of the mean brake force of the brake system decreases by 9%, 7% respectively with the increase sliding speed.

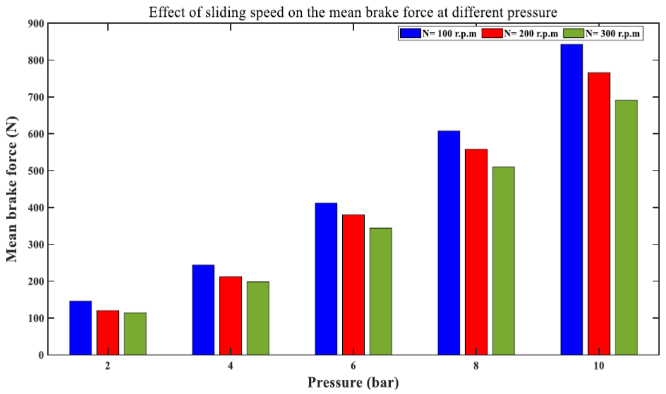


Figure (15) Effect of sliding speed on the mean brake force of the brake system at different pressure.

The presented results in Figure (16) show the effect of the sliding speed on the mean friction coefficient of the brake system at different oil pressure. The results indicated that, the increase of the sliding speed cause a decrease of the mean friction coefficient of the brake system. Also, Figure (16) shows that, the mean friction coefficient of the brake system at 300 r.p.m is less than the mean friction coefficient of the brake system at 200 r.p.m and 100 r.p.m. At the oil pressure 10 bar the increase of the sliding speed from 100 r.p.m to 200 r.p.m causes an decrease on the mean friction coefficient from 0.406 to 0.38 and he increase of the sliding speed from 200 r.p.m to 300 r.p.m causes an decrease on the mean friction coefficient from 0.38 to 0.39.

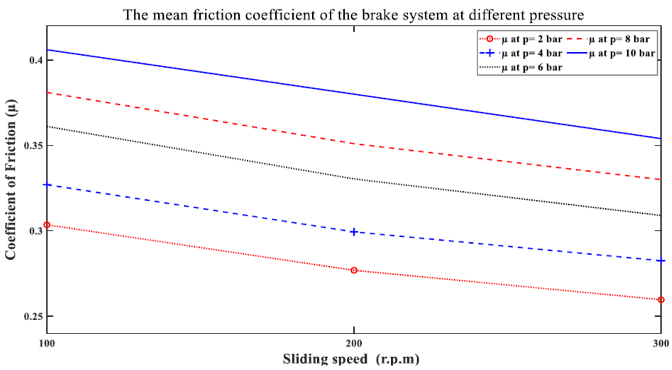


Figure (16) Effect of sliding speed on the mean friction coefficient of the brake system at different pressure.

4.3 Comparison between the conventional brake system and the anti-lock brake system and its effect on brake performance

The effect of brake oil pressure on the brake force of the conventional brake system and Anti-lock braking system (ABS) as a function of time at sliding speed 300 r.p.m and pressure 6 bar, 8 bar and 10 bar is presented in Fig (17) Fig (18) and Fig (19). The results explain that, the brake forces of the conventional brake system and Anti-lock braking system are increased with increasing the brake oil pressure. The increase with Anti-lock braking system is greater than with the conventional brake system. The brake forces of the conventional brake system and Anti-lock braking system fluctuate with no identical trend at each constant pressure with the brake time. The fluctuation of the brake force is due to the variation of the friction coefficient with the time. The presented results in Fig. (20) show that, the increase of the brake oil pressure leads to increase the mean brake force of the conventional brake system and the anti-lock brake system, but the mean brake force of the anti-lock brake system is higher than the mean brake force of the conventional brake system at each pressure.

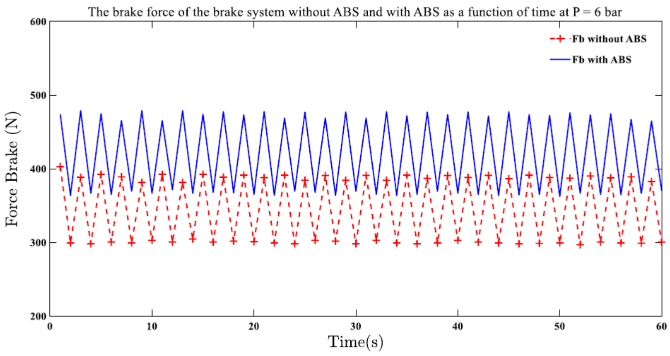


Figure (17) Variation of brake force of the brake system without ABS and with ABS as a function of time at pressure 6 bar and sliding speed 300 r.p.m.

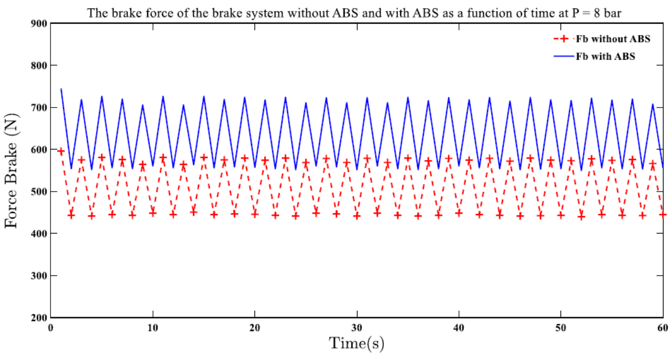


Figure (18) Variation of brake force of the brake system without ABS and with ABS as a function of time at pressure 8 bar and sliding speed 300 r.p.m.

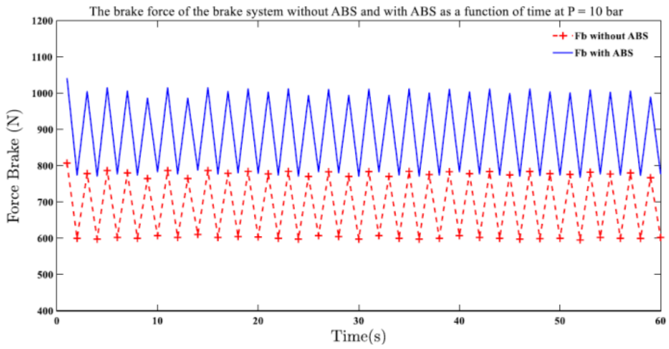


Figure (19) Variation of brake force of the brake system without ABS and with ABS as a function of time at pressure 8 bar and sliding speed 300 r.p.m.

A comparison between the conventional brake system and Anti-lock braking system are presented in Figure (20). It can be seen from the figure that the brake forces for Anti-lock braking system is better than conventional brake system especially at high Pressure. The mean brake forces of the conventional brake system are 344, 509, 690 N and the mean brake forces of the anti-lock brake system are 420, 637, 891 N at brake oil pressure of 6, 8 and 10 bar respectively. At each constant pressure, the value of the mean brake force of the anti-lock brake system increases by 12%, 21%, 29% respectively over the value of the mean brake force of the conventional brake system

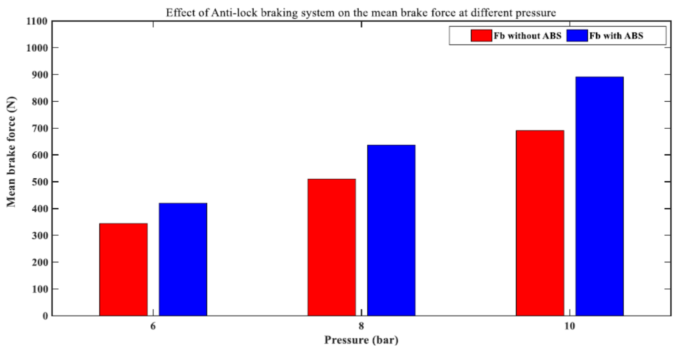


Figure (20) Effect of the Anti-lock braking system on the mean brake force at sliding speed 300 r.p.m and different pressure.

The presented results in Figure (21) show the effect of the brake oil pressure on the mean friction coefficient of the conventional brake system and Anti-lock braking system at different sliding speed. The results indicated that, the increase of the oil pressure cause an increase of the mean friction coefficient of the brake system.

A comparison between the conventional brake system and Anti-lock braking system are presented in Figure (31). It can be seen from the figure that the mean friction coefficient for Anti-lock braking system is better than conventional brake system especially at high Pressure. At pressure 10 bar and with increases sliding speed the mean friction coefficient for Anti-lock braking system increases by 14%, 11.8%, 10%

respectively over the value of the mean friction coefficient of the conventional brake system

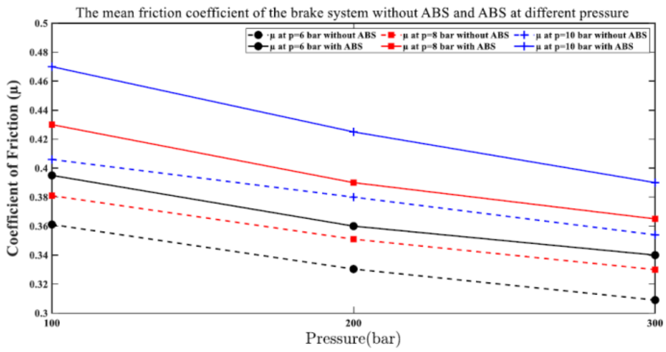


Figure (28) Effect of the Anti-lock braking system on the mean friction coefficient at different pressure.

5. Conclusions

The main conclusions from the present study can be summarized in the following points:

- The brake forces of the brake system are increased with increasing the brake oil pressure. The brake forces of the brake system fluctuate with no identical trend at each constant pressure with the brake time. The fluctuation of the brake force is due to the variation of the friction coefficient with the time.
- at all sliding speeds the mean brake force increases with the increase brake oil pressure. At sliding speed 100 r.p.m, the mean brake forces of the brake system are 145, 242, 411, 608, 842 N at brake oil pressure of 2, 4 ,6 ,8 and 10 bar respectively.
- At sliding speed 300 r.p.m, the mean brake forces of the brake system are 114, 197, 344, 509, 690 N at brake oil pressure of 2, 4, 6, 8 and 10 bar respectively. At increasing brake oil pressure from 2 bar to 4 bar and from 4 bar to 6 bar and from 6 bar to 8 bar and from 8 bar to 10 bar, the value of the mean brake force of the brake system increases by 74%, 71%, 47%, 35%, respectively with the increase brake oil pressure.
- the increase of the oil pressure causes an increase of the mean friction coefficient of the brake system. The highest value of the mean friction coefficient of the brake system at 10 bar. Also, the minimum value of the coefficient of friction at 2 bar
- the brake forces of the brake system are decrease with increasing the sliding speed. The brake forces of the brake system fluctuate with no identical trend at each constant sliding speed with the brake time.
- At brake oil pressure 10 bar, the mean brake forces of the brake system are 842, 764, 690 at sliding speed of 100, 200 and 300 r.p.m respectively. At increasing sliding speed from 100 r.p.m to 200 r.p.m and from 200 r.p.m to 300 r.p.m, the value of the mean brake force of the brake system decreases by 9%, 7% respectively with the increase sliding speed.
- the brake forces for Anti-lock braking system is better than conventional brake system especially at high Pressure. The mean brake forces of the conventional brake system are 344, 509, 690 N and the mean brake forces of the anti-lock brake system are 420, 637, 891 N at brake oil pressure of 6, 8 and 10 bar respectively. At each constant pressure, the value of the mean brake force of the anti-lock brake system increases by 12%, 21%, 29% respectively over the value of the mean brake force of the conventional brake system
- the mean friction coefficient for Anti-lock braking system is better than conventional brake system especially at high Pressure. At pressure 10 bar and with increases sliding speed the mean friction coefficient for Anti-lock braking system increases by 14%, 11.8%, 10% respectively over the value of the mean friction coefficient of the conventional brake system.

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