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Study On Mechanical and Thermal Behaviour of Rotor Brake Using Computer Aided Engineering Software

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Abstract: The disc brake system is one of the most essential parts of a moving vehicle since it helps to keep the drivers and passengers safe. A disc brake system is a kind of brake that uses callipers to press pairs of pads against a disc or rotor to create friction. The purpose of this study was to model and simulate disc brakes rotor using computer-aided engineering software, as well as to investigate the impact of mechanical and thermal behaviour on the designated disc brake. The disc brake simulation has be carried out using the finite element method in SolidWorks 2019 with four suggested materials: gray cast iron, titanium alloy, aluminium metal composite (AMC), and stainless steel with two alternative mesh density variations. Thermal distribution, stress, displacement, and strain are the comparisons to be assessed in variation of nodes and materials of disc brake. Each behaviour has its own set of best materials. Aluminium metal composite, has the lowest thermal distribution with value of 230 K for both Proton Saga Standard 1.3 AT and Honda City 1.5L E. Stainless steel has the greatest stress with the value 1000 MPa and 967.2 MPa for Proton Saga and Honda City respectively. In term of displacement, aluminium metal composite has highest displacement compared to other materials with value 0.5769 mm for Proton Saga and 0.5795 mm for Honda City. Aluminium metal composite is also has highest strain with the value of 4.238×10^{-3} and 3.938×10^{-3} for Proton Saga and Honda City respectively.

Keywords: Disc Brake, Simulation, Thermal, Mechanical, Gray Cast Iron, Titanium Alloy, Aluminium Metal Composite, Stainless Steel.

1. Introduction

The purpose of the braking system is to generate friction to decelerate a vehicle by converting kinetic energy into thermal energy between the brake pads and rotor faces, and then dissipating that heat into the atmosphere [1]. There are several major components in the braking system which are the pedal, drum and disc brakes, a brake booster and drive rod, the master cylinder, valves and lines, and

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emergency and anti-lock brakes are the major components of the vehicle braking system [2]. In certain kinds of automobiles nowadays, such as cars, motorcycles and even bicycles, disc brakes could also be installed. This is due to its role in decelerating or stopping the speed of the vehicles from travelling. On the front axle, and also on the rear, disc brakes are mounted. A disc brake uses a calliper mounted with brake pads to grasp a rotating disc or rotor to stop a wheel from turning. Two types of rotor braking have been found to be used concurrently on both the front and rear axles nowadays. They use disc brakes on the front axle, while drum brakes are used on the rear axle.

The disc rotor brakes have been analysed with different type of methodology such as through experiment or through the simulation with the help of engineering software. However in experiment method to analyse disc brake, it could not analysed the contact pressure distribution that happens on the disc brake which the simulation method is used in here. This is due to simulation method could analyse numerical analysis of the disc brake where it could predict the failure of the disc brake and improvement that could be made on the production of disc rotor brake. This project provides the systematic explanation of disc brake stress analysis by computer assisted engineering (CAE) software analysis. The stress distribution on the disc rotor during operation and estimation of failure regions can be studied by CAE or more precisely, finite element analysis (FEA).

1.1 Problem statement

The disc brake rotor’s material has been evolved since it has been introduced into the world due to the scientists and researchers still want to find the best material for the disc brake rotor that could give its high performance and at the same time is cheap and affordable to the users. There are several materials that have been used to make disc brake rotor which the popular being gray cast iron itself. Meanwhile, materials such as steel are widely chosen by the car racers due to it could handle heat better than gray cast iron, it is thinner and weightless. However it is also has downside where it is not durable like others.

Customers choose solid disc brakes and gray cast iron disc brakes because they are less expensive than other designs and materials. Cheap disc brakes, on the other hand, perform poorly and are risky to use. This project will focus more on numerical analysis of the mechanical and thermal behaviours between various materials and different nodes with the help of simulation in engineering software.

1.2 Ventilated disc brake

In a ventilated disc, two annular discs are separated by vanes or pillars or both to provide a passage for the air to circulate. Ventilated disc brake are favoured over solid rotors because of an increase in heat transfer surface area and a decrease in disc mass [3]. The majority of new trucks have ventilated brake discs, but solid discs or rotors are an alternative for certain off-road and older vehicles. For ventilated disc brakes, there are three different types of propellers that are straight radial, curve radial and pillar vanes which it acts almost the same as centrifugal function where to draw air into the centre of the rotor.

1.3 Material of disc brake

In addition to having different types of disc brake designs, different kinds of materials have also evolved as for the disc brakes to give their best performance and at the same time it could be purchased at a reasonable price. The disc brakes play an important part in braking systems due to the intense load on the brake discs and the extreme stress between the brake discs and brake pads during the braking process require the discs to withstand fatigue cracks and deformation, increase the material surface wear resistance, and minimise brake noise [4].

Therefore the best disc brake material can reduce the accident rate as it able to efficiently absorb and dissipate heat. Thus it will reduce the distance and the time needed to stop the vehicle. The rotor should have a good cooling rate to help minimize the risk of brake failure due to overheating of the brake pads and prolong the life of the pad as the hotter the pads are, the faster the wear of the brake pads, resulting cost overruns due to the need to replace the brake pads.

2. Materials and Methods

The materials and methods section, otherwise known as methodology, describes all the necessary information that is required to obtain the results of the study.

2.1 Materials

There are four different proposed materials that will be applied on the designated disc brake. The table of material properties for gray cast iron in Table 2.1 [5], titanium alloy in Table 2.2 [6], aluminium metal matrix composite (AMC) in Table 2.3 [7] and stainless steel in Table 3.17 [8] are shown below. Ceramic brake pads are utilised because it produces the least noisy, generate the least amount of dirty brake dust, and are stable over a large temperature range.

Table 2.1 Properties material for gray cast iron

Properties	Values
Density (g/cm^3)	7.2
Melting point (°C)	1200 – 1300
Elastic modulus (GPa) (Tension)	125
Poisson's ratio	0.25
Thermal conductivity (W/m • K)	42.0 – 62.0
Specific heat J/(kg • K)	460
Coefficient of thermal expansion (x10^{-6} °C)	8.1 – 19.3 (20°C)

Table 2.2 Properties material for titanium alloy

Properties	Values
Density (Kg/m^3)	4.41x10^3
Tensile strength (MPa)	896
Young Modulus (GPa)	110
Poisson's ratio	0.25
Thermal conductivity (W/m •°C)	7.1
Specific heat J/(kg • °C)	528
Thermal shock resistance (°C)	763

Table 2.3 Properties material for aluminium composite metal

Properties	Values
Compressive strength (MPa)	406
Friction coefficient (μ)	0.35
Wear rate (x10^{-6} mm^3/N/m)	3.25
Specific heat (kJ/kg • K)	0.98
Specific gravity (Mg/m^3)	2.7

Table 2.4 Properties material for stainless steel

Properties	Values
Modulus of Elasticity (GPa)	195
Poisson's ratio	0.25
Density (kg/m^3)	7900
Coefficient of thermal expansion (1/K)	7.5x10^{-5}
Thermal conductivity (W/m • K)	16.1
Specific heat (J/g • K)	510

Table 2.5 Properties material for ceramic brake pad

Properties	Values
Density (Kg/m^3)	2.3x10^3
Tensile strength (MPa)	172.34
Compressive strength (MPa)	551.49
Poisson's ratio	0.22 – 0.3
Thermal conductivity (W/m •K)	1.4949
Specific heat J/(kg • K)	877.96

2.2 Methods

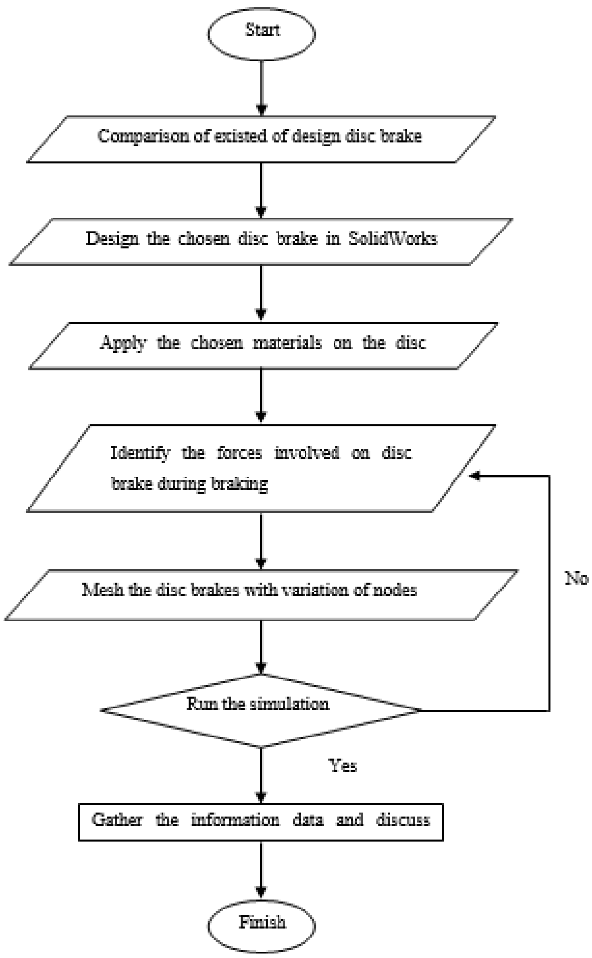

Figure 1: Flowchart

The method of study where the disc brakes will be built virtually using SolidWorks 2019. The simulation will be run using finite element method with the aid of SolidWorks 2019 with four proposed materials and different types of mesh density. The comparisons to be measured in variation of nodes and material of disc brake are as follows which are thermal distribution, stress, displacement and strain.

2.3 Designation of disc brake

Stopping distance	$d = \frac{v^2}{2\mu g}\ eq.1$ Where; d – stopping distance (m) v – velocity of the car (m/s) μ – coefficient of friction g – acceleration due to gravity $d = \frac{22.22^2}{2(0.7)(9.81)}$ $d = 35.95\ m$
Force	$a = \frac{v^2}{2s}\ eq.2$ $a = \frac{22.22^2}{2(35.95)}$ $a = 6.87\ m/s^2$ $F = m\ x\ a$ Where; m – mass of the vehicle a – acceleration F = 7316.55 N (for Proton Saga 1.3L Standard AT) F = 7735.62N (for Honda City 1.5L E)
Torque	$T = \frac{F}{4} x R_w\ eq.3$ Where; T – torque R_w – radius of wheel

	T = 528.25 Nm (for Proton Saga 1.3L Standard AT) T = 583.07 Nm (for Honda City 1.5L E)
Force brake pedal	$F_{bp} = F_d \ x \ \{L_1 \div L_2\} \ eq. 4$ F_{bp} = 500 x 4 = 2000 N Where; F_d = 500 N (assumption)
Hydraulic pressure by the master cylinder	$P_{mc} = \frac{F_{bp}}{A_{mc}} \ eq. 5$ P_{mc} = 7.02 MPa
Hydraulic pressure transmitted to the calliper	$P_{cal} = P_{mc} \ eq. 6$ P_{cal} = 7.02 MPa
One-sided linear mechanical force	$F_{cal} = P_{cal} \ x \ A_{cal} \ eq. 7$ F_{cal} = 4961.74 N
Clamp force generated by the calliper	$F_{clamp} = F_{cal} \ x \ 2 \ eq. 8$ F_{clamp} = 9923.47 N
Frictional force generated	$F_{friction} = F_{clamp} \ x \ \mu_{bp} \ eq. 9$ $F_{friction}$ = 3969.39 N Where; μ_{bp} = 0.4 (assumed)
Effective radius	$T_r = F_{friction} \ x \ R_{eff} \ eq. 10$ R_{eff} = 0.1467 m (for Proton Saga 1.3L Standard AT) R_{eff} = 0.1469 m (for Honda City 1.5L E) Thus, the effective rotor radius for Proton Saga 1.3L Standard AT is 0.1467 or 146.7 mm then the effective diameter will be 293.4 mm Thus, the effective rotor radius for Honda City 1.5L E is 0.1469 or 146.9 mm then the effective diameter will be 293.8 mm
Kinetic Energy	$KE = \frac{1}{2} m v^2 \ eq. 11$ Where; KE – kinetic energy

	KE = 262.91 kJ (or Proton Saga 1.3L Standard AT) KE = 277.97 kJ (for Honda City 1.5L E)
Total Heat Energy	Q_g = KE eq.12 Q_g = 262.91 kJ (for Proton Saga 1.3L Standard AT) Q_g = 277.97 kJ (for Honda City 1.5L E) So, heat generated in 1 rotor, Q_g = 65727.5 J for Proton Saga 1.3L Standard AT So, heat generated in 1 rotor, Q_g = 69492.5 J for Honda City 1.5L E
Stopping time	$t = \frac{v}{a}\ eq. 13$ Where t – time t = 3.23 s
Power generated in one rotor	$P = \frac{Q_g}{t}\ eq. 14$ P = 20349.07 Watts (for Proton Saga 1.3L Standard AT) P = 21514.71 Watts (for Honda City 1.5L E)

Relative velocity of air (v)	22.22 m/s
Diameter of the rotor	0.295 m
Reynold’s number, Re	$Re = \frac{\rho\ x\ v\ x\ d}{u}\ eq. 15$ Where; ρ – density of air v – velocity d – diameter of disc brake u – absolute viscosity Re = 74843.52
Nusselt number, Nu	$Nu = 0.0266(Re)^{0.805}x(Pr)^{0.333}\ eq. 14$ Where; Pr – Prantdl Number Nu = 197.49

Convective heat transfer coefficient, h	$$h = \frac{Nu(k)}{d} \; eq.16$$ Where; k – Thermal conductivity h = 40.06 Watts/m^2 · K

3. Results and Discussion

The results and discussion section presents data and analysis of the study. This section can be organized based on the stated objectives, the chronological timeline, different case groupings, different experimental configurations, or any logical order as deemed appropriate.

3.1 Results

Table 3.1 shows the percentage difference in thermal distribution between four suggested materials and two different cars at step 33 are determined in this section. However, only the highest temperature distribution and fine mesh density are included in the comparisons.

Table 3.1 Percentage different of thermal distribution of different materials and two different cars at step 33

	Proton Saga 1.3L Standard AT		Honda City 1.5L E	
Material of disc brake	Highest temperature distribution (K)	Percentage of different (%)	Highest temperature distribution (K)	Percentage of different (%)
Gray cast iron	315.5	55.2	315.5	55.2
Titanium alloy	571.6	-	571.6	-
Aluminium Metal Composite (AMC)	230	40.24	230	40.24
Stainless steel	438.1	76.64	428.1	76.64

Table 3.2 shows the percentage difference in stress behaviour between four suggested materials and two different cars are determined in this section. However, only the highest stress and fine mesh density are included in the comparisons.

Table 3.2 Comparison of stress behaviour of four different materials and two different cars

Material of disc brake	Proton Saga 1.3L Standard AT		Honda City 1.5L E		Yield strength (MPa)
	Highest stress (MPa)	Percentage of different (%)	Highest stress (MPa)	Percentage of different (%)	
Gray cast iron	201.3	20.13	200.3	20.71	-
Titanium alloy	366.9	36.69	397.9	41.14	827.4

Aluminium metal composite (AMC)	591.2	59.12	472.7	48.87	220
Stainless steel	1000	-	967.2	-	172.4

Table 3.3 shows the percentage difference in displacement behaviour between four suggested materials and two different cars are determined in this section. However, only the highest displacement and fine mesh density are included in the comparisons.

Table 3.3 Comparison of displacement behaviour for different materials and two different cars

	Proton Saga 1.3L Standard AT		Honda City 1.5L E	
Material of disc brake	Highest displacement (mm)	Percentage of different (%)	Highest displacement (mm)	Percentage of different (%)
Gray cast iron	0.3039	52.68	0.3073	53.03
Titanium alloy	0.2407	41.72	0.2683	46.30
Aluminium metal composite (AMC)	0.5769	-	0.5795	-
Stainless steel	0.4312	74.74	0.4527	78.12

Table 3.4 shows the percentage difference in strain behaviour between four suggested materials and two different cars are determined in this section. However, only the highest strain and fine mesh density are included in the comparisons.

Table 3.4 Comparison of strain behaviour for different materials for two different cars

	Proton Saga 1.3L Standard AT		Honda City 1.5L E	
Material of disc brake	Highest strain	Percentage of different (%)	Highest strain	Lowest strain
Gray cast iron	$2.040x10^{-3}$	48.14	$1.898x10^{-3}$	48.19
Titanium alloy	$2.682x10^{-3}$	63.28	$3.289x10^{-3}$	83.52
Aluminium metal composite (AMC)	$4.238x10^{-3}$	-	$3.938x10^{-3}$	-
Stainless steel	$3.561x10^{-3}$	84.03	$3.499x10^{-3}$	88.85

3.2 Discussions

Titanium alloy disc brake has the highest thermal distribution in both Proton Saga 1.3L Standard AT and Honda City 1.5L E, it has been used as a benchmark. Both Proton Saga 1.3L Standard AT an Honda City 1.5L E has same different percentage have same value with the highest one is titanium alloy followed by stainless steel (76.64%), gray cast iron (55.2%) and the lowest percentage of thermal distribution is aluminium metal composite (AMC) (40.24%).

Stainless steel disc brake has the highest stress in both Proton Saga 1.3L Standard AT and Honda City 1.5L E, thus it has been used as a benchmark. For Proton Saga 1.3L Standard AT, the with the highest one is stainless steel disc brake followed by aluminium metal composite (AMC) disc brake (59.12%), titanium alloy disc brake (36.69%) and the lowest percentage of stress analysis is gray cast iron disc brake with value of 20.13%. For Honda City 1.5L E, with the highest one is stainless steel disc brake followed by aluminium metal composite (AMC) disc brake (48.87%), titanium alloy disc brake (41.87%) and the lowest percentage of stress analysis is gray cast iron disc brake with value of 20.71%. Meanwhile the gap different percentage between two different cars for aluminium metal composite (AMC) disc brake is 10.25%, titanium alloy disc brake is 4.45% and gray cast iron disc brake is 0.04%.

Aluminium metal composite (AMC) disc brake has the highest displacement in both Proton Saga 1.3L Standard AT and Honda City 1.5L E, thus it has been used as a benchmark. For Proton Saga 1.3L Standard AT, with the highest one is aluminium metal composite (AMC) disc brake followed by stainless steel disc brake (74.74%), gray cast iron disc brake (52.68%) and the lowest percentage of stress analysis is titanium alloy disc brake with value of 41.72%. For Honda City 1.5L E, with the highest one is aluminium metal composite (AMC) disc brake followed by stainless steel disc brake (78.12%), gray cast iron disc brake (53.03%) and the lowest percentage of stress analysis is titanium alloy disc brake with value of 46.30%. Meanwhile the gap different percentage between two different cars for stainless steel disc brake is 3.38%, titanium alloy disc brake is 4.58% and gray cast iron disc brake is 0.35%.

Aluminium metal composite (AMC) disc brake has the highest strain in both Proton Saga 1.3L Standard AT and Honda City 1.5L E, thus it has been used as a benchmark. For Proton Saga 1.3L Standard AT, with the highest one is aluminium metal composite (AMC) disc brake followed by stainless steel disc brake (84.03%), titanium alloy disc brake (63.28%) and the lowest percentage of stress analysis is gray cast iron disc brake with value of 48.14%. For Honda City 1.5L E, with the highest one is aluminium metal composite (AMC) disc brake followed by stainless steel disc brake (88.85%), titanium alloy disc brake (83.52%) and the lowest percentage of stress analysis is gray cast iron disc brake with value of 48.19%. Meanwhile the gap different percentage between two different cars for stainless steel disc brake is 4.82%, titanium alloy disc brake is 20.24% and gray cast iron disc brake is 0.05%.

4. Conclusion

There are different best materials for each behaviour, for example, aluminium metal composite has the lowest thermal distribution due to its ability to resist high temperatures. Stainless steel has the greatest stress due to its ability to resist enormous impacts without deforming, shattering, or even bending. In term of displacement, aluminium metal composite has highest displacement compares to other materials. Aluminium metal composite is also has highest strain due to it is ductile material where it could withstand significant plastic deformation.

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