The thermal and stress analysis of disc brake

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Abstract: Braking system has huge importance in vehicles. The disc brake is one of the most important amongst the brake rotors. Brake rotors generate opposing torque on the shaft of the wheel thus converts the kinetic energy of the wheel to heat. The braking components are used to decelerate the vehicle by friction developed on to the wheel when brake is applied. The heat is produced during friction, which will cause negative effects on the brake assembly. This study is to analyze the motor cycle disc brake, which affects the surface of the disc. In order to get those effects on the disc surface the thermal stress analysis and thermal deformation is analyzed using ANSYS. This analysis is used to avoid the damage of the disc due to heat generation. In this study, different materials are compared to choose optimum one for the better performance to deformation, temperature and stresses.

Keywords: Disc brake, Friction, Deformation, Materials, Thermal analysis

INTRODUCTION:

Motor cycle plays vital role in our day-to-day life. If some obstacle comes in the path of moving vehicle, braking system is used to stop or decelerate the vehicle to avoid collision. But failure of braking system can cause accidents, hence study of braking system is mandatory. Sung Soo Kang and Seong-Keun Cho [10], studied geometry of vents in motorcycle disk brake. The thermal analysis is carried out in ANSYS. They compared the results for ventilated disc and solid disc for maximum temperature and concluded the importance of ventilated disc. Thilak [12], studied the importance of disc brake and materials required to make it. Cast iron is widely used for disc brakes but now a days those discs are made up from carbon-carbon composites (CCC) or ceramic matrix composites (CMC). He performed transient thermo-elastic analysis for repetitive braking and compared the results obtained. Sarip [11], modelled an assembly of disc brake with brake pads and wheel hub and fixed with nut bolt fitment. He applied pressure to carry out the braking operation by means of friction. The friction is necessary to stop a vehicle, these brake pads acts as the friction material to decelerate the vehicle speed. Guru Murthy et al [4], studied the operation of disc brake. They modelled the disc brake in CATIA and analysis is carried out in ANSYS. They took carbon ceramic composite material for study and calculated normal force, shear force, piston force and braking distance. Thermal and modal analysis is also carried out to obtain heat flux and deflection.

During continuous braking, the temperature of the brake increases. As the heat increases continuously, the effectiveness of the brake reduces and it may lead to damage of the brake rotor [1-3]. The critical performance requirements for a brake rotor includes good thermal conductivity, low wear rate, long durability, low vibration, heat resistant and high cooling rate [5-8]. For this purpose, disc brake is widely used. The best combination of the discs like the disc material, pad thickness and vent diameter are chosen. The brakes should be very strong and flexible to stop the vehicle immediately in fraction of seconds. The rider must have proper control on the vehicle during braking. The rider must control the vehicle not to have skidding of the vehicle during braking. The effectiveness should not be reduced up to its usage. Brakes should have very less wear property.
METHODOLOGY:

Modelling

It is difficult to model the exact disc brake for transient thermoelastic behavior hence in this study, the geometry of disc brake is modelled using some assumptions. These assumptions are developed to reduce the complexity in the mathematical calculations. The assumptions are made depending on the accuracy required during modeling [7]. The disc material is homogenous and isotropic. The disc should be stress free before the application of brake. Brakes should be applied on both the wheels. The thermal conductivity of the vehicle should be uniform throughout the disc. The disc brake is modelled in CATIA. The design is developed by using the disc of the Hero Honda Ambition bike of 135 cc as shown in figure 1.

![Figure 1. Solid model of 240mm disc brake](image1)

Meshing

The finite element analysis is the basic concept, which is used to analyze the structure. It is very difficult to analyze the entire structure once is difficult so in order to reduce the complexity we use meshing. The meshing consists of nodes and elements. The combined network of nodes and elements is called mesh. For this study, tetra mesh is used as shown in figure 2.

![Figure 2. 3-D meshing of a solid model](image2)

Type of Element : Solid90
Degrees of freedom : $K_{xx}$, $K_{yy}$, $K_{zz}$, $C$
Mesh size : 1.2

In thermal analysis, the functional is derived from governing differential equation with its boundary conditions. To get differential equation conversation of heat energy is applied to a control volume $dx$, $dy$, $dz$ which has heat conduction rates $q_x$, $q_y$, $q_z$ in $x$, $y$, $z$ directions. Heat conduction rates in opposite direction $q_{x+dx}$, $q_{y+dy}$, $q_{z+dz}$ can be given as [9].
where,

\( K_c \) is conductivity and \( T \) is temperature.

Conservation of energy can be expressed as,

\[
\text{Rate of heat increment in the volume (} E_{st} \text{)} = \text{Rate of heat transfer across its surfaces} + \text{Rate of internal heat generation (} E_g \text{)}
\]

(3)

where,

\[
E_{st} = \rho c \left( \frac{\partial T}{\partial t} \right) dx \, dy \, dz
\]

(4)

\[
E_g = \varphi dx \, dy \, dz
\]

(5)

where, \( \varphi \) is rate at which energy is generated per unit volume

Substitute equations (1), (2), (4), (5) in equation (3) gives the following,

\[
- \frac{\partial q_x}{\partial x} dx \times \frac{\partial q_y}{\partial y} dy \times \frac{\partial q_z}{\partial z} dz + \varphi dx dy dz = \rho c \left( \frac{\partial T}{\partial t} \right) dx \, dy \, dz
\]

(6)

To determine temperature distribution along the disc, boundary conditions have to be substituted in equation (6).

Boundary Conditions

After the completion of finite element model, boundary conditions are applied for thermal as well as structural analysis. The thermal boundary conditions of the disc brake are adiabatic and applied at inner radius as well as outer radius of disc brake with initial temperature \( T=25^\circ C \) along the radius of the disc.

Selection of the best material for the disc

The best material for the disc is selected based on the operating condition so that it can withstand at a constant hydraulic pressure \( P=1.05 \text{ MPa} \). In this study, results obtained for displacement, stresses and nodal temperature distribution are compared for different materials. Cast iron, stainless steel and carbon-carbon composites are taken under consideration. The analysis is carried out in ANSYS and by comparing the results, optimum material is selected. This study will also give the combination of material and vent which increases the life of the disc.
RESULTS AND DISCUSSION:

Design statement

The disc brake is designed for the motor cycle having the kerb weight of 143 kg. The motor cycle running at a speed of 60 km/hr, and it is brought to rest in 4 seconds on applying the brake. The radius of the rolling wheel is 480 mm and it is assumed that the kinetic energy of the rotating parts is 10% of the kinetic energy of the moving bike. The weight of the rider is assumed as 65 kg.

The optimum material for required application is obtained by comparing various parameters. To study the thermoelastic behavior of brake, a constant pressure of 1.05 Mpa is applied. The thermal boundary conditions are applied on the disc as mentioned. The temperature applied is as per the material obtained in the design calculations for the upper pad or on outer surface area of the disc for which most of the part is covered by the pad of the caliper. The material properties and operation conditions used for the validation are shown in Table 1 for the steady state condition of the 3 various materials of disc is as follows:

Disc brake calculations

From the above conditions,

\[ m_1 = 143 \text{ kg; } m_2 = 65 \text{ kg; } \]
\[ m = m_1 + m_2 = 143 + 65 = 208 \text{ kg} \]
\[ R = \text{rolling radius of the wheel} = 480 \text{ mm} \]

Velocity of the moving vehicle; \( v_1 = 60 \text{ km/hr} = 16.66 \text{ m/s} \)

Velocity of the vehicle after braking; \( v_2 = 0 \text{ km/hr} = 0 \text{ m/s} \)

**Step-1:**

\[ E_v = \text{kinetic energy of the motor cycle in Joules} \]
\[ E_r = \text{kinetic energy in the rotating parts} \]
\[ E_v = 0.5 \times m \times (v_1^2 - v_2^2) \]
\[ E_r = 0.5 \times 208 \times (16.66^2 - 0^2) \]
\[ E_v = 28865.7824 \text{ J} \]
\[ E_r = 0.1 \times E_v \]
\[ E_r = 2886.57824 \text{ J} \]

**Step-2:**

The total energy of the disc can be calculated by the following equation [2],

Total energy = \[ E = E_v + E_r \]  
\[ E = 28865.7824 + 2886.57824 = 317252.36 \text{ J} \]

**Step-3:**

\[ E = T_b \times \theta_b \]

\( \theta_b \) = Angular displacement of the brake during braking period given by,

\[ \theta_b = \omega \times t - 0.5 \times \alpha \times t^2 \]

where, \( \omega = \text{Angular velocity in rad/sec.} \)

\[ \omega_1 = v_1/R = 16.66/0.48 = 34.7 \text{ rad/s} \]

\( \alpha = \text{Angular acceleration in rad/sec}^2 \)
\[ \alpha = (\omega_1 - \omega_2)/t = (34.7 - 0)/4 = 8.677 \text{ rad/s}^2 \]  
\[ \theta_b = (34.7 \times 4) - (0.5 \times 8.677 \times 4^2) = 69.384 \text{ rad} \]  

Table 1. Properties of different materials

| Material properties          | Cast iron | Stainless steel | Carbon-carbon composites |
|------------------------------|-----------|-----------------|--------------------------|
| Thermal conductivity (K)     | 57        | 17.2            | 400                      |
| Density (\( \rho \))         | 7200      | 7800            | 1800                     |
| Specific heat (c)            | 452       | 500             | 1420                     |
| Poisson’s ratio (\( \gamma \)) | 0.3       | 0.3             | 0.3                      |
| Thermal expansion (\( \alpha \)) | 11        | 16              | 0.31                     |
| Elastic modulus (E)          | 100       | 190             | 50.2                     |
| Coefficient of friction (\( \mu \)) | 0.1       | 0.1             | 0.1                      |
| Room temperature (T_1)       | 25        | 25              | 25                       |
| Temperature in disc (T_2)    | 221.8     | 202.88          | 87.6425                  |
| Hydraulic pressure (P)       | 1.05      | 1.05            | 1.05                     |

Now from equation (9),

\[ T_b = E/\theta_b = \text{Torque required to stop the wheel} \]  

As, two brake pads are used

\[ E = E/2 \]  

\[ T_b = \frac{15876.18}{69.384} \]  

\[ T_b = 228.816 \text{ N-m} \]  

\[ T_b = 228.816 \times 10^3 \text{ N-mm} \]  

Step-4:

Temperature and Energy dissipation calculations;

Let us assume 50% of the heat generated is dissipated to the surroundings during braking hence,

\[ E = E_i = \text{Energy calculated in the design (15876.18 J)} \]  

m = mass of the disc brake assembly = 2.5 kg (Assumed)

Material 1: Cast Iron

\[ E = m \times c_p \times \Delta T \]  

\[ E_i = \left( E_{i-1}/2 \right) + E_1 \]  

For 1st braking,

\[ E_i = m \times c_p \times \Delta T \]  

\[ \Delta T = E_i / (m \times c_p) \]  

\[ \Delta T = 15876.18 / (2.5 \times 452) = 14.05^\circ \text{C} \]  

For 2nd braking,

\[ E_2 = m \times c_p \times \Delta T \]  

\[ E_2 = (E_1/2) + E_1 \]
\[ E_2 = 23814.27 \]
\[ \Delta T = 21.07^\circ C \]

Hence, study is carried out for 8 brakes and found out that, for 8th braking, \( \Delta T = 27.9896^\circ C \)

Initial temperature on the disc is \( T = 25^\circ C \)

After 1st braking \( T_1 = 25 + 14.05 = 39.05^\circ C \)

2nd braking \( T_2 = 39.05 + 21.07 = 60.12^\circ C \)

3rd braking \( T_3 = 84.71^\circ C \)

4th braking \( T_4 = 111.05^\circ C \)

5th braking \( T_5 = 138.27^\circ C \)

6th braking \( T_6 = 165.93^\circ C \)

7th braking \( T_7 = 193.81^\circ C \)

8th braking \( T_8 = 221.08^\circ C \)

Thermal and stress analysis is carried out on the cast iron disc. The results such as nodal stresses and Von misses stress distribution are shown in figure 3 and figure 4. The rise in temperature and energy dissipation along the disc and average displacement are shown in figure 5 and figure 6.

![Figure 3. Nodal stresses distribution](image1)

![Figure 4. Distribution of Von misses Stress](image2)

![Figure 5. Energy dissipation in braking steps](image3)

![Figure 6. Average displacement](image4)
Material 2: Stainless Steel

\[ E = m \cdot c_p \cdot \Delta T \]  \hfill (20)

\[ E_1 = 15876.18 \text{ J} \]
\[ \Delta T = 12.07^\circ \text{C} \]
\[ E_2 = 23814.25 \text{ J} \]
\[ \Delta T = 19.05^\circ \text{C} \]

Hence, study is carried out for 8 brakes and found out that, for 8th braking, \( \Delta T = 25.30^\circ \text{C} \)

Initial temperature on the disc \( T = 25^\circ \text{C} \)

After 1st braking \( T_1 = 25 + 12.07 = 37.07^\circ \text{C} \)
2nd braking \( T_2 = 37.07 + 19.05 = 56.12^\circ \text{C} \)
3rd braking \( T_3 = 78.97^\circ \text{C} \)
4th braking \( T_4 = 102.78^\circ \text{C} \)
5th braking \( T_5 = 127.38^\circ \text{C} \)
6th braking \( T_6 = 152.38^\circ \text{C} \)
7th braking \( T_7 = 177.58^\circ \text{C} \)
8th braking \( T_8 = 202.8^\circ \text{C} \)

Thermal and stress analysis is carried out on the stainless steel. The results such as nodal stresses and von misses stress distribution are shown in figure 7 and figure 8. The rise in temperature and energy dissipation along the disc and average displacement are shown in figure 9 and figure 10.

![Figure 7. Nodal stresses distribution](image)

![Figure 8. Distribution of Von misses Stress](image)

![Figure 9. Energy dissipation in braking steps](image)

![Figure 10. Average displacement](image)
Material 3: Carbon-carbon Composite

\[ E = m \cdot c_p \cdot \Delta T \]  \hspace{1cm} (21)

\[ E_1 = 15876.18 \text{ J and } \Delta T = 4.472^\circ \text{C} \]
\[ E_2 = 23814.29 \text{ J} \]
\[ \Delta T = 6.708^\circ \text{C} \]

Hence, study is carried out for 8 brakes and found out that, for 8th braking, \( \Delta T = 8.909^\circ \text{C} \)

Initial temperature on the disc \( T = 25^\circ \text{C} \)

After 1st braking \( T1 = 25 + 4.472 = 29.472^\circ \text{C} \)

2nd braking \( T2 = 29.472 + 6.708 = 36.18^\circ \text{C} \)

3rd braking \( T3 = 44.006^\circ \text{C} \)

4th braking \( T4 = 52.391^\circ \text{C} \)

5th braking \( T5 = 61.055^\circ \text{C} \)

6th braking \( T6 = 69.8595^\circ \text{C} \)

7th braking \( T7 = 78.7335^\circ \text{C} \)

8th braking \( T8 = 87.6425^\circ \text{C} \)

Thermal and stress analysis is carried out on the carbon-carbon composites. The results such as nodal stresses and von misses stress distribution in the disc are shown in figure 11 and figure 12. The rise in temperature and energy dissipation along the disc and average displacement are shown in figure 13 and figure 14. The results for cast iron, stainless steel and carbon-carbon composites are presented in table 2.
Table 2. Comparison of Various Disc Parameters

| Material parameters          | Cast iron | Stainless steel | Carbon-carbon Composites |
|-----------------------------|-----------|-----------------|--------------------------|
| Diameter                    | 240       | 240             | 240                      |
| Maximum temperature         | 221.8     | 202.8           | 91.55                    |
| Minimum temperature         | 25        | 25              | 25                       |
| Deflection                  | 0.194     | 0.108           | 0.441                    |
| Von Misses Stresses         | 97.88     | 94.44           | 97.37                    |
|                             | 0.239     | 0.26            | 0.392                    |

CONCLUSION:

The steady state thermal analysis of the disc brakes is repeated in brake application that has been performed along with the theoretical design. Based on the results from ANSYS, the thermo elastic behaviors of the Carbon-Carbon composite, Stainless steel and Cast-iron disc brakes are investigated. In structural analysis deflection of disc, Von misses stresses and nodal stresses distribution is calculated. Same in case of thermal analysis heat flux distribution and nodal temperature distribution is calculated. All these parameters give the information that for a particular brake application which material is best suitable one. The present study can provide a useful design tool and improve the brake performance of disc brake system. Comparing the different results obtained from analysis, it is concluded that disc brake with 240 mm diameter and of stainless-steel material is the best possible combination for the present application.

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