Thermo-Structural Analysis of Disc Brake for Maximum Heat Dissipation

Amar Ambekar[1], Amit Bharti[2], Shashank Shekhar[3], Anushtup Biswas[4]

Abstract— Disc brakes are widely used for regulating the speed of the vehicle by hindering the rotation of a wheel. During each braking cycle, disc brakes are subjected to high thermal loads due to the squeeze action between pad-disc pair. Material selection and design of a brake plays an important role in the dissipation of heat generated. The present work attempts to increase the surface area for maximum heat dissipation of a disc brake by introducing different patterns of holes, slots and groove combinations in the base design which is a plain disc. For analysis purpose, the geometrical parameters such as the outer and inner diameter of plain disc are fixed as 240 mm and 140 mm respectively with reference to the standard dimensions of disc brake used in Honda Unicorn bike. Thermo-structural analysis is carried out on the seven different geometric models of disc brakes with Carbon fiber reinforced silicon carbide material (C/SiC). Steady state temperature variations, transient structural deformations and Von Mises stresses were determined. A rotor with minimum deformation, low stress level in comparison with the existing designs were developed. The results show that the Model-3 with elongated holes at the outer surface has a relatively lower temperature which is about 49.3% lower as compared to base model indicating higher heat dissipation.

Keywords— disc brake, heat dissipation, thermo-structural analysis

I. Introduction

Disc brakes are commonly used in modern bikes owing to higher stopping power compared to traditionally used drum brakes. The energy absorbed by the brake is dissipated in the form of heat to the surrounding atmosphere. The material used for disc brake should possess the properties like high co-efficient of friction, high compressive strength, less wear, low weight and high thermal conductivity.The commonly used materials for a brake in automotive industry are cast iron, titanium alloys, aluminum Composite, C/C-SiC ceramic materials. “More than 2000 different materials and their variants are now used in commercial brake components” [1]. Heat dissipation from the brake disc is an important design aspect which has significant influence on thermal deformation in the disc brake. Shinde et al. [2] carried out structural and thermal analysis on two different cut patterns of disc brake of a two wheeler for maximum heat transfer rate using ANSYS Fluent and Workbench. Jadav et al. [3] optimized the disc brake of a motor cycle to reduce the cost and weight of the disc assembly. The authors also used the materials such as asbestos, semi metallic, metallic, low steel and carbon for disc brake pad and their performance was studied. Sushma et al. [4] carried out the thermal and Structural Analysis of disc Brake with square and circular grooves for two wheeler dealing with heat distributions. Structural and thermal studies were carried out to analyze the extreme cases of heat distributions in the brake systems. Numerical methods were used to predict the temperature behavior. Pravin et al. [5] carried out a structural and thermal analysis of a disc brake used in Bajaj pulsar bike by modifying the shape of the rotor disc. The material used for the disc brake was SUS M 410. The optimum shape of the rotor that resulted in less temperature variation, stress levels and deformation was determined and manufactured. Further thermal and vibrational analysis were done experimentally on the optimized disc brake. Manjunath et al. [6] carried out a coupled a thermal-structural analysis on solid and ventilated disc using ANSYS Workbench to determine the best possible design, material and rotor disc. The present work attempts to increase the surface area for maximum heat dissipation of a disc brake by introducing different patterns of holes, slots and groove combinations in the base design which is a plain disc.

II. Material Selection

The materials used in brakes should possess some combination of properties such as good compressive strength, higher friction coefficient, wear resistant, light weight and good thermal conductivity. The temperature storage capacity of the disc brake should be high so as to prevent cracking or distortion from thermal stress until the heat can be dissipated. The most commonly used material for automotive brake rotor include cast iron, Aluminium Metal Matrix Composite, Titanium alloys and their composites. In the present work, the disc brake is modelled with Carbon fibre reinforced silicon carbide material (C/SiC). The properties of C/SiC brake disc material are shown in table I. Brake discs based on C/C-SiC are extremely lightweight and show a structural resistance at temperature over 1000 °C. In combination with their low density, high thermal shock resistance and good abrasive resistance, these C/C-SiC composites are promising candidates for advanced friction systems [7].

TABLE I: Properties of C/SiC brake disc material [7]

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Material Properties	Disc
Thermal conductivity , k (W/m °C)	40
Specific heat, C_p (J/Kg °C)	800
Density ρ (kg/m^3)	2450
Thermal expansion, α (10^{-6} / °C)	2.8e^{-5}
Poisson's ratio, ν	0.27
Modulus of Elasticity, E (GPa)	30
Friction Coefficient, μ	0.27
Hydraulic pressure, P (MPa)	1.2
Angular velocity, ω (rad/s)	50

TABLE II: Vehicle data [8]

Item	value
Outer diameter of disc brakes- D [mm]	240
Inner diameter of disc brake – d [mm]	120
Initial Velocity – u [m/s]	22.22
Mass of bike - m_1 [kg]	144

III. Modelling And Design Calculations

The present work attempts to increase the surface area for maximum heat dissipation of a disc brake by introducing different patterns of holes, slots and groove combinations in the base design which is a plain disc. For analysis purpose, the geometrical parameters such as the outer and inner diameter of plain disc are fixed as 240 mm and 140 mm respectively with reference to the standard dimensions of disc brake used in Honda Unicorn bike [8]. Disc brake with seven different geometric designs were modelled using CATIA V6 modelling software and analysis was carried out using ANSYS Workbench. Table II provides the dimensions of disc brake used Honda Unicorn bike [8]

A. *Design Calculations [9]*

Kinetic energy

Total mass on the vehicle, M = 210 kg, Initial speed, u = 80 km/hr = 22.22 m/s; Final speed, v = 0 m/s, $KE = \frac{1}{2}M(u^2-v^2) = \frac{1}{2} \times 210 \times 22.22^2 = 51841.48\ J$

Stopping distance $= \frac{u^2}{2a} = \frac{22.22^2}{2\times10} = 24.68\ m$; Deceleration, a = 10 m/s2

Braking Power, $P = \frac{Q}{t}$; For braking time of t = 4 s, $P = \frac{51841.482}{4} = 12960.3705\ W$; Heat flux, $q = \frac{4P}{\pi(D^2-d^2)}$ $= 381982.78\ W/m^2$;

Heat flux on wheel brake, $q' = q * 0.5 = 190991.3916\ W/m^2$

For breaking time of t = 5 s, $P = \frac{51841.482}{5} = 10368.296\ W$; Heat flux, q $= \frac{4P}{\pi(D^2-d^2)}$ = 315586.214 W/m2

Heat flux on wheel brake, $q' = q * 0.5 = 157793.107\ W/m^2$

For breaking time of t = 6 s, $P = \frac{51841.482}{6} =$ 8640.25W ; Heat flux, q $= \frac{4P}{\pi(D^2-d^2)}$ = 254655.27 W/m2

Heat flux on wheel brake, $q' = q * 0.5 = 127327.635\ W/m^2$

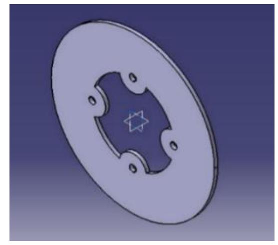


Fig. 1: Basic 3D model of a plain disc brake

IV. Meshing

The model of the disc brake shown in figure 1 was meshed using the hex-dominant meshing choosing tri/quad elements with majority of being the hex type. The number of elements in the computational domain is varied by varying the element size from 5 mm to 1 mm as shown in table III. The number of elements were found to vary from 3979 to 412978 and the corresponding values of Emax (Von-Mises stress) was noted to determine the optimal mesh. From table III, it is clear that the variation of Emax with further reduction in the element size beyond 2 mm has negligible variation in Emax of not more than 0.018 %. Hence, the element size of 2 mm is selected as the optimal mesh size and all the design modifications used further in the analysis are meshed with atleast 2 mm element size.

TABLE III: Grid independency test results

Element size (mm)	Number of elements	Von-Mises stresses, E_{max}	Percentage variation of E_{max}
5	3979	107.2	-
4	8231	107.06	0.13 %
3	19244	106.87	0.17 %
2	53369	106.79	0.074 %
1	412978	106.77	0.018 %

V. Modeling

Wavy circumference of Model-1 increases the surface area. The slots are made parabolic to fit in the constrained space. The outer profile of Model-2 is designed as a sprocket that helps to reduce the unsprung weight. The holes reduce aquaplaning of the pads and are easy to produce. Model-3 is designed with a rotor that has mass removed from the low temperature zone which reduces the weight and helps in material reduction. Elongated holes of model 3 at the outer surface reduces aquaplaning and increases heat dissipation. Ribs in Model-4 are added to strength and stiffness of the inner part of the rotor where material has been removed. Triangles of Model-5 hold large loads without collapsing or having their structure altered. Model - 6 are of floating rotors with slots. Model-7 is designed with floating rotors with holes. The material removal is more uniform in this model as compared to the previous Model-6.

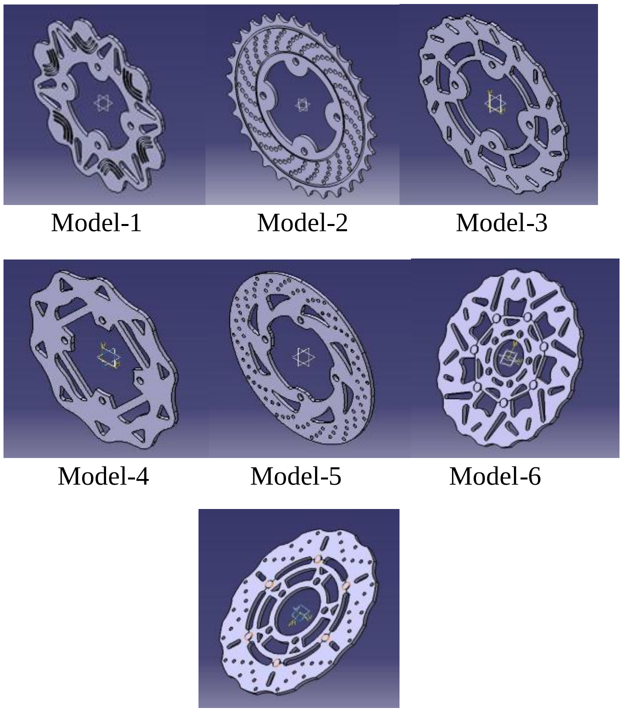


Fig.2: Geometric models of disc brakes

VI. Boundary Conditions

A. Boundary Conditions For Structural Analysis:

Rotational speed, ω= 50 rad/s is applied on the disc brake. Pressure, P = 1.2 MPa is applied on both the sides of the pads, Fixed support is given to the inner surface of the holes in the disc brake rotor, which connects the wheel hub to the rotor.

B. Boundary Conditions For Thermal Analysis:

Heat flux of 0.157 W/mm2 is applied on the brake pad; Convective film coefficient of 300 e-6 W/mm2 K is applied on the rotor and the radiative heat is considered negligible on the disc and the pads [10].

VII. Analysis And Results

Steady state thermal analysis was carried out by applying the value of heat flux, for repeated breaking on different models of disc brake to study the temperature distribution along the disc. The analysis is initiated with Model-1 whose simulation results are used as reference to develop the modified design of Model-2. The temperature distribution of Model-2 is used as the basis for Model-3 and so on. A total of seven models are consider in the analysis as shown figure 2 and meshed view of the all the seven geometries of disc are shown in figure 3. The higher temperature zones are identified and modification in the shape is made by increasing the surface area for heat dissipation through increased number of holes and grooves at higher temperature zones. Further the static structural analysis was carried out for these seven models. The deformation, stress, temperature distribution were determined as shown table IV.

Fig.3: Meshed models of disc brakes

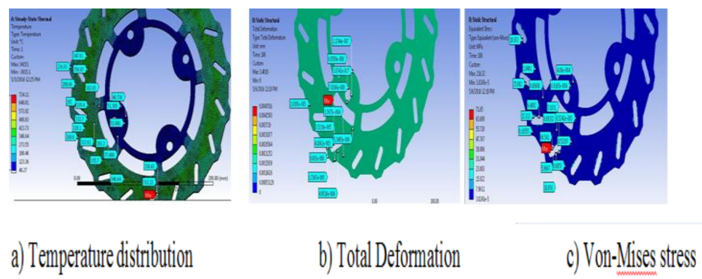
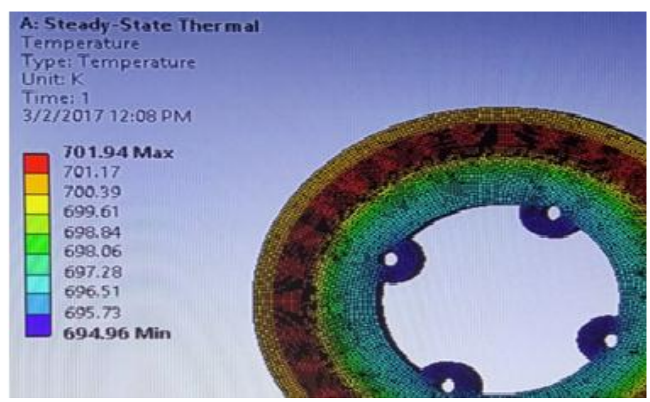
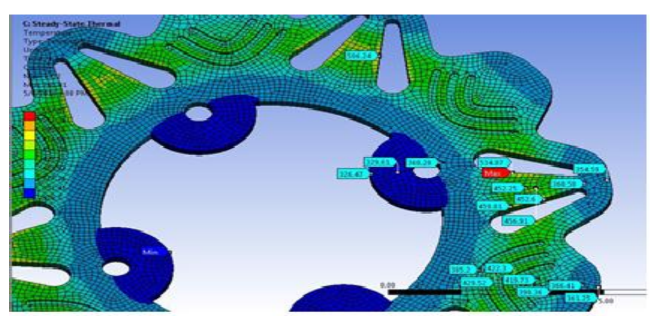


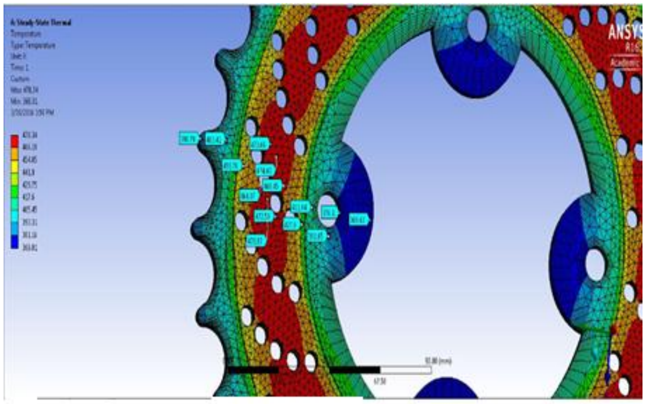
Fig.4: Analysis results of Model-3



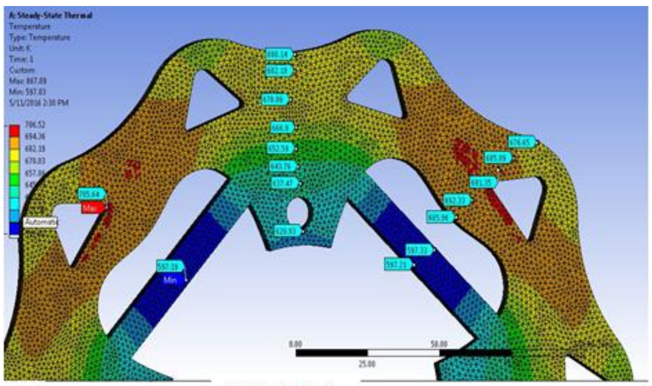
Base Model



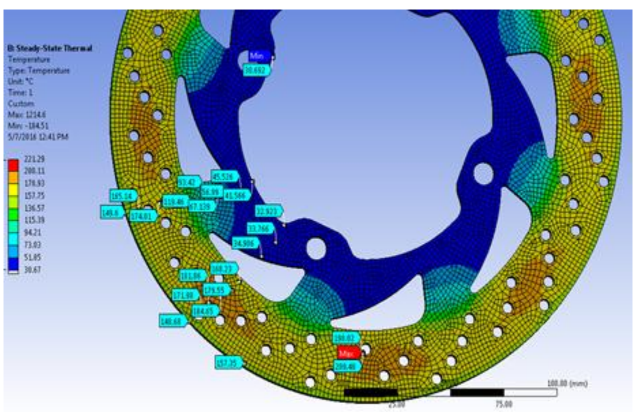
Model-1



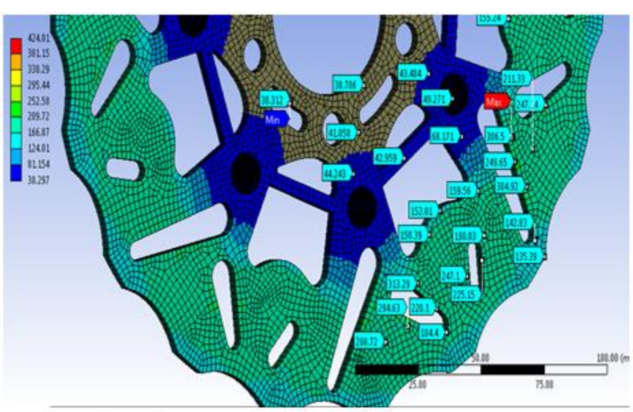
Model-2



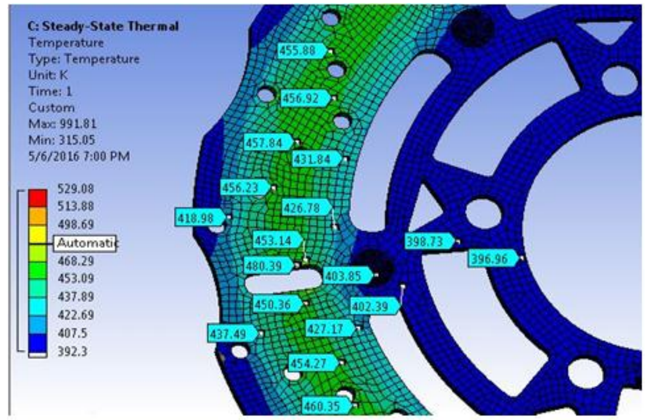
Model-4



Model-5



Model-6



Model-7

Fig.5: Results of Thermal Analysis

Figure 4a and 4b show the temperature distribution over the disc and total deformation of the disc brake respectively obtained from the static structural analysis for Model-3. Figure 4c gives the details of the Von-Mises stresses over the disc. The results obtained for temperature distribution, total deformation and Von- Mises stress are tabulated in table IV. It is observed that Model-3 has the least disc temperature with a corresponding stress value of 66.54 MPa. The reduction in the disc temperature for Model-3 is found to be about 49.3 % as compared to the base model leading to increased heat dissipation from the disc. Owing to lower disc temperature, the maximum stress induced in the disc for Model-3 is found to be about 37.7% lower as compared to the base model. Model-6 has a relatively higher disc temperature relative to the various modified designs owing to poor heat dissipation from the disc. The deformation in the disc is found to be negligibly small for all the models considered in the analysis which is far less than the permissible deformation of 0.5 mm [11]. Further transient structural analysis is carried out on the disc brake Model-3 to determine the maximum stress that is developed in transient mode. Table V gives the details of input data used in structural transient analysis. The results of transient structural analysis are shown in table VI which shows that the maximum stress developed is about 75 MPa which is far lower as compared to the base model. The temperature on the disc brake for all the design are shown in figure 5.

TABLE IV – COMPARISON OF THE RESULTS OBTAINED AFTER ANALYSIS OF THE MODELS

Model no.	*Max deformation (mm)*	*Min deformation (mm)*	*Max Stress (MPa)*	*Min stress (MPa)*	*Max Temperature (K)*
Base model	$7.9531e^{-003}$	$9.6238e^{-005}$	106.79	$8.314e^{-002}$	701.94
1	$6.4637\,e^{-003}$	$1.4097\,e^{-005}$	38.215	$5.525e^{-003}$	534.87
2	$1.9735e^{-004}$	$1.0623e^{-007}$	15.27	$3.0614e^{-004}$	474
3	$\mathbf{4.1062e^{-003}}$	$\mathbf{7.0266e^{-008}}$	**66.541**	$\mathbf{6.196\,e^{-004}}$	**356.07**
4	$3.1633e^{-004}$	$3.1842e^{-007}$	35.226	$8.1837e^{-004}$	705
5	$3.8092\,e^{-004}$	$5.845\,e^{-007}$	16.824	$3.3613\,e^{-004}$	482.48
6	$4.4913\,e^{-004}$	$7.0223\,e^{-005}$	26.634	$2.6001\,e^{-002}$	579.5
7	$3.2007\,e^{-007}$	$1.07\,e^{-007}$	20.951	$4.3326\,e^{-004}$	480.39

TABLE V: Input data for Structural transient analysis (split time analysis)

Time (s)	Pressure (MPa)	Angular velocity, ω (rad/s)
0	0	50
1	0.4	45
2	0.8	40
3	1.2	30
4	1.2	20
5	1.2	10
6	1.2	0

TABLE VI: Structural transient analysis results.

Time (s)	Max. deformation (mm)	Min deformation (mm)	Max. stress (MPa)	Min. stress (MPa)
0	0	0	0	0
1	$1.8027e^{-003}$	$7.1539e^{-005}$	31.75	$1.3799e^{-004}$
2	$5.0879e^{-003}$	$1.8839e^{-004}$	53.379	$4.54e^{-003}$
3	$7.0637e^{-003}$	$3.1992e^{-004}$	74.708	$1.2309e^{-002}$
4	$6.9641e^{-003}$	$3.2096e^{-004}$	73.879	$1.2519e^{-002}$
5	$7.0846e^{-003}$	$3.5512e^{-004}$	74.096	$1.6743e^{-002}$
6	$6.8413e^{-003}$	$3.2463e^{-004}$	73.97	$9.1856e^{-003}$

VIII. CONCLUSIONS

- It is observed that Model-3 has the least disc temperature of 356.07 K with a corresponding maximum stress value of 66.54 MPa.
- The disc temperature for Model-3 is found to be about 49.3% lower as compared to the base model indicating higher heat dissipation.
- The results of transient structural analysis shows that the maximum stress developed is about 75 MPa which is far lower as compared to that for the base model.
- Model-6 has a relatively higher disc temperature relative to the various modified designs owing to poor heat dissipation from the disc.

REFERENCES

[1] Blau P. J. (2001). Compositions, functions, and testing of friction brake materials and their additives. ORNL/TM-2001/64. Oak Ridge National Lab., TN (US). https://doi.org/10.2172/788356

[2] Shinde V.V., Sagar C. D. & Baskar P. (2014). Thermal and Structural Analysis of Disc Brake for Different Cut Patterns.Vol 11.

[3] Jadav C. & Gawande K. R. (2014). An approach to optimize the disc brake of a motor cycle. International Journal for Research in Applied Science and Engineering Technology .Vol 2.

[4] Sushma C. V., Reddy. P. R., Reddy. P. S & Ramayee L. (2015). Thermal and Structural Analysis of Disc Brake with Square/Circular Groove for Two Wheeler. International Advanced Research Journal in Science, Engineering and Technology, Vol. 2.Issue-7.

[5] Pravin Jawarika N, Subim Khanshirsagar N. & Balaji D.K. (2016) Structural Optimization, Thermal and Vibration Analysis of Two Wheeler Disc Brake Rotor. International Journal of Innovative Research in Science and Engineering. Vol 2.

[6] Manjunath T. V. & Suresh P. M. (2013). Structural and thermal analysis of rotor disc of disc brake. International Journal of Innovative Research in Science, 2(12), 7741-7749.

[7] Krenkel W. & Langhof, N. (2014). Ceramic Matrix Composites for High Performance Friction Applications. In Proceedings of the IV Advanced Ceramics and Applications Conference, 13-28.

[8] Specifications, CB Unicorn. Retrieved from https://www.honda2wheelersindia.com / unicorn / specifications

[9] Mahadevan K. & Balaveera Reddy K. Design Data Handbook for Mechanical Engineering in SI and Metric Units. 4E. CBS Publishers.

[10] Baskara Sethupathi P., Muthuvel A., Prakash N. & Louis S. W. (2015). Numerical Analysis of a Rotor Disc for Optimization of the Disc Materials. Journal of Mechanical Engineering and Automation, 5(3B), 5-14.

[11] Rudolf L. (1992). Brake design and safety. Society of Automotive Engineers. Warrandale, Inc, USA,11-157