

Design and Analysis of Braking System for ISIE ESVC

Kush Soni, Gaurang Vara, Ishit Sheth, Harshil Patel

*Department of Mechanical Engineering,
Chandubhai S. Patel Institute of Technology
CHARUSAT University, Changa, Gujarat- 388421, India.*

Abstract

Weight reduction is one of the prime concerns for a race car; especially solar electric cars. It was decided to reduce the weight of brake system by using the disc rotor and calipers of a bike instead of using a bulky hat type disc rotor. In this paper, the component selection of braking system is discussed. Various calculations of braking force, braking torque and brake bias are shown. Also, the safety of using bike's rotor is validated by calculations and thermal analysis. This brake system was implemented by team Prithvi for the event ESVC 17 organized by ISIE and accredited by Ministry of New and Renewable Energy, Government of India and by Ministry of MSME, Government of India.

Keywords: Solar Electric Car, Thermal Analysis, Braking System, ANSYS.

INTRODUCTION:

Brake system is one of the vital systems of a formula 3 race car. Its perfect functioning in all the conditions is a necessity for the safety point of view. Our primary aim was to come up with a braking system that is simple and has an optimized weight along with being reliable. As per the rule book of ESVC, it was compulsory for the system to consist of two independently operated hydraulic circuits. Also, all the four wheels must lock simultaneously. In order to implement full proof safety, we also had to keep a brake over travel switch.

For the braking system, we have used disc brakes in all three wheels. All three wheels have a HERO caliper with rotor to provide braking force. The car has a brake pedal which directly actuates the master cylinder of the brake without any other mechanism or connectors. Three hydraulic fluid lines are connected individually to all the three wheels of the car from a four outlet master cylinder (one outlet being kept closed). All the criteria selected by us for braking system are mainly to provide a safer and a quicker response of brakes. The calipers which are used have two pistons which are useful to provide enough clamping force to the rotor. Larger area of the brake pads increases the surface contact between the pads and the rotor which eventually helps to lock the wheels quicker. We have used disc brakes as they weigh less, wear of brake pads is also less and have high pressure intensity than drum brakes.

LITERATURE SURVEY:

This survey includes study of different research papers on

brake calculations, analysis and design modifications which may help to attain a far more strong, durable and effective braking system.

- Lakkam, Suwantaroj, Puangcharoenchai, Mongkonlerdmanee and Koetnuyom [1] determined the film coefficient of convective heat transfers by investigating thermal gradients on the disc rotor. They experimentally determined the convective heat transfer coefficient and used it to perform numerical simulation by finite element method. Thus, they studied the temperature diffusion and heat ventilation of front and back vented brake discs.
- Sheikh and Srinivas [2], wanted to study the amount of deformation due to tangential Force and pressure loading. So, in their work, they performed analysis without considering the effects of thermal expansion. They performed thermal + structural analysis of disk rotor of Honda Civic using ANSYS.
- Iersel [3] used a computer controlled test rig to find out the friction coefficient of brake pads. The brake pads were tested at various conditions and it was shown that optimal operative temperature lies around 220. Also, it was shown that the resulting brake torque depends linearly on brake pressure.

SELECTION OF COMPONENTS:

A. Brake rotor and Calipers:

It is beneficial to select a rotor having the diameter as large as can be accommodated in the rims of the car. This is because of the reason that for the transmission of same torque, with the increase in diameter, the respective force decreases. Hence a bike's front rotor with diameter of 170 mm was selected for a 10 inch wheel rim. The rotor was petal typed to facilitate heat transfer. The thickness of the disc was 3.5mm and suitable calipers with dual pistons were selected.

B. Master Cylinder:

A tandem type master cylinder was selected so that independent two hydraulic circuits can be obtained and it can be obtained by a single control from brake pedal. It contained DOT3 as brake oil. A diagonally split-connections were given to the wheels so that the car maintains stability in case of failure of one of the circuits. The circuit is made up of rigid pipes followed by flexible brake lines going to the calipers through a Benjo bolt.

C. Brake Pedal:

The brake pedal was machined from checkered Aluminum plate having thickness 5mm. It was designed to withstand a force of 2000N at the footrest. The leverage of the pedal was set to 2.5:1.

BRAKE CALCULATIONS:

Note that all the relationships assume 100% efficiency in the whole system. All the dimensions are in S.I. units.

$$\text{Pedal ratio} = L_2 / L_1 = 0.100 / 0.040 = 2.5$$

$$F_{bp} = F_d \times (L_2 / L_1) = 250 \times 2.5 = 625 \text{ N}$$

Where,

F_{bp} = force output of the assembly

F_d = force applied to the pedal pad by the driver

L_1 = distance from the brake pedal arm pivot to the output rod clevis attachment

L_2 = distance from the brake pedal arm pivot to the brake pedal pad

A. The Master Cylinder:

Diameter of master cylinder piston = $D_{mc} = 0.01905 \text{ m}$

$$\begin{aligned} \text{Area of master cylinder piston} = A_{mc} &= (\pi/4) \times D_{mc}^2 \\ &= 2.849 \times 10^{-4} \text{ m}^2 \end{aligned}$$

$$\begin{aligned} \text{Pressure generated by the master cylinder} = P_{mc} &= F_{bp} / A_{mc} \\ &= 625 / 2.849 \times 10^{-4} = 2.194 \text{ MPa} \end{aligned}$$

Where, P_{mc} = hydraulic pressure generated by the master cylinder

A_{mc} = effective area of the master cylinder hydraulic piston.

B. The Caliper:

Diameter of caliper piston = $D_{cal} = 0.026 \text{ m}$

$$\begin{aligned} \text{Area of caliper piston} = A_{cal} &= (\pi/4) \times D_{cal}^2 \\ &= 5.3066 \times 10^{-4} \text{ m}^2 \end{aligned}$$

$$\begin{aligned} \text{Pressure transmitted to calliper} = P_{cal} &= P_{mc} \\ &= 2.194 \text{ MPa} \end{aligned}$$

One sided linear mechanical force generated by the caliper will be equal to:

$$\begin{aligned} F_{cal} = P_{cal} \times A_{cal} &= 2.194 \times 10^6 \times 5.307 \times 10^{-4} \\ &= 1164.356 \text{ N} \end{aligned}$$

Where, A_{cal} = the effective area of the calliper

The clamping force will be equal to twice the linear mechanical force as follows:

$$\begin{aligned} F_{clamp} &= 2 \times F_{cal} = 2 \times 1164.358 \\ &= 2328.712 \text{ N} \end{aligned}$$

C. The Brake Pad:

The frictional force is related to the caliper clamp force as follows:

$$\begin{aligned} F_{friction} &= F_{clamp} \times \mu_{bp} = 2328.716 \times 0.4 \\ &= 931.485 \text{ N} \end{aligned}$$

Where, μ_{bp} = the coefficient of friction between the brake pad and the rotor

D. The Rotor:

The torque is related to the brake pad frictional force as follows:

$$\begin{aligned} T_r = F_{friction} \times R_{eff} &= 931.485 \times 0.07875 \\ &= 73.354 \text{ Nm} \end{aligned}$$

Where, T_r = torque generated by the rotor

R_{eff} = the effective radius of the rotor (measured from the rotor center of rotation to the center of pressure of the caliper pistons)

As the rotor is mechanically coupled to the hub and wheel assembly and the tyre is assumed to be rigidly attached to the wheel, the torque will be constant throughout the entire rotating assembly as follows:

Torque on Tyre (T_t) = Torque on wheel (T_w) = Torque on rotor (T_r)

E. The Tyre:

The force reacted at the ground will be equal to:

- Force on the front tyre,

$$\begin{aligned} F_{front} &= T_t / R_{front} = 73.354 / 0.2032 \\ &= 361 \text{ N} \end{aligned}$$

Where, R_{front} = effective rolling radius of front tyre

- Force on the rear tyre,

$$\begin{aligned} F_{rear} &= T_t / R_{rear} = 73.354 / 0.2032 \\ &= 361 \text{ N} \end{aligned}$$

Where, R_{rear} = effective rolling radius of rear tyre

The total braking force reacted between the vehicle and the ground,

$$F_{total} = (2 \times F_{front}) + (F_{rear}) = (2 \times 361) + (361) = 1083 \text{ N}$$

F. Deceleration of vehicle in motion:

The deceleration of the vehicle will be equal to:

$$a_v = F_{total} / m_v = 1083 / 220$$

$$= 4.928 \text{ m/s}^2$$

Where, a_v = deceleration of vehicle

m_v = mass of vehicle

G. Braking distance of vehicle:

The theoretical braking distance of a vehicle in motion can be calculated as follows:

$$d = v^2 / 2a_v = (11.111)^2 / (2 \times 4.928)$$

$$= 12.526 \text{ m}$$

Where, v = velocity of vehicle

d = braking distance

H. Braking time of vehicle:

The theoretical braking time of a vehicle in motion can be calculated as follows:

$$T_{stop} = (v \times m_v) / F_{total} = (11.111 \times 220) / 1083$$

$$= 2.257 \text{ sec}$$

I. Weight distribution:

From the vehicle's center of gravity,

$$V_t = F_{total} = 1083 \text{ N}$$

$$V_f = (V_t \times CG_r) / WB = (1083 \times 0.716) / 1.644$$

$$= 471.672 \text{ N}$$

Where, V_f = front axle vertical force

CG_r = distance from the rear axle to the CG

WB = wheel base (distance from the front axle to the rear axle)

V_t = Total vertical force of vehicle

$$V_r = (V_t \times CG_f) / WB = (1083 \times 0.928) / 1.644$$

$$= 611.328 \text{ N}$$

Where, V_r = rear axle vertical force

CG_f = distance from front axle to the CG

Now,

$$\text{Percentage front weight} = (V_f / V_t) \times 100$$

$$= (471.672 / 1083) \times 100$$

$$= 43.552 \%$$

$$\text{Percentage rear weight} = (V_r / V_t) \times 100$$

$$= (611.328 / 1083) \times 100$$

$$= 56.448 \%$$

J. Dynamic impacts of vehicle:

Absolute weight transferred from the rear axle to the front axle,

$$WT = (a_v / g) \times (h_{cg} / WB) \times V_t$$

$$= (4.928 / 9.81) \times (0.350 / 1.644) \times 1083$$

$$= 0.502 \times 0.213 \times 1083$$

$$= 115.8 \text{ N}$$

Where, WT = absolute weight transferred from rear axle to front axle

g = acceleration due to gravity

h_{cg} = height of CG from the ground

In order to calculate the steady-state vehicle axle vertical forces during a given stopping event, the weight transferred must be added to the front axle static weight and subtracted from the rear axle static weight as follows:

$$V_{f,d} = V_f + WT = 471.672 + 115.8$$

$$= 587.472 \text{ N}$$

Where, $V_{f,d}$ = the front axle dynamic vertical force for a given deceleration

$$V_{r,d} = V_r - WT = 611.328 - 115.8$$

$$= 495.528 \text{ N}$$

Where, $V_{r,d}$ = the rear axle dynamic vertical force for a given deceleration

K. Effects of weight transfer on tyre output:

Under static conditions, the maximum braking force that an axle is capable of producing is defined by the following relationships:

$$F_{tyres,f} = \mu_f \times V_f = 0.7 \times 471.672 = 330.170 \text{ N}$$

Where, $F_{tyres,f}$ = the combined front tyre braking force

μ_f = coefficient of friction between front tyre and road

$$F_{tyres,r} = \mu_r \times V_r = 0.7 \times 611.328$$

$$= 427.93$$

Where, $F_{tyres,r}$ = the combined rear tyre braking force

μ_r = coefficient of friction between rear tyre and road

However, as a result of weight transfer during a deceleration event the maximum braking force that an axle is capable of producing is modified as follows:

$$F_{tyres,f,d} = \mu_f \times V_{f,d} = 0.7 \times 587.472$$

$$= 839.246 \text{ N}$$

Where, $F_{tyres,f,d}$ = dynamic force on front tyre

$$F_{\text{tyres,r,d}} = \mu_r \times V_{r,d} = 0.7 \times 495.528$$

$$= 346.87 \text{ N}$$

Where, $F_{\text{tyres,r,d}}$ = dynamic force on rear tyre

L. Calculating optimum brake balance:

Under static conditions,

$$(F_{\text{tyre,f}} / V_f) = (F_{\text{tyre,r}} / V_r)$$

However, as the brakes are applied the effects of weight transfer must be considered, as the ratio of front and rear vertical forces will change as follows:

$$(F_{\text{tyre,f,d}} / V_{f,d}) = (F_{\text{tyre,r,d}} / V_{r,d})$$

M. Thermal Calculations:

$$\text{Kinetic Energy (KE)} = (1/2) \times m_v \times V_v^2$$

$$= (1/2) \times 220 \times (11.111)^2$$

$$= 13579.975 \text{ J}$$

Where, m_v = mass of the vehicle

V_v = velocity of vehicle

For the braking kinetic energy is converted into thermal energy,

$$\text{KE} = m_b \times C_p \times \Delta T_b$$

$$\Delta T_b = (\text{KE}) / (m_b \times C_p)$$

$$= 13759.975 / (0.683 \times 450)$$

$$= 44.77^\circ\text{C}$$

Where, m_b = mass of braking system components which absorbs energy

C_p = specific heat of braking system components which absorbs energy

ΔT_b = Temperature increase in the braking system components which absorbs energy.

Nathi, Charyulu, Gowtham and Reddy [1] have calculated the heat flux for rotor by the following equation in their work, Assuming 70% energy on the front wheel and considering the energy of the one wheel, we get;

$$\text{Heat Flux} = \frac{\text{Heat Generated} \times .7}{\text{Stopping time} \times \text{Area of rubbing} \times 2}$$

$$= (13579.975 \times .7) / (2.257 \times 0.0213 \times 2) = 98868.0235 \frac{\text{W}}{\text{m}^2}$$

Film Co-efficient:

$$\text{Pr} = \frac{C_p \mu_v}{k} = \frac{1007 \times 1.983 \times 10^{-5}}{0.024} = 0.8320 > 0.6$$

Where,

C_p = Specific heat of air at constant pressure

μ_v = Dynamic viscosity of air

k = Thermal Conductivity of air = $0.024 \text{ W/m}^\circ\text{C}$

$$\text{Re} = \frac{V \times x}{\nu} = (1 \times 11.111 \times 2 \times 3.14 \times 0.085) / (0.00002) = 296000$$

Where,

V = Velocity of air = 40kmph = 11.111m/s

x = Distance travelled by air = $2\pi r$

r = radius of disc = 85mm = 0.085m

ν = kinematic viscosity = $2 \times 10^{-5} \text{ m}^2/\text{s}$

So,

$$\text{Nu} = 0.0296 \times P_r^{\frac{1}{4}} \times R_e^{\frac{1}{4}} = 663.28$$

$$\text{Nu} = \frac{h \times x}{k} = 663.28$$

$$\text{Film Coefficient} = h = \frac{\text{Nu} \times k}{x} = 227.4 \text{ W/m}^2 \text{ }^\circ\text{C}$$

THERMAL ANALYSIS

Steady state thermal analysis coupled with static structural analysis was performed in ANSYS 15. The CAD model of rotor was created in DS SolidWorks as per the real rotor of Yamaha Ray and then was exported for analysis.

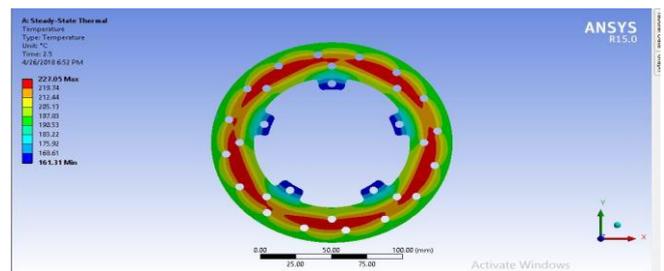


Figure 1: Temperature

Figure 1 shows the maximum and minimum temperature zones in the disc rotor with the values being in $^\circ\text{C}$.

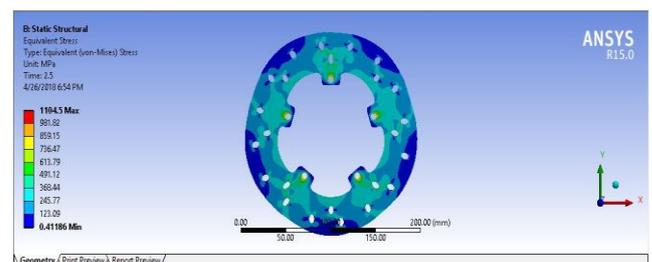


Figure 2: Equivalent Stress

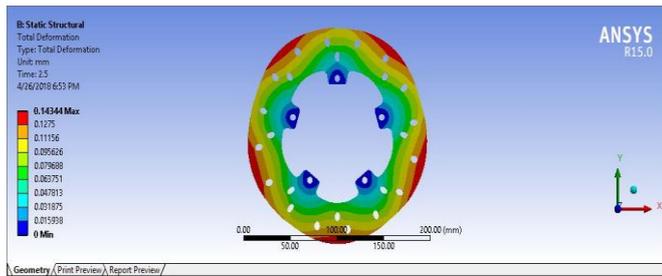


Figure 3: Total Deformation

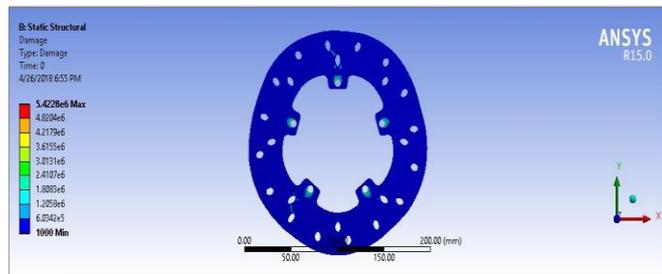


Figure 4: Damage

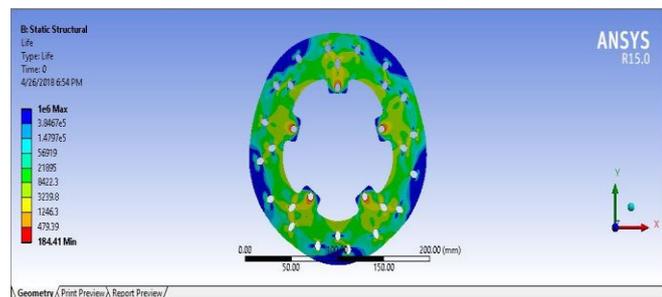


Figure 5: Life

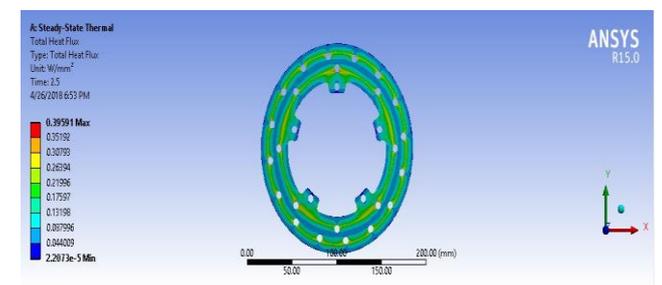


Figure 6: Total Heat Flux

CONCLUSION

In this paper, numeric computations have been done to obtain braking forces, braking torque, clamping forces at calipers, brake bias and other important parameters in a braking system. Comparison has been done between the clamping force in the front wheel of bike and the clamping force in one of the front wheels of car. It shows that it is safe to use the rotors of bike in a formula car with the mentioned specifications. Normal brake assemblies used in commercial cars with hat type rotors weighs around 17kg per wheel. On implementing bike's brake assembly in the solar electric car, this weight reduces to 3kg per wheel. Thus, considerable weight reduction is achieved. Thermal Calculations for heat flux are done and film coefficient is determined which helps in the thermal analysis. The results of coupled steady state thermal and static structural analysis in Ansys have been shown. These results are quite satisfactory.

REFERENCES

- [1] Supachai Lakkam, Kullayot Suwantaraj, Phupoom Puangcharoechai, Songwut Mongkonlerdmanee and Saiprasit Koetniyom, "Study of heat transfer on front – and back-vented brake discs", Songklanakarin J. Sci. Technol., Nov. – Dec. 2013.
- [2] Ameer Fareed Basha Shaik, Ch. Lakshmi Srinivas, "Structural and thermal Analysis of disc brake with and without crossdrilled Rotor of Race car."
- [3] S.S. van Iersel, "Measuring brake pad friction behavior using the TR3 test bench", DCT no. 2006.118. Eindhoven, September, 2006.
- [4] Faramarz Talati and Salman Jalalifar, "Analysis of heat conduction in a disk brake system.", 2009
- [5] Thomas D. Gillespie, "Fundamentals of Vehicle Dynamics."
- [6] nptelhrd. Mod-01 Lec-03 Vehicle Load Distribution – Acceleration and Braking, Retrieved from <https://www.youtube.com/watch?v=qxNTQozl5fE>.
- [7] "Values of Convective heat transfer coefficient, dynamic viscosity, kinematic viscosity", www.engineeringtoolbox.com
- [8] Yunus A. Cengel, "Heat and mass transfer."
- [9] Manjunath T V, Dr. Suresh P M. "Structural and Thermal Analysis of Rotor Disc of Disc Brake.", IJIRET Vol. 2, Issue 12, December 2013.