Design and Experimental Analysis of Hydraulic Braking System for All-Terrain Quad Bike

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Abstract: ***In preceding years, mechanical braking systems, often relying on cables, rods, or levers, were the standard in braking applications. These systems exhibited notable limitations, including inconsistent brake force distribution, high maintenance requirements, and reduced efficiency under high-speed and high-load conditions, ultimately affecting overall braking performance. Hydraulic braking systems have been widely adopted to address these shortcomings, particularly in the automotive sector, due to their enhanced reliability and efficiency. Building on these advancements, the current study focuses on the design and development of a hydraulic braking system with a dual-actuation circuit tailored for a quad bike, a specialized All-Terrain Vehicle (ATV). The dual actuation circuit mitigates the drawbacks associated with single-circuit systems by optimizing key parameters critical to braking performance, such as force distribution and response time, thereby significantly improving braking efficiency. The study incorporates a systematic approach to material selection for the brake disc, ensuring optimal thermal conductivity, wear resistance, and structural integrity under high-stress and high-temperature conditions. Material selection was conducted to meet the specific demands of high-performance ATV braking systems, balancing manufacturability and cost-effectiveness. The research methodology included extensive analytical iterations to determine appropriate braking parameters. A Finite Element Analysis (FEA) was conducted on critical components, such as the brake disc to evaluate stress distributions, deformation, and thermal performance under dynamic conditions. Simulation results were validated experimentally, employing a test rig designed to replicate real-world ATV braking scenarios. Additionally, a design trade-off analysis was performed to balance parameters like design space, manufacturability, and cost constraints, ensuring a practical yet optimized braking system. The comprehensive characterization of the hydraulic braking system and its dual actuation circuit provides a robust framework for enhancing braking systems in similar ATVs. The findings offer a novel pathway for integrating hydraulic braking designs into off-road vehicle development, emphasizing reliability and performance.***

Keywords: hydraulic braking systems, quad-bike, All-Terrain Vehicle (ATV), dual actuation

1. Introduction

All-terrain vehicles (ATVs) are indispensable for off-road applications, often operating in environments marked by rugged terrains, unpredictable obstacles, and extreme weather conditions. These vehicles are designed to excel in challenging situations, from steep inclines and uneven paths to muddy trails and rocky landscapes [1-5]. A critical component of an ATV's performance and safety is its braking system, which provides the control and stopping force required to navigate such demanding environments [6-13]. The braking system's role is not limited to halting the vehicle; it also ensures operational stability, safety, and precision, enabling drivers to execute sharp maneuvers, descend slopes safely, and maintain control on diverse terrain [14-20]. Traditionally, mechanical braking systems, including drum brakes and mechanical disc brakes, were commonly employed in ATVs [21-25]. These systems relied on cables and mechanical linkages to transmit force from the brake lever to the braking components. While adequate for basic applications, these traditional systems were often prone to performance issues under harsh conditions. Mechanical brakes struggled with wear and tear, especially when exposed to contaminants like mud, sand, and water, which could compromise their effectiveness. Additionally, they lacked the consistent force distribution and reliability needed for high-performance vehicles like ATVs operating under variable loads and conditions [26-31]. The transition to hydraulic braking systems marked a significant advancement in addressing these limitations [32,33]. Hydraulic brakes use fluid to transmit force, providing several key advantages over mechanical systems. They deliver superior braking power, better modulation, and more consistent performance across varying conditions [34]. Hydraulic systems are less affected by environmental factors, ensuring reliable operation even when exposed to moisture and debris. They minimize maintenance needs and make them ideal for off-road vehicles frequently subjected to rugged conditions. While hydraulic braking systems represent a substantial improvement, single-circuit actuation systems present their own set of challenges [35]. These systems rely on a single hydraulic circuit to distribute braking force across all wheels. In ATVs, which often operate on steep inclines and uneven terrain, this design can lead to uneven force distribution, compromising stability and performance. A failure in a single circuit can result in a complete loss of braking power, posing significant safety risks.

Despite the advancements in hydraulic braking systems, there is a lack of comprehensive and systematic studies focused on the complete design and optimization of braking systems for quad bike ATVs. Most existing research addresses individual components, such as brake discs or calipers, without integrating these elements into a cohesive system. This fragmented approach leaves gaps in understanding how various components interact under real-world conditions, especially in the context of dual-actuation hydraulic braking systems. Moreover, existing studies often fail to account for the unique stresses and operational demands of ATVs, such as exposure to extreme temperatures, abrasive contaminants, and high mechanical loads. This lack of holistic analysis hinders the development of optimized braking systems tailored specifically for ATVs, which require durability, reliability, and performance under the most challenging conditions.

This study aims to address these gaps by presenting a comprehensive design framework for a hydraulic braking system with dual actuation for ATVs quad bike segment. By incorporating advanced simulation techniques and experimental validation, the research seeks to optimize each component, from the brake disc and calipers to the hydraulic circuits and actuation mechanisms. The findings are expected to set a new benchmark for ATV braking systems, enhancing safety, reliability, and performance. By systematically analyzing and integrating all aspects of the braking system, this research not only contributes to the field of ATV engineering but also provides a foundation for future developments in off-road vehicle safety and durability.

2. Methodology

A detailed methodology, as illustrated in Figure 1, was followed throughout the research to ensure a systematic and structured approach to the development of the braking system for the ATV quad bike. This methodology encompassed all key aspects necessary for an optimized and reliable braking system design.

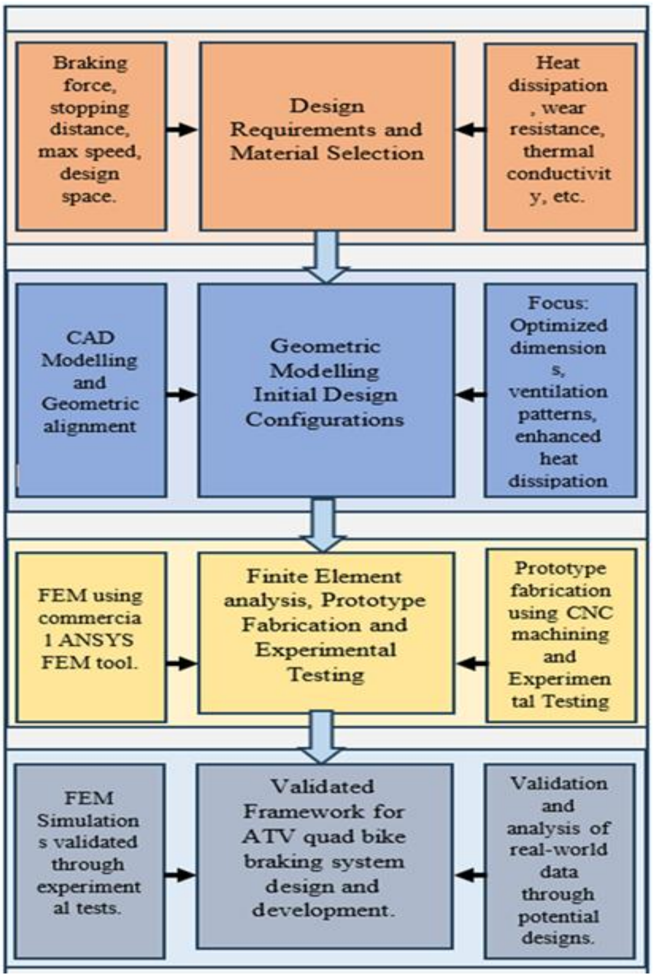

Figure 1: Methodology

This methodology presents a clear, step-by-step approach for the design, analysis, prototyping, and testing of an ATV brake disc, offering a comprehensive structure for future studies in this area.

3. Design and Analysis

3.1 Braking system Design parameters numerical study

In order to evaluate the braking system's essential parameters such as brake disc diameter, braking force, stopping distance, etc., some of the Initial considerations for the vehicle, i.e., quad bike, according to the off-road usage were implemented, which predominantly include Total mass of vehicle including driver, wheelbase, CG, etc. This consideration gave an initial insight into the dependable variable's contribution to the necessary conditions provided.

Table 1: Initial consideration

Parameter	*Symbol*	Unit	Value
Total mass of vehicle with rider	m	kg	230
Weight	W	N	2256.3
Wheelbase	L	mm	1070
Center of Gravity height	H	mm	628
CG distance from front axle	L_1	mm	549
CG distance from rear axle	L_2	mm	521
Velocity	V	m/s	8.33
Coefficient of between off-road tires and ground	μ_g	-	0.6
Coefficient of between brake pad and disc	μ_c	-	0.4
Coefficient of rolling resistance.	f_r	-	0.03
Rolling Radius	R	m	0.2921
Mechanical Leverage Front	-	-	6
Mechanical Leverage Rear	-	-	5
Diameter of TMC	-	mm	19.05
Diameter of MC	-	mm	13
Caliper Piston Diameter	-	mm	25.4
No. of piston in front caliper	-	-	2
No. of piston in rear caliper	-	-	4
Force by Rider front	F_f	N	461.07
Force by Rider rear	F_r	N	49.05

Table 1. Presents the primary base vehicle parameters considered for the overall braking system design. These parameters include the total vehicle mass, incorporating the maximum driver weight. Additionally, the vehicle's wheelbase was considered to define a constrained design space. The maximum vehicle velocity was taken into account, along with key coefficients such as the friction between off-road tires and the ground, as well as the friction between the brake pad and disc. The leverage of the front and rear brake pedals varied based on the forces exerted by the driver, ensuring an optimized distribution of braking forces. This approach helped in reducing the weight of the designed components while maintaining effective braking performance.

Based on the input parameters, the analytical solutions for the front and rear brake system design are presented in Table 2 and Table 3. The key outputs, including clamping force, frictional force, disc radius, actual braking torque, and wheel forces, were determined for both the front and rear braking systems. The combined effect of these parameters was then analyzed to evaluate the vehicle's stopping distance and the time required to come to a complete stop due to deceleration as tabulated in Table 4.

Table 2: Front brakes calculation

Parameter	Unit	Formula	Value
Resultant tractive force	N	$F_t = \mu W \frac{L_2 + H(\mu + f_r)}{L}$	1163.5
Front axle weight	N	$F_{aw} = W \frac{L_2}{L}$	1098.6
% Weight	-	$\frac{F_{aw}}{\text{Total Weight}} x100$	48.69
Braking Torque	Nm	T= F_t x R	339.85
Force in TMC	N	$F_{TMC} = F_f$ x Mechanical Leverage Front	2766.4
Pressure in TMC	MPa	$P_{TMC} = \frac{F_{TMC}}{\text{Area of TMC}}$	9.7108
Force in Caliper	N	$F_{caliper}=P_{TMC}$ x $Area_{caliper}$ x losses factor	2952.3
Clamping Force	N	$F_c= F_{caliper}$ x No. of piston	5904.6
Frictional Force	N	$F_{pad} = \mu_c$ x F_c	2361.8
Disc radius	mm	$r_f = \frac{\text{T x 1000}}{\text{No.of caliper x Fpad}}$	71.94
Disc radius considered	mm	R_f	75
Actual Braking Torque on each wheel	Nm	$T_a = \frac{F_{pad} \text{ x } R_f}{1000}$	188.94
Force on front wheel	N	$F_{fw} = \frac{\text{No. of wheels x } T_a}{R}$	1293.7

Table 3: Rear brakes calculation

Parameter	Unit	Formula	Value
Resultant tractive force	N	$R_t = \mu W \frac{L_1 - H(\mu + fr)}{L}$	194
Rear axle weight	N	$R_{aw} = W \frac{L_1}{L}$	1157.7
% Weight	-	$\frac{\text{Raw}}{\text{Total Weight}} x100$	51.31
Braking Torque	Nm	T= R_t x R	56.67
Force in MC	N	$F_{MC} = F_r$ x Mechanical Leverage Front	245.25
Pressure in MC	MPa	$P_{MC} = \frac{\text{FMC}}{\text{Area of MC}}$	1.85
Force in Caliper	N	$F_{caliper}=P_{MC}$ x $Area_{caliper}$ x losses factor	655.85
Clamping Force	N	$F_c= F_{caliper}$ x No. of piston	2623.4
Frictional Force	N	$F_{pad} = \mu_c$ x F_c	1049.4
Disc radius	mm	$r_r = \frac{\text{T x 1000}}{\text{No.of caliper x Fpad}}$	54
Disc radius considered	mm	R_r	100
Actual Braking Torque	Nm	$T_a = \frac{F_{pad} \text{ x } R_r}{1000}$	104.94
Force on rear wheel	N	$F_{rw} = \frac{T_a}{R}$	359.26
Total Braking Force	N	$F_{TBF} = F_{fw} + F_{rw}$	1652.9 6
Dynamic load transfer	N	$F_{daw} = W \frac{\mu_g \text{ x } H}{L}$	794.5
Weight distribution ratio	-	-	70:30

Table 4: The calculation for stopping distance and time

Parameter	Unit	Formula	Value
Deceleration	m/s^2	$a = \frac{F_{TBF}}{m}$	7.187
Stopping Distance	m	$s = \frac{V^2}{2a}$	4.83
Time required to stop the Vehicle	sec	$t = \frac{V}{a}$	1.16

Table 5: Calculation for heat flux

Parameter	Unit	Formula	Value
Kinetic Energy	J	$KE = \frac{mV^2}{2}$	7979.7
Power	W	$P = \frac{KE}{t}$	6879
Power to front wheel	W	$P_F = \frac{0.7P}{2}$	2407.65
Power to rear wheel	W	$P_R = 0.3$ P	2063.7
Area of front disc	mm^2	A_f	16000
Area of rear disc	mm^2	A_r	20000
Heat Flux Front	Wb/ mm^2	$HFF = \frac{P_F}{A_f \text{ x t}}$	0.1297
Heat Flux Rear	Wb/ mm^2	$HFR = \frac{P_r}{A_r \text{ x t}}$	0.0889

The heat flux generated based on the input parameters, along with the designed disc area for the front and rear brake discs, is presented in Table 5.

3.2 Material Selection

The Digital Logic Method (DLM) [6] was employed for the optimal material selection of brake discs, considering a systematic trade-off among three candidate materials. Five critical properties were evaluated to enhance the brake disc performance: *Yield strength, Density, Thermal conductivity, Wear resistance, and Cost*. By implementing the DLM formulation, a weighted scoring approach was applied to rank the materials based on their performance metrics. The analysis concluded that Carbon Composites is the best in terms of performance, but is not affordable. Stainless Steel 410 (SS 410) is the best practical material considering affordability, strength, thermal conductivity, and wear resistance, featuring a heat-treated martensitic microstructure and alloyed with iron, chromium, manganese, and nickel, emerged as the optimal choice for brake disc fabrication. Its superior combination of mechanical and thermal properties ensures enhanced braking efficiency and durability. The performance metrics of the evaluated materials, determined through the Digital Logic Method, are summarized in Table 6.

Table 6: Performance metric on DL method implementation

Scaled Properties						
Material	1	2	3	4	5	**PI**
GCI	0	13	100	0	100	33
Carbon Composites	100	100	0	100	0	**70**
SS 410	**66**	**05**	**40**	**33**	**99**	**44**
SS 316	11	0	17	0	97	16

3.3 Geometric modelling

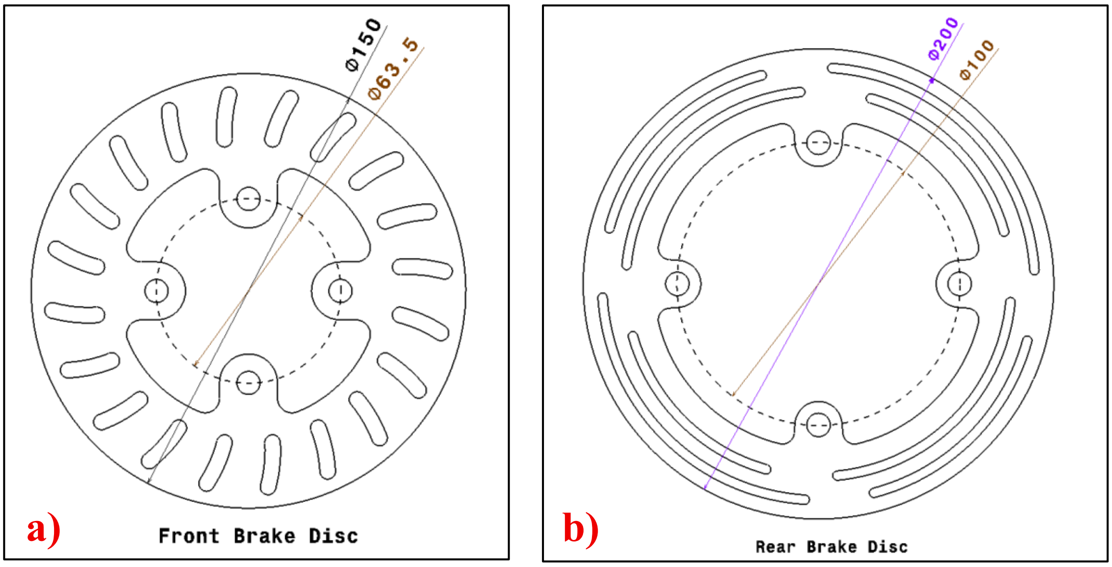

Figure 2: a) Front Brake Disc, b) Rear Brake Disc

According to the Parameters evaluated through numerical implications in section 3. The geometry of the brake discs for both front and rear was defined, and thereby the CAD models were prepared using the commercial parametric tool CATIA V5. For the front brake disc, the overall diameter was 150mm, with a Pitch Circle Diameter (PCD) of 63.5 mm Figure 2 a). The rear brake disc consisted of an overall diameter of 200mm with a PCD of 120mm Figure 2 b). The mild formats of these parametric sets were generated preferably. iges and step formats to ensure smoother transitions between the parametric and simulation tools with negligible geometric differences. The models were thereby assessed with static structural and steady-state thermal analysis using the commercial FEA software ANSYS.

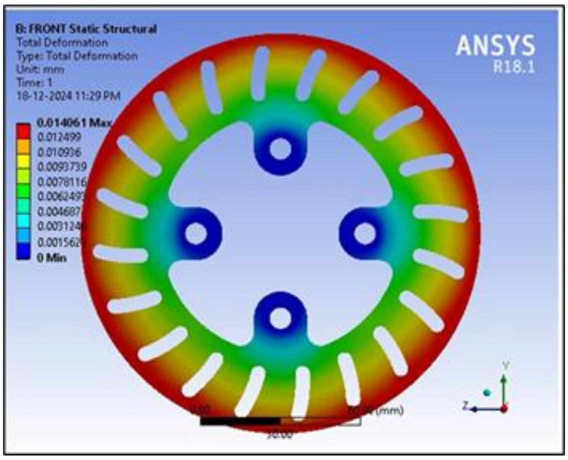

Figure 3: Front Disc Static Structural - Total Deformation

4. Results and discussion

4.1 Simulation Studies

For the static structural analysis, the brake discs were assigned fixed support, applied forces, and momentum to determine the total deformation and equivalent stress. In thermal analysis, parameters such as radiation, heat flux, convection, and temperature were considered to evaluate the disc's temperature rise and total heat flux distribution. The results from both analyses, based on the predefined parameters, are presented in Table 7.

Table 7: Output Parameters of Analysis

Output Parameters	*Front Disc*	*Rear Disc*
Static Structural		
Total Deformation (in mm)	0.014	0.019
Equivalent Stress (in MPa)	94.13	57.83
Steady State Thermal		
Temperature (in °C)	84.84	54.51
Total Heat Flux (W/mm^2)	0.7611	0.4246

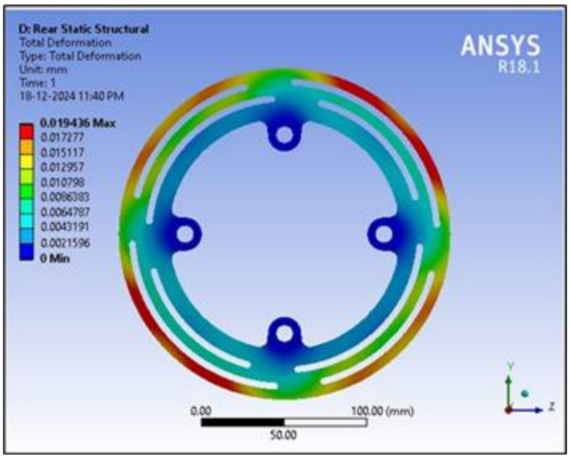

Figure 4: Rear Disc Static Structural - Total Deformation

A minimal amount of total deformation was observed, with the majority occurring at the outer portion of the brake discs for front as well as rear, as shown in Figure 3 and Figure 4. This is attributed to the concentrated force applied by the brake pads during braking.

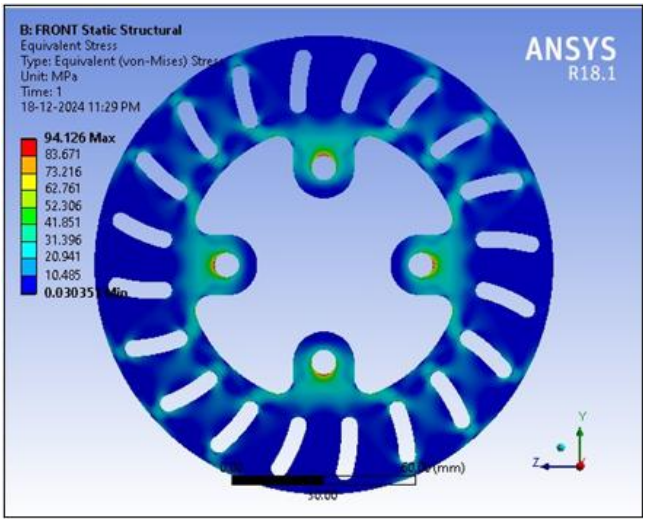

Figure 5: Front Disc Static Structural - Equivalent Stress

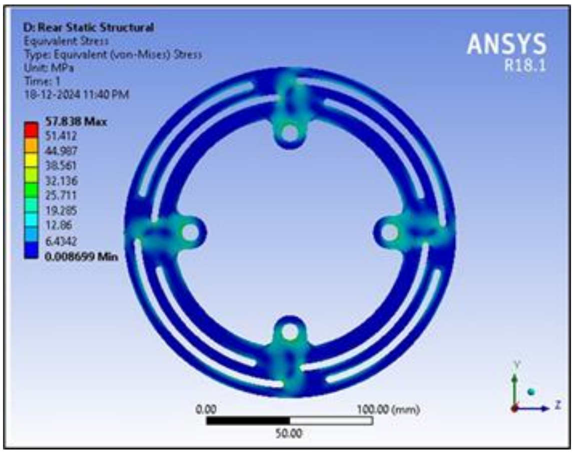

Figure 6: Rear Disc Static Structural – Equivalent Stress

As in Figure 5 and Figure 6, the equivalent stress that is generated in both of the discs is lower than the Allowable Stress. Therefore, the disc designs are safe under loading conditions.

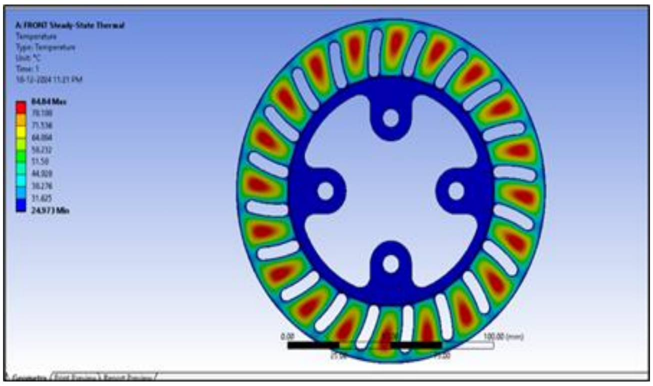

Figure 7: Front Disc Steady State Thermal- Temperature

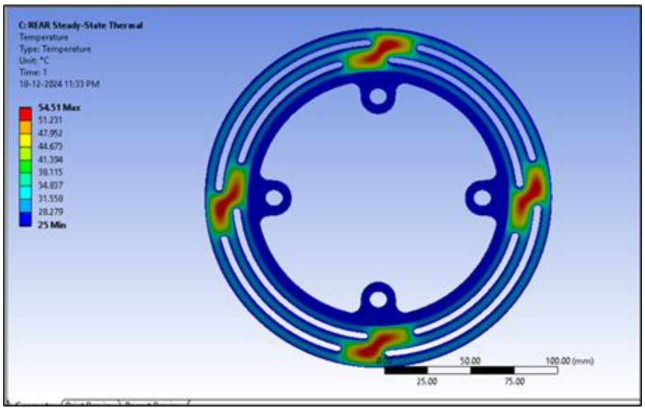

Figure 8: Rear Disc Steady State Thermal- Temperature

By taking all the inputs into consideration, the thermal analysis results show that the temperature of the front brake disc will be raised up to 84.84 °C Figure 7, while the rear brake disc will be raised up to 54.51 °C Figure 8.

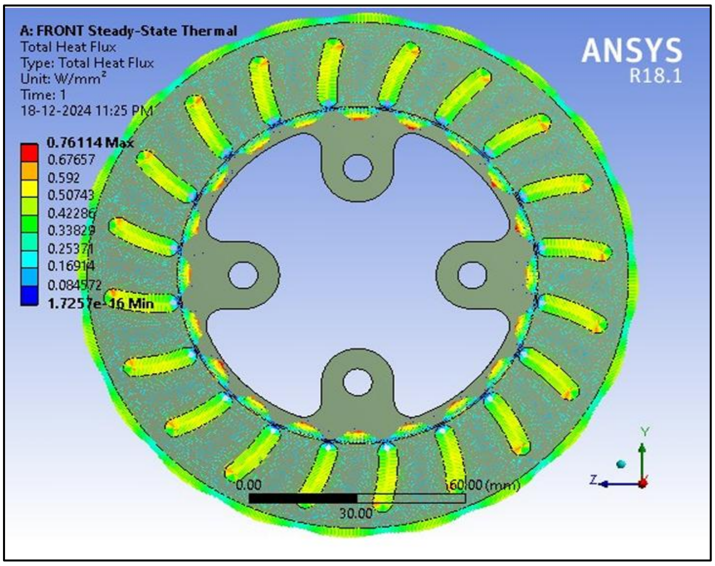

Figure 9: Front Disc Steady State Thermal- Total Heat Flux

Paper ID: SR25629162502 DOI: https://dx.doi.org/10.21275/SR25629162502

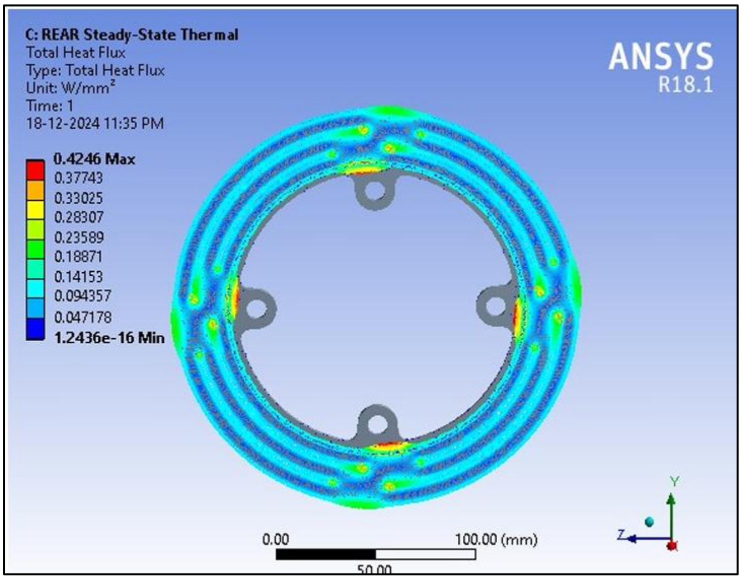

Figure 10: Rear Disc Steady State Thermal- Total Heat Flux

The above Figures, Figure 9. and Figure 10. demonstrate the heat flux flows through and along the front and rear brake discs, respectively. The actual image of various components of the wheel assembly, along with the brake discs, is as shown in Figure 11.

Figure 11: Front Wheel Assembly (Brake Disc with Knuckle)

4.2 Validation of analysis results

To validate the analysis and simulation results, an experimental setup was developed for the ATV quad bike's braking system. The system was fabricated in accordance with the computationally derived geometrical dimensions, and the SS410 material brake discs were manufactured to these specifications. During validation, the brake was applied in real-world scenarios using the established inputs and analysis results. The simulation primarily focused on parameters such as equivalent stress, total deformation, total heat flux, and temperature increase in the brake disc. However, due to practical limitations, only the temperature increase could be experimentally evaluated using a thermal gun. The temperature values recorded from the thermal gun Testo 882 were compared with the simulation results, revealing a close correlation that confirmed the accuracy of the thermal analysis, as shown in Figure 12. This validation enhances the reliability of the simulation model, although more advanced experimental techniques would be necessary to validate the remaining parameters.

Figure 12: Thermal image of Front Brake Disc

5. Conclusion

This research work focuses on the design and development of a hydraulic braking system with a dual actuation circuit for a quad bike (ATV), aiming to enhance braking efficiency and reliability. The study integrates advanced analytical techniques and material selection to optimize performance under dynamic conditions. By addressing the limitations of

traditional braking systems, the research provides a novel approach to off-road vehicle braking system design. Below are some of the key findings from the research work:
1) **Improved Braking Efficiency**: Dual actuation circuit enhances force distribution and response time.
2) **Optimized Material Selection**: The implementation of the DL method ensures thermal conductivity, wear resistance, and structural integrity.
3) **Numerical Study**: Finite Element Analysis (FEA) suggested the design suitability in accordance with the loading conditions.
4) **Enhanced Reliability**: experimental validation design. Ensured the practical implementation of the proposed design strategy.
5) **Practical Application**: Provides a robust framework for future quad bike off-road vehicle braking systems.

Acknowledgements

The authors would like to acknowledge the financial and technical support provided by and K K Wagh Institute of Engineering Education & Research, Nashik, Maharashtra, India, and Team Brahmastra Quad.

Conflict of Interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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