Caliper Configuration for Off-Road Vehicles: An Elaborate Examination of a Cost-effective Novel ATV Braking System

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Abstract - This research endeavors to elucidate the conceptualization and development of a bespoke brake caliper intricately tailored to cater to the idiosyncratic demands of an All Terrain Vehicle (ATVs), thereby effectively ameliorating the inherent challenges stemming from the incongruity between conventional Original Equipment Manufacturer (OEM) calipers and the intricate mechanics of ATVs. Employing a systematic and structured engineering methodology, this investigation is distinctly centered around the conception and realization of a brake caliper distinguished by its optimal design, harmoniously aligned with the distinctive configuration of ATV wheel assemblies. In deliberate juxtaposition to the ubiquitous utilization of cast iron, typically associated with commercial OEM calipers, this study consciously opts for the judicious selection of High-Grade Aluminium (Al7050) as the material of preeminence, encompassing both the caliper and its encasing housing. This strategic choice emanates from a meticulous consideration of a multifaceted array of pivotal factors, including but not limited to weight reduction imperatives, economic efficiency, and the simplification of the intricate machining processes inherent in the manufacturing process. The deployment of well-established and entrenched engineering principles leads to the methodical calculation of requisite forces indispensable for efficacious braking and clamping mechanisms. This computational endeavor serves as the guiding beacon directing the subsequent realization of the bespoke caliper and its encompassing housing, a feat accomplished with exactitude through the utilization of state-of-the-art Computer Numerical Control (CNC) machining techniques, emblematic of precision and intricacy. Notably, the experimental evaluations conducted within this study serve to accentuate and underscore the discernible augmentation in the performance of the braking system, intrinsically entwined with a pronounced and appreciable reduction in the overall mass characterizing the wheel assembly of the ATV. Evidently, these outcomes lucidly underscore the tangible and appreciable advantages proffered by the innovative and astute design paradigm advocated within this research endeavor.

Key Words: Brake caliper, fixed caliper, ATV Brakes, braking systems, Solidworks, All Terrain Vehicles.

1.INTRODUCTION

Within the intricate framework of an automotive braking system, the brake caliper assumes a pivotal role as a paramount constituent. Its function is notably distinguished by its indispensable responsibility of not only housing the friction pads but also facilitating the crucial transmission of clamping force onto the rotor. In response to the driver's command for deceleration, a cascade of orchestrated events transpires: pressure exerted at the posterior aspect of the piston engenders a forceful impetus upon the brake pads, inducing their assertive engagement with the disc or rotor. This harmonized interaction precipitates the gradual reduction of the vehicle's velocity[1]. Essential to the efficiency and longevity of the braking apparatus is the imperative of equable pressure dispersion over the friction pads. This endeavor assumes paramount importance, as it substantiates the imperative objectives of uniform pad attrition and judicious heat dissipation. As such, the integrity of the frictional interface is scrupulously upheld, thereby prolonging the operational life of the braking system while averting potential thermal degradation[2]. Noteworthy within the scope of this project is the concerted aspiration to effectuate a reduction in the aggregate weight characterizing the wheel assembly. This endeavor is ingeniously orchestrated through a judicious confluence of sagacious material selection and a measured approach to material allocation, conspicuously divergent from the conventional OEM brake paradigm. An amalgamation of prudent engineering judgment and material science acumen is harnessed to usher forth this distinct shift in design philosophy[3]. Conspicuously detailed in Figure 1.1, the elucidated brake caliper assembly is showcased in an exploded view, encapsulating the intricate nexus of components that collectively underpin its operational essence. This illustrative portrayal serves to offer an enticing glimpse into the meticulous engineering endeavors that animate the core of this project's pursuit [4][5].

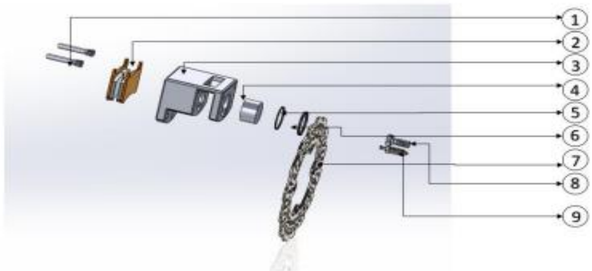

Chart -1: Exploded view of the caliper assembly

1. Brake pad mounting pins
2. Brake pads
3. Brake caliper body
4. Caliper piston
5. Dust seal
6. Oil seal
7. Brake rotor
8. Bleeder nut
9. Banjo nut

2.Types of calipers

The categorization of brake calipers is predicated upon their operational modality and underlying kinematic mechanisms.

- Floating Caliper
- Fixed Caliper

2.1Floating caliper

In the context of the floating caliper configuration paradigm, the piston's positioning takes place within the inner confines of the caliper assembly. This assembly is entirely encased upon a solitary guiding pin, commonly referred to as the "guide pin," which is itself encircled by a constraint limiting its motion along a unidirectional axis. Positioned on the outer periphery of the caliper structure, a brake pad is meticulously arranged to maintain an ongoing interface with the rotor. Its primary function is to safeguard the structural integrity of the rotor by mitigating the possibility of undesirable bending. Simultaneous with the actuation of the brake pedal, a meticulously orchestrated sequence of events is initiated. The application of pressure at the posterior aspect of the piston generates a compelling impetus, thereby compelling the friction pads into assertive engagement with the rotor. This collective effort imparts a reactionary force onto the caliper, instigating its orchestrated motion along the guiding pin. This precisely coordinated motion subsequently culminates in the constrictive envelopment of the rotor, thereby effectuating the clamping action[6].

2.2Fixed caliper

Fixed calipers are characterized by their intrinsic structural integrity, rendering them as monolithic and indivisible entities, with no inclusion of mobile components beyond the pistons and brake pads. This establishes them as unyielding units in contradistinction to their floating counterparts. The quintessential divergence lies in the conspicuous absence of slider pins or guiding pins in fixed calipers, demarcating a pronounced differentiation between the two caliper variants. A salient attribute emblematic of fixed calipers is their substantively distinct composition, presenting as a singularly cohesive and compacted unit devoid of intervening gaps. This unifying attribute exerts profound implications upon the operational dynamics and mechanical characteristics of fixed calipers. It eclipses the architectural configuration of floating calipers, as fixed calipers unswervingly feature pistons positioned on both sides of the assembly. Integral to the hydraulic underpinnings, the outboard pistons within the fixed caliper array are endowed with hydraulic pressure through the conduits of one or multiple hydraulic channels. This intricate hydraulic network intricately orchestrates the dissemination of pressurized fluid, furnishing equitably balanced and symmetrically distributed clamping forces. This symmetrical endowment is pivotal in conferring an equitable and congruous allocation of braking potency, culminating in the unison augmentation of braking performance and efficacy[7].

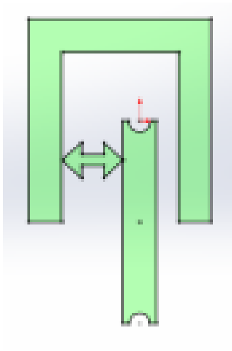

Chart -2: Floating caliper (Caliper housing slides)

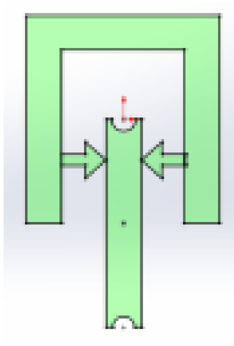

Chart -3: Fixed caliper (caliper housing remains stationary)

2.3The problem in using OEM calipers ATVs

The integration of extant Original Equipment Manufacturer (OEM) brake calipers into the wheel assembly of All Terrain Vehicles (ATVs) presents a myriad of intricate challenges. These challenges arise from the necessity to operate under conditions characterized by elevated mechanical forces, thus giving rise to an inherent dilemma. The existing configuration of these OEM calipers, as dictated by prevailing market standards, inevitably leads to a convergence of substantial dimensions and intricate geometric complexities. Consequently, aligning such calipers with the imperatives of optimal braking performance for ATVs is beset with deficiencies and incongruities. This, in turn, results in an overall reduction in the collective efficacy of the braking system[16]. A prominent manifestation of this incompatibility lies in the propensity of the prevailing OEM brake caliper constructions to deviate from the prerequisites emblematic of ideal ATV braking conditions[17]. This incongruity is conspicuously evident through the marked amplification in the structural massiveness and the intricate convolution of the caliper assembly. These characteristics serve as the driving force behind the deviation from the requisites underpinning optimized ATV braking mechanisms, ultimately leading to a compromise in the overarching metrics of braking performance. In view of these challenges, the integration process invariably necessitates supplementary intervention through the prism of additional machining endeavors. This step becomes imperative to bridge the gap between the inherent complexities of the OEM caliper constructs and the prerequisites intrinsic to the ATV wheel assembly.

2.4Seal groove geometry

The concept of "seal groove geometry" represents a highly intricate and multifaceted field within engineering, encapsulating a multidimensional fusion of geometric attributes that exert a profound influence on the mechanics governing piston retraction subsequent to braking events. This geometric construct serves as a convergence point for meticulous design considerations, encompassing factors such as dimensional intricacies, shape complexities, and spatial relationships, all of which collectively orchestrate the dualistic function of achieving impermeable fluid containment while simultaneously coordinating the precise withdrawal of the caliper piston. In essence, seal groove geometry embodies an amalgamation of geometric profiles meticulously engineered to accommodate sealing elements within the interstice delimited by the caliper and the piston. This orchestrated geometry concurrently functions as an architectural mechanism conducive to optimizing fluid-tight boundaries, thus preventing the inadvertent escape of brake fluids and the consequent degradation of hydraulic integrity. Simultaneously, this geometric configuration harnesses its intrinsic attributes to facilitate the methodical retraction of the caliper piston post-braking. This process involves a harmonized interplay between intricate shape intricacies and nuanced surface curvatures, creating an environment that inherently encourages piston withdrawal in a controlled and efficient manner. In summary, seal groove geometry amalgamates geometric ingenuity with hydraulic efficacy, manifesting as a pivotal domain that navigates the dual objectives of fluid integrity preservation and orchestrated piston retraction, thereby serving as the cornerstone for the comprehensive functionality and performance enhancement of braking systems[10].

2.5Banjo nut and bleeder nut

A crucial component within the brake system is the "banjo nut," distinguished by its specific configuration featuring a small orifice on its lateral aspect. This perforation plays a pivotal role in facilitating the smooth conveyance of pressurized brake fluid into the caliper chamber. Central to this hydraulic interface is the "banjo bolt," whose connection with the nut is meticulously secured through the judicious interposition of annealed copper washers on both sides. The convergence of these elements, exemplified by the precisely calculated torque applied to the banjo bolt, establishes an airtight conduit, thereby creating a controlled pathway for the transmission of brake fluid via the aperture embedded within the bolt's sidewall. In response to the manipulation of the brake pedal, a dynamic interplay is initiated. This process results in the forceful propulsion of pressurized brake fluid, precisely channeled through the banjo fitting into the caliper. Consequently, this hydraulic influx triggers a sequential cascade, affecting the progressive movement of the piston in conjunction with the brake pad. This meticulously choreographed collaboration induces the gradual deceleration of the vehicle[11][12][13]. Furthermore, the "bleeder nut" serves as an essential component designed to meticulously counteract the entrapment of air within the hydraulic circuitry. During maintenance procedures, the introduction of air into the brake system presents a potential quandary. This infusion of air creates the latent potential for detrimental performance anomalies to manifest during operational engagement. The operational functionality of the bleeder nut relies on its ability to temporally modulate the system's pressure. By selectively manipulating the bleeder nut, controlled adjustments to fluid pressure induce the systematic expulsion of trapped air through an aperture situated within the nut, effectively restoring the operational integrity of the brake system.

2.6Material selection

The prevailing landscape of commercially procurable Original Equipment Manufacturer (OEM) calipers predominantly manifests through their cast iron composition. However, an array of multifarious considerations encompassing parameters such as cost mitigation, mass diminution, commendable mechanical attributes, and the amelioration of machining intricacies coalesce to inform the resolute selection of High-Grade Aluminium (Al7050 T6) material for the constitutive construction of both the caliper and the encompassing caliper housing within the scope of this undertaking. Encapsulated within the subsequent table are the intricate details spotlighting the mechanical characteristics intrinsic to the Al7075 T6 alloy[14][15]. In the contemporary landscape of commercially available Original Equipment Manufacturer (OEM) calipers, the predominant material of choice has conventionally been cast iron. Nevertheless, a diverse array of multifaceted considerations, encompassing factors such as cost optimization, mass reduction, favorable mechanical properties, and the simplification of machining complexities, synergistically converge to guide the steadfast preference for the utilization of High-Grade Aluminium (Al7050 T6) material in both the foundational construction of the caliper and the surrounding caliper housing within the ambit of this endeavor. Presented herein is a comprehensive table elucidating the intricate particulars pertaining to the intrinsic mechanical attributes of the Al7075 T6 alloy.

Table -1: illustrates the mechanical property and value for the material

S.NO	PROPERTY	VALUE
1	Density	2810 kg/m^3
2	Young's modulus	72GPa
3	Yield strength	503MPa
4	Ultimate tensile strength	590MPa
5	Poisson ratio	0.33
6	Hardness (Rockwell)	87 HRB

3.Design of brake caliper

3.1Data and assumptions

The vehicular dynamics are defined by a set of specific data and foundational assumptions. The master cylinder, with a diameter of 15.875mm, plays a crucial role in the braking system, while the caliper piston, boasting a diameter of 32mm, contributes to the overall braking force. The mass of the vehicle is a substantial 330kg, influencing its stability and handling characteristics. The center of gravity, positioned at a height of 32 inches, further shapes the vehicle's dynamic behavior during motion.

The coefficient of friction, an essential determinant of braking efficacy, is precisely stipulated at 0.7, signifying the nuanced interplay between the constituent elements of the braking system. Concerning longitudinal spatial parameters, $\square_1$ delineates the expansive 792.48mm distance, embodying the separation between the front center of gravity and the designated point of reference. Simultaneously, $\square_2$ elucidates the longitudinal span of 528.32mm, precisely characterizing the spatial relationship between the rear extremity and the gravitational center. The wheelbase (L) of the vehicle, a fundamental metric with profound implications for stability dynamics, is meticulously defined at 52 inches, thereby underscoring its pivotal role in shaping the vehicular equilibrium.

The wheel diameter, crucial for traction and overall performance, is specified at 22 inches. Additionally, the factor dg, representing the longitudinal weight distribution, is assigned a value of 0.8. This, in conjunction with the specified longitudinal distances, contributes to the dynamic equilibrium of the vehicle. In summary, these data and assumptions intricately define the parameters and characteristics influencing the vehicular dynamics, encompassing braking efficiency, weight distribution, and overall stability during motion.

3.2Mathematical model and calculations

The mechanical arrangement of the pedal system is distinguished by a pedal ratio (PR) characterized at 6:1,

Pedal Ratio (PR) = $\frac{Length\ of\ pedal\ from\ pivot\ point}{Length\ of\ master\ pushrod\ from\ pivot}$

Representing the proportion between the pedal's length from the pivotal point and the master pushrod's extension from the same pivot. The consequential brake pedal force (P_f) is established by the multiplication of the pedal ratio by the applied force on the pedal, resulting in 2354.4 N,

Brake pedal force (P_f) = PR * F_p,

Subsequently, the pressure on the master cylinder (P_{mc}) is computed by dividing the brake pedal force by the cross-sectional area of the master cylinder, yielding 11.894 N/mm^2, Pressure on master cylinder (P_{mc}) = $\frac{Brake\ pedal\ force}{area}$,

This pressure serves as the foundation for determining the force exerted on the caliper piston (F_{cp}), culminating in a value of 9566.446 N,

Force on caliper piston (F_{cp}) = P_{mc}* area

The clamping force is then ascertained by doubling the force on the caliper piston, resulting in a clamping force of 19132.892 N,
Clamping force =F_{cp}*2,

Transitioning to the analysis of static and dynamic loads, the static load at the front axle (STF) and rear axle is meticulously calculated based on the respective weight distributions yielding 1294.4 N and 1942.38 N, respectively.
Static load at front axle (stf) = $\frac{W*L_2}{L}$,
Static load at rear axle = $\frac{W*L_1}{L}$,

The dynamic load interrelation at the front and the dynamic load interpretation at the rear are deduced through intricate formulas, yielding values of 2804.74 N and 432.55 N, respectively.
Dynamic load interrelation at front (w) = $\frac{w(L_2+(\frac{d}{g})\ h)}{L}$,
Dynamic load interpretation rear (W_{rd}) = $\frac{w(L_1-(\frac{d}{g})\ h)}{L}$,

Frictional torques at the front (T_f) and rear (T_r) are determined by incorporating the coefficient of friction (μ) in conjunction with wheel loads and radii, resulting in values of 548 Nm and 84.5 Nm, respectively.
Frictional torque at front (T_f) = μ * (w)* r,
Frictional torque at rear (T_r) = μ * W_{rd}* r,

The frictional force (F_f) is then computed as a percentage of the clamping force,
Frictional force (F_f) = 0.4 * Clamping force, considering 93% efficiency, resulting in 7117.435 N.

The effective radius is subsequently derived as the ratio of the front frictional torque to the frictional force, yielding a value of 76.99 mm,
Effective radius = $\frac{T_f}{F_f}$,

Furthermore, the diameters of the rear disc (R_d) and front disc (F_d) are computed as 185 mm and 160 mm, respectively,

Rear disc diameter (R_d) = [(Effective radius) * 2 (caliper piston rod)],

Finally, the traction on the tires (F_t) and the cumulative traction on all four wheels are calculated, revealing values of 20242.901 N and 8171.844 N, respectively.
Traction on tyres (F_t) = $\frac{T_f}{static\ rolling\ radius(srr)}$,

Traction on 4 wheels = F_t * 4

3.3Determination of stopping distance

The displacement covered by an automotive entity, from the moment the operator initiates the braking system to the point at which the vehicle comes to a complete halt, encompasses the fundamental concept known as "braking distance" or "stopping distance." This measurable parameter arises as a result intricately dependent on the interaction between two primary factors, specifically the propulsive traction force applied to the vehicle and the velocity at which the vehicle is advancing. In the realm of scientific formulation, the comprehensive relationship defining the quantitative determination of the stopping distance is represented through a mathematical equation, symbolizing the intricate synergy that binds these variables.

stopping distance $= T_f * d = \frac{1}{2}mv^2 - \frac{1}{2}mv^2,$

$$D = \frac{1}{2}mv^2$$

3.3.1stopping distance at 40kmph

$D = ½ * 330 *m\ 11.11 * \frac{11.11}{T_f} * 4$

$D = ½ * 330* \frac{11.11^2}{8171.844}$

D = 2.5m

3.3.2stopping distance at 50kmph

$D = ½ * 330 * 13.88 * \frac{13.88}{8171.844}$

D = 3.88m.

3.4D-modeling of caliper

Utilizing the advanced capabilities of a sophisticated three-dimensional modeling tool, the intricate contours of the brake caliper were meticulously delineated and subsequently integrated into a comprehensive assembly, hinting at the computational insights that underlie its design. Within the scope of this modeling endeavor, a deliberate convergence of essential parameters governing the specifications of the wheel assembly and the piston's diameter was thoughtfully incorporated. This approach culminated in the meticulous generation of a visually representative representation that seamlessly aligns with the numerical computations, as exemplified in the referenced depiction labeled as "Figure 4".

Chart -4: Brake caliper assembly

3.5Analysis and result

After meticulously fine-tuning the design parameters of the caliper, we initiated an extensive analysis process employing Finite Element Analysis (FEA) tools. This analytical endeavor involved a meticulous examination of the mechanical behavior of the brake caliper. We manually integrated the mechanical properties specific to aluminum 7075 T6 into the engineering database, establishing a coherent synergy between theoretical formulations and practical material characteristics. Employing a meshing approach characterized by a default fine-coarse configuration, we discretized the geometric entity into discrete elements to facilitate comprehensive computational assessments. Within this analytical framework, the primary focus was on the caliper body, which was subjected to the influence of three distinct loads, each representing an independent force vector with distinct implications for the structural integrity and functional responsiveness of the caliper.

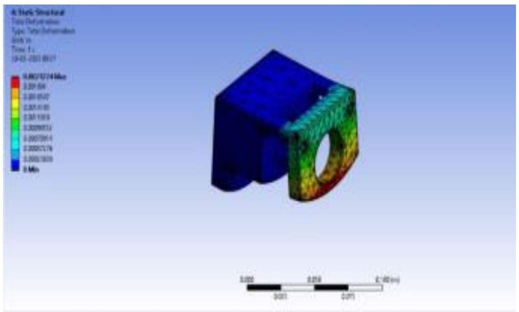

Chart -5: Total deformation

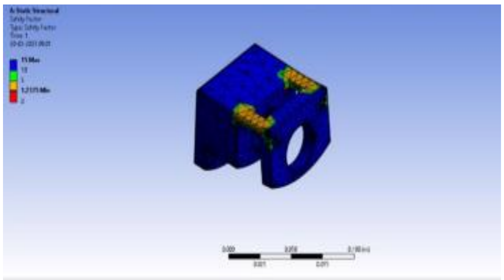

Chart -6: Factor of safety

1.Pressure on master cylinder = 11.894n/mm²

2.Force on the inboard side of the caliper = 9500 n

3.frictional force (F_t) = 7117.435 n

A stringent boundary condition, symbolic of an immovable constraint, was scrupulously enforced upon the lowermost pins, effectively constraining their degrees of freedom. Through a systematic computational methodology, forces of noticeable magnitude and resultant reaction forces were methodically integrated into the anatomical structure of the caliper body. The intricate mechanistic interactions within this analytical framework converged to yield solutions pertaining to two integral aspects. Firstly, the scope of interest encompassed the meticulous determination of the overall system's aggregate deformation, a crucial elucidation encapsulated within the illustrative representation designated as "Figure 10.1." Furthermore, the domain of analysis extended to the derivation of a critical performance metric, the factor of safety, discerned through the depiction documented as "Figure 10.2." These nuanced outcomes collectively constitute the tangible results generated by this meticulous analytical undertaking.

4.Results and Discussion

The undertaking within this investigation encompassed a comprehensive orchestration of both the modeling and analytical phases dedicated to characterizing the caliper. This rigorous investigative process extended its scope to include the meticulous validation of the obtained results. As a testament to the innovation behind this endeavor, a strategic confluence of factors was fastidiously harnessed. These factors encompassed the astute utilization of aluminum as a discerning material choice, accompanied by the conscientious pursuit of minimizing the caliper's architectural configuration. This dual-pronged approach was intricately devised with the overarching objective of instigating a notable reduction in the caliper's overall mass. This constituted a deliberate effort aimed at effectuating a substantial weight reduction within the framework of the caliper's structural paradigm.

5.Conclusion

At the core of the architectural blueprint for the braking system lies the intricate computation of braking force, which emerges as the pivotal linchpin, serving as the foundational cornerstone that underpins its design. Of paramount significance is the cardinal mandate stipulating that the resulting braking force must consistently surpass the requisite threshold. This definition of the necessary braking force substantiates itself as the benchmark against which the adequacy of the generative force is assessed, thereby establishing an immutable criterion for system efficiency. In tandem with this mathematical calculation is the pragmatic determination of the requisite clamping force, a critical endeavor in plotting the trajectory for bore diameter determination and the concurrent selection of piston count. Beyond the realm of computation, the domain of design seamlessly converges with considerations of spatial allocation and assembly constraints. This intricate orchestration highlights the awareness of spatial limitations as well as the practical feasibility of assembly procedures, holding significant material importance within the design paradigm of the caliper body. Within the intricate framework of caliper engineering, the seal groove geometry emerges as an architectural motif of exceptional importance. It serves as a multifunctional entity, fulfilling a dual role. Firstly, as a guardian of hermetic integrity, the seal groove geometry imperatively prevents hydraulic leakage between the piston and the caliper. Simultaneously, it plays an indispensable role in facilitating the required piston retraction once the mandated clamping force has been applied, encapsulating a dynamic interplay of sealing and mechanical functionality. The calculation of stopping distance, an ostensibly elementary parameter, serves as a predictive anchor intricately linked to the overarching prognosis of the system's braking performance. A comprehensive perspective is engendered, wherein the determination of stopping distance exerts its influence on the global efficacy of the entire braking apparatus. The strategic predilection for material selection injects the design ethos with profound ramifications. Through the incorporation of aluminum, the architectural recalibration yields a tangible reduction in the overall mass of the caliper, thereby crystallizing a consequential embodiment of weight attenuation, ultimately bestowing the system with heightened attributes of lightweight construction.

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