OPTIMIZING BRAKE DISC STRUCTURE THROUGH HEAT DISSIPATION AND MASS REDUCTION USING OPTISLANG

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ABSTRACT

A disc brake system comprises a rotor and opposing brake pads that, when actuated, generate frictional force to convert kinetic energy into heat, thereby decelerating the vehicle. During this process, the kinetic energy of the vehicle's motion is converted into thermal energy, with part of the heat absorbed by the brake disc and the remainder dissipated into the surrounding environment. The amount of heat the brake disc absorbs significantly impacts its long-term durability. Therefore, selecting a material with excellent heat dissipation, sufficient mechanical strength, and cost-effectiveness is crucial. This study aims to analyze the heat generated during braking and evaluate the thermal dissipation efficiency of different materials. Three material types are considered: gray cast iron, C45 steel, and aluminum. The brake disc model is designed and analyzed in SolidWorks and ANSYS to simulate thermal and structural performance. optiSLang is employed to optimize the brake disc design regarding mass and temperature distribution by utilizing the Design of Experiments (DoE) method and sensitivity analysis. Through a systematic evaluation of various design parameters, an optimized configuration has been identified that enhances braking temperature management while reducing total mass by 10.85%, from 5.13 kg to 4.58 kg, and thickness by 10.46%. The results indicate that C45 remains the most effective material for brake discs, owing to its superior heat dissipation properties and lower overall mass.

Keywords: *Disc brake, heat dissipation, Finite Element Analysis (FEA), sensitivity analysis, multi-objective optimization, single-objective optimization, machine learning, metamodel, design of experiment.*

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1. INTRODUCTION

Brakes are a crucial component in modern transportation. They serve the purpose of slowing down or completely halting the movement of vehicles. The importance of brakes is immense; it can be said that brakes enable us to go faster and feel confident doing so. Without braking systems, it is doubtful that anyone would dare to drive or ride in a vehicle. The market offers various brake types, including disc, drum, hydraulic, and pneumatic. Anil Babu Seelam [1] designed and analyzed a brake rotor for high-speed cars by comparing stainless steel and grey cast iron using static structural and steady-state thermal analysis in ANSYS to determine the optimal material for improved performance and longevity. Researchers like Swapnil R. Abhang and D.P. Bhaskar [2] conducted thermal and modal analysis in ANSYS on a carbon ceramic matrix disc brake for two-wheelers, calculating normal force, shear force, piston force, brake distance, deflection, heat flux, and temperature to evaluate its efficiency in enhancing braking performance and safety. At the same time, Anuj B Jariwala et al. [3] studied a brake drum's thermal and structural behavior, emphasizing mate-rial selection to withstand high temperatures and stresses while minimizing vibration and noise for enhanced braking performance and comfort. Subhasis Sarkar [4] performed a finite element analysis to investigate the temperature distribution of a brake rotor, identifying critical temperatures during operation and comparing different materials, including AMMC, Asbestos, and GCI, to recommend an optimal material based on thermal performance. A. Tiwari has conducted a structural analysis of a solid disc brake [5] and conducted a transient structural analysis ANSYS 14.0 to evaluate the performance of structural steel under cyclic braking conditions, analyzing friction contact power, nodal displacement, and deformation to determine the most suitable material for improved braking efficiency, stability, and extended service life. For drum brakes, A. Kumarhas [6] evaluated a finite element analysis of an internal expanding brake drum to evaluate thermal and mechanical stress distribution, ensuring stress levels remain within allowable limits for medium-heavy-duty vehicles. Another advanced research conducted by Yi Zhang, Hu Zhang, and Chao Lu [7] developed a multi-objective optimization model for drum brakes to maximize braking efficiency while minimizing volume and temperature rise, using a Differential Evolution Cellular Multi-Objective Genetic Algorithm (DECell), which outperforms NSGA-II in speed, stability, and diversity of optimal design solutions. Singh [8] performed finite element analysis to design and optimize a drum brake by evaluating different materials, including aluminum alloys, metal matrix composites, titanium alloys, and CE (Controlled Expansion) alloys. Structural and thermal analyses in ANSYS 16.0 examined stress distribution, deformation, and heat transfer under various braking conditions. Material selection methodologies have also been central to brake design optimization. Maleque et al. [9] proposed a systematic material selection framework that considers performance attributes such as thermal conductivity, wear resistance, and manufacturability to support informed decision-making in disc brake development. Noise and vibration issues, particularly brake squeal, were thoroughly examined by Huang, Krousgrill, and Bajaj [10], who modeled automotive drum brakes and performed parameter sensitivity analysis to understand the conditions contributing to squeal generation. Their work highlighted the role of friction characteristics and structural dynamics in acoustic instability. Similarly, Lee et al. [11] analyzed drum brake squeal using shoes with non-uniform cross-sections, demonstrating how geometric asymmetry can be employed to reduce noise via modal decoupling strategies. Gowthami and Balaji [12] conducted structural and thermal analyses of drum brakes, providing insight into stress concentration zones and validating their design through simulation-based deformation and temperature distribution studies. Finally, Kushal and Sharma [13] adopted a reverse engineering approach to improve the performance of two-wheeler brake drums, applying ANSYS simulations to optimize design geometry, reduce weight, and enhance overall functionality.

Despite progress in simulation techniques, several challenges persist. Most studies have not integrated advanced optimization tools such as ANSYS optiSLang, which can perform sensitivity analysis and multi-objective optimization. Moreover, research relies solely on idealized simulation conditions, lacking validation through experimental data or real-world testing. Although widely discussed, material selection primarily revolves around conventional choices, with limited exploration into newer composites or hybrid materials. Acoustic concerns, particularly brake squeal, have been examined through modal analysis, but often with oversimplified models that do not account for nonlinear contact or transient dynamics. Integrating mechanical brake design with electronic control systems and sustainability considerations, including recyclability and environmental impact, remains underexplored mainly in current literature.

This method identifies the optimal design based on predefined criteria and constraints like temperature, stress, and mass. The process begins with selecting an initial set of design parameters, which are then analyzed using finite element analysis (FEA) to assess their performance. Sensitivity analysis is performed using Ansys optiSLang, allowing the creation of a machine learning model that can accurately predict output parameters based on input variables. This surrogate model significantly reduces computational effort while maintaining accuracy. Finally, an optimization step is conducted within optiSLang to determine the best design parameters that satisfy the given objectives. This approach enhances the efficiency of the design process, providing engineers with a robust framework for optimizing brake components under multiple operational conditions.

2. METHODOLOGY

2.1. Background

This study employs a structured computational workflow to optimize the performance of brake components using Design of Experiments (DoE), Finite Element Analysis (FEA), and multi-objective optimization in ANSYS optiSLang. The process is designed to identify the best combination of input parameters that minimize thermal and structural geometry while satisfying engineering constraints.

The optimization goal is defined as a multi-objective problem, which can be expressed as [14]:

$$\min_{X\in\Omega} f(X) = \left[f_1(X), f_2(X), ..., f_n(X)\right] \quad (1)$$

Subject to $g_j(X) \le 0$, (j = 1,…,m) and $h_k(X) = 0$, (k = 1,…,l), where $X = [x_1, x_2, ..., x_p]$ is the vector of design variables, $f_i(X)$ is the objective functions (e.g., minimize stress, temperature, or mass); $g_j(X)$, $h_k(X)$ are inequality and equality constraints, Ω is the feasible design space.

A DoE technique is used to explore the design space by generating structured samples of input parameters. The number of simulations N required depends on the number of parameters p, often approximated as:

$$N = a.p + b \quad (2)$$

Where a and b are method-specific constants, each sample X_i is later evaluated in simulation. optiSLang performs global sensitivity analysis to determine the influence of each variable xi on a given response Y. The first-order sensitivity index is:

$$S_i = \frac{V_{X_i}\left(E\left[Y|X_i\right]\right)}{V(Y)} \quad (3)$$

V(Y) is the total variance of the output and $E\left[Y|X_i\right]$ is the conditional mean. This helps focus optimization on the most influential parameters.

2.2. Case study: Thermal analysis of brake disc using ANSYS software

In this case study, a disc brake rotor thermal analysis is conducted based on vehicle operating conditions, as shown in Table 1.

This study focuses on gray cast iron, C45 steel, and aluminum alloy due to their general use, availability, and cost-effectiveness in mass-produced brake systems. These materials offer a practical balance of thermal and mechanical properties, making them suitable for optimization within the constraints of standard automotive applications.

Table 1. Process parameters and their levels

Parameter	Value	Unit
Vehicle mass	2325	N
Gravitational acceleration	9.8	m/s^2
Coefficient of adhesion	0.7	-
Initial velocity	22.22	m/s
Initial temperature	25	°C

The pre-braking kinetic energy of the vehicle:

$$E_k = \frac{1}{2}mv_o^2 = 573959.3\,(J) \quad (4)$$

Braking time: For optimal braking performance, the braking force generated should match the road-tire adhesion, with $j_{max} \approx 6.9 m/s^2$:

$$\Delta T = \frac{v_0}{j_{max}} = \frac{22.22}{6.9} = 3.2\,(s) \quad (5)$$

Braking-induced heat:

$$P_{heatpower} = 0.7\frac{E_k}{t} = 12553.6\,(W) \quad (6)$$

Thermal distribution on the surface of a front brake disc:

$$P_f = \frac{0.6P_{heatpower}}{2} = 37666.1\,(W) \quad (7)$$

Thermal distribution on the surface of a rear brake disc:

$$P_r = \frac{0.4P_{heatpower}}{2} = 25110.7\,(W) \quad (8)$$

In this study, thermal and structural simulations of the disc rotor were conducted using ANSYS, with boundary conditions reflecting typical operating conditions. The ambient temperature was set at 25°C, and the braking force was derived from the vehicle's kinetic energy. These consistent conditions were used across all materials for fair comparison and optimization using ANSYS optiSLang. The material properties and their heat transfer coefficient used in the simulations are summarized in Table 2.

Table 2. Material properties and their heat transfer coefficient

Property	Gray Cast Iron	C45 Steel	Aluminum Alloy
Density (kg/m^3)	7200	7850	2700
Young's Modulus (GPa)	110	190	68
Poisson's Ratio	0.27	0.27	0.33
Thermal Conductivity (W/mK)	45	49.8	200
Specific Heat Capacity (J/kgK)	510	486	900
Coefficient of Friction	0.2	0.4	0.4

2.3. Design optimization using ANSYS optiSLang

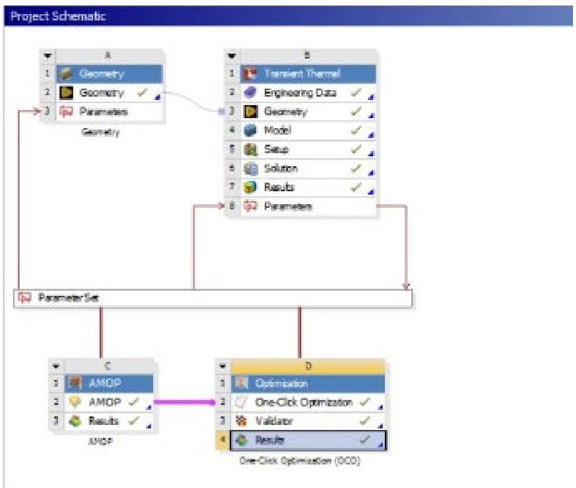
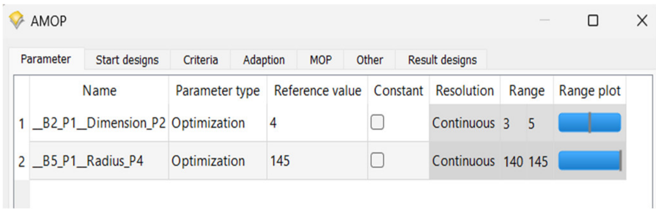


Fig. 1. Optimization problem procedure from finite element analysis

The process begins with the Geometry component, where the brake disc model is created and parameterized. This geometry is then linked to a Transient Thermal analysis system, which includes the setup of material properties, meshing, boundary conditions, and time-dependent thermal loads to simulate the braking process. All design parameters are managed in the Parameter Set, allowing for systematic variation during the optimization process. The thermal analysis results are connected to the AMOP (Adaptive Metamodel of Optimal Prognosis) component, which is used to perform Design of Experiments (DoE) and sensitivity analysis. This step helps identify the influence of each parameter on thermal performance and mass. The AMOP results are then fed into the Optimization system. One-click optimization (OCO) is applied to calculate an optimal brake disc design based on defined objectives, such as minimizing mass while maintaining acceptable temperature distribution. This integrated workflow efficiently explores the design space and supports data-driven decision-making for material and geometry selection (see Fig. 1).


AMOP

Parameter | Start designs | Criteria | Adaption | MOP | Other | Result designs

	Name	Parameter type	Reference value	Constant	Resolution	Range	Range plot
1	__B2_P1__Dimension_P2	Optimization	4	☐	Continuous	3 5	
2	__B5_P1__Radius_P4	Optimization	145	☐	Continuous	140 145	

Fig. 2. Input parameters for Sensitivity and Optimization Analysis

The two geometric parameters introduced into the model for optimization are the B2_P1_Dimension_P2 (the thickness of the brake disc) and the B5_P1_Radius_P4 (the radius of the brake disc). The thickness parameter is allowed to vary within the range of 3 to 5 mm. In comparison, the radius can vary between 140 and 145 mm (see Fig. 2). For the optimization study, the primary objective is to minimize the mass of the brake disc to enhance the lightweight design and overall system efficiency. A thermal constraint is applied to ensure safety and performance, where the maximum temperature during braking must remain below 90°C.

3. RESULTS AND DISCUSSION

3.1. Result of thermal analysis

After analyzing the disc brake temperature when braking at a speed of 80km/h with the original geometry among three types of materials: gray cast iron, C45 steel, and aluminum alloy, the results showed that the highest temperatures were 83.43, 80.37, and 88.06 degrees Celsius, respectively. To ensure that the brakes can withstand heat and dissipate heat well, C45 steel material is a suitable choice for making brake discs.

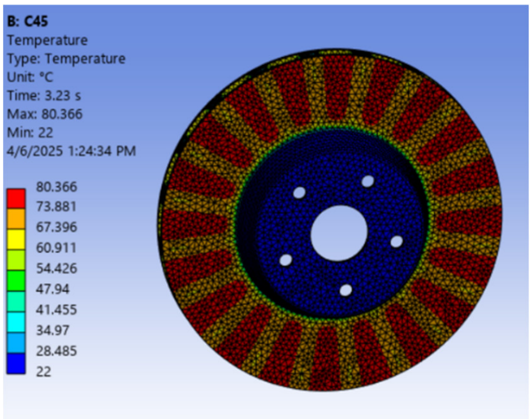


Fig. 3. Results of the thermal analysis on disc brakes with original geometry

3.2. Result of optimization analysis

3.2.1 Sensitivity analysis

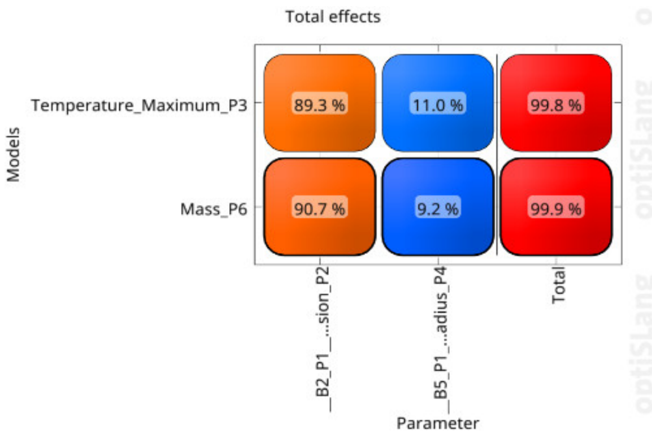


Fig. 4. Chart of CoP matrix

Temperature_Maximum_P3: _B2_P1__Dimension_P2 has the most substantial impact, accounting for 89.3%. __B5_P1__Radius_P4 only has a small influence, accounting for 11.0%. The Dimension_P2 parameter overwhelmingly influences both maximum temperature and mass, making it the top priority for optimization. It likely relates to key geometric factors like disk diameter, thickness, or surface area exposed to air. Adjusting this parameter significantly affects thermal performance and weight, but changes must preserve mechanical strength and heat resistance. The total effect reaches 99.8%, indicating that the parameters have covered almost the entire impact on the maximum temperature result.

Mass_P6: __B2_P1__Dimension_P2 also has the main impact, accounting for 90.7%. __B5_P1__Radius_P4 plays a secondary role, with an influence of 9.2%. The total effect reaches 99.9%, showing that the model accurately predicts mass based on the two input parameters. Brake disk design often involves trade-offs between mass and thermal performance. A lighter disk improves efficiency but may overheat, while a heavier disk enhances cooling at the cost of weight. Dimension_P2's dual influence requires careful optimization to meet both goals.

3.2.2. Optimization result

The green points indicate designs that satisfy all constraints, while the red points represent designs that violate constraints or fail. The blue line shows the optimization process's convergence trend, indicating the objective value's gradual improvement according to the evaluated designs. Displaying this history helps us observe the distribution of designs, track the optimization progress, and identify the convergence trend toward the best design. This chart shows that design No. 295 is evaluated by the software as the most optimal design according to the defined criteria.

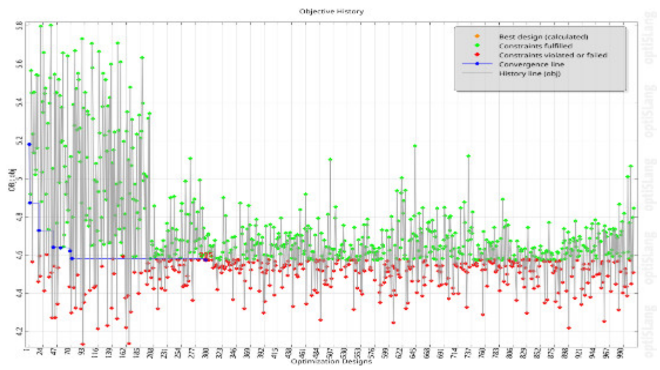


Fig. 5. History Chart

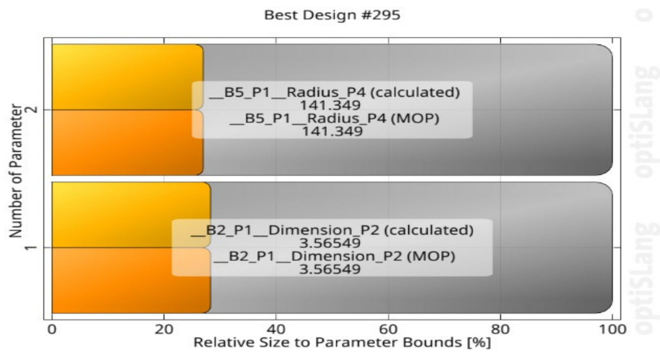


Fig. 6. Optimal design parameter value chart

The chart above shows the optimal design parameters (No. 295), comparing the values predicted by the response surface (MOP) and the actual values calculated by the solver. Specifically, the Radius_P4 (radius) parameter has a value of 141.349 in both methods, and the Dimension_P2 (thickness) parameter also has the same value of 3.56549. This shows the high accuracy of the response surface model in predicting the optimal value, helping to reduce computation time while ensuring reliable results (Fig. 5).

The actual calculated result shows a maximum temperature value of 89.7768, while the value predicted by the response surface (MOP) is 90, indicating a negligible error. Similarly, the actual mass value is 4.58154 compared to 4.57475 for the MOP, demonstrating the high accuracy of the response surface model in predicting the optimal results (see Fig. 7).

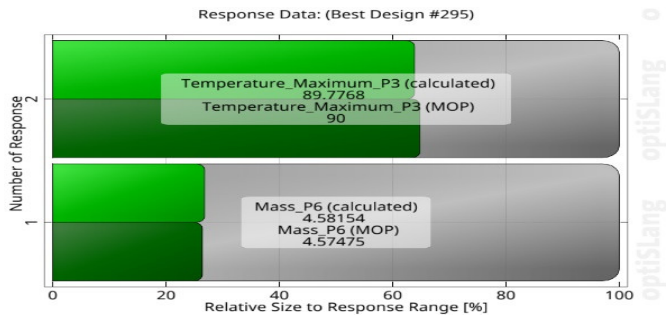


Fig. 7. Optimal design output parameter value chart

3.3. Limitations

The study demonstrates the thermal benefits of the optimized brake disc design but has several limitations. It focuses solely on thermal performance, excluding key braking factors such as torque, effectiveness, and pad-disc interaction. Consequently, the proposed parameters may not ensure overall braking performance. The optimization follows a deterministic approach, assuming ideal manufacturing without variability. No tolerance or robustness analysis was conducted to account for real-world uncertainties. As a result, the design may not remain effective under material or geometric deviations. Future studies should include braking performance metrics in the optimization process. Incorporating robust design techniques, such as Monte Carlo simulations or worst-case analyses, will improve stability. The methodology will also be expanded using Design for Six Sigma (DFSS) to enhance reliability and manufacturability from the early design stages.

4. CONCLUSION

This study relies on simulation to reduce the cost, time, and complexity of physical testing. While experimental validation is ideal, the focus is establishing a predictive design framework using ANSYS and optiSLang as a basis for future experimental work. This work presents a comprehensive methodology for disc brake design, identifying an optimal configuration based on key performance criteria, temperature distribution, and mass. Using ANSYS for thermal analysis and optiSLang for sensitivity and optimization, it demonstrates how design variables such as disc radius and thickness affect outputs like maximum braking temperature and total mass. The optimized design achieved a mass of 4.58kg, temperature of 89.78°C, and thickness of 3.56mm, with improvements of 10.85% in weight and 10.46% in thickness. These results were obtained through machine learning-assisted exploration of design variants.

Scientifically, the study advances the understanding of simulation-based optimization by integrating finite element analysis and surrogate modeling in thermo-mechanical systems. It also offers a structured approach to evaluating parameter sensitivity and trade-offs in thermal optimization. Industrially, the workflow is practical and transferable and supports manufacturers in developing lightweight, thermally efficient, and cost-effective brake discs within machining and material constraints.

While the optimization yielded precise geometric values (e.g., thickness = 4.58154mm), these represent idealized results. In practice, such values are rounded to standard tolerances with negligible impact on performance. Future research should incorporate robustness analysis to evaluate the influence of manufacturing tolerances, material variability, and real-world conditions, enhancing durability and reliability.

By relying on simulation, this work reduces the cost, time, and complexity of physical testing. Although experimental validation remains ideal, this study lays a predictive foundation for future empirical investigations using ANSYS and optiSLang.

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