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Investigation on Thermal and Modal Analysis of Brake Disc Made of SS410 And SS304 Using ANSYS

Mohit Vishnoi[1,*], Mamatha Teetha Gangadhar[2], Neeraj Verma[3], Kunal Patel[4], Subodh Singh[5], Beena Maurya[6]

Abstract

The Primary purpose of the investigation is to investigate the vibration and noise that are present in the braking system. As a result of the application of braking force, the kinetic energy of the vehicle was transformed into heat, sound, and vibrational energy. The dynamic structural characteristics of the components that make up the braking system are closely linked to the modal behaviour, which refers to the vibration modes that are displayed by the system. As a result of the complexity of the braking system, numerical finite element analysis (FEA) models are utilised. A modal analysis is utilised in order to make a prediction regarding the vibration modes of the various components that make up the brake system. It is necessary to gain essential insights into the dynamic behaviour of components while they are operating, and identifying the modal frequencies and vibration modes is accomplished. The gathering of essential insights into the dynamic behaviour of the components while they are in operation is made possible through the determination of the modal frequencies and vibration modes. The comparison of the results of the numerical modelling of SS410 and SS304, which were produced from finite element analysis, improves the design and performance optimisation of the braking system while also providing a comprehensive understanding of the modal behaviour of the brake disc.

Keywords: Stainless steels; ANSYS; modal analysis; frequency; vibration; total deformation

INTRODUCTION

The brakes are among the most critical components of an automobile. The brake system comprises a brake disc (or rotor), an actuator, brake pads, a master cylinder, and a brake line. The part that moves is the brake rotors, which rotate together with the tyre [1]. By converting energy, it primarily serves to halt the body from moving. A disc brake is a wheel brake that decelerates wheel rotation through friction generated by pressing brake pads against a brake disc with calipers. Typically, the brake disc or rotor is composed of stainless steel [2]. This is linked to the tyre and axle. Friction slows or stops the disc and attached tyre. Brakes transform motion to heat, vibration and sound, and if they become too significant, brake system lose its effectiveness, a phenomenon known as brake fade.

Classification of Brake System Based on Transformation of Energy

- *Hydraulic brakes:* These brakes use hydraulic fluid to transmit force and convert kinetic energy into heat energy through friction [3].
- *Electric brakes:* Electric brakes utilize an electrical system to generate braking force, often through electromagnetic or electro-dynamic principles.
- *Mechanical brakes:* Mechanical brakes rely on mechanical means to generate friction and transform kinetic energy into heat energy.

***Author for Correspondence**
Mohit Vishnoi

[1,3]Assistant Professor, Department of Mechanical Engineering, JSS Academy of Technical Education, Noida, Uttar Pradesh, India
[4,5,6]Research Scholar, Department of Mechanical Engineering, JSS Academy of Technical Education, Noida, Uttar Pradesh, India
[2]Professor, Department of Mechanical Engineering, JSS University, Noida, Uttar Pradesh, India

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Classification Of Brake System Based on Direction of Acting Forces (Mechanical Brakes)

- *Axial brakes:* Axial brakes apply force parallel to the axis of rotation since the forces applied on the brake drum only travel axial direction.
- *Radial brakes*: The forces operating on the brake drum in radial brakes are perpendicular to the axis of rotation and in a radial direction. Two subgroups of radial brakes can be distinguished:
- *External brakes*: These brakes have the brake shoes or pads positioned on the outer surface of the brake drum or rotor, exerting force from the outside.
- *Internal brakes*: Internal brakes have the brake shoes or pads positioned inside the brake drum or rotor, exerting force from the inside.

WORKING PRINCIPLE OF DISC BRAKES

Disc brakes work on the principle of converting kinetic energy into heat energy through friction. They consist of several key components, including a brake disc (rotor), brake pads, calipers, and a hydraulic system. The working principle of disc brakes can be summarized as follows:

1. *Application of braking force*: Hydraulic pressure is generated in the master cylinder when the driver applies pressure to the brake pedal [4]. The transmission of this pressure to the callipers is the responsibility of the braking lines.
2. *Squeezing of brake pads:* The calipers house the brake pads, which are positioned on either side of the brake disc. The hydraulic pressure forces the caliper pistons to move, thereby squeezing the brake pads against the brake disc.
3. *Friction generation:* As the brake pads make contact with the rotating brake disc, friction is generated. This friction creates a resistance force that slows down the rotation of the disc.
4. *Kinetic energy conversion*: The kinetic energy of the moving vehicle is transferred to the brake disc. As the disc slows down, the vehicle also decelerates.
5. *Heat dissipation*: The conversion of kinetic energy into heat energy occurs during the friction process. The brake disc is designed with fins or ventilation channels to facilitate heat dissipation and prevent overheating.
6. *Brake pad replacement*: Over time, the brake pads wear out due to the frictional forces. Periodic replacement of brake pads is necessary to maintain optimal braking performance.
7. *Hydraulic system*: The hydraulic system ensures efficient transmission of the braking force from the brake pedal to the calipers. It utilizes hydraulic fluid to transmit the pressure generated by the driver's input.

The effective use of friction to slow down and stop the vehicle is the foundation of the working principle of disc brakes [5]. The safety and control of the vehicle are guaranteed by the design and materials of disc brakes, which are engineered to deliver consistent and reliable braking performance. Vibration and noise generated by automotive brakes have been enduring concerns since the advent of braking systems. The challenge resides in discerning the fundamental causes of these difficulties [6]. The characteristics of vibrations are non-repetitive owing to factors such as pressure, velocity, and temperature, complicating comprehensive investigation of the phenomenon. During braking, low-frequency vibrational energy transmits through the vehicle structure, causing resonance with other components. Simultaneously, high-frequency vibrations produce elevated noise levels. A common cause of disc brake squeal is the increased friction coefficient resulting from the interaction between the brake pads and the brake disc. This friction-induced structural instability may produce screaming. [7-10].

Therefore, it is imperative to conduct an assessment of noise, vibration, and harshness (NVH) to mitigate resonance issues in the brake system. Brake noise can be categorised based on the sources of excitation and their associated frequencies. Squealing is an often-noted sound while braking, typically occurring between the frequency range of 1 kHz to 16 kHz. This research specifically analyses scream within the frequency range of 1 kHz to 3 kHz. This work investigates the properties of squeal within this frequency band to enhance knowledge of the issue and formulate ways to limit brake noise [9]. Examining the excitation sources and frequencies linked to squeal is crucial for engineering brake systems that reduce undesirable noise and enhance overall driving comfort.

Objectives

- *Disc design*: Develop a disc employing a load analysis methodology for a disc braking system.
- *Temperature distribution*: Determine the steady-state temperature distribution within the system.
- *Heat flux and heat transfer*: Analyze the system's internal heat flux and heat transmission mechanisms.
- *Natural frequency determination*: Identification of the natural frequencies and mode shapes of the disc brake system.
- *Mode shape visualization*: Visualize the mode shapes associated with different natural frequencies.
- *Resonance avoidance*: Determine critical frequencies and avoid resonance conditions.

MATERIALS AND METHODOLOGY

For this research work, the following steps as shown in the form of flow chart (ref. figure 1) were undertaken to analyse the results.

- Selection of specific material
- Heat flux calculation
- Brake disc designing using CAD Model
- The ANSYS design importing
- Create a meshing for the analysis of the model
- Determining the transient thermal response by implementing the boundary conditions
- Modal analysis for finding natural frequency
- Analyzing the output

LITERATURE REVIEW

Joshi Et Al. (2022)

The study illustrates the significant heat loads that the brake disc experiences during the energy conversion procedure. These pressures highlight how crucial it is to select the right material for the discs in order to ensure their effectiveness and durability. Using several grades of stainless steel, such as SS 304, SS 410, SS 321, and SS 310, the study analyses the disc of the Formula Student Vehicle and runs simulations to evaluate thermal loads and fatigue [1].

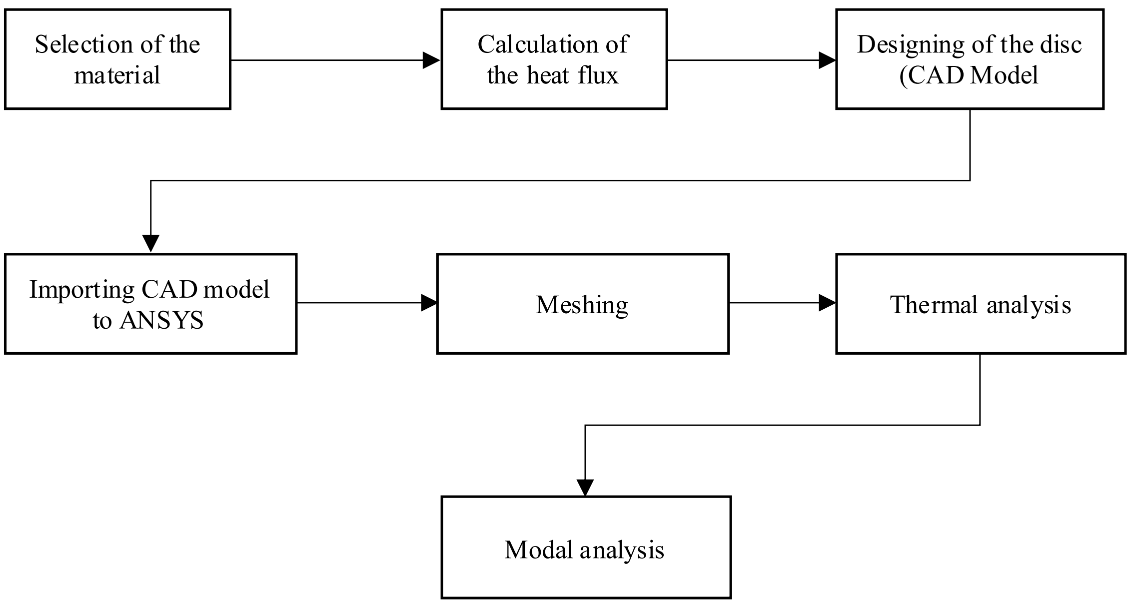

Figure 1. Flow chart of the methodology.

Darekar Et Al. (2020)

The primary aim of this study is to enhance vehicle brake discs and analyse the thermal dynamics of the dry contact between the brake disc and brake pads during braking. Thermo-structural analysis is employed to evaluate disc deterioration and van der Waals pressure. The project involves the design, analysis, and improvement of solid and vented disc brakes using SOLIDWORKS, H.P., and ANSYS [2].

Negi Et Al. (2018)

The objective of this project is to design and conduct static testing on a brake disc. Thermal and structural analyses are employed to assess temperature gradients and heat fluxes during deformation. The results indicate that the disc structure is deemed secure under normal operating conditions. No notable deformations or hotspots were observed in the disc [3].

Pathak Et Al. (2017)

This research investigates the application of structural steel and grey cast iron as materials for disc brakes. The disc's performance is evaluated by computing the Von Mises stress and deformation. Standard disc brakes on two-wheelers are modelled, and modal analysis is performed using ANSYS software. The study aims to enhance the disc plate's longevity, optimise disc brake performance, and determine the optimal profile structure by analysing stress, deformation, and heat dissipation on the disc plate [4].

Kumbilvelil Et Al. (2014)

Through modifications to the design, the primary purpose of this investigation is to reduce the amount of heat deformation that occurs in disc brakes. In order to accomplish this, perforations are incorporated into the inside surface of the disc, which in turn facilitates the movement of air through the atmosphere. This airflow mitigates thermal stress and diminishes the probability of crack formation. Thermal analysis is utilised to assess the degree of thermal deformation and overall heat dissipation in the disc. The performance analysis indicates that the disc should possess the optimal design. [5].

Iordache Et Al. (2017)

The study uses finite element analysis to investigate the modal behaviour of a brake disc. It emphasises the significance of modal analysis in the development of reliable braking systems and discusses how experimental research can corroborate a numerical model [6].

Bhardwaj Et Al. (2019)

This article addresses the design of conventional and peripheral brake rotors utilising SolidWorks software. The rotors' performance is evaluated by structural and modal analysis using ANSYS software. The natural frequencies obtained from the investigation closely align, indicating the models' correctness [7].

Table 1. Properties of the different Stainless-Steel Materials.

Properties	SS-304	SS-410
Density (g/cm^3)	7.8	7.7
Thermal Conductivity (W/mk)	16.4	24.8
Ultimate Tensile Strength (MPa)	504	509
Ultimate Yield Strength (MPa)	214	291
Specific Heat Capacity (J/kg K)	501	461
Brinell’s Hardness (HB)	93	95
Poison Ratio	0.28	0.27-0.28
Young Modulus (GPa)	193-201	190-209

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Kharate Et Al. (2014)

The subject of brake squeal and its connection to friction-induced vibrations is addressed here. To analyses a commercial brake disc and find its natural frequency and mode form pattern, it uses FEA and EMA. A trustworthy correlation in the dynamic properties of the brake components is found when the FE model is compared to experimental findings [8].

Warade Et Al. (2014)

this study focuses on circular plates with radial cracks, commonly used in various engineering applications. The natural frequencies and mode shapes are investigated through experimental and FEM analyses, with the results showing close agreement [11].

MATERIAL COMPARISON

Stainless steel is the material that the disc brake is made of. Typically, grey cast iron, composite materials, etc. are used to make disc brakes. Despite its high price, stainless steel is employed because of its great corrosion resistance, reduced wear, good strength, low coefficient of friction, and high thermal efficiency. However, there are various grades of stainless steel, and each one is unique. By examining each characteristic, comparisons for the best were made. The SS 304 and SS 410 have the following characteristics.

The different properties of stainless-steel grades mention in Table 1 are used to perform the modal analysis to compare the two grades of the steels.

RESULTS AND DISCUSSIONS

Heat Flux Calculation

STEP-1:

Kinetic Energy (K.E.) = $0.5 * m * v^2$

$= 0.5 * 230 * (13.8*13.8)$

= 21900.6 Joules

The total kinetic energy generated by the All-terrain vehicle (ATV) moving at a speed of 13.8 m/s is 21,900.6 J. where “m” and “v” represents the mass and the velocity of the vehicle respectively.

STEP-2:

The heat generated = total kinetic energy Heat generated = 21900.6 J

STEP-3:

Area of the two surfaces in contact= $\pi * (0.170^2 – 0.115^2)$

$= 0.0492195\ m^2$

STEP-4:

Heat Flux = Heat Generated / time / rubbing area

= 21900.6 / 1.7 / 0.0492195

$= 261739.877\ W/\ m^2$

Design of Disc Brake

Brake disc design and analysis to preserve the specifications needed for all-terrain vehicles (ATVs). Vehicle weight, braking force, and dynamic weight transfer all affect disc brake design. Acceleration, hub-mounted disc brake assembly, etc.

Cad model of the disc brake

In order to generate the CAD model of the brake disc, SOLIDWORKS was utilised. These disc brakes, which are often referred to as slotted disc brakes, have slots that improve heat dissipation and save weight. Both the front and rear tires of the vehicle are of comparable brands, and the disc brakes are designed to dissipate heat as efficiently as possible while making the vehicle as lightweight as possible.

Table 2. Disc design parameters

S N.	Parameter	Value
1.	Total weight (Kg) of the Vehicle	230
2.	Average velocity (Km/hr) of the Vehicle	50
3.	Disc outer diameter (mm)	170
4.	Disc inner diameter (mm)	115

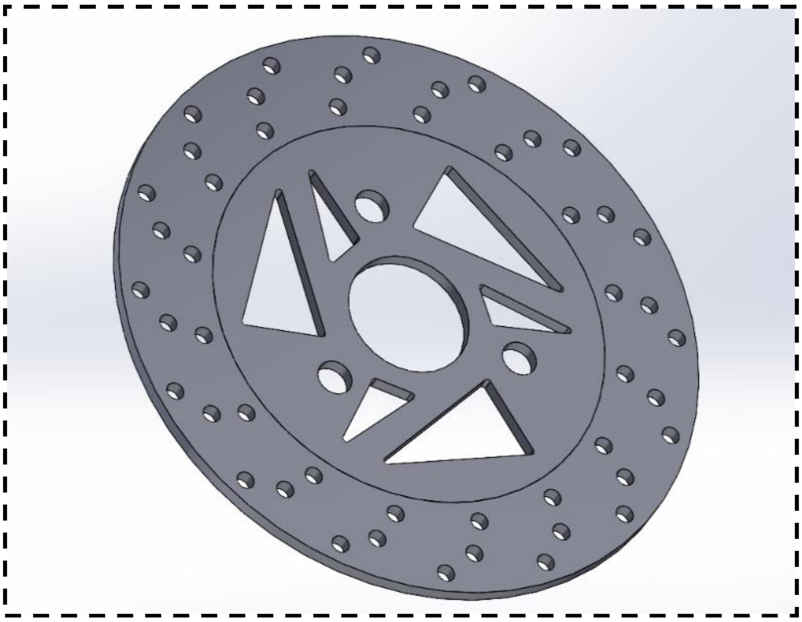

Figure 2. CAD model of the brake disc

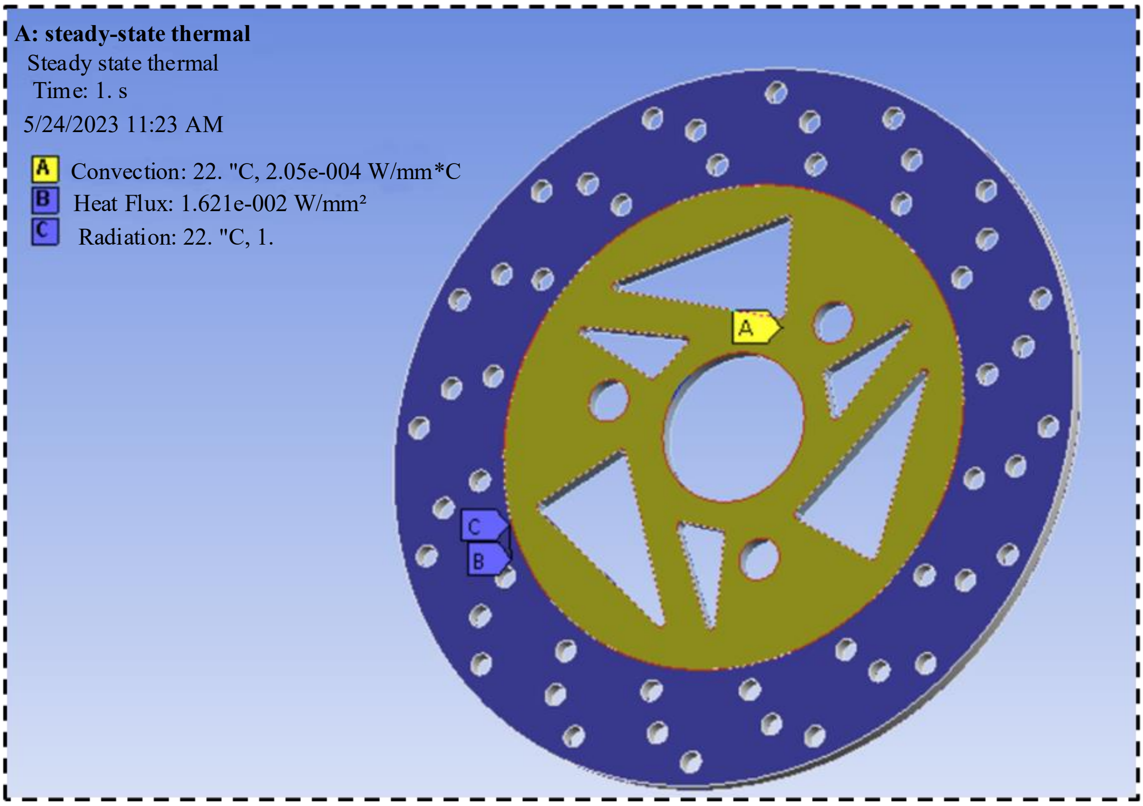

Figure 3. Application of boundary conditions on the brake disc for thermal analysis.

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Design parameters

Table 2 presents the design parameters evaluated in vehicle design and analysis. Examine the design specifications and requirements for an all-terrain vehicle (ATV).

Figure 2 presents the brake disc design intended for the analysis. The disc is engineered to optimise heat dissipation for enhanced braking performance while minimising weight.

Boundary Conditions Used for Thermal Analysis

Convection: 22℃
Heat flux :1.621x10 W/mm^2
Radiation:22℃

In the above Figure 3, it shows how the boundary conditions are applied on the brake disc. These are boundary conditions to perform the thermal analysis.

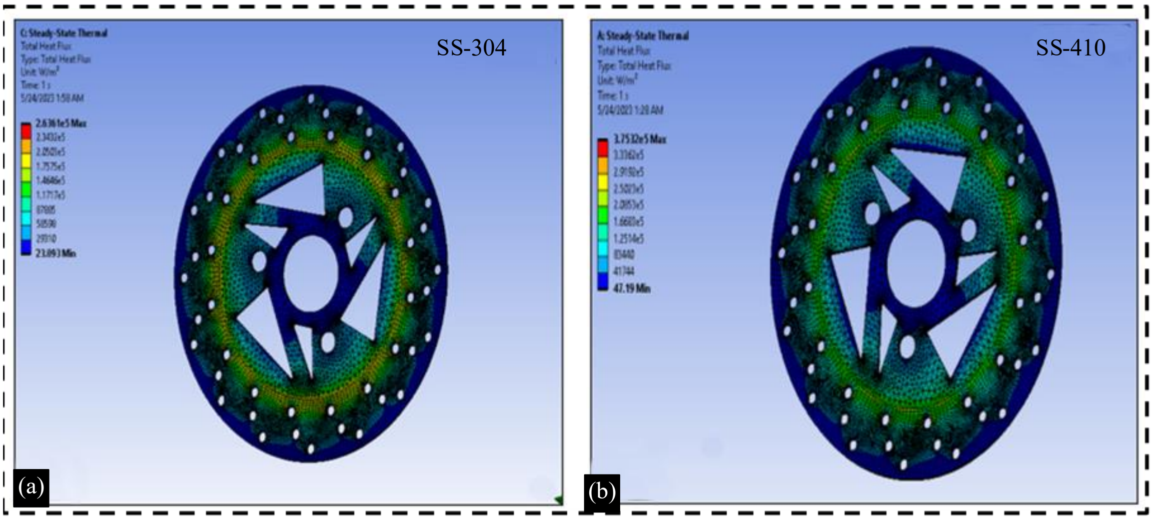


Figure 4. Comparison of the brake disc on the basis of Heat Flux for materials, a) SS-304, and b) SS-410.

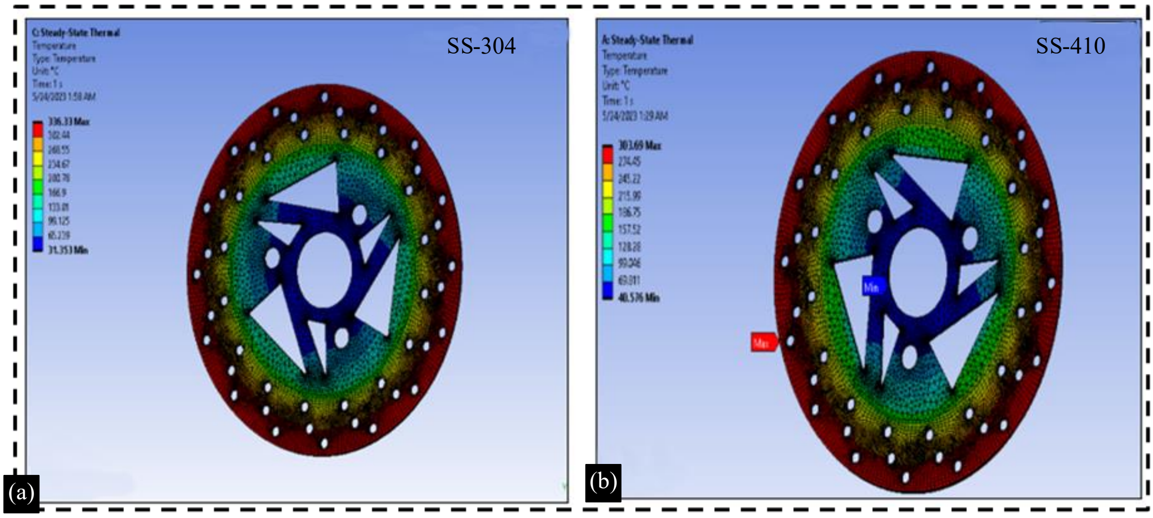


Figure 5. Comparison of brake disc on the basis of Maximum Temperature for materials, a) SS304, and b) SS410.

Table 3. Result of the Thermal Analysis for SS304 AND SS410.

Material property	SS 304	SS 410
Heat Flux (W/m^2)	2.6x10^5	3.7x10^5
Maximum temperature (°C)	336.3	303.69

The Figures 4a-4b and figures 5a-5b show the results of thermal analysis i.e. heat flux and maximum temperature respectively. Moreover, the values of the heat flux and maximum temperature has shown in Table 3.

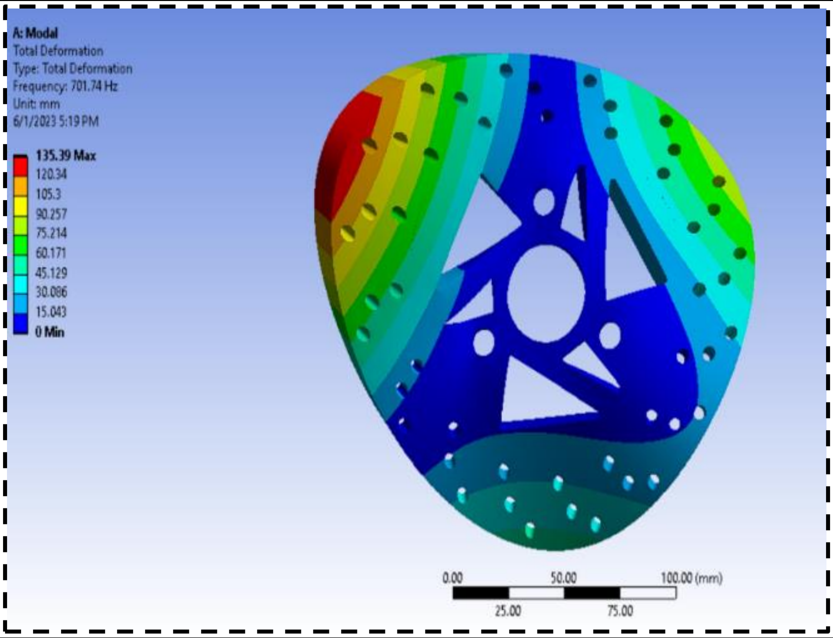
Simulation Result of Modal Analysis

Using FEA-based free vibration analysis, the first six natural frequencies and mode shapes of both discs were evaluated. Boundary conditions with zero displacement limitations were used during the simulation. For both brake rotor designs, structural steel was used in their construction during the finite element analysis. The obtained results showed minor differences between the two discs, when designed for a wheel size with a 12-inch radius. For the SS410 material disc brake rotor, the frequencies ranged from 701.74 Hz to 1687.5 Hz, while for the SS304 material disc brake rotor, the frequencies ranged from 685.9 Hz to 1651.8 Hz.

The frequency results demonstrate clear and significant distinctions between the two materials. In the observed deformation, the frequencies for the SS304 material discs are consistently lower than those of the SS410 material disc rotor across the first to sixth mode. The total deformation of both the materials are almost same. However, the observed frequencies for the six modes are higher for the SS410 rotor. This indicates that the SS410 disc rotor is capable of accommodating higher frequencies without altering the geometry of other automobile components, even after experiencing maximum deformation.

Table 4 and Table 5 shows the first six modes of Natural Frequencies of the two selected material SS410 and SS304 after the Modal Analysis.

Table 4. Result for Model Analysis for SS 410.

Mode shapes	Frequency	Mode analysis
1.	701.74	

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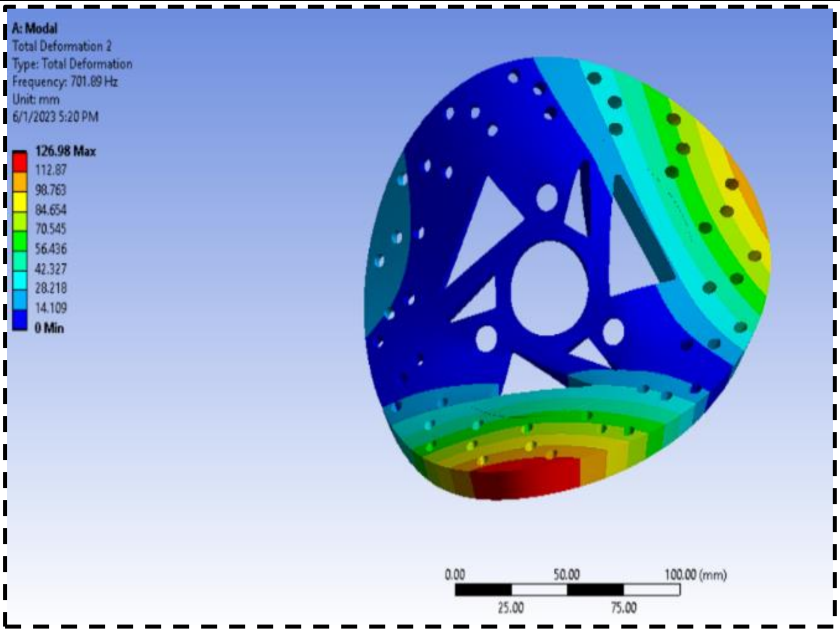
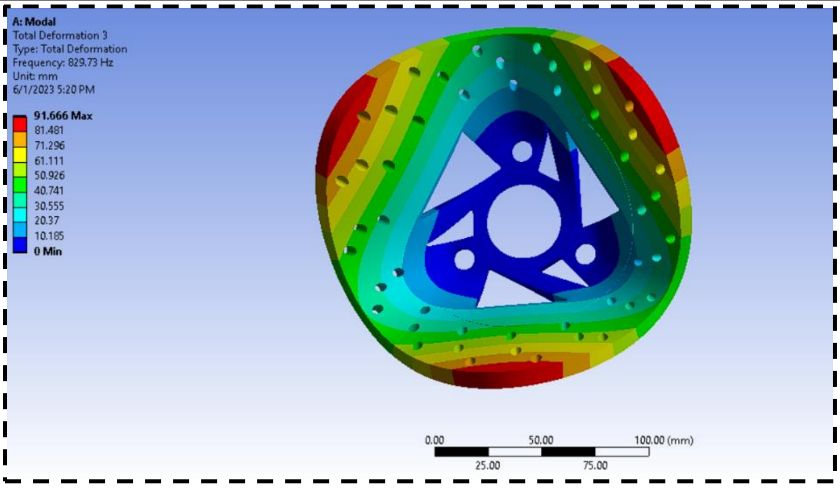
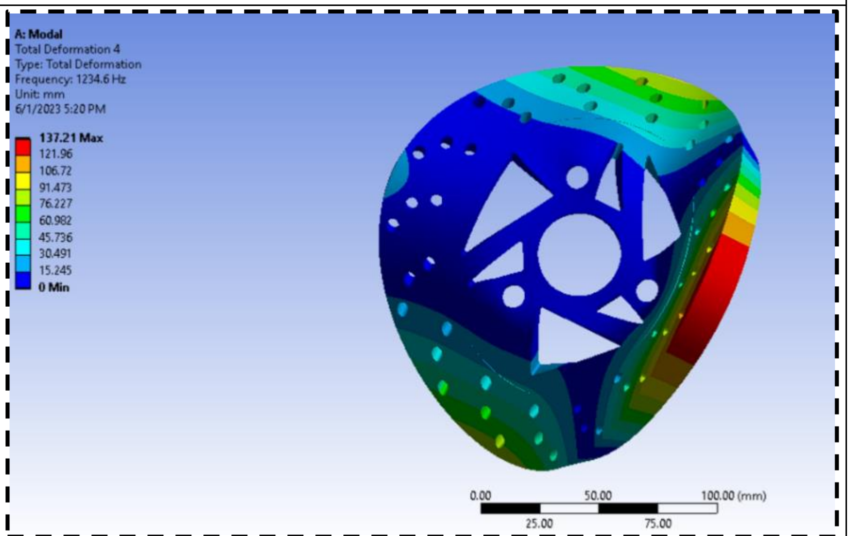
2.	701.89	
3.	829.73	
4.	1234.6	

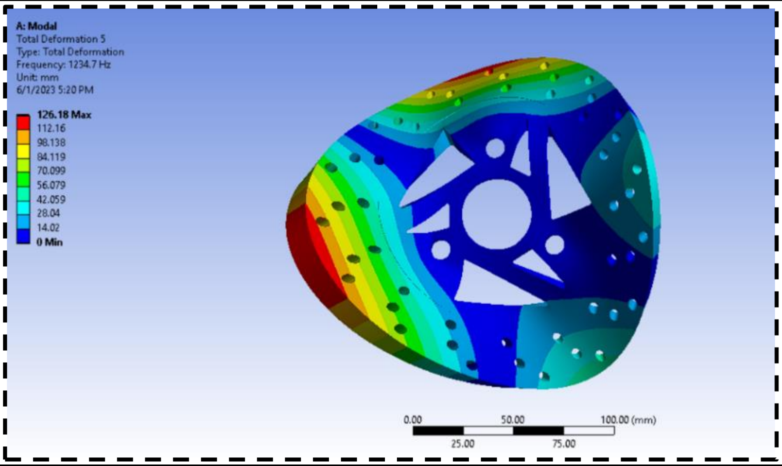
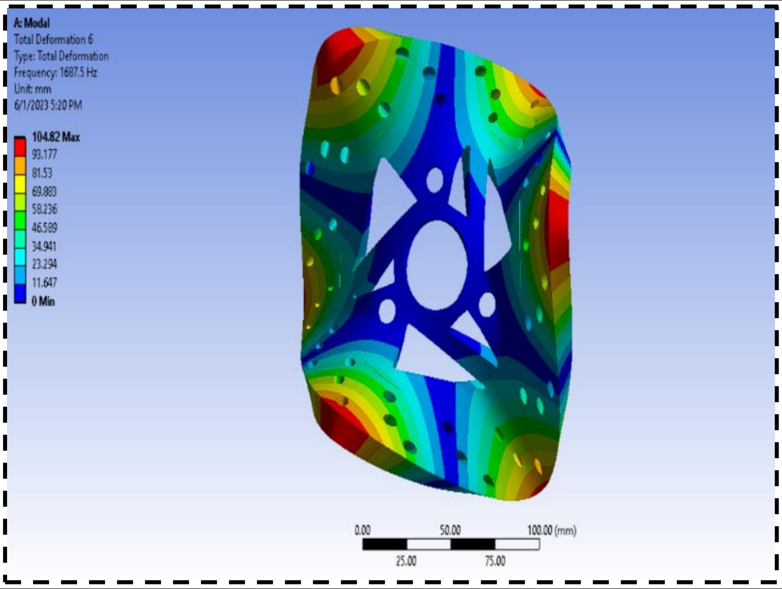
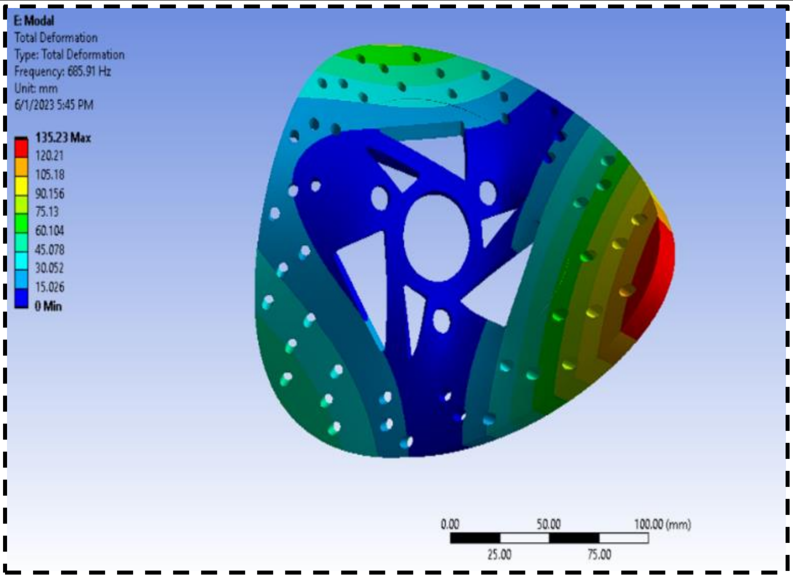
5.	1234.7	
6	1687.5	

Table 5. Result for model analysis for SS 304.

Mode shapes	Frequency	Mode analysis
1.	685.91	

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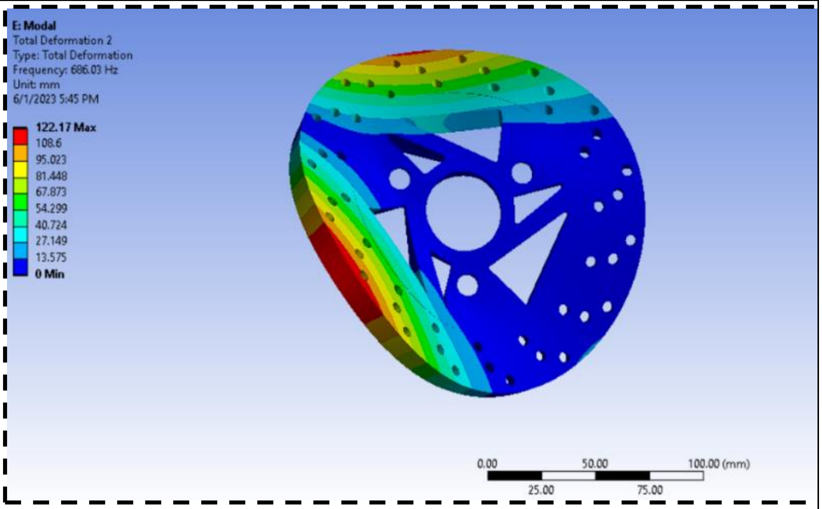
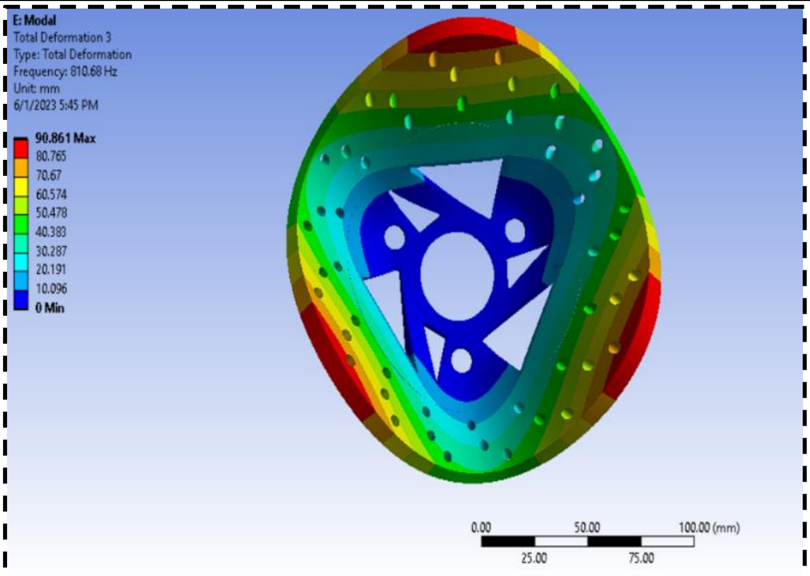
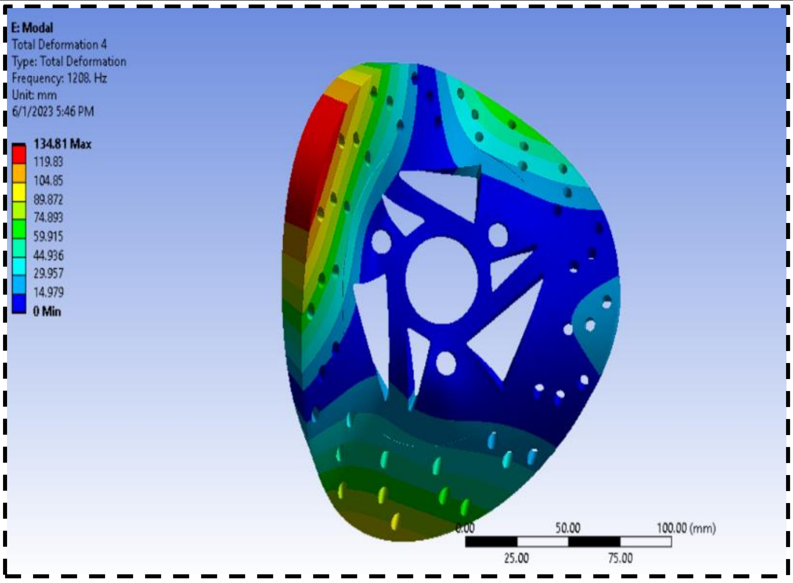
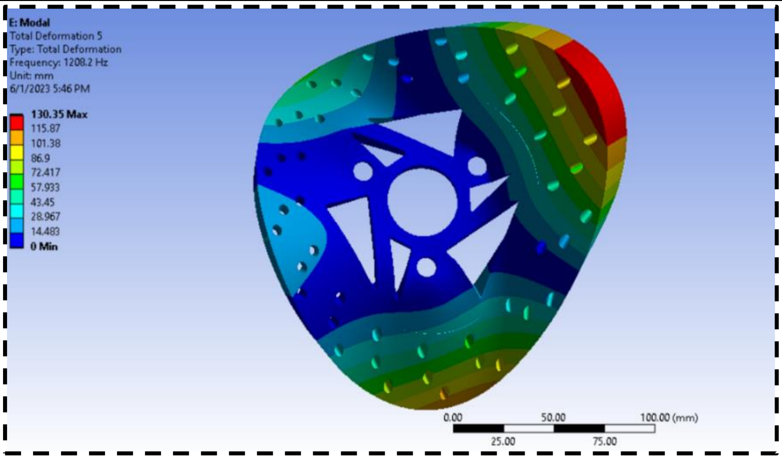
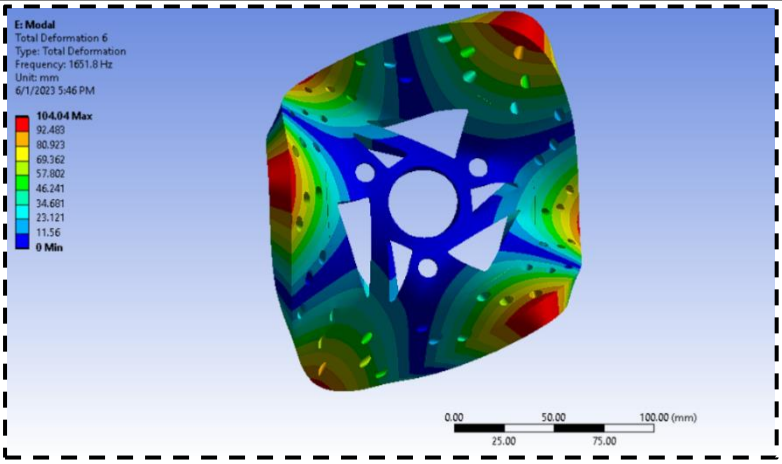
2.	686.03	
3.	810.68	
4.	1208	

5.	1208.2	
6.	1651.8	

CONCLUSIONS

1. The study conducted Transient Thermal analysis and Modal analysis in ANSYS Mechanical to analyse the temperature distribution and thermal behaviour of the brake disc during braking and natural frequencies.
2. The maximum temperatures of brake discs made of different stainless-steel grades (SS304, SS321, SS410, and SS310) were compared, and it was found that SS410 stainless steel discs exhibited lower maximum temperatures, indicating a reduced susceptibility to brake wear at high temperatures.
3. Comparing the heat flux from the analysis, SS410 emerged as the superior stainless-steel grade among SS310, SS321, SS410, and SS304. This suggests that SS410 is more effective at dissipating heat and maintaining lower temperatures during braking.
4. These findings provide valuable insights for optimizing brake disc design, enhancing braking performance, and reducing wear under high-temperature conditions.
5. Modal analysis of best two result i.e. SS410 and SS304 was analysed and found SS410 had higher value of natural frequency as compare to SS304, it means SS410 is stiffer and has a higher stiffness-to-mass ratio as compare to SS304. A higher natural frequency means that the material can vibrate at higher frequencies.

FUTURE SCOPE

- *Multi-physics analysis*: Modal analysis can be combined with other analysis techniques, such as structural, thermal, or acoustic analysis, to study the behaviour of SS410 components under various operating conditions. Investigating the interaction between different physical phenomena can provide a comprehensive understanding of the performance and reliability of SS410 as brake rotor.

- *Vibration control and optimization*: Modal analysis can guide the design and optimization of SS410 structures to mitigate unwanted vibrations. By identifying the critical modes and their frequencies, one can develop strategies to dampen or avoid resonance effects, leading to improved performance and longevity of SS410 brake disc.
- Modal analysis can support the development and optimization of Advance manufacturing technique, complex geometry can be manufactured. By analysing the dynamic behaviour, refinement in production techniques, improve material properties, and enhance the overall quality and performance of SS410 parts.

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