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***Application of Engineering Optimisation
Process on engineering***

By

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Abstract:

Using the solid works tool CAD modelling of the rotor, design is carried out and from analysis Gray cast iron material is used. This was theoretically investigated through the Cambridge Engineering Selector material selection tool based on a number of design requirements as highlighted under the material selection in the criteria section.

Using five designs, frequency analysis is carried out. Results, for plain rotor design mode shapes 9 and 10, showed frequency over 1000 Hertz, which indicates the possibility of squeal. Design modification is required in order to avoid such issues.

Thermal analysis for all the five designs were carried out, of which slotted cuts showed the lowest surface temperature, and this was closely identical to the results obtained by other researchers. Issues were noticed in the thermal analysis that showed negative values due to issues in the solid works tool. To prove this, a small cylinder was subjected to similar thermal loading, resulting in negative temperature.

More numbers of cuts were added on the rotor surface that showed high thermal build up in the sharp edges region. This further increased when more cuts were added, indicating there is a limit to which the surface area can be taken out, beyond which will have significant thermal stress leading to brake fade and inefficiency in the brake performance.

Results for both thermal and frequency is shown in the enclosed report and this includes mode shapes in all designs and for two different mesh sizes. Having a too large mesh size will result in unreliable results and this should be avoided. Choosing a reasonable mesh size is highly important due to a balance that needs to happen between the computation time consumed and the accuracy of the results.

Acknowledgements

I would like to begin with thanking the Government of Qatar for offering me the opportunity to continue my BEng. I would also like to thank my mother and brother for supporting my education. Finally, I would like to thank my supervisors, Kelvin Lake and Richard Morgan, for instructing me in this report.

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Glossary of terms:

CAD - Computer Aided Design – is a computer based modelling tool used to develop 3-dimensional parts and assemblies for visualisation purposes. It offers collision detection, which acts as critical information for robust design and detect early issues in design (Bilalis, 2000). Solid works' 2016 version is used in the enclosed report. The detailed drawing module allows the user to provide all the required information for successful manufacturing.

CAE - Computer Aided Engineering – allows the user to analyse the model for a particular load case. Number of types of simulation available in solid works such as flow simulation (external and internal), static stress analysis, non-linear analysis, thermal analysis, motion analysis (kinematics problems), frequency, fatigue, centrifugal and many more (ePlan, 2011). In this enclosed report, the author has considered frequency and thermal analysis (transient). CAE modelling has become an integral part of the modern-day design process, as this will allow to predict early failure based on the load inputs provided. It offers an opportunity to realise the possible areas of failure and hence re-design if needed for robust design (Joseph P. Elm & John E. Robert , 2003).

OEM – Original Equipment Manufacturer – are the companies who provide the end product. For example, ABC cars offers a car which has a number of parts and assemblies that are not essentially produced by them. The direct parts suppliers such as, engine suppliers and gearbox suppliers, are called Tier 1 suppliers to OEM. The brake assembly is provided to ABC cars by their Tier 1 suppliers (Elsa A. Olivetti, et al., n.d.).

PDP - Product Development Process – is a holistic approach taken for the design, development and validation of a design. Most commonly, this process will use a Product Design Specification (PDS) against which all the design activities, testing and validation occurs around it in order to meet it. The PDS is, however, the voice of customer transformed into technical language.

Reasons for and project relevancy:

Engineering analysis is widely applied in modern-day engineering to signoff a design that evolve from a product development process. Morris (2008) presented the below graph to explain the advantages CAE tools can bring to the product development process. The CAE tool will aim to engineer the product robustly by considering the customer requirements during the concept phase. This shift-left from the traditional engineering will enable the designers to develop a product that is fit for purpose and meet the Product Design Specification (Morris, 2008).

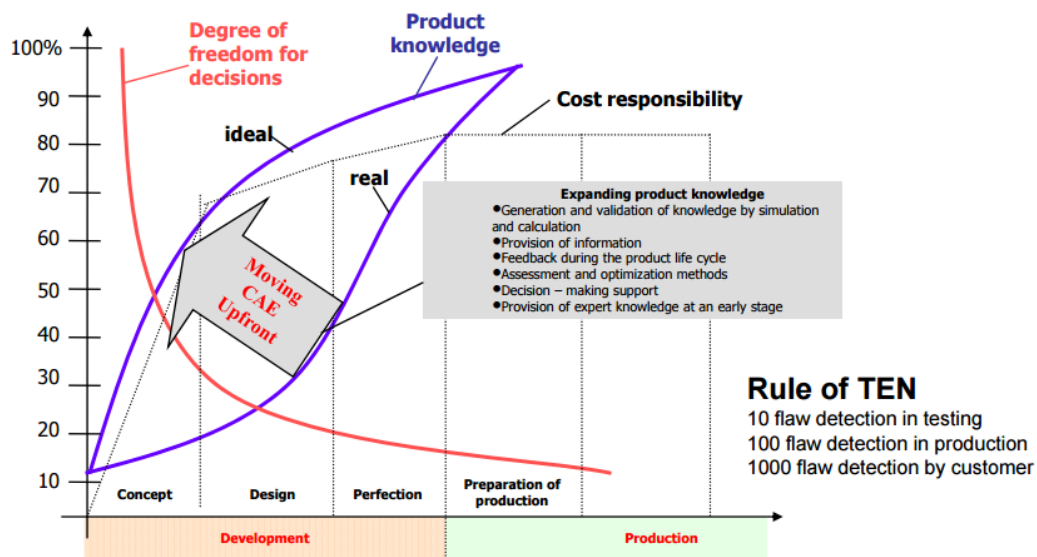


Figure 1. Using of CAE in early stages of product development (Morris, 2008)

Traditional engineering approaches consider longer lead time to engineer a product and is vastly due to the tools and techniques available. Virtual engineering has evolved rapidly over the last few decades that has the ability to mimic the real time operating conditions/environment to develop a robust design (G. Pahl & W. Beitz, 1984).

Aircraft, automotive, oil and gas, consumer products, industrial engineering and a number others are the front runners to effectively use such tools and techniques in order to develop a product. This has also set intense competition within the industry that has benefited the consumers to get the best product possible with significantly reduced cycle time (John R. Hauser & Ely Dahan, 2007).

Drivers/Targets	Current	2020	2025	2030	2040
Computer Power (Cals/Sec/\$1k)	10 ¹²	10 ¹⁴	10 ¹⁶	10 ¹⁸	10 ²¹
Vehicle Software Complexity	1x	10x	1000x	100,000x	10 ⁸ x
New Concept to Job 1		5 years	4 years	3 years	18 months
Proof of Concept to Job 1		4 years	3 years	2.5 years	12 months
Development costs (2015 Product)	100%	-25%	-50%	-75%	
Validation in Virtual Environment	<1%	20%	70%	90%	95%+

Figure 2 on going plan to improve software capability in virtual engineering (Jackson, 2016)

Jackson (2016) suggested the current ability of virtual engineering has enabled the car manufacturers to set intense competition. Meanwhile, there is ongoing work to further improve the ability of software as per the above figure. This will significantly reduce the time needed to bring a product to the market. This is the major breakthrough that has enabled design engineers to develop a product mostly based on virtual engineering and still make them fit for purpose, as well as, meet all the targets as per the Design Specification (Jackson, 2016).

The benefits of using engineering analysis does not supersede the traditional methods of testing and validation. Rather a modern approach is used to validate the design based on product design specification and working through it using computer based simulation programme (Marco Aurisicchio, et al., 2013).

These programmes are comprised of complex algorithms written as software coding that will analyse the product as similar to the way it is intended to perform in-service. Some simple designs will undergo engineering sign-off based on engineering simulations without the need of physical testing (P.G. Maropoulos & D. Ceglarek, 2010), however, some complex designs will still undergo physical testing before the sign-off. In either of the instances there are advantages and contributions to the overall product development process, such as, time and cost save alongside and, more importantly, enable engineers to predict engineering failures (Carlson, 2012).

For example, a consumer product such as, a handle of a tea kettle, can be analysed using simulation loads without the need for physical testing, as the operating conditions in this instance are straightforward and the likelihood of this changing is minimal. As long as the handle is able to withstand the maximum operating load along with sensible Factor of Safety, it will ensure no failure in service (Alan R. Parkinson, et al., 2013).

Another example is if a component like Engine Mounting system used in a car to reduce the noise, vibrations and harshness issues, will have a combination of rubber elements inside a metallic shroud that is complex to analyse using simulation methods or a

bush used in suspension is difficult to predict its behaviour using virtual tools (Joseph P. Elm & John E. Robert , 2003).

But the underpinning point of using engineering analysis either as an assembly or at a part level has proven to add significant value to the product development process. Any modelling software will break down the model into small element sizes and analyse them to the applied load. It has therefore become a practice across the industry in order to develop robust engineering solutions and ensure the consumers get the best value for this money (Joseph P. Elm & John E. Robert , 2003).

In this respect, the thesis will consider two types of engineering analysis to validate the design and compare them to real time results. Though the analysis is basic and simplified, due to hardware limitations and abilities of solid works tools, the work involves applying boundary conditions similar to the real time and understanding its ability to withstand the loads. From literature review work carried out, the results obtained from simulations are correlated to draw conclusions. The two-analysis included in this thesis are (i) Thermal analysis (ii) Frequency analysis. Both these results are compared and concluded that virtual engineering analysis can enable engineers to save significant time, cost and value to the product development process.

Therefore, there is a strong relevancy for engineering companies to invest in virtual tools for robust engineering. Companies such as, Mercedes, BMW, Jaguar Land Rover and Tesla, within automotive applications are heavily relying on virtual engineering and simulation analysis, as this has enabled them to set tough competition in the market, yet meet customer needs (Kojima, 2000). The benefits are just limited to cost and saving time, however, significant reduction is product development process (Lasse Christoffersen, et al., 2009).

Reason for choosing the topic:

The author of this report is intended to take up a position in the industry related to product development, where the job heavily involve design optimisation (ALI BELHOCINE & MOSTEFA BOUCHETARA, 2015). Any perquisite knowledge on how engineering analysis and design optimisation work in the industry will be beneficial. Therefore, the design and optimisation of the brake rotor is expected to set platform for better a understanding at an academic level (Manjunath T V & Dr Suresh P M, 2013). This experience will enable the author to apply for job roles that involve the use of engineering simulation tools and optimising the design for a highly-engineered component.

Other reasons for choosing the topic is to establish the cost saving virtual tools that can add to the product development process, and recommend how industries can invest in their engineering team in developing skills and capabilities that can enable bringing products to the market compared to a conventional product development approach.

Furthermore, the author poses strong skills in CAD and CAE that will be applied on the chosen components to demonstrate the benefits of using these tools. Upon meeting the objectives, the plan is to provide a list of recommendations to companies who currently do not utilise CAD/CAE tools.

Conclusively, one of the reasons for choosing the project is to gain prior industry knowledge prior to choosing a job in this domain.

Project Relevancy:

The project aims to carry out engineering analysis and optimisation to demonstrate how virtual engineering have added value to the modern product development process. Industries have achieved cost and time saving as a result. From consumer goods to aviation, there has been unique advantages the CAE tools has offered. Therefore, optimisation has become an integral part of the product development process.

The report considers automotive brake rotor into consideration for design and optimisation and this is accomplished by understanding the operating conditions and applying the principles to understand the component design requirements. Upon successfully completing the design, CAD modelling is carried out to be followed by applying loads on the brake rotor to validate the initial design is fit for purpose and seek opportunities to optimise the design that can result in weight saving without compromise in product durability (i.e. Fatigue and Strength).

In order to measure if the component is fit for service, “component target” is defined and this is based on minimum 2 Factor of Safety. The number of other requirements such as, manufacturing process, minimum radius, material elongation, etc. that contribute to

component durability is considered. The overall design optimisation process is then aimed to meet the targets, which will ensure the component is fit for purpose and is also designed to meet packaging requirements.

In order to achieve the above, literature review section of the report will carry out secondary research to establish the in-service loading conditions that is then transformed into Product Design Specification.

Project aims:

The project aims to achieve the below,

1. Literature review on engineering analysis and its significance on product development process
2. Background research on CAD/CAE tools' utilisation in engineering applications
3. Apply engineering analysis on an automobile Disc Brake Rotor
4. Demonstrate weight save based on the results obtained from engineering analysis
5. Provide recommendations based on the findings from the investigation obtained via the optimisation process
6. Technical report compilation and presentation of CAE results obtained from the investigation and presentation

The above aims and objectives are set in order to follow industry standard process of design and validation of a component. Most brake rotors are commonly analysed for thermal analysis and frequency studies. They are essential to understand if the brake rotor is capable of withstanding the Kinetic Energy of the system and also be able to work within the acceptable frequency range. Since the vehicle power transmission and wheels have certain frequencies, the design of the brake rotor frequency becomes an important consideration.

In this respect, the CAE analysis tool (Solid works Simulation) plays a major role in the modern-day engineering of components. Its benefits extend in saving cost, weight and time consumed to engineer a product.

The thesis offers an opportunity to explore some of the challenges that posed while carrying out CAE analysis. This is mainly due to the number of factors such as, mesh size, ways in which boundary conditions applied, complexity of the geometry and some particular features that oppose for meshing. Hence, unrealistic results are possible.

Therefore, the literature review play a role in comparing the results obtained in this thesis allows comparison with other researchers that are carried out in the past.

Details and specifics of the above CAE issue is discussed in detail in the sections below.

Timing plan:

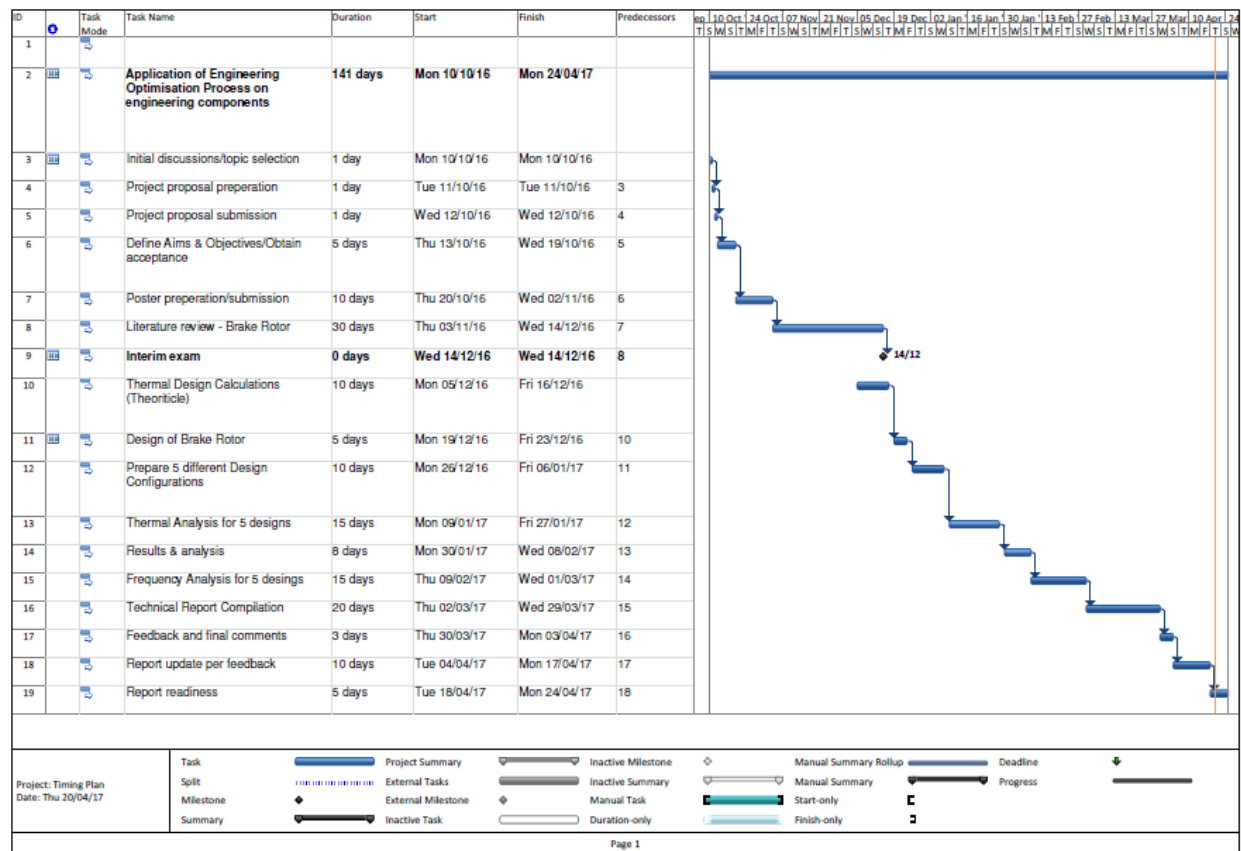


Figure 3. Project Timing Plan

Background:

Engineering optimisation, by definition, means providing appropriate inputs for an analysis model for an output as needed by engineers. Engineering models are often referred to as Analysis models. In order to make calculations, inputs are required where the inputs are called as analysis variables. The number of design variables along with quantities, contribute to analysis variables and they include material properties, boundary conditions (loading), operating environment, etc.

With all the required inputs, the analysis models will then compute the outputs called the analysis functions. The enclosed proposal will consider each of the chosen engineering components as analysis models and evaluate the output based on the analysis variables/inputs (Alan R. Parkinson, et al., 2013).

Though engineering optimisation has a long-lasting history, its application is finding extensive usage in the modern engineering era. Complex algorithms compute the outputs, however, it is important that the output is dependent on the user's inputs and the algorithms does not check for the accuracy of inputs. Though results obtained from CAE process can closely correlate to real time results, it is highly important that the inputs are accurate in the first place. It is therefore necessary for the user to fully understand the operating conditions, load acting methods, type of loads along with its magnitude and other operating environment that can influence the accuracy of the results. This includes thermal aspects, corrosive environment, etc.

Conventional engineering process involves developing prototypes specifically for testing purposes and design validation, which is time and cost consuming activity that could be replaced with CAE/virtual engineering analysis. Therefore, the main focus in this investigation is to establish and recommend how CAE techniques and design optimisation process can replace the use of physical testing methods in some of the specific applications. On the other hand, a number of OEMs rely on CAE to fully validate their products and they mainly include Powertrain and Chassis structural components such as, Engine Brackets, Sub-frames, etc.

However, it is important to note the virtual engineering methods does not supersede the conventional methods of testing in specific applications such as vehicle crash, aero engine turbine blade-off, etc. as they still need physical validations due to the nature of applications (Rao, 2009).

One of the ways to justify and to recommend the use of virtual engineering methods is by choosing components and validating them against the design requirements and by

meeting the required performance targets which is discussed more in detail in the main body of the technical report.

Tools and facilities requirement:

The author has categorised the tools and facilities below needed for the project.

1. Online resources: This includes journals, articles and published engineering optimisation papers by companies on specific components. Conference papers that discusses the significance on optimisation process in modern engineering. Published case studies also utilised during the literature review gathering process. This also includes eBooks.
2. CAD system: Upon choosing the most appropriate Solid works (latest version) is utilised to design/develop the parametric component.
3. CAE tool: Simulation Xpress module within Solid works is used to accomplish the CAE analysis required for the optimisation process.
4. Others: Other sources include online articles and consultancies who offer specialised engineering analysis work and YouTube videos that offer a background to CAE analysis.

Industrial partners:

The intended plan is to choose components that are used in the automotive domain, therefore, the plan is to approach OEMs who are involved in designing and developing those components. One of the companies planned to approach is Jaguar Land Rover Ltd. in the West Midlands as they are heavily involved in using virtual tools to engineer their components.

An alternative plan is to identify an engineering consultancy who is engaged only in component analysis, as this will enable better understanding in terms of product in-service loading and failure modes. Using such information, the optimisation can be carried out more robustly.

Chapter 1 - Methodology:

Figure 4 shows the project methodology before a final design of optimised brake rotor is obtained. The literature review forms the basis of the thesis as number of secondary design data and previous studies will assist to carryout initial design. Once the required data is gathered, CES material selection tool is used to choose appropriate material that is suitable to meet the component target along with satisfying the component level and system level targets.

Two main analysis are considered in the enclosed report: (i) Thermal analysis (ii) Frequency analysis.

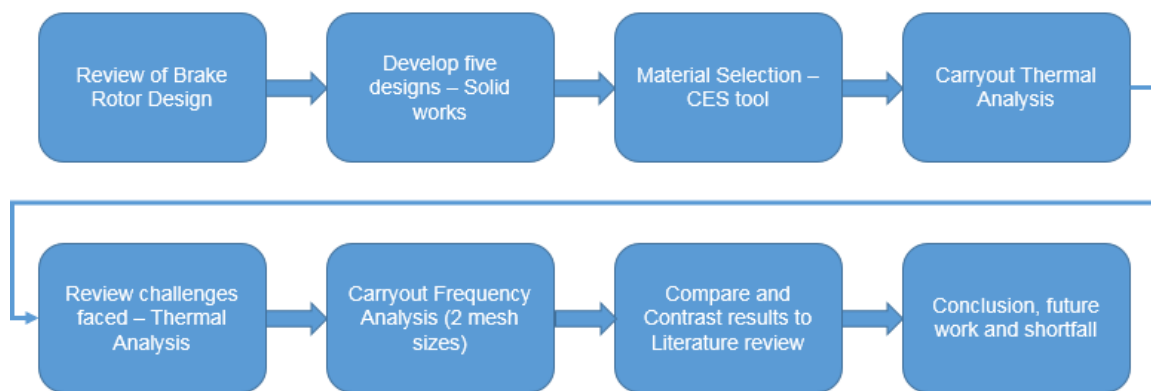


Figure 4. Project Methodology

Thermal analysis is accomplished by considering basic heat transfer equations followed by component modelling in Solid works and applying relevant boundary conditions to mimic the real time working of the brake rotor. The key focus is to establish the absolute maximum temperature from the rotor and compare with previous reviews conducted by other researchers.

The frequency analysis is carried out for two different mesh sizes for all the five designs due to the great differences in the results seen between 1.67mm and 5mm mesh sizes.

In particular, the frequency analysis is aimed to understand the operating frequency of brake rotor when compared to other rotational parts in the vehicle.

The proposed methodology will enable to finally develop an optimised brake rotor that is fit for purpose and cost effective yet meets the targets. This is accomplished by the use of the FEA method and comparing the obtained results to that obtained by other researchers.

Chapter 2 - Literature review:

For a road vehicle, whether it is for individual use or for commercial use, braking system is required to control the powertrain system to accelerate and decelerate in order to maintain the speed (Swapnil R. Abhang & D.P.Bhaskar, 2014). The braking system in the 21st century has mainly advanced in three disciplines.

First, Material Science and engineering has offered technologically advanced engineering friction couples that is at the heart of the braking system). These friction couples provide efficient friction forces that is required for most efficient stopping distances under the most arduous conditions where the thermal loading in such environments are in excess of 800 degree centigrade (A.A. Adebisi, et al., 2011). These materials also offer a good recycling ability, as they are mostly made from scrap iron. Friction materials are also naturally occurring mineral fibres and friction modifiers, which can together be recycled with less contribution to environmental issues (G. Cueva, et al., 2003).

Second, advanced mechanical engineering design methods have offered benefits from designing robust and high-strength braking systems that can be optimised in order to deliver the best performance to suit the consistent and controllable braking forces and torque to a wide range of user operating conditions (Manjunath T V & Dr Suresh P M, 2013).

Coupled with this is the advanced CAD and CAE techniques allowed to investigate on stress concentration identification and structural strength failure analysis. Advances in design have been possible through advanced modelling and simulation techniques that led to the ventilated disc brakes and sliding callipers (Munisamy, 2008).

Third, the integration of mechanical systems with electronic control of braking systems and its components via software programming have benefited the road vehicles, and the industry has moved into an active vehicle safety area. Nearly 40 years ago, conventional anti-lock braking systems demonstrated the benefits of safety in braking systems by maintaining directional control while braking under heavy deceleration (Siva Teja Golla, et al., 2012). This led to the development of intelligent control of braking systems, as this offers controlled braking such as, offering traction control, reduction of wheel spin and ability of maximising brake torque based on the adhesion conditions for each type based on the road surface conditions and especially in hazardous manoeuvres (Day, 2014).

Any road vehicle is subjected to extensive legislation standards in every part of the world. European Law states every road vehicle shall have a working braking system that meet legislation requirements along with meeting service and secondary braking systems as this will enable to bring the vehicle to rest even in events when one of the parts within the

braking system has failed (Pillath, 2016). Furthermore, the parking brake should hold the vehicle safely in an incline (RSA, 2017).

Literature review on brake rotor is aimed to carry out specific areas of research that will provide an in-depth understanding in the component operating environment, system level and component level loading, and both system level and component level design requirements. These areas of research are outlined in the below sections under relevant sub-chapters within the literature review. The idea of carrying out research in the areas mentioned is to set the basic framework for the brake rotor on which engineering optimisation is carried out. The main areas of research required for the component design include (i) Design considerations for Brake Rotor (ii) Component level loading and constraints (iii) Structural response (iv) Previous failure and failure modes.

2.1 Design considerations on brake rotor/disc:

Before the design aspects of brake rotor is considered, it is relevant to develop an understanding on the history of braking systems and this is accomplished by considering the fundamentals of brake discs and this is based on physics (Newton laws). As per the law, it suggests that when a car brakes and slows down, the kinetic energy of the car is transferred into heat energy. The amount of energy that is lost is a dependant factor of Frictional Force (F) and also the distance of frictional force acting. This is called, Work done, and given by the below equation.

$$\text{Work Done} = \text{Frictional Force} \times \text{Distance} \text{ (Craddock, 2015)}$$

An illustration of brake disc rotor is shown in Figure 5.

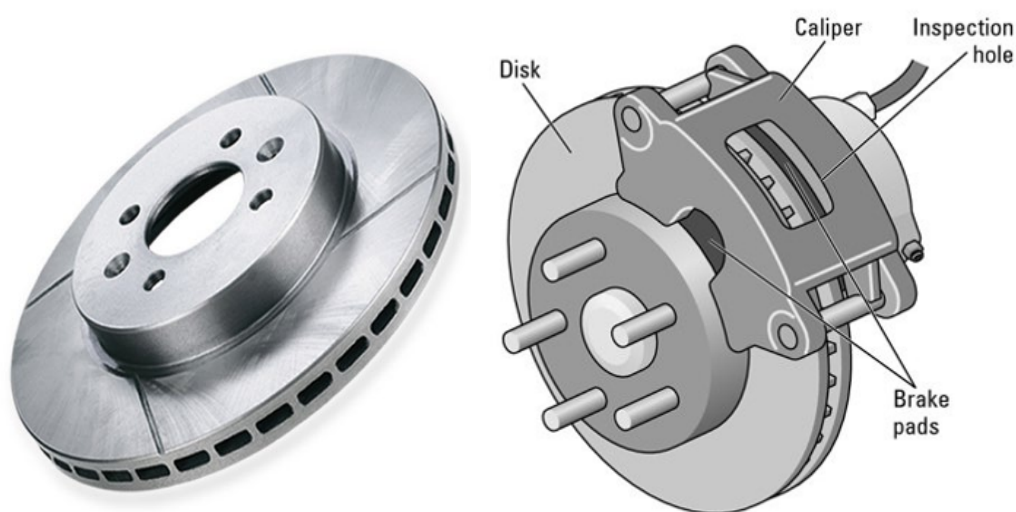


Figure 5. Brake Disc Rotor (Adbbrakes, 2016)

The fundamental purpose of brakes is to stop the vehicle from a certain velocity and this is done by a "foundation brake" (Day, 2014). Automotive foundation brakes can be classified into two distinct types (i) Drum Brake- here the stators are brake shoes that are fitted with frictional lining, expanded towards to press against the rotor inner surface as similar to the form of brake drum. In the disc brake the brake pads are the stators that are clamped on the rotor outer surface.

Design of the current rotor

Drilled rotors consist of lateral holes drilled on the rotor surface as shown below. This will allow the heat to 'escape' as thermal build-up will lead to brake fading. The heat is a result of friction generated between the brake pads and rotor.



Figure 6. Type of Brake Rotor Designs

Any foreign substances such as, dirt ingress, will result in poor braking performance and affect the stopping power. These holes will provide a means for mud or water and will be removed from the brake pad interface area. The most common used rotor designs are shown below in Figure 7 shows a Drum brake and Disc brake.

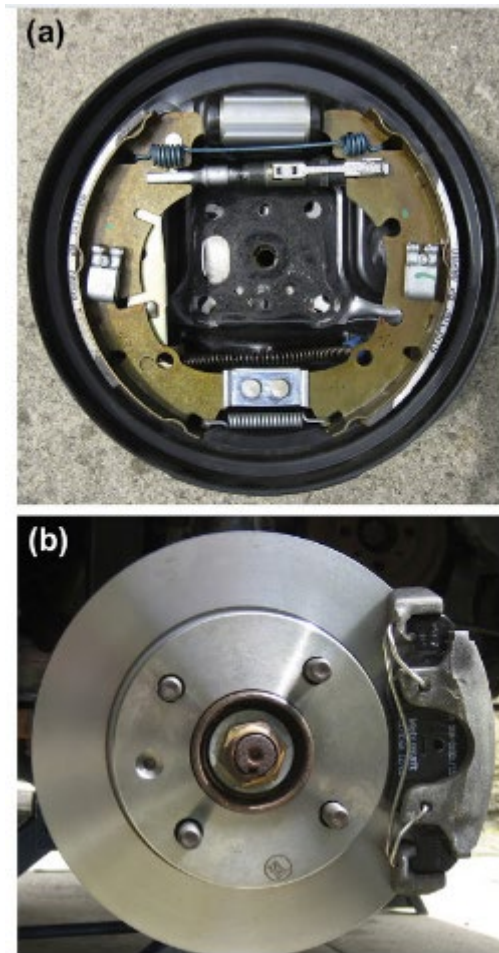


Figure 7. Internal component of (a) Drum brake and (b) Disc brake (Day, 2014)

Furthermore, the foundation brake also consists of a torque plate that is bolted to either steering knuckle or axle. This mechanism will provide the force via the actuation system, which is then applied to the brake pads. The brake actuation system comprises of three types of components: (i) Electrical (ii) Mechanical (iii) Electronic components. These components will recognise the driver braking behaviour via the pedal force that is applied to control the vehicle speed (Gritt, 2012).

They provide the unbalanced forces by generating torque (retarding torque), which is to apply the force at the tire to the road interface. The fundamental design of foundation brakes is based on Newton's first, second and third laws of physics. The Law of Thermodynamics dictates that energy can neither be created nor be destroyed, but it can only be converted or transferred (Baskara Sethupathi P, et al., 2015).

Heat transfer in brake rotor occurs in two ways: (i) Conduction (ii) Convection.

2.2.1 Conduction heat transfer:

The governing equation for Conduction is given by Fourier's Law of Heat Conduction. This is expressed as heat flow per unit area which is proportional to the temperature gradient. The equation is given by,

$$q = \frac{-kA\partial T}{\partial X}$$

q is the heat flux that is perpendicular to the surface area (denoted by A)

A is the surface area where the heat flow occurs during braking (m^2)

k is the thermal conductivity of the material ($W/m - k$)

T is the temperature ($^{\circ}C$)

x is the perpendicular distance to the rotor surface where the heat flux has travelled

The basic thermal equation that is applicable for Brake rotor is given by,

2.2.2 Convection heat transfer:

$$E = \frac{\sigma}{e}$$

Where's

E is the Young's modulus of the material

e is the material Strain

σ is the Stress

$$e = A \times dT$$

$$\sigma = e \times E$$

$$\sigma = A \times E \times dT \text{ (Paul Kendall \& Alex Perez, 2016)}$$

To move the vehicle, we use some of the energy in the fuel into Kinetic energy with the aid of power train system (Limberg, 2014). To stop the vehicle, the kinetic energy is converted into heat energy during braking. Therefore, this will enable us to define two major functions of braking systems: (i) To generate torque (ii) To convert and transfer energy (Limberg, 2014).

The brakes were originally invented during the Roman Times and developed over a period of time. It was in 1966 that the trend for disc brakes started on several high-performance

vehicles. The higher level of braking performance was specified in the 1976 revision of FMVSS 105 (stopping distance requirement). The system level brake assembly illustration is shown in Figure 8.

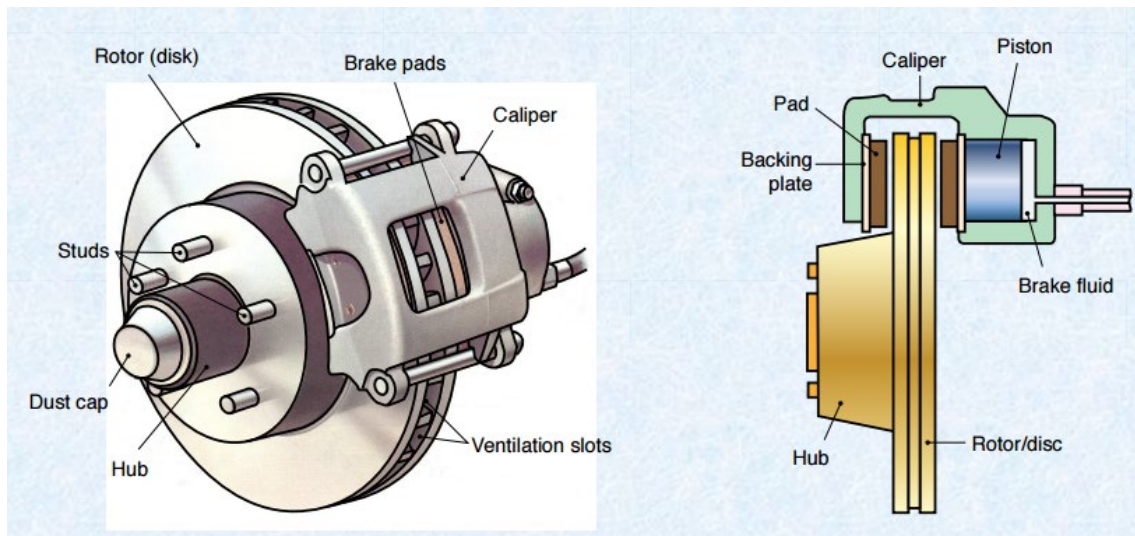


Figure 8. Brake Assembly illustration (Hamrock & Jacobson, 2014)

The rotor/disc within the brake assembly undergo compressive stresses due to applied brakes and results in converting kinetic energy into heat energy. The term friction plays a major role in designing the disc in particular such as, (i) Surface Finish (ii) Friction material (iii) Heat effects. Brake Fade is often very common within the passenger car brakes - the tendency of repeated high energy stops, which tend to cause overheat and lost braking effectiveness, can lead to fail (Greibe, 2007).

This is possible when the rotors are forced to absorb heat generated from braking than they can dissipate. The design intent of the swept area on the disc is to provide friction surface for the linings to rub against and can create friction together. The friction that is created at the interface of the lining and the disc is responsible for vehicle stopping.

From the above research, the fundamental design parameters that will need considering on brake rotor are: (i) Creating good friction surface on the disc swept area (ii) Manufacturing material that is capable of excellent heat dissipation (iii) Material and geometry capable of taking compressive stresses due to braking events/Brake Fade (iv) Tolerances on the disc surface/swept area (Limberg, 2014).

2.2 Loading and constraints:

Brake rotors undergo a wide range of loading during its operation such as, rubbing force due to deceleration, thermal stresses as a result of braking events, compressive load, etc. However, the most critical type of load on the rotor is the thermal stress, which causes the material to expand, wear, develop cracks due to surface imperfections, etc. The surface temperature of the brake rotor depends on the ability of thermal conductivity of the material used. Due to the nature of the brake disc operation, the component is also subjected to fatigue, which develops cyclic stresses in the material which lead to fatigue failure. This, in turn, influences the fatigue characteristics of the material (Koetnuyom, 2000).

2.3 Structural response:

The most important factor to recognise with braking rotors is friction. A vehicle in motion has a certain amount of kinetic energy. We need to remove this energy in order stop the vehicle and, therefore, use brake pads. This is where the friction is introduced and, as we know, energy cannot be created nor destroyed and in this case, it is converted into heat. It is then vital that the materials used can withstand this diffusion and parameters surrounding it.

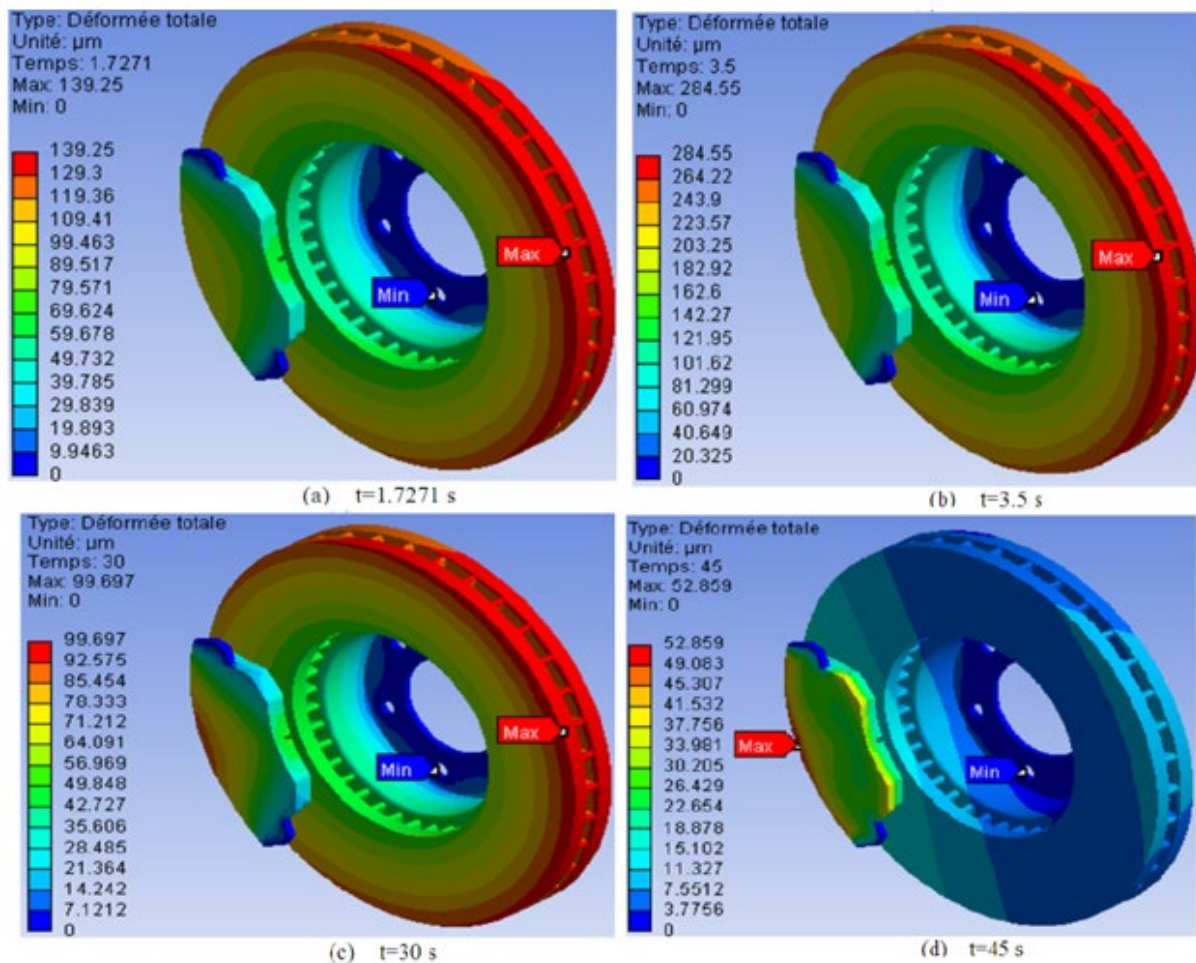


Figure 9. Transient Structural Response illustration (Baskara Sethupathi P, et al., 2015)

Brake squeal is one of the complicated dynamic problem the automotive industry has been living with. The result of brake squeal has resulted in warranty costs on the brake manufacturers and this needs to be reduced to an extent. Damping is one of the most commonly used methods to reduce squeal noise. This damping material will be added as an additional layer on to the brake rotor (M. Triches Jr, et al., 2004).

Brake noises can be categorised into three ranges: (i) Low frequency noise, low frequency squeal (ii) Low frequency squeal (iii) High frequency squeal. Low frequency noise issues are associated with frequencies in the order 100 to 1000 Hz. Groan and brake moan noises are examples of such low frequency events. As a result, these types of problems are associated with energy that will be transmitted as vibration response via the brake assembly along with chassis components such as suspension.

Squeal problems in brakes occur particularly when the frequency is around 1000 Hz or when the system experiences high amplitude mechanical vibrations. Two theories define the reasons for brake squeal. Stick Slip is one of the phenomenon of this issue.

This theory suggests the squeal is due to self-excited vibration of brake system that is due to static friction co-efficient greater than sliding friction co-efficient and its relation is given by,

$$\frac{\delta f}{\delta V_r} < 0$$

Where's

f is the co-efficient of sliding friction

V_f is the relative sliding velocity

Sprag Slip is another theory that explains the brake squeal. It demonstrates the self-excited vibration of brake and high level of vibration due to improper selection of brake parameters. As the co-efficient of friction increases, the frequency of two system modes move close to each other (Hyeongill Lee & Rajendra Singh , 2003).

These frequencies that are close to each other will eventually overlap the mode shapes and thereby becoming unstable. During the squeal events, the brake system is unable to dissipate the friction forces into the system that will result in high level vibration amplitude (M. Triches Jr, et al., 2004).

There are mode shape differences between the low frequency and high frequency squeals. This results in the mode shapes differences in the modal coupling. For low frequency issues the modal coupling is when out-of-plane modes of brake rotor and due to brake pad bending modes.

High frequency squeal is due to in-plane modes of rotor. This coupling of modes is shown in the figure 10.

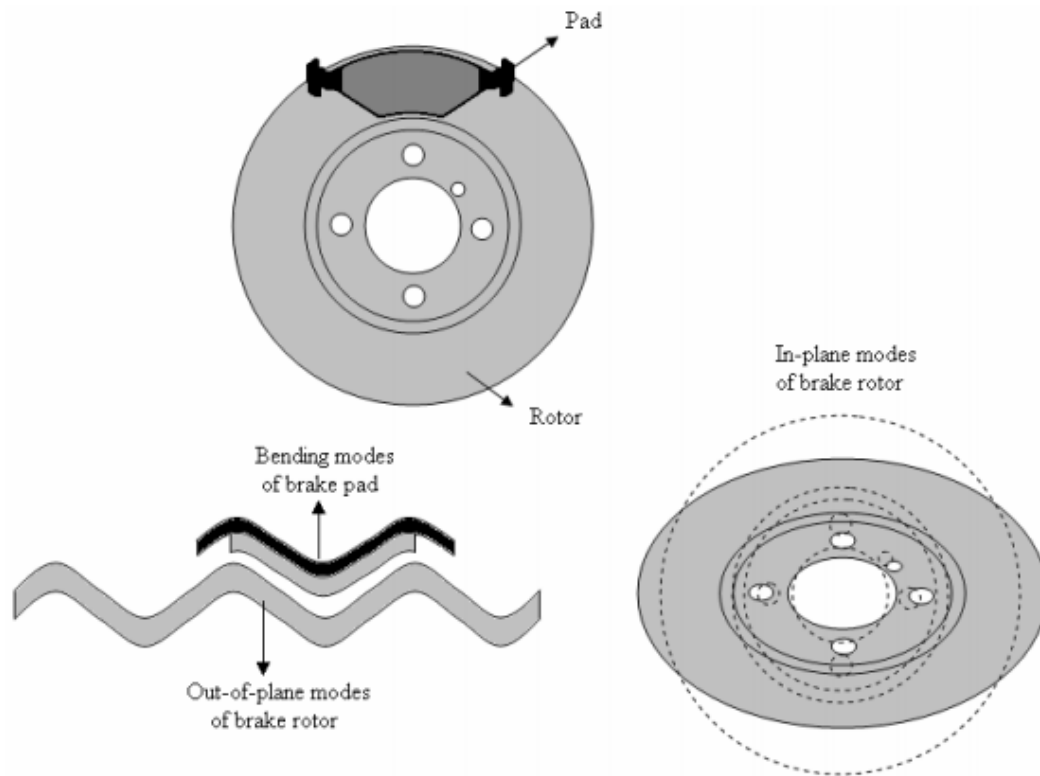


Figure 10

The rotor has the highest stiffness in the in-plane direction as opposed to out-of-plane. Hence, the resonance frequencies in the in-plane is higher than out-of-plane. High frequency squeal occurs between 8 to 16 kHz, whereas low frequency squeal occurs between 1 to 7 kHz. But as the human ear is most sensitive to the low frequency, it is considered as undesirable and the most annoying type of brake noise. This needs to be eliminated in the design (M. Triches Jr, et al., 2004).

Figure 11 shows the modal parameters obtained for Brake rotor,

Vibration Mode	Resonance Frequency (Hz)	Mode shape	Damping Loss Factor (%)
1	1090	2 nd bending	0.247
3	2210	3 rd bending	0.128
6	3600	4 th bending	0.108
10	5320	5 th bending	0.130
13	7320	6 th bending	0.176

Figure 11. Brake Rotor Modal Parameters (M. Triches Jr, et al., 2004)

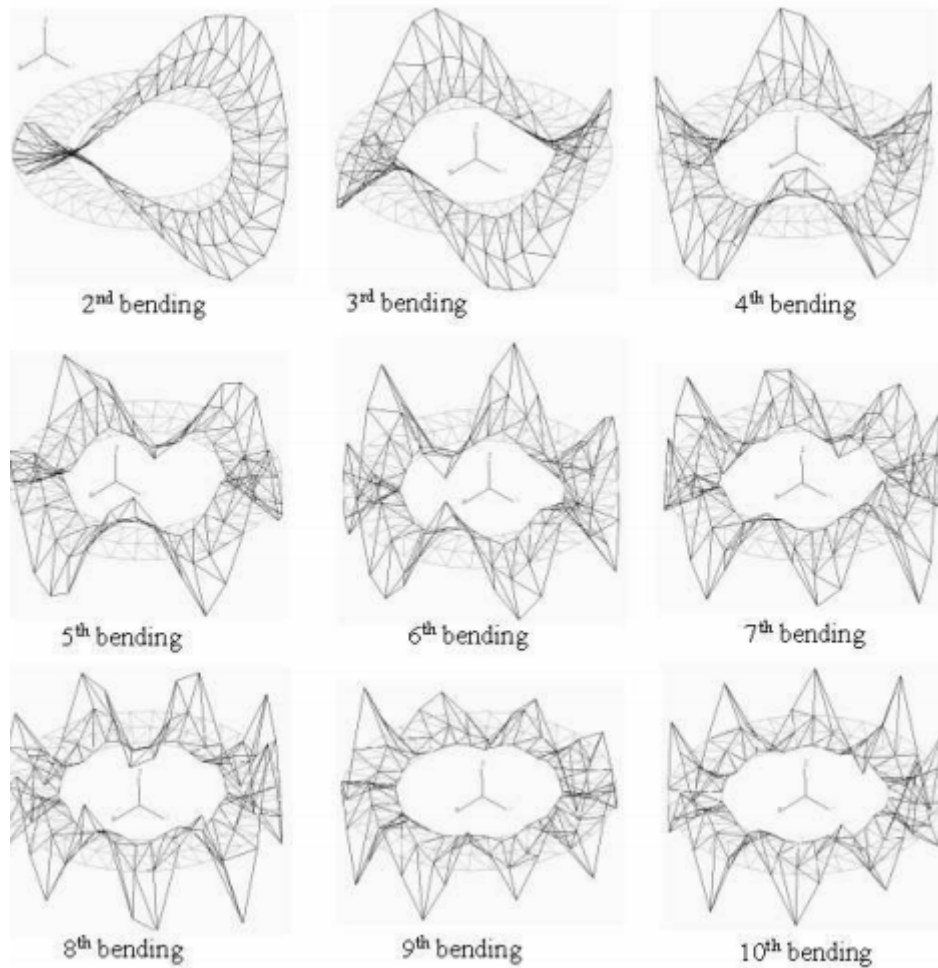


Figure 12. Mode Shapes (M. Triches Jr, et al., 2004)

Therefore, it is important to consider the structural response of the brake system in order to avoid the undesirable noise that is sensitive to human ears. To avoid this squeal noise, all the parts of the brake system such as, the pad and rotor, should not be designed to vibrate together and will create a coupled system mode. In phase vibration, when the components have same frequency and wavelength, they will have geometrical match. This scenario will minimise the friction damping and will behave as a loud speaker, thus radiating noise.

2.4 Manufacturing process and engineering materials:

The first car was developed between 1890 and 1895 by Karl Benz, F.W. Lanchester, Albert de Dion and Georges Bouton and it was in 1902 when Lanchester submitted patent for disc brakes. Considerable technological development on brake was made by Herbert Frood who was also responsible for patenting the first patented abrasive material. Conventionally to achieve the stability in operation, cost effectiveness and for ease of production, Gray Cast Iron were extensively used (Ihm, 2012).

It was only high end applications such as, motorsport applications, aerospace, etc. used materials such as, carbon composites. Gray Cast Iron was extensively used for casting process and the cast tool were mostly grouped like in Figure 13. The casting process will always have machining allowance in order to achieve the surface finish that cannot be achieved by a casting tool. Pompon (1998) suggested that in order for the brake rotor to achieve the required hardness, composition and desired structure allowance is required as this could be achieved only at a certain depth from the surface. This means that a minimum of 25 percent is a standard practice, which will then achieve desired finish and strength after the machining operation.

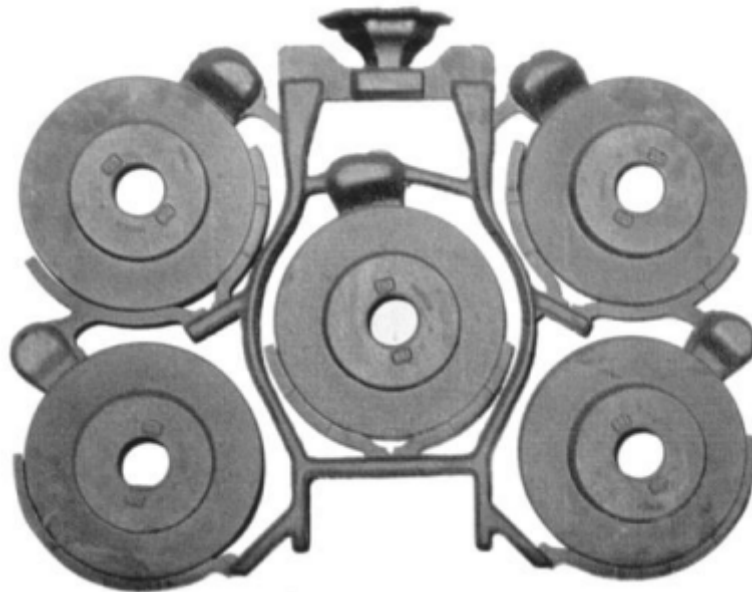


Figure 13. Casting Tool Design (WOLNY, R & RYGALLO, A, 2010)

2.5 Brake constrain method and loading:

Brake rotors are typically held into place by slotting the wheel nuts into the provided holes. They are then further constrained by bolts (numbers of bolts differ in each rotors). This ensures the disc does not move or become imbalanced. Vibrations or movements can cause many malfunctions for braking systems.

2.6 Previous studies and findings from previous studies:

Structural and thermal analysis is an ongoing study for brake discs. Given the gathered information, work is being done to try and incorporate all the pros to provide a better brake disc that can cope with the surge in vehicle technology. As vehicles become more advanced, we have seen an increase in their mass. Therefore, the braking system

is being asked to do more than it would and hence a better, cheaper disc is essential. Hybrid discs are being provided that include both drilled and slotted methods made of carbon ceramics. Unfortunately, these are very expensive and are limited to supercars and Formula One cars.

Other than material and surface altering, different methods are also being used and investigated for braking improvement. As noted, heat conductivity is important as it affects material behaviour – rather than using a material than has better thermal capacities, what is known as ‘vanes’ are implemented. These vanes located on the edges of the rotor promotes air flow and evens temperature across the surface area. This implementation reduces temperatures by about 100-150 degrees Fahrenheit.

2.7 Importance of previous studies:

Brake discs make up one component of a complex and important braking system. They are essential in vehicles today and are preferred over the old use of brake drums. Dynamically, the latest disc technology provides excellent stability and control which is crucial for safety. Other developments such as, Anti Braking Systems, have been introduced to better the dynamics; they are designed to keep the wheel of a vehicle moving whilst the brakes are applied rather than completely stopping them instantly which could cause unwanted skid.

Further research is to be carried out concerning these important components. An assessment of current designs will provide us with limitations which we can then use to propose a new design. The prime focus to achieving an improved brake rotor is material choice, geometry of the disc and method of loading/constraint. The use of the CAE software will enable us to conduct these thorough comparisons.

Chapter 3 – Design Calculations:

3.1 Quantifying a load case

In order to quantify the load case for a typical brake disc, we need to understand how much force a typical brake disc inherits from the brake pads. This determines the friction incurred onto the brake disc, which allows us to understand the thermal scenario. It is important to note that the force exerted onto brake discs differ vastly depending on the mass of the vehicle, the velocity at which the vehicle is moving, the distance at which the vehicle needs to be stopped and the age/quality/thickness of the brake pads, amongst other factors. For the sake of simplicity, we will disregard the effects that the brake pad thickness and quality have, and focus on the mechanical physics such as, velocity and displacement. These parameters will be taken at a common and likely scenario. Hence, we must satisfy the equation:

$$F = ma$$

Where:

F is Force (N)

m is Mass (kg)

a is Acceleration (m/s)

Our case will focus on the average car mass in the U.S., which is 3977lbs [$\sim 1800\text{kg}$] (United States Environmental Protection Agency, 2012). We must determine the deceleration of a typical car stopping scenario; we can find this deceleration by multiple different methods. However, before this, we must reasonably assume a speed at which the vehicle is travelling and the distance required to complete this stop. Therefore, based on the average free flow vehicle speed in the UK for roads at 30mph limits, the value is found to be 31mph in 2015 (Department for Transport, Free flow vehicle speed statistics, 2015). We will take an arbitrary value for the displacement, as there is no statistics given for the average distance. We will assume a scenario where 100m is the distance required to come to a complete stop. Finally, the essential parameters needed to work out the typical force exerted onto a brake disc are:

Mass

Velocity

Displacement

However, to satisfy the equation of force, we need to know the value of acceleration, or in this case deceleration. Using the kinetic formula:

$$V^2 = U^2 + 2as$$

Where:

V is Final velocity (as the objective is to bring the vehicle to stationary)

U is Initial velocity

S is Displacement

Therefore, the results are the force needed to bring a car to a halt travelling at 31mph within a distance of 100m. We must note that this is the total force, so we must divide this force between the 4 braking systems. Not all vehicles have 4 braking disc and pad systems; some opt for a two-brake drum and two-disc system. However, as we are dealing with brake disc/pads we shall assume a car that has an all disc/pad braking system.

In addition, to calculate the heat power, the kinetic energy formula is used:

$$KE = \frac{1}{2} m \times v^2$$

To calculate heat power, convert Joules to Watt. The heat power P in watt (W) is equal to the energy E in joules (J). Divided by the time period in seconds (s), our heat power is 4695 Watt.

$$\text{heat Power} = \frac{E}{t}$$

Forces acting on inner and outer faces of rotor due to contact with Brake Pads.

	Values	Units
Rotor outer diameter	0.345	mm
Rotor manufacturing material	Gray Cast Iron	-
Brake Pad area	6.05E-02	mm ²
Pad manufacturing material	Asbestos	-
Co-efficient of Friction (Wet)	0.07 to 0.13	-
Co-efficient of Friction (Dry)	0.3 to 0.5	-
Maximum Operating Temperature	400	°C
Maximum Pressure	1.00E+06	Mpa
Tangential Force between the Brake Pad and Rotor (Inner face)	-	-
$F_{Tr \text{ Inner}} = \mu \times 1 \times F_{R \text{ Inner}}$	-	-
$F_{Tr \text{ Inner}}$ is the Normal force between pad and brake rotor (inner)	-	-
μ_1 = Coefficient of friction	0.5	-
$F_{RI} = P_{\text{max}} / 2 \times A$ (Pad brake area)	-	-
$F_{Tr \text{ Inner}} = \mu \times 1 \times F_{RI}$	-	-
FTRI	15,119	N
Tangential Force between Pad and Rotor are the same due to same material and surface area.	-	-
Assuming same friction co-efficient and normal forces on inner and outer faces,	-	-

Brake Torque = $FT \times R$

Where, FT is total Brake Torque (Summation of Inner and Outer normal forces)		-
R = Radius of Rotor	0.173	m
FT = FT inner + FT Outer	30237.825	N
FT = $F_{Tr \text{ Inner}} + F_{Tr \text{ Outer}}$	5216.025	Nm

Brake Distance:

Using equation for Work Done - $FT \times X$		-
Where x is the brake distance in m or distance travelled by vehicle before it comes to rest		-
FT = FT Inner + FT Outer		-
Kinetic Energy = $\frac{1}{2} m \times v^2$		-
m = Vehicle mass	1,800	kg
v = Velocity	31.300	m/s
$FT \times x = \frac{1}{2} m \times v^2$	29.160	m

Gray Cast Iron - Rotor Material:

Heat Generated (Q)	$m \times C_p \times T$	J/s
--------------------	-------------------------	-----

m is vehicle mass	1800	kg
Flux (q)	Q/A	w/m ²
Thermal Gradient	q/k	k/m
Specific Heat Capacity	800	J/kg °C
Time taken Stopping the Vehicle	3	Seconds
Developed Temperature difference	15	°C
Heat Generated (Q)	21600000	Joules

Table 1. Design Calculations (Swapnil R. Abhang & D.P.Bhaskar, 2014) (Amrisha, 2016)

In order to carry out an FE analysis on any brake disc, we must quantify the rotational speed of the disc, as well as, knowing the force that is being applied to the disc. Setting the disc to rotate whilst the pads clamp down onto it will provide us with an accurate representation of the thermal/frictional behaviour. Finding the rotational velocity of the disc is then found by the following formula:

$$\omega = \frac{d\theta}{dt} = \frac{\theta}{t} = \frac{V}{r}$$

Where:

ω is Angular velocity (rads/s)

V is Linear velocity (m/s)

r is Radius of rotational path (m)

$\omega = 31.3/0.345=90.72$ rad/s (John Bird & Carl Ross, 2014)

Chapter 4 – Design and Analysis of brake rotor:

The designs and analysis will consider 2 types of simulations: (i) Thermal analysis (ii) Frequency analysis.

4.1 Material selection process:

Using the Cambridge Engineering Selector tool, material selection process is carried out for the brake rotor. Though research suggested that Cast Iron has been used historically, the CES tool should enable insight to the mechanical properties and other properties that will drive the performance of the brake rotor (M.A. Maleque, et al., 2010). The images below show the material selection criteria (Ashby, 2010).

Using Level 3 CES database, 5 candidate materials are identified. Using slope value of 1 non-ferrous material is eliminated by providing inputs such as, the Young's modulus, raw material price, thermal conductivity and recycling ability (Ashby, 2010). From the listed 5 ferrous metals, Cast Iron is the chosen option for the brake rotor based on its cost affectivity and its suitability for brake rotor application as listed in the application section within the CES tool results.

High temperatures and constant stress means that the materials used must be able to withstand such environments. They must be stiff, be able to hold a good surface, transfer heat without deforming as well as good strength.

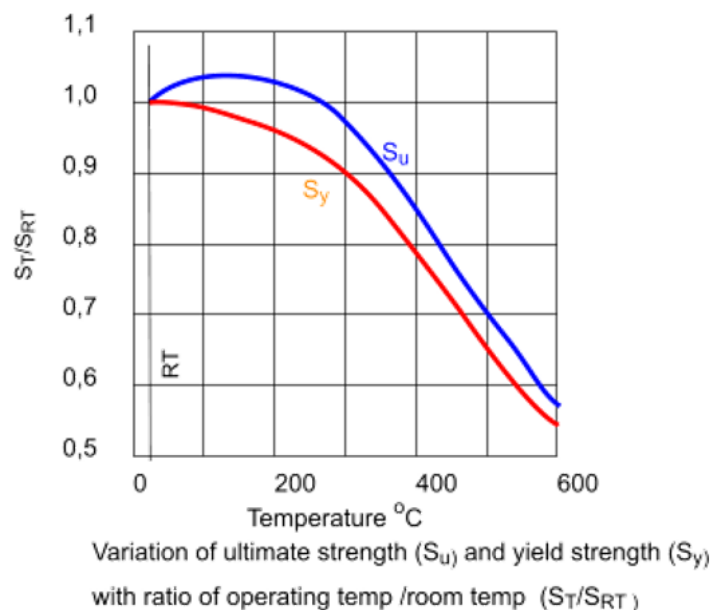


Figure 14. Material Behaviour due to Stress

The material selection is dependent on the following:

- Compressive strength
- Coefficient of friction
- Wear resistance
- Thermal conductivity
- Lightweight
- Cost

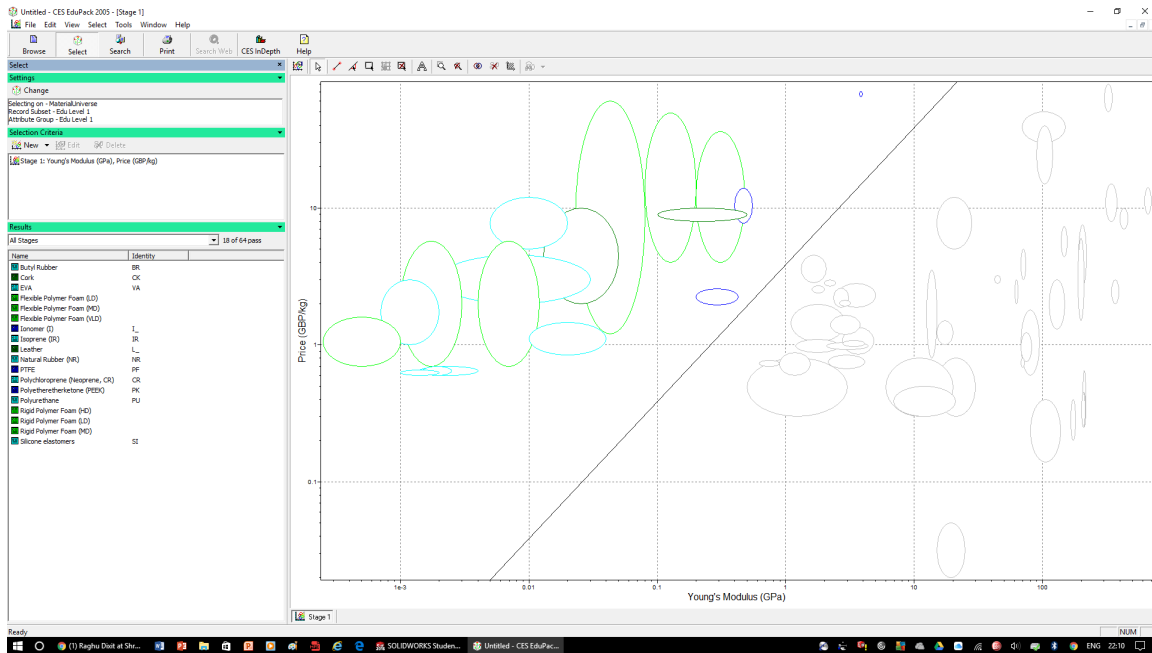


Figure 15. Stage 1 - Graph of Young's Modulus Vs Price (Ashby, 2010)

Figure 16. Stage 2 - Limit stage (Ashby, 2010)

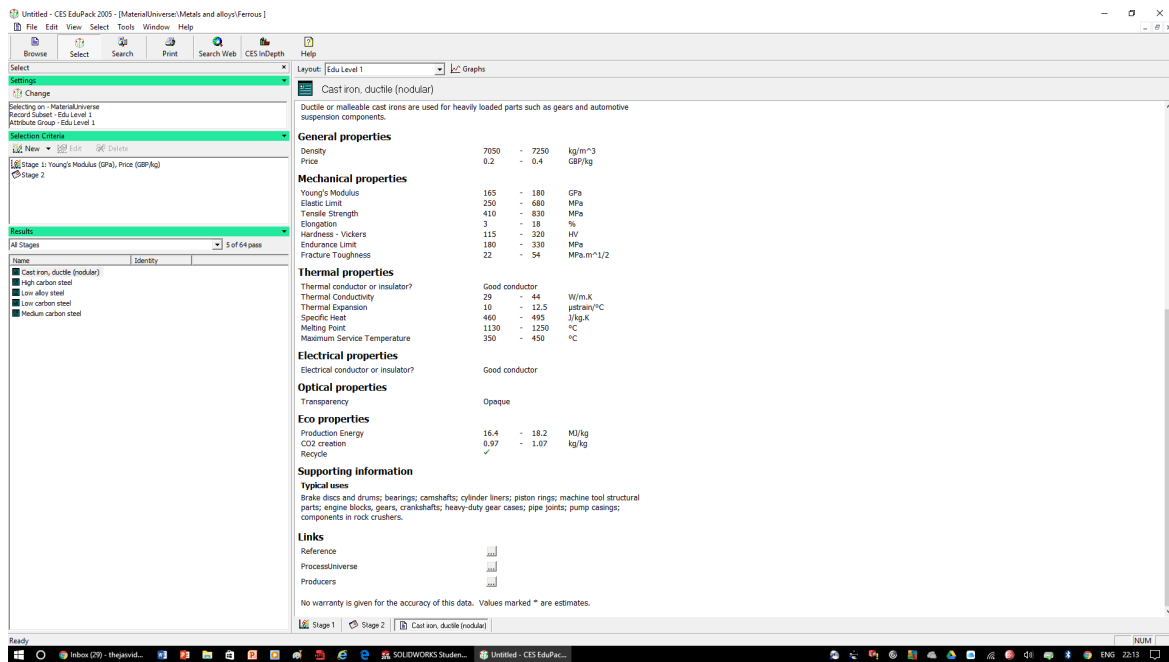


Figure 17. Cast Iron Mechanical Properties and its Applications (Ashby, 2010)

Weight – 1803.18 grams – Based on Solid works mass properties.



4.3 Thermal analysis:

Thermal analysis is carried out on the brake rotor with the below boundary conditions. Plots for five simplified designs are presented in the below section. The table below summarises the differences between the designs and is in line with the research carried out based on the market standard designs available.

Sl. No.	Description
Design 1	Plain Rotor (no features for cooling or ventilation, not very common design in the current trend, however seen on economical/small passenger cars where the mass of the vehicle is low and brakes does not undergo significant thermal loading)
Design 2	Drilled Holes – Drilled holes are most commonly seen designs to avoid gas trap, allow water trap when driven in puddles and finally to reduce the heat generation effects on braking performance issues.
Design 3	Slotted Cuts – Less surface area due to larger cuts which will improve the heat dissipation. Suitable for performance cars.
Design 4	Drilled Holes and Slotted Cuts – Used when more performance is needed, usually used on cars that has more mass (over 2000 kgs) and need good cooling/heat dissipation.
Design 5	Curved Slotted Cuts – Alternative design to straight slotted cuts, slightly larger surface area taken out from the rotor surface, better cooling.

Table 2. Designs Description Summery

The thermal analysis studies used the below boundary conditions for all the five different configurations.

Applying material to the rotor **Gray Cast Iron**.

Boundary conditions:

Convection = $90 \text{ w/m}^2 - k$. This is based on research for Gray Cast Iron. This is the material constant (Anon., 2017) .

The bulk ambient temperature: 293 Kelvin. For the brake rotor is set up.

Initial Temperature = 25° C. The initial temperature of the brake rotor is set to ambient

Heat power = 4695 w. (Calculation steps shown in earlier section under Design Calculations – Chapter 3)

Time Period = 3 s

Heat power is generated in the event of braking. The pedal force that is exerted by the user applied pressure at the brake pads and the rotor interface during the braking event. In this analysis, Transient analysis is carried out with braking time set to 3 seconds. Heat power is calculated by determining the Kinetic Energy of the car.

Figure 19 shows the mesh details applied to the brake rotor.

Mesh Details	
Study name	Thermal - Trail 1 Simplified (-Default-)
Mesh type	Solid Mesh
Mesher Used	Standard mesh
Automatic Transition	Off
Include Mesh Auto Loops	Off
Jacobian points	4 points
Element size	10.4984 mm
Tolerance	0.524918 mm
Mesh quality	High
Total nodes	23973
Total elements	13870
Maximum Aspect Ratio	12.189
Percentage of elements with Aspect Ratio < 3	92.4
Percentage of elements with Aspect Ratio > 10	0.0216
% of distorted elements (Jacobian)	0
Time to complete mesh(hh:mm:ss)	00:00:02

Figure 19. Mesh Details (Kurowski, 2015)

4.4 Design 1 – Simplified Rotor:

The thermal plot shown below for the simplified design shows a peak temperature of 395.32°C in the interface where the brake pads rub against the rotor surface. This is the amount of heat generated during the braking event from an initial 25°C to 395.32°C in a time span of 3 seconds.

The transient analysis has considered a number of factors into consideration such as, the brake material, material properties, the braking time and surface area on the rotor. This value correlates to the previously carried out research by other researchers. Work carried out by (A. Belhocine & M Bouchetara, 2017) on a plain brake rotor made from Gray Cast Iron (FG15 Grade) showed a peak operating temperature of 401.55°C during 1.88 seconds of the total braking time. Evidence of this result is shown in Figure 20.

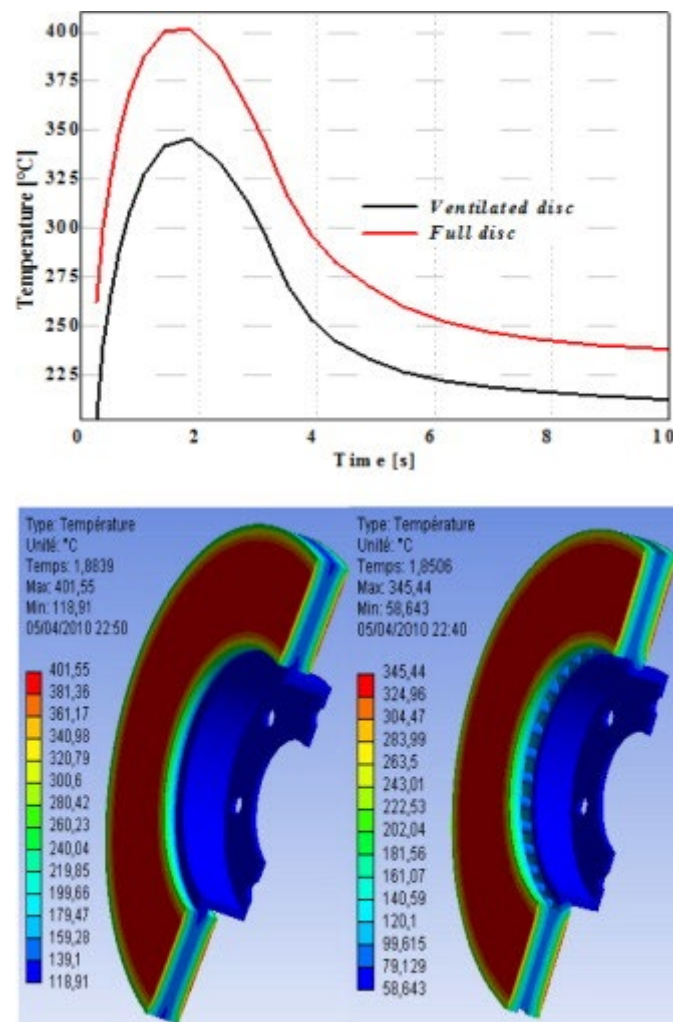


Figure 20. Plain Rotor Peak Operating Temperature (A. Belhocine & M Bouchetara, 2017)

The minimum temperature seen in the analysis 120°C can be compared against the 118.91°C seen from the results presented by other researchers. Therefore, the variation in results are closely correlated to each other. On this basis, thermal analysis for rest of the design configurations are carried out. Plots are presented below.

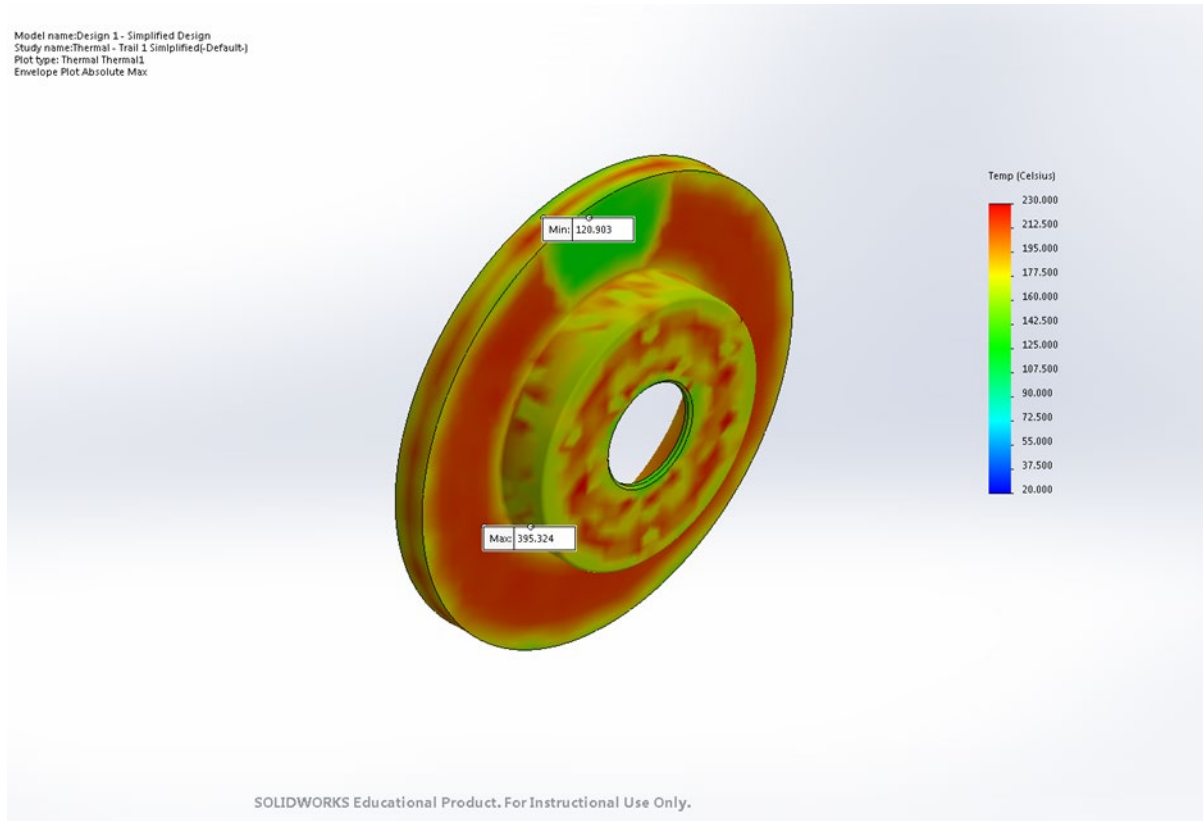


Figure 21. Thermal Plot - Simplified Rotor (Ch.V.Sushma, et al., 2015)

4.5 Design 2 – Drilled Holes

Similar boundary conditions as per Design 1. Plot shows the peak temperature of 401.19°C and minimum 117.41°C.

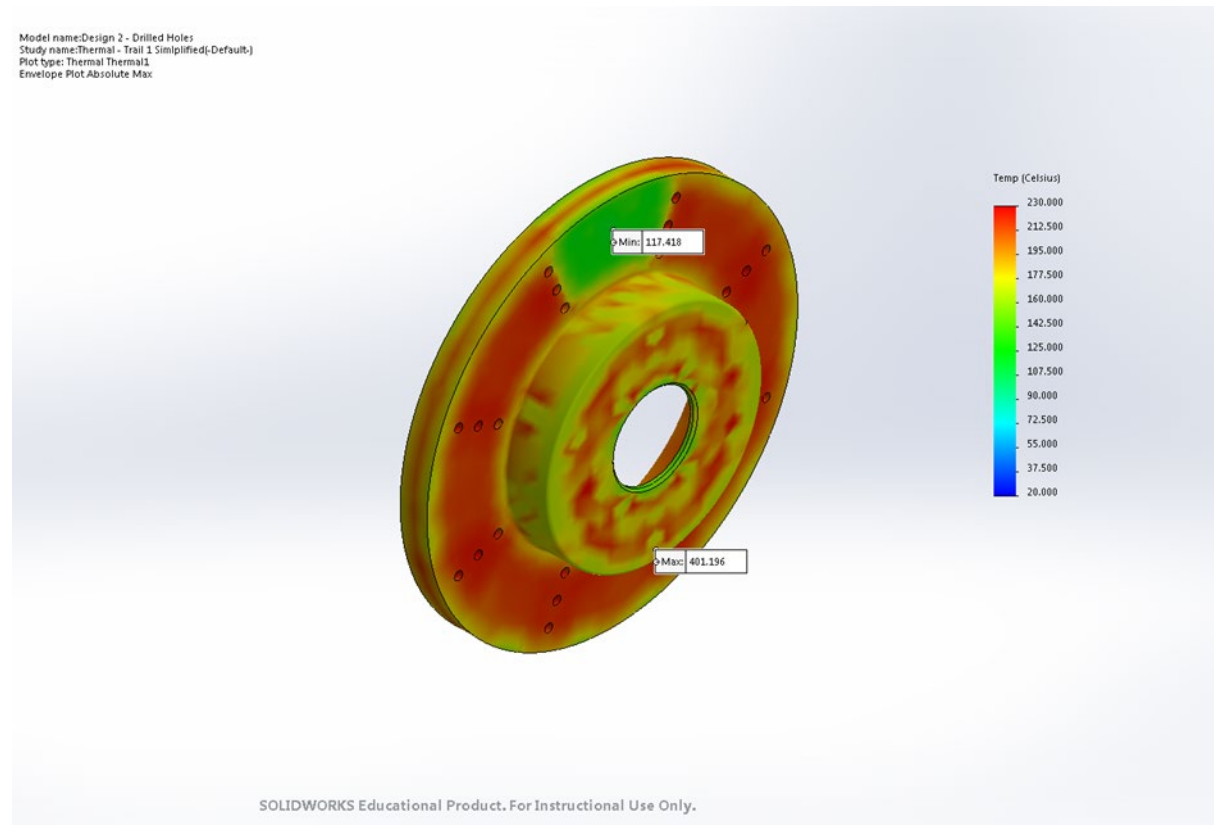


Figure 22. Thermal Plot - Drilled Holes I (ALI BELHOCINE & MOSTEFA BOUCHETARA, 2015)

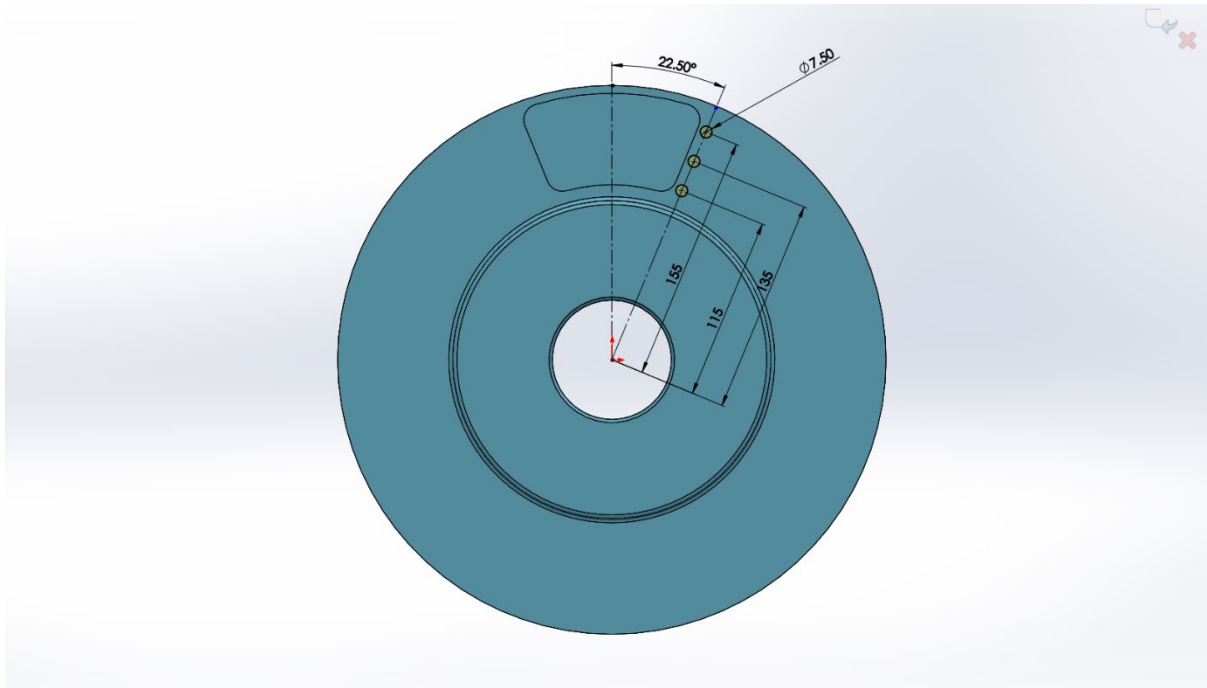


Figure 23. Drilled Holes

Three drilled holes are placed circumferentially as shown in Figure 23. A circular pattern operation is carried out across 360° of the brake rotor, therefore, adding a total of 24 holes of Ø7.5mm each.

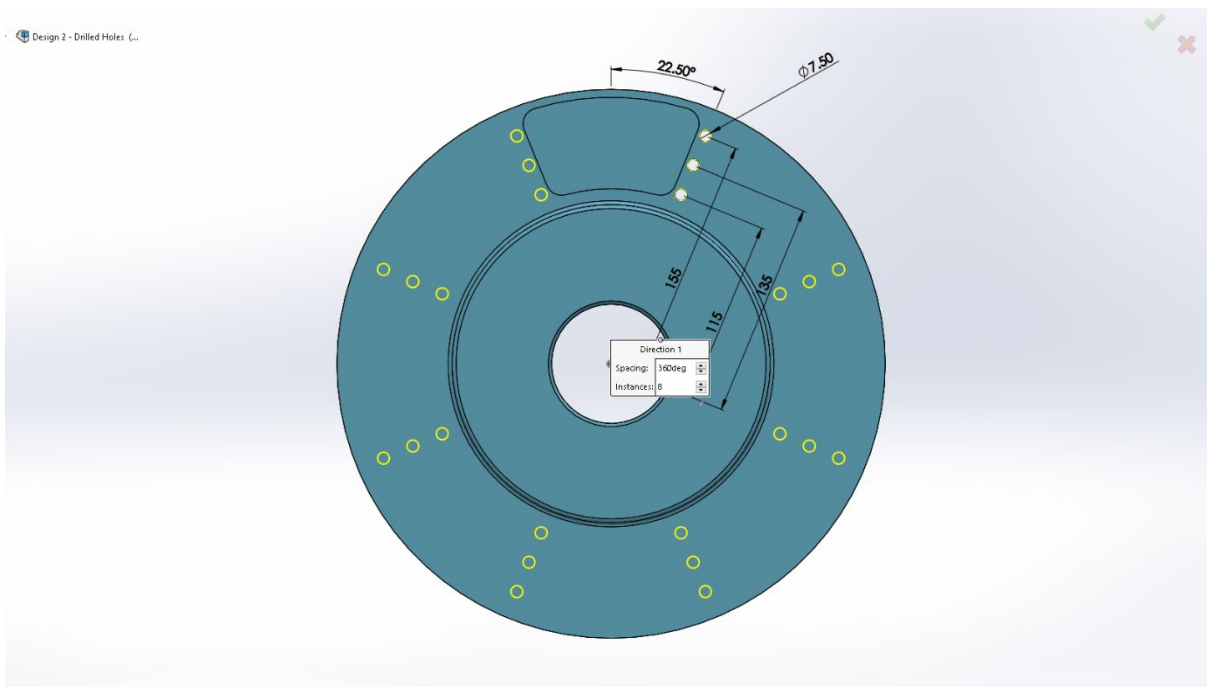


Figure 24. Detailed view of Drilled Holes

To prove that, cutting more material increases the temperature the holes were increased to a total 33 holes of Ø7.5mm each, as is shown in Figure 25.

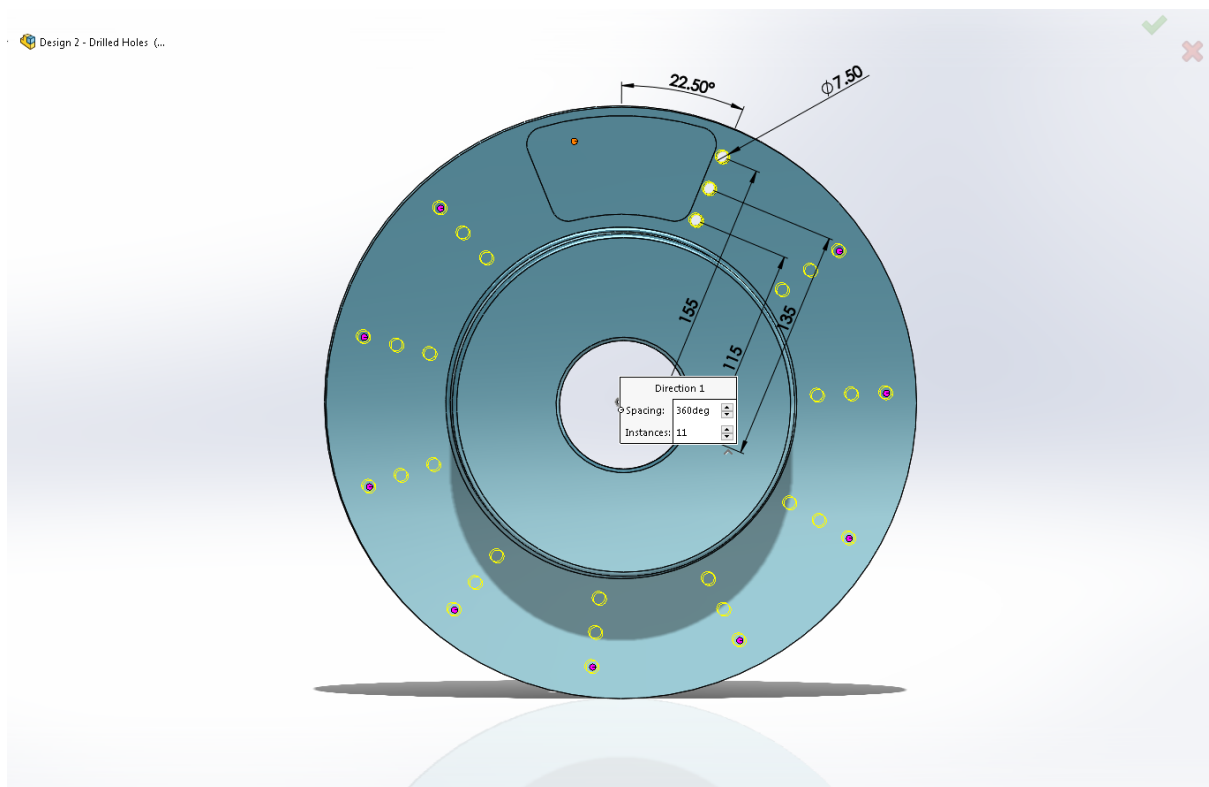


Figure 25. Increasing Holes of Drilled Rotor

Model name: Design 2 - Drilled Holes
Study name: Thermal - Trail 1 Simplified (Default)
Plot type: Thermal Thermal1
Envelope Plot Absolute Max

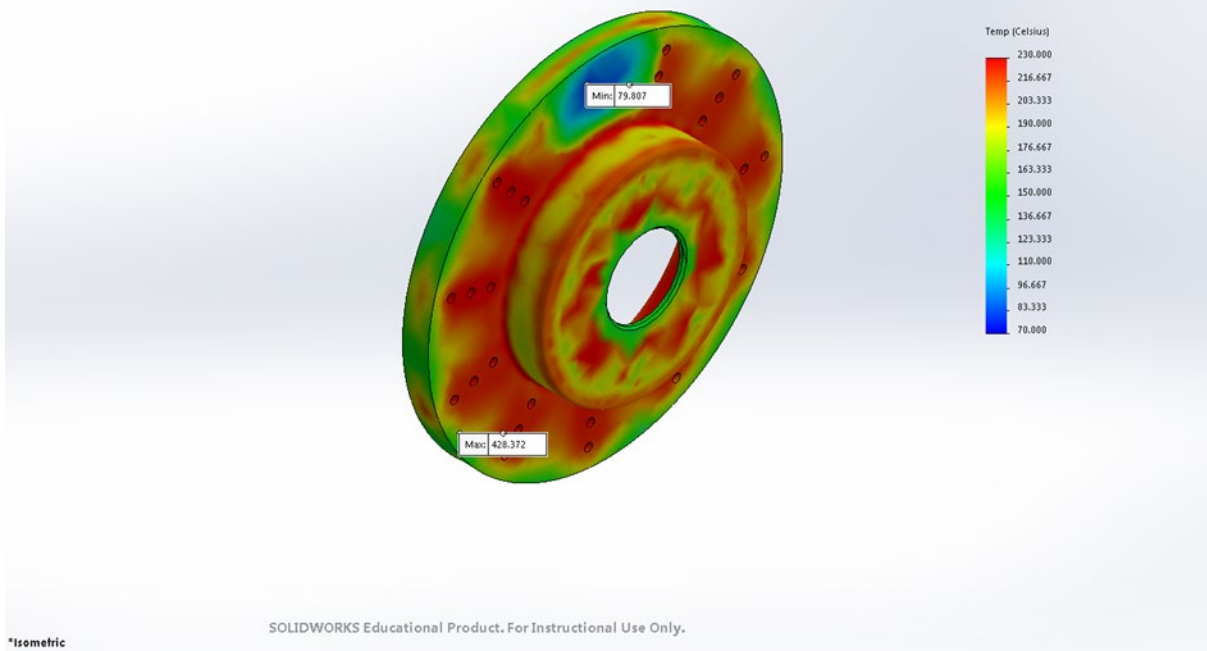


Figure 26. Thermal Plot - Drilled Holes II

As is shown in Figure 22 and Figure 26, the results of the thermal analysis are as expected – when more materials are removed from the component, the heat dissipation is increasing.

4.6 Design 3 –Straight Slotted Cuts

Repeating the above procedure, the maximum and minimum temperature seen for Design 3 is 389.96°C and 120.22°C. The slots are added on the surface area of the rotor in order to promote heat dissipation.

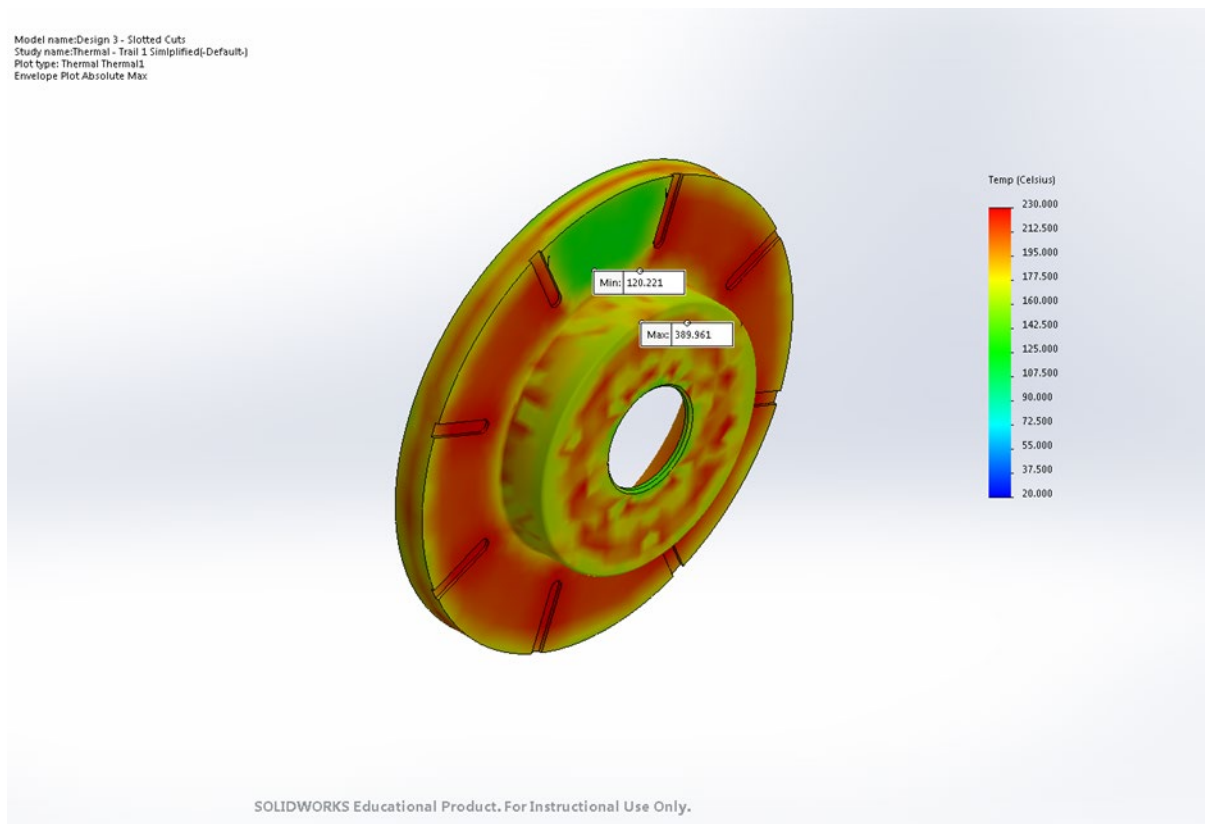


Figure 27. Thermal Plot - Straight Slotted Cuts

Design modifications are shown in figure 28 straight slots were added across the rotor.

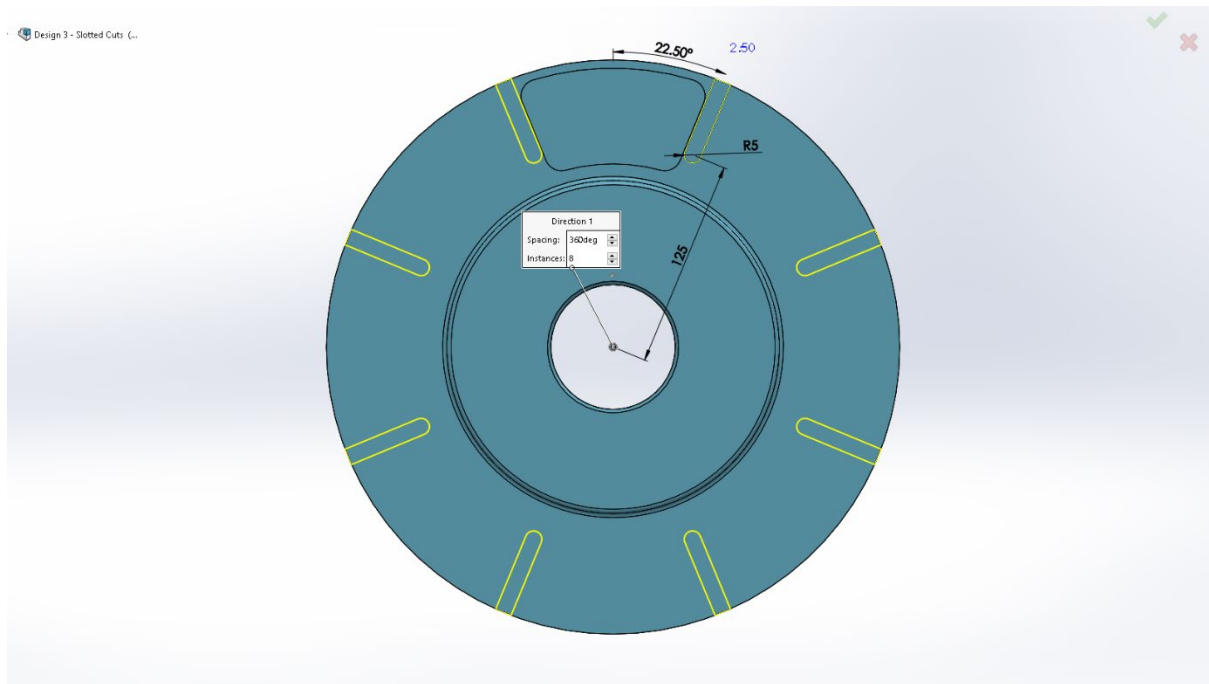


Figure 28. Straight Slotted Cuts

This Rotor is one of the most commonly used design in the modern brake rotors.

4.7 Design 4 – Drilled Holes and Slotted Cuts

Design 4 is the combination of both holes and slots (design 2 and 3 combined) to contribute for more heat dissipation and as a result the maximum temperature developed in this design is 390.26°C. This resulted in 3% reduction in temperature build up. This signifies the presence of cuts/slots on the rotor surface will result in better heat dissipation.

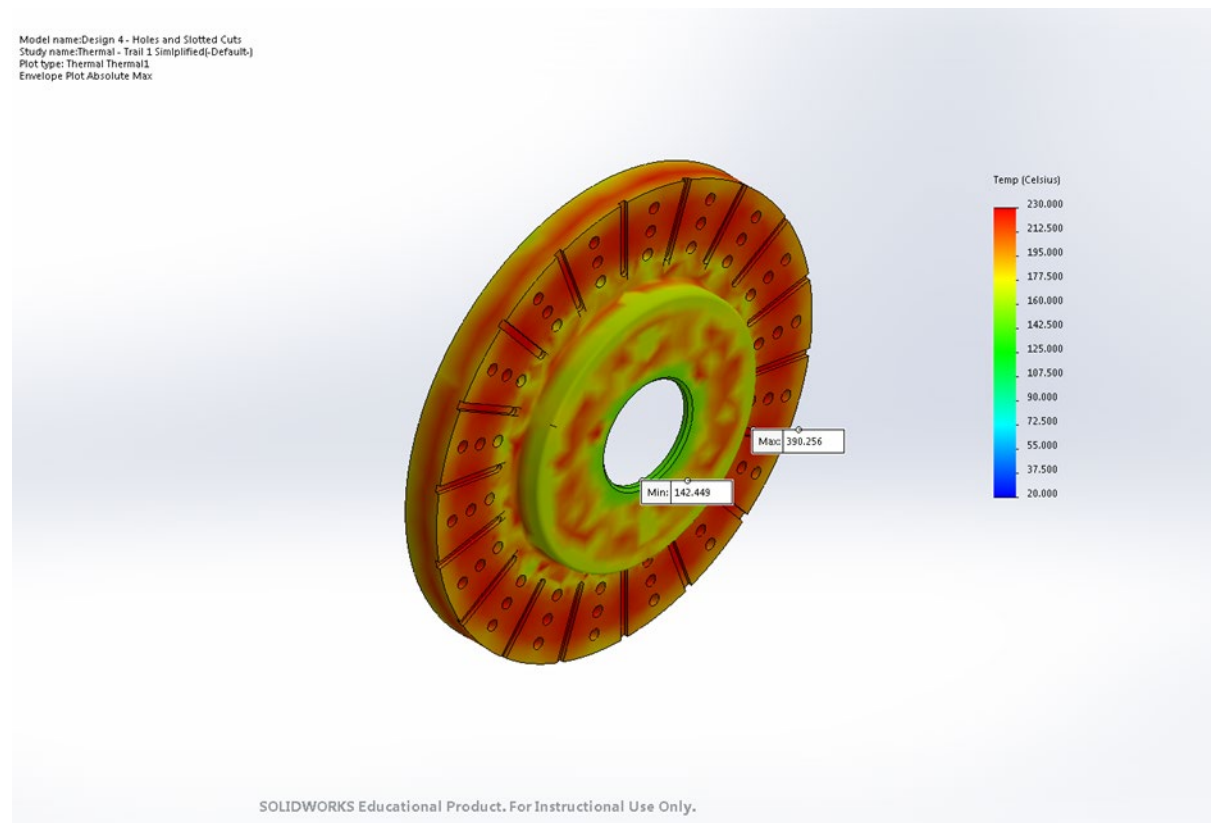


Figure 29. Thermal Plot - Drilled Holes and Slotted Cuts

4.8 Design 5 – Curved Slotted Cuts

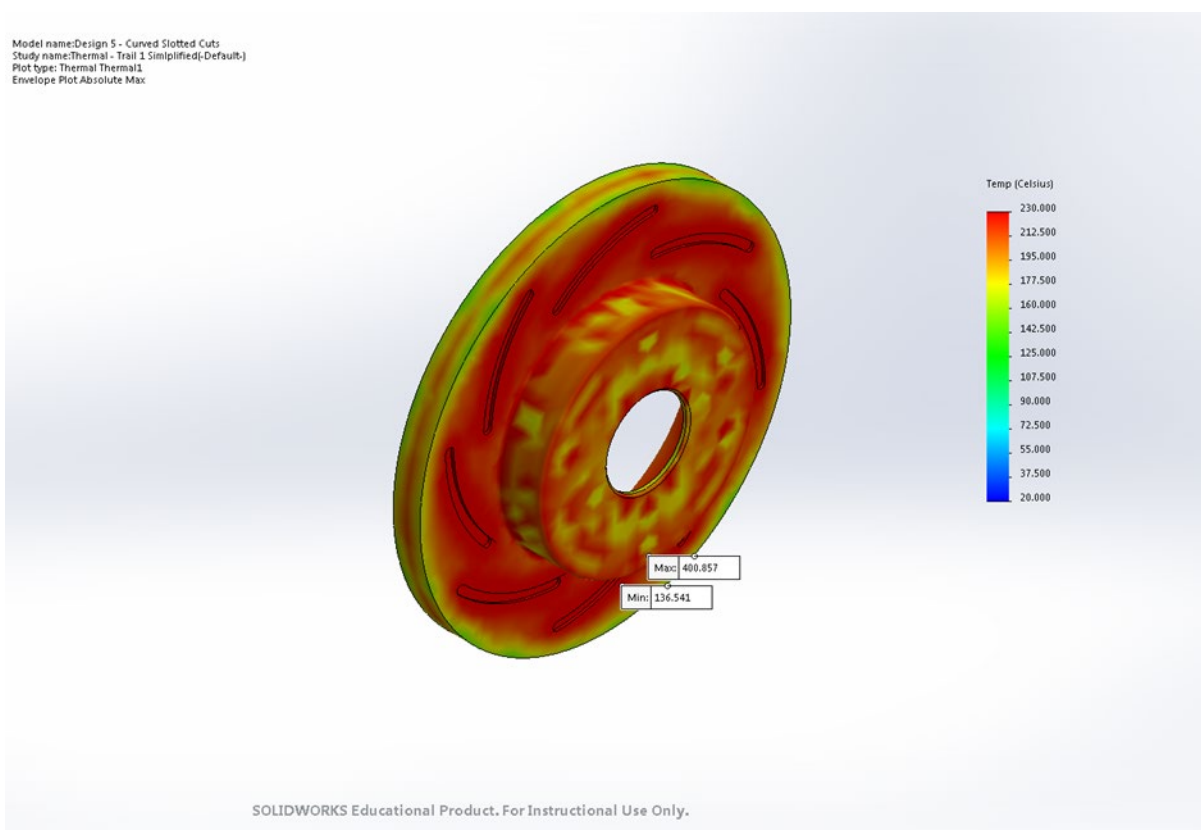


Figure 30. Thermal Plot - Curved Slotted Cuts

A summary of the results obtained from the analysis for five design configurations are tabulated in the table below. A graph plotted between design configuration and temperature shows Design 3 has the lowest temperature, which is desirable for better heat dissipation. Therefore, this is the chosen and recommended design based on the results obtained from Thermal analysis.

Configurations name	Maximum Temperature (in °C)	Description
Design 1	395.32	Plain Rotor
Design 2	401.19	Drilled Holes
Design 3	389.96	Slotted Cuts
Design 4	390.25	Drilled Holes and Slotted Cuts
Design 5	400.85	Curved Slotted Cuts

Table 3. Results Summary

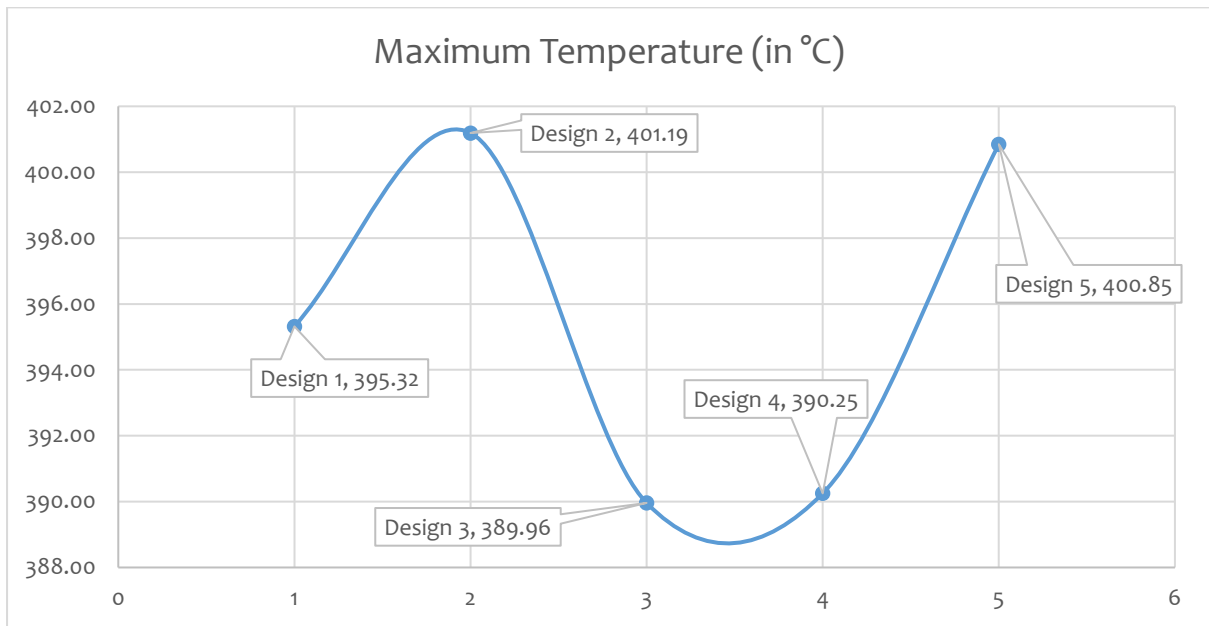


Figure 31. Graph of Various Designs Vs Rotor Temperature

4.9 Observations and discussions – Thermal analysis:

From the Thermal analysis carried out, some of the key observations were noticed and summarised below. Some of the challenges faced are also discussed below along with reasons.

1. In terms of absolute maximum temperature, Plain rotor design stood third from the top and is due to the fact that there are no features or operations carried out in the interface where it interacts with brake pads.
2. Regions where cut-outs/slots are made shows high temperature build up due to sharp corners which acts as stress raisers. A similar observation is made based on Von-Mises stress in the region where sharp corners are present. This will lead to conclude the presence of sharp corners acts as stress raisers and this should be avoided. Therefore, it is recommended to have either fillet or chamfer to reduce stress raisers.
3. The interface where the Heat Power is applied, due to brake pad interface and load transfer, is expected high stress (or concentration of high peak). This is not the case in the enclosed report when the setting in the Thermal analysis is set to a maximum value. Negative values were seen in the area where there is no heat power. This was one of the major challenges and the only way to obtain realistic peak temperature is by changing the maximum value to "Absolute Maximum Value". However, this value is closely comparable with the results obtained by other researchers for an approximately similar heat power, convection co-efficient for Gray Cast Iron and the initial temperature of 25°C.

Model name: cylinder thermal analysis
 Study name: Thermal 1(-Default-)
 Plot type: Thermal Thermal1
 Time step: 4 time : 4 Seconds

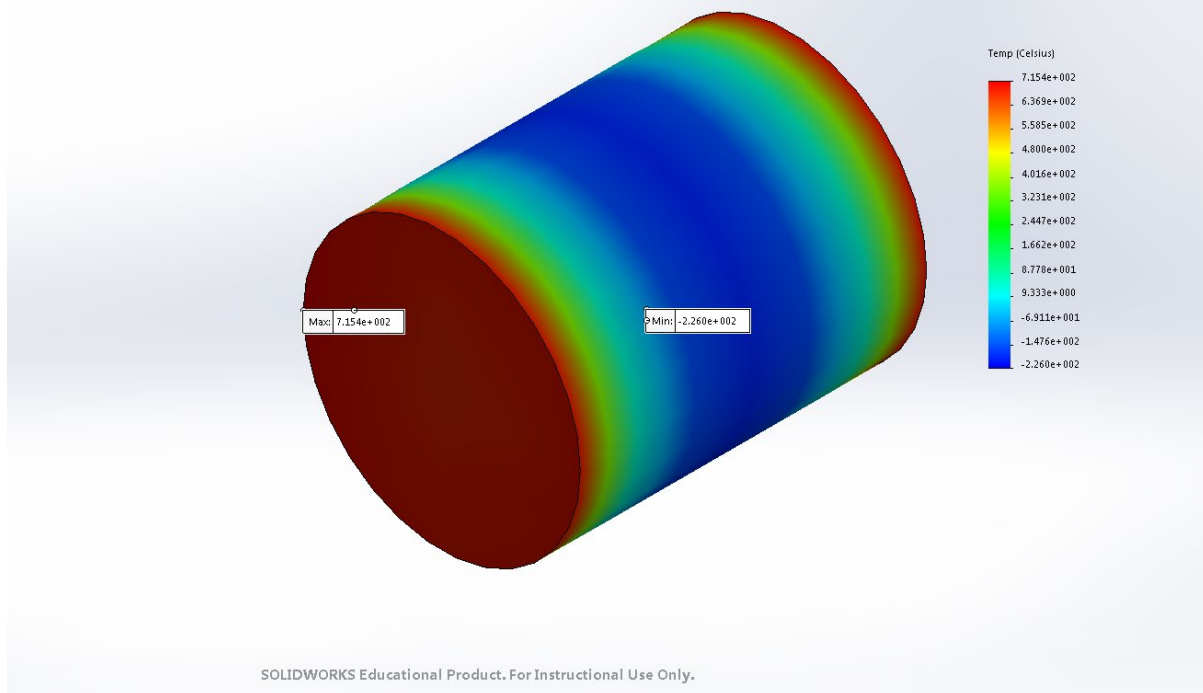
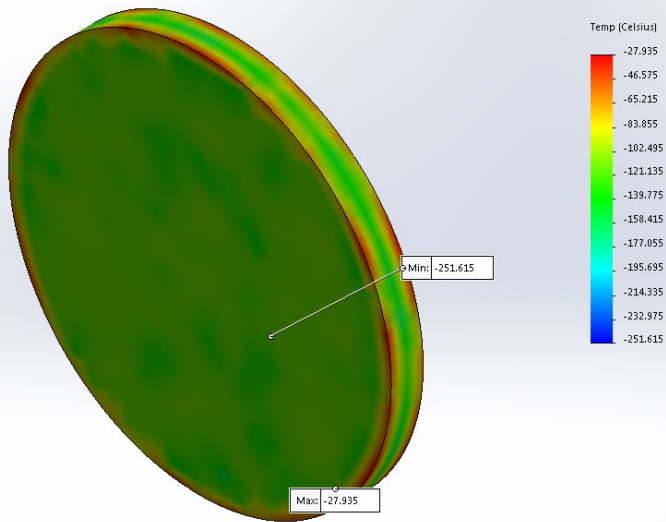


Figure 32. Negative Temperature on a Cylinder

4. In order to check the error state for the above point (Point 3), a small sized cylinder is created and analysed for thermal stresses with exactly similar boundary conditions. Results showed negative value for the simplified design, which concluded the error state is not a result of complex geometry but rather in the inconsistency in Solid works. The number of images are presented to justify this under the Appendices section of the report.

Model name: cylinder thermal analysis 360
Study name: Thermal 1(-Default-)
Plot type: Thermal Thermal1
Envelope Plot Max



SOLIDWORKS Educational Product. For Instructional Use Only.

Figure 33. Negative Temperature on Rotor

4.10 Frequency analysis:

Five different designs are considered for the analysis. The rotor with various key features are modelled and this includes slot cuts, drilled holes, combination of drilled holes, and slot cuts and straight cuts.

Finite Element methods allow engineers to model dynamic responses to analyse structural performance. It offers advantages to understand the structural behaviour of complex geometries. However, the accuracy of such CAE modelling is questionable, hence many researchers tend to analyse the same problem and validate via experimental procedures.

Hence for the completeness of the frequency analysis and for robust design, it is essential to compare the theoretical results to experimental and determine the variation in results.

Previous researchers used a flow chart as per the below suggested by (shodhganga, 2012).

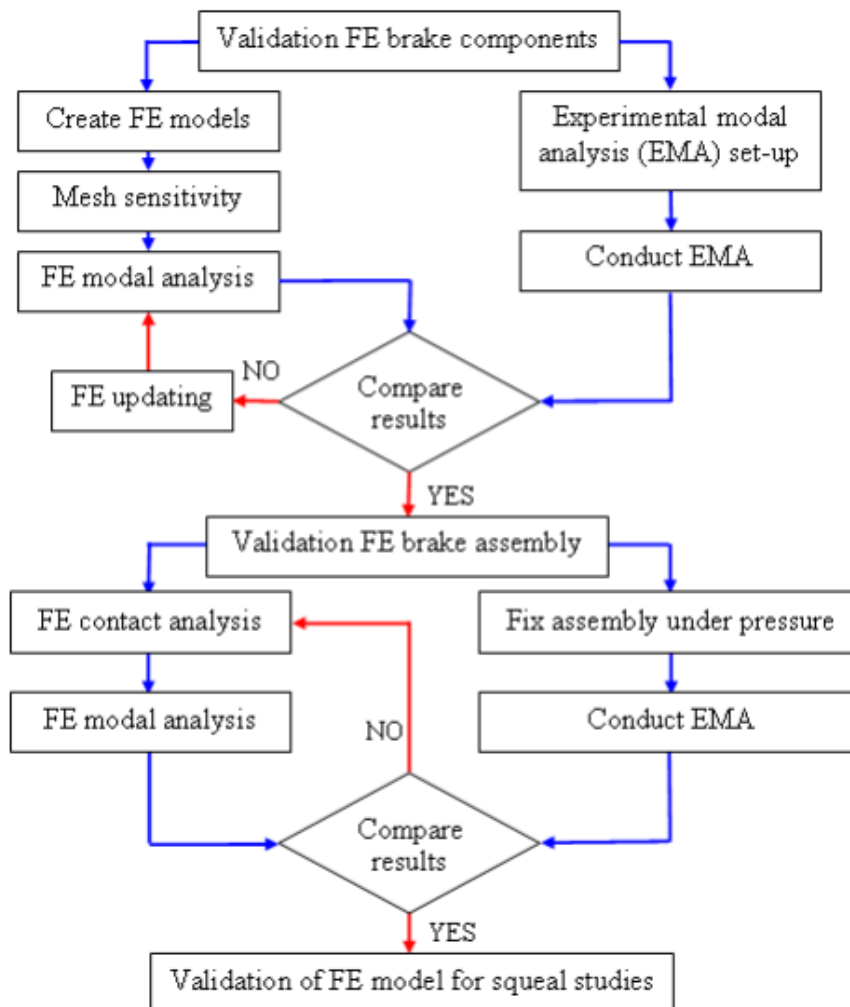


Figure 34. Flow Chart Theoretical and Experimental results comparison (shodhganga, 2012)

Rotor and brake pads were subjected to Modal analysis. The rotor itself had the below chosen locations to understand the structural response. Excitation were made with the aid of hammer. Accelerometer were used for measurement of the excitation frequency.

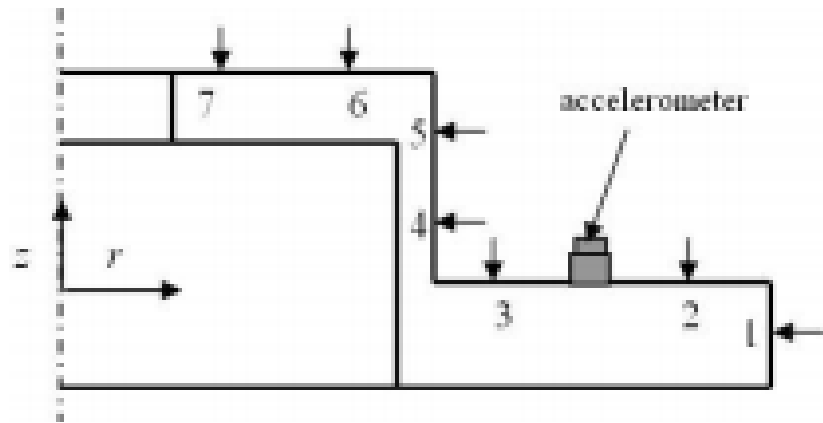


Figure 35. Excitation on Brake Rotor (shodhganga, 2012)

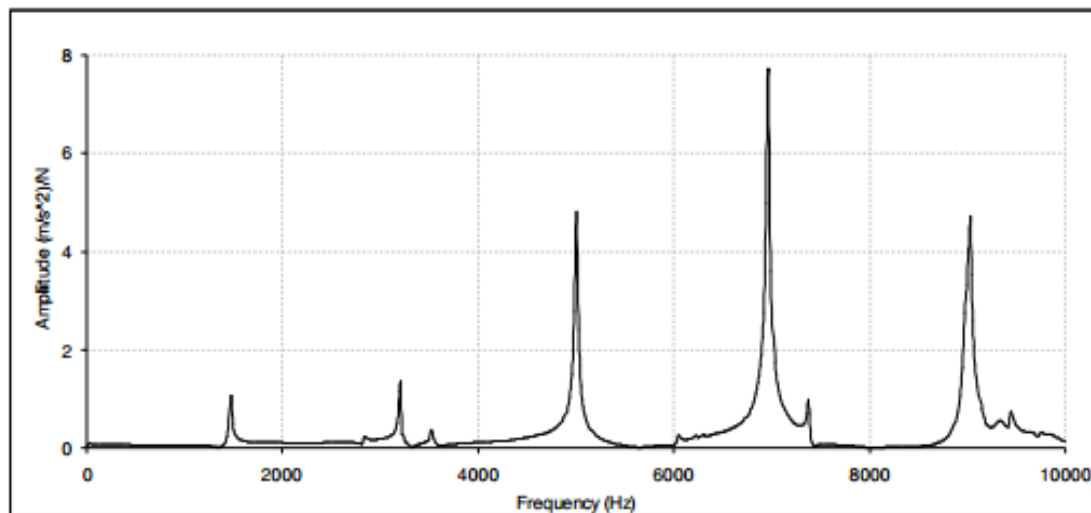


Figure 36. Excitation response graph (shodhganga, 2012)

The frequency analysis is carried out for the complex five designs. Below are the sequential steps used to run the analysis.

- Open the relevant brake rotor in Solid works, run Simulation – Frequency analysis
- Apply material for the brake rotor
- Adding fixtures (added at the axis of the rotor/rotational axis)
- Forces applied where the Heat Power is generated (interface of Rotor to brake pads). This is essential in order to ensure the braking load is applied during a breaking event.
- Mesh the rotor CAD model
- Run the analysis and obtain "List of Resonant Frequencies" to obtain all mode shapes.

Five different rotor designs are sought that are used for Frequency analysis to understand the mode shape. Frequency analysis is carried out for 10 mode shapes. A meshed model with a bearing support at the centre hole is shown below. A similar procedure is applied to all the discs throughout the study. Results are plotted in tables (shown below).

The five designs are considered for the frequency analysis. Using the procedure above, analysis is carried out. The only differences between each of the design configurations are the heat dissipation cuts that are performed to understand the structural response alongside resonant frequencies. This procedure is repeated for 2 different mesh sizes. Discussions are presented for the variation in results between two different mesh sizes and investigated the reasons for the variation.

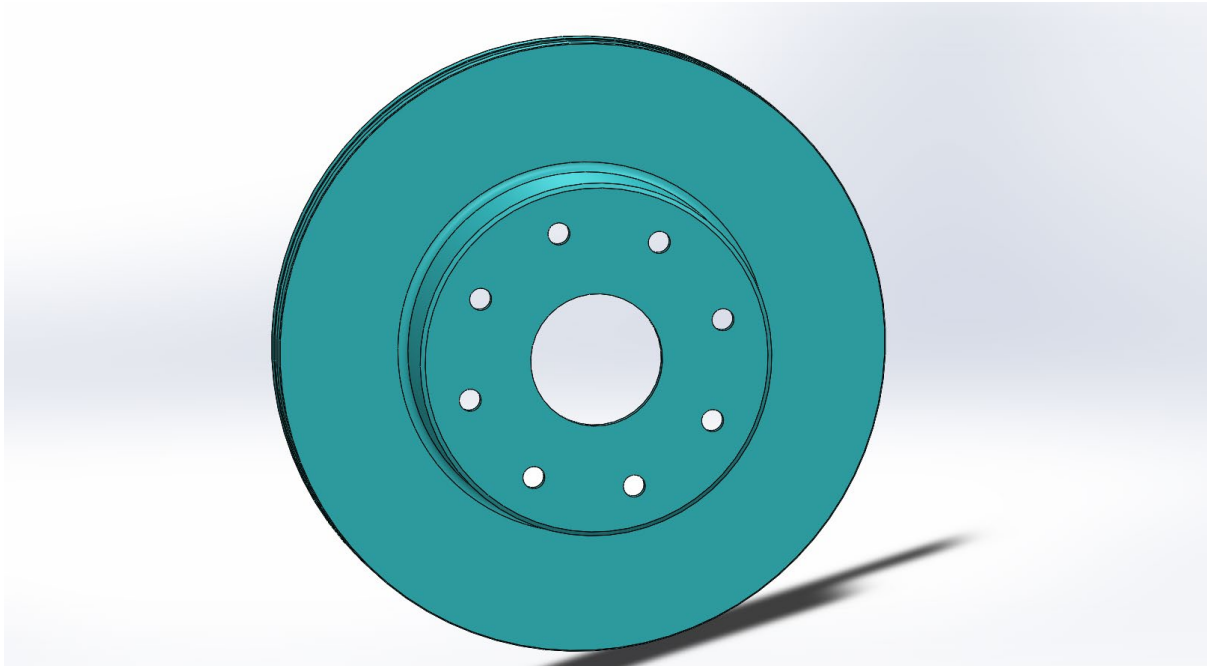


Figure 37. Plain Disc

Isometric view of the plain disc is shown in Figure 37. The material is the same as used in Thermal analysis and it is the Gray Cast Iron.

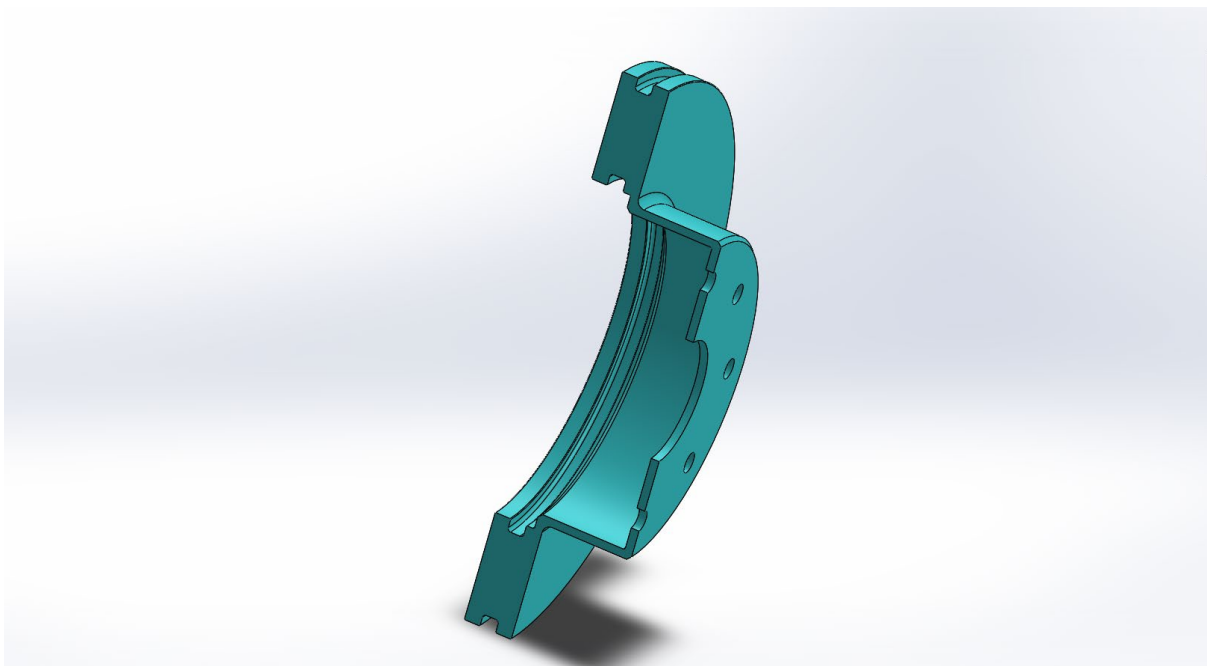


Figure 38. Section view of Rotor - Plain Design

Circular holes are added on the rotor surface as shown in the Figure 39. The intention of adding the holes is to create better heat dissipation during braking events, as this will enable better performance.

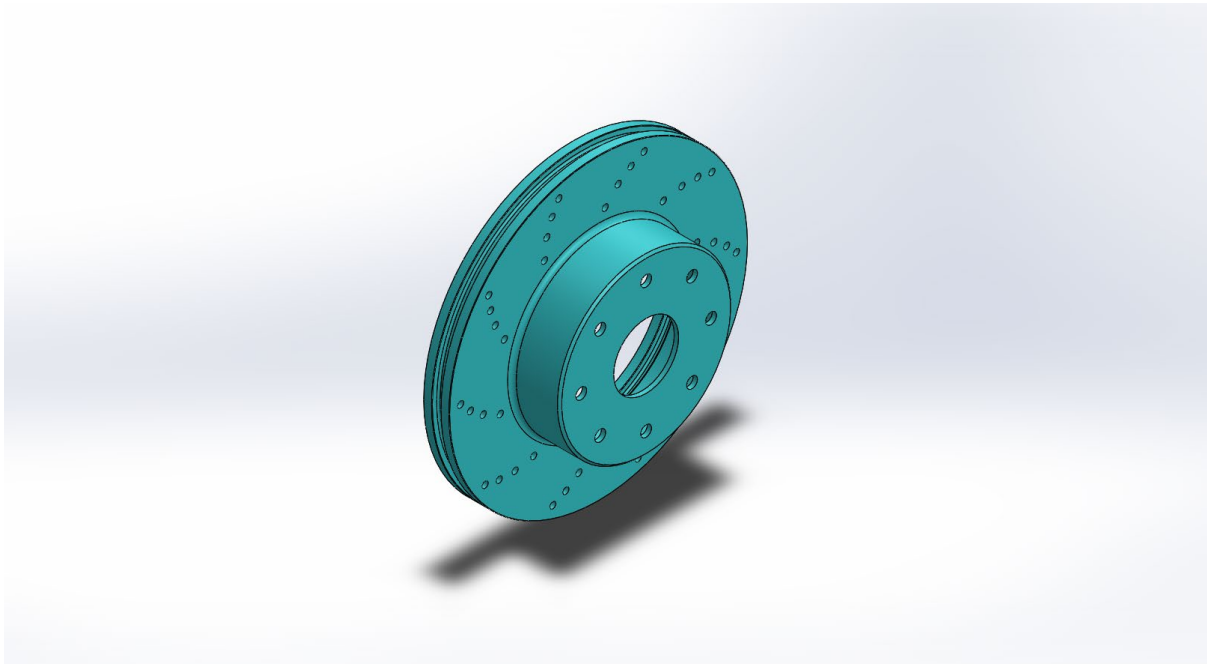


Figure 39. Drilled Holes

Adding features will however reduce the stiffness of the rotor and this difference will be seen from the frequency analysis results. The system will resonate at higher frequency compared to the plain rotor.

Figure 40. shows the rotor provided with curved slotted cuts. This version will create more surface area and hence the thermal performance of the brake rotor will be better. However, the penalty is that the system will be less stiff.

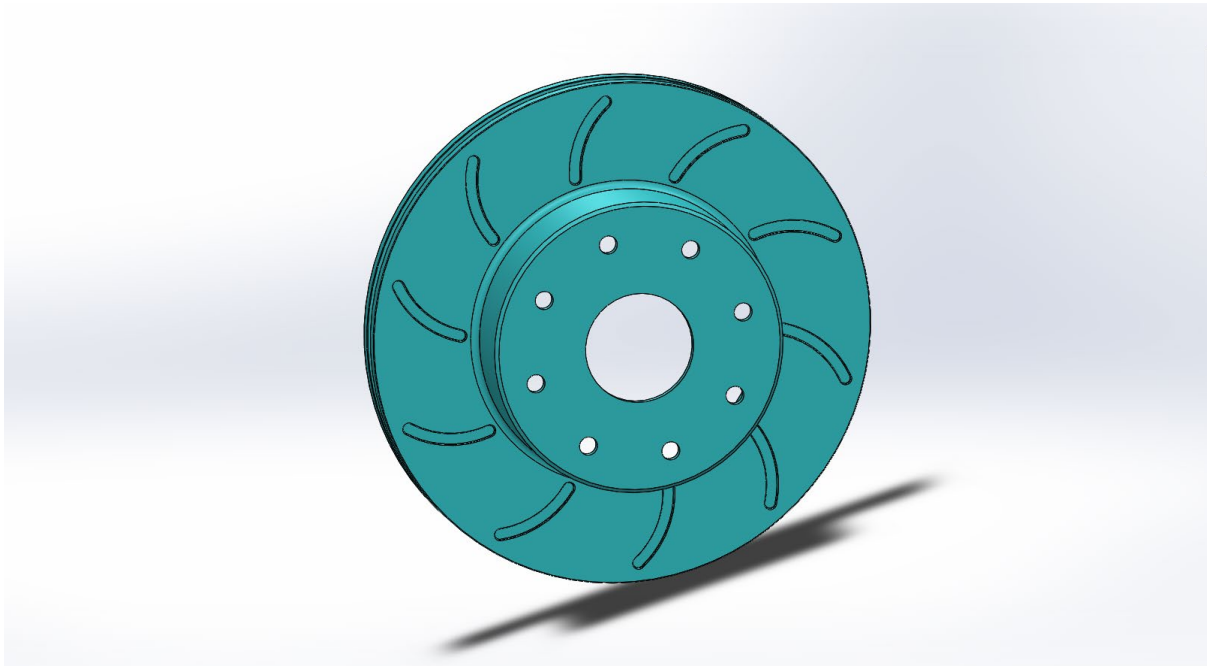


Figure 40. Curved Slotted Cuts

Figure 41. is a combination of Drilled Holes and Curved slotted cuts as it considers both of the features for better thermal performance. This particular design is not cost-effective due to the large number of cuts which will need multiple secondary operations and costly tooling.

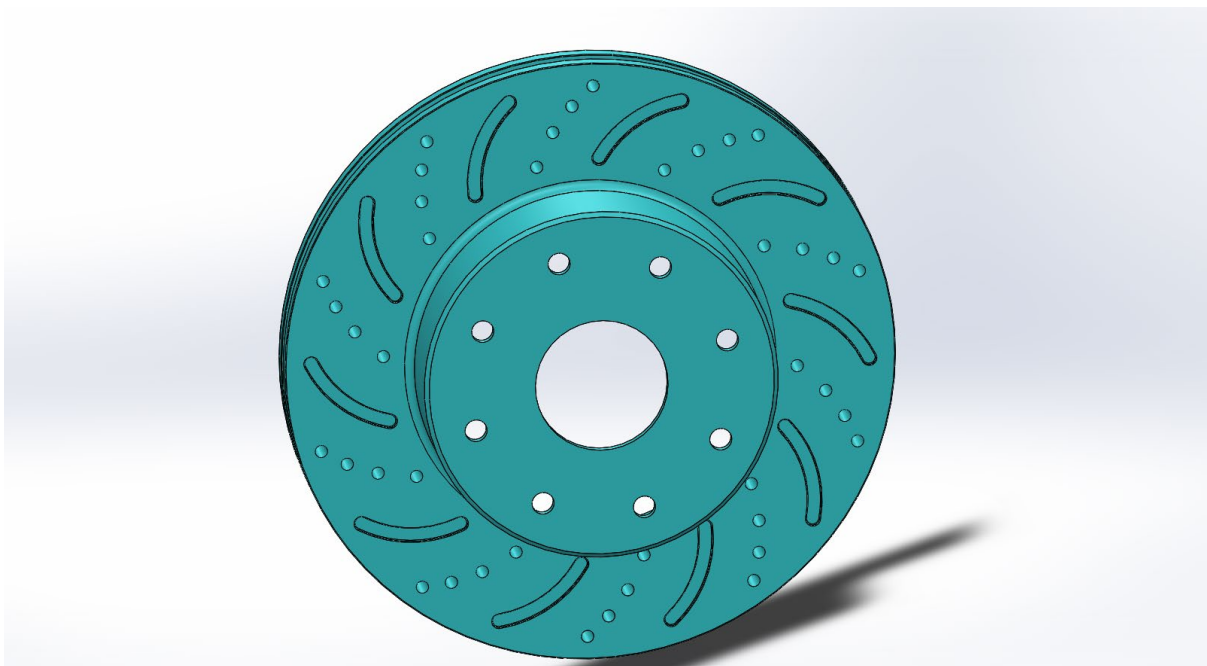


Figure 41. Drilled Holes and Curved Slotted Cuts

In Figure 42, the final design for frequency study has straight cuts that are relatively easy to manufacture and lesser tooling set up due to straight cuts. There is possibility of making these cuts a part of the casting tool. However, it could be challenging from casting draft angle perspective and most importantly the surface finish that can be achieved may not be desirable for the rotor application.

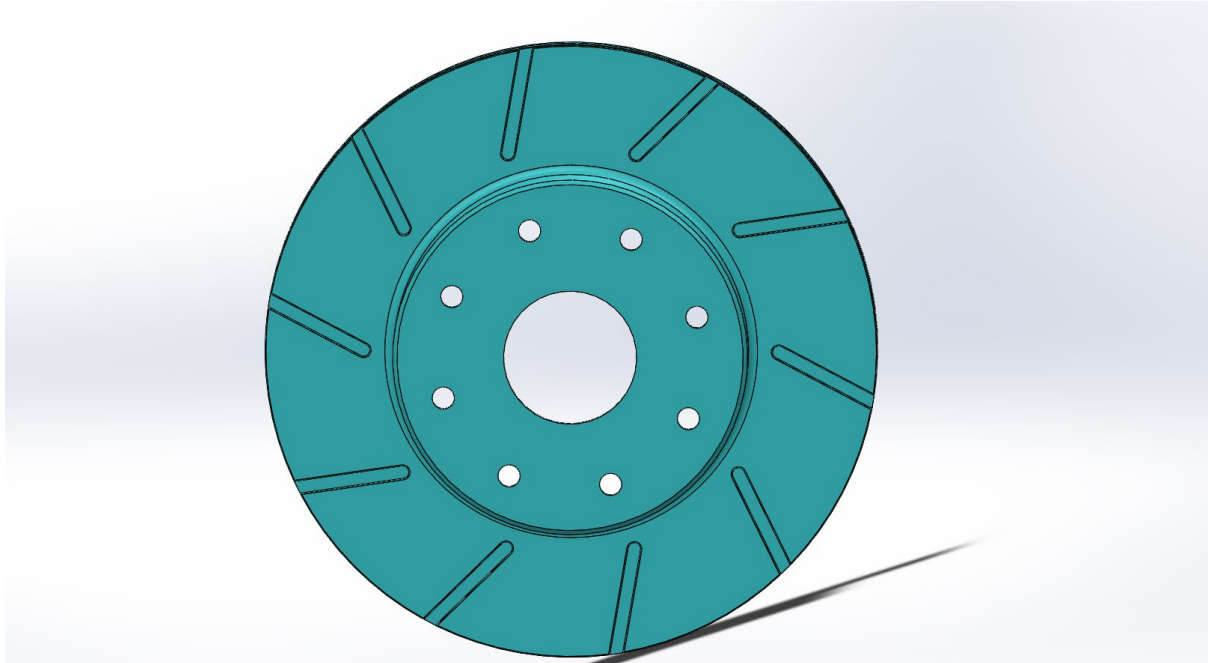


Figure 42. Straight Slotted Cuts

A meshed model for the frequency study is shown in Figure 43. Due to the fine mesh applied, the figure shows dense mesh on the rotor. Engineering studies usually should use fine mesh, as this will result in reliable and accurate results. However, with the penalty of high computing time.

Model name: Design.4
Study name: frequency.1(-Default)-
Mesh type: Solid Mesh



Figure 43. Meshed Model for Frequency Analysis

4.11 Frequency Analysis results:

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	2776.80	441.95	0.002263
2	2805.40	446.50	0.002240
3	4427.70	704.69	0.001419
4	5330.40	848.36	0.001179
5	5335.00	849.10	0.001178
6	5811.20	924.88	0.001081
7	6530.60	1039.40	0.000962
8	6533.10	1039.80	0.000962
9	9364.90	1490.50	0.000671
10	9372.30	1491.70	0.000670

Table 4. Frequency Analysis Results for 5mm Mesh Size - Plain Rotor

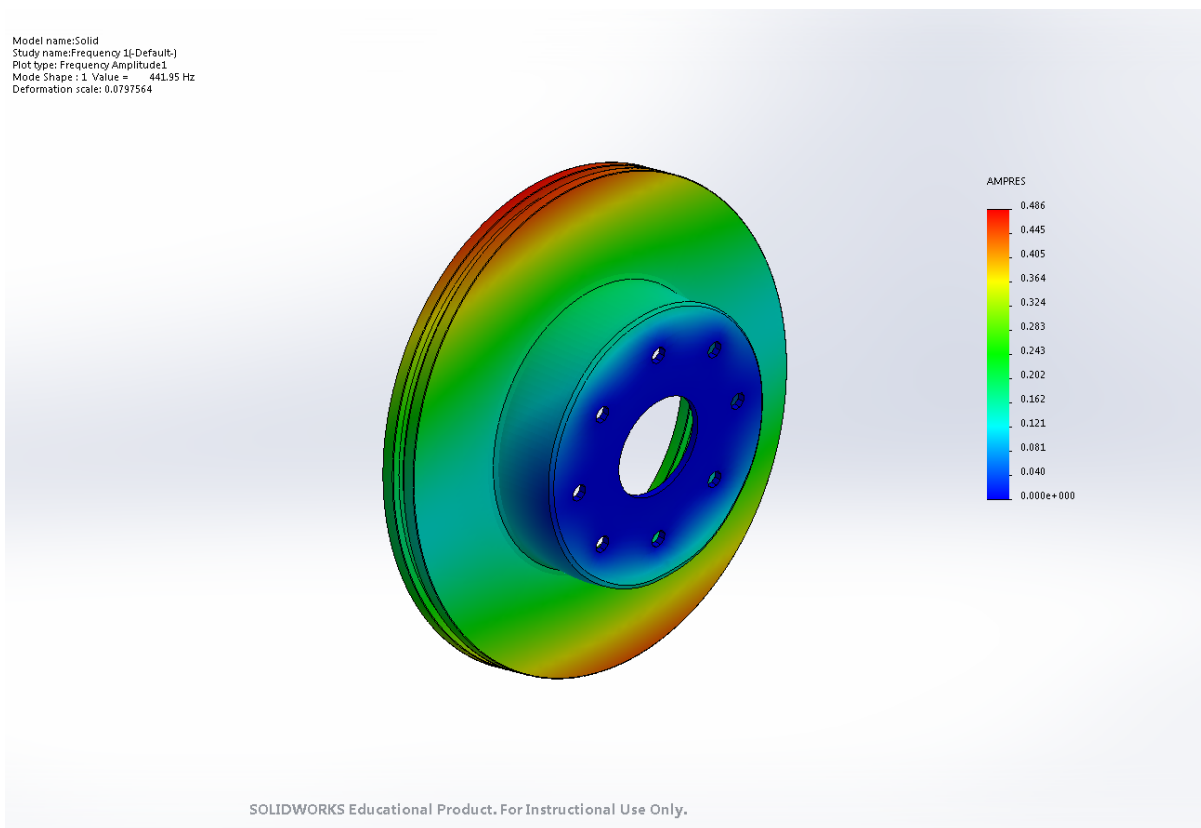


Figure 44. Frequency Analysis Results for 5mm Mesh size - Plain Rotor

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	2169.60	345.30	0.002896
2	2173.70	345.95	0.002891
3	3595.10	572.19	0.001748
4	4968.20	790.71	0.001265
5	4968.50	790.76	0.001265
6	5729.40	911.87	0.001097
7	6112.20	972.79	0.001028
8	6113.70	973.03	0.001028
9	8676.40	1380.90	0.000724
10	8677.00	1381.00	0.000724

Table 5. Frequency Analysis Results for 1.67mm Mesh Size - Plain Rotor

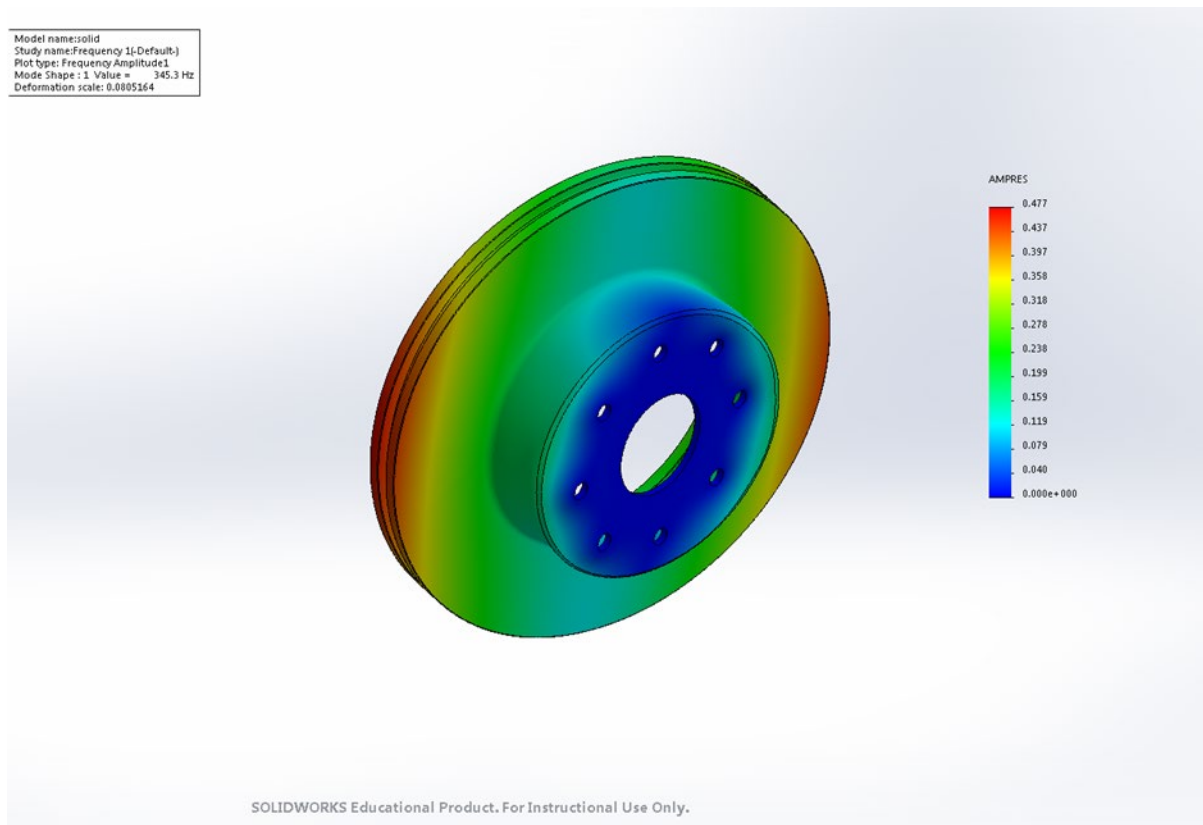


Figure 45. Frequency Analysis Results for 1.67mm Mesh Size - Plain Rotor

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	2800.8	445.76	0.002243
2	2818.6	448.6	0.002229
3	4432.3	705.42	0.001418
4	5294.9	842.72	0.001187
5	5297.9	843.18	0.001186
6	5872.1	934.57	0.00107
7	6558.9	1043.9	0.000958
8	6563.7	1044.6	0.000957
9	9327.3	1484.5	0.000674
10	9337	1486	0.000673

Table 6. Frequency Analysis Results for 5mm Mesh Size - Drilled Holes

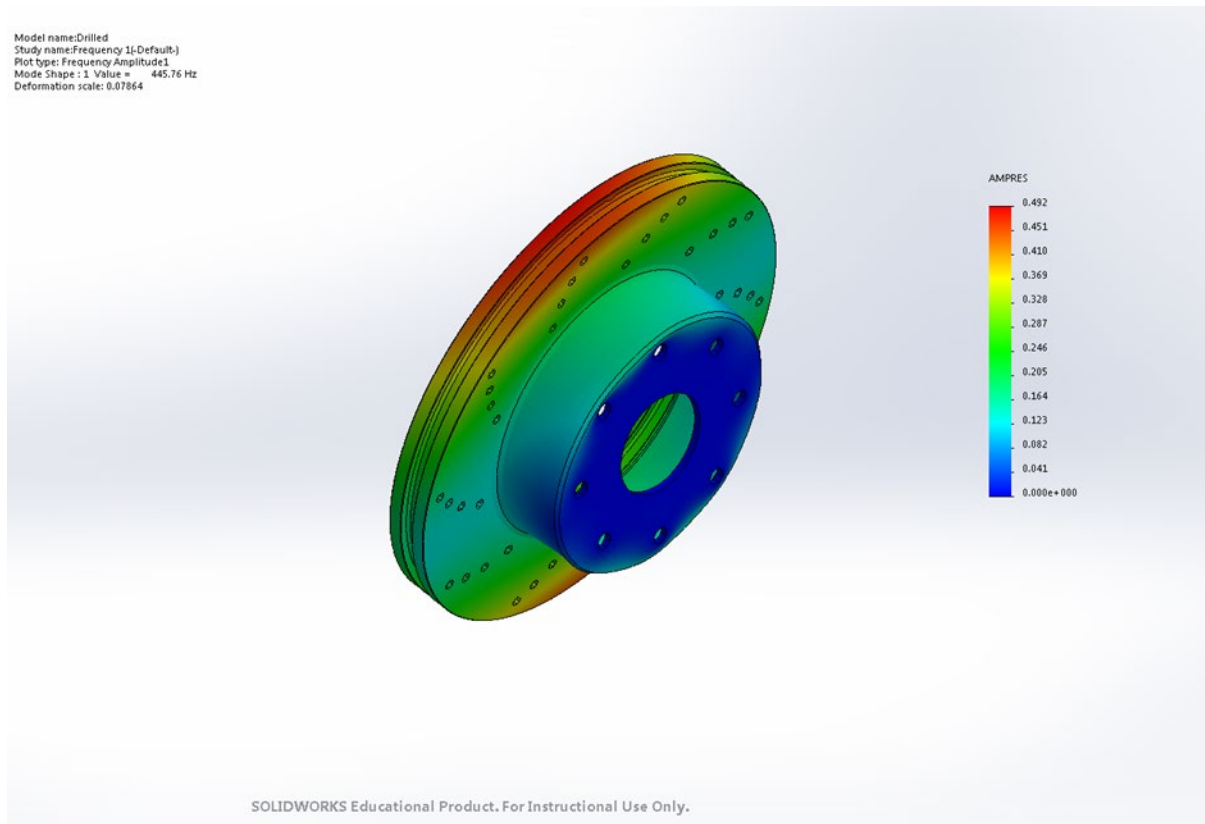


Figure 46. Frequency Analysis Results for 5mm Mesh Size - Drilled Holes

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	2189.8	348.52	0.002869
2	2192.8	348.99	0.002865
3	3605.5	573.83	0.001743
4	4910	781.46	0.00128
5	4910.6	781.55	0.00128
6	5795.8	922.43	0.001084
7	6134.3	976.31	0.001024
8	6135.6	976.51	0.001024
9	8588.7	1366.9	0.000732
10	8589.7	1367.1	0.000731

Table 7. Frequency Analysis Results for 1.67mm Mesh Size - Drilled Holes

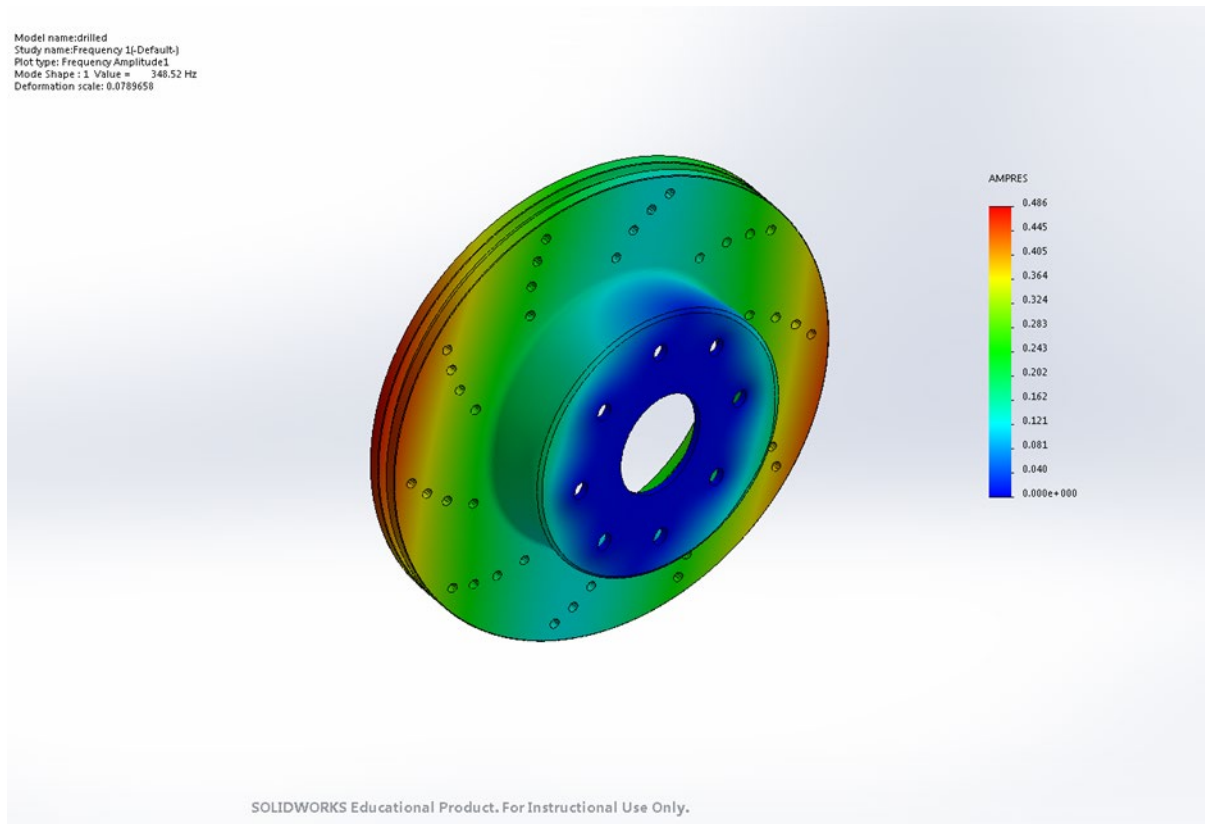


Figure 47. Frequency Analysis Results for 1.67mm Mesh Size -Drilled Holes

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	2793	444.52	0.00225
2	2804.5	446.36	0.00224
3	4424.3	704.15	0.00142
4	5313.6	845.68	0.001183
5	5317.9	846.38	0.001182
6	5822.6	926.7	0.001079
7	6524.5	1038.4	0.000963
8	6528.3	1039	0.000962
9	9337.2	1486.1	0.000673
10	9344.7	1487.3	0.000672

Table 8. Frequency Analysis Results for 5mm Mesh Size - Curved Slotted Cuts

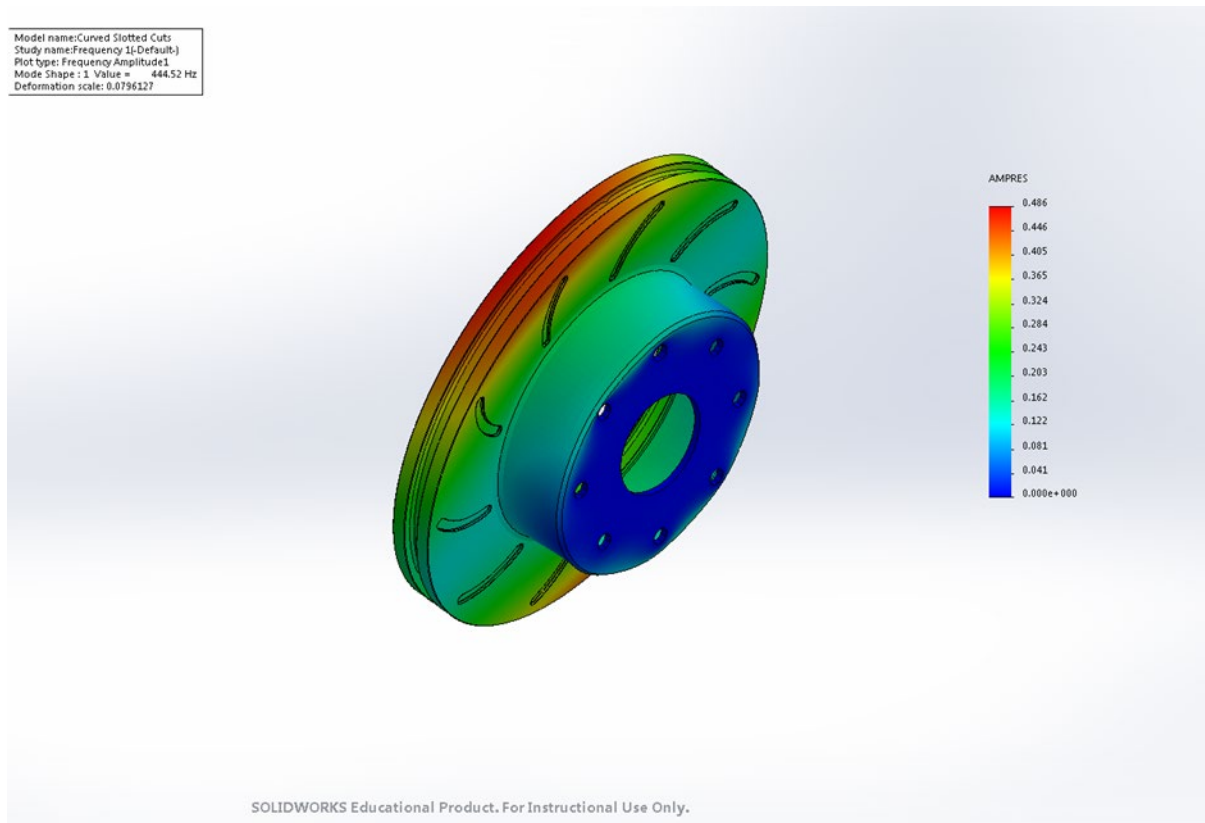


Figure 48. Frequency Analysis Results for 5mm Mesh Size - Curved Slotted Cuts

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	2789.7	443.99	0.002252
2	2795	444.84	0.002248
3	4427.1	704.59	0.001419
4	5312.4	845.5	0.001183
5	5317.1	846.24	0.001182

Table 9. Frequency Analysis Results for 5mm Mesh Size - Straight Slotted Cuts

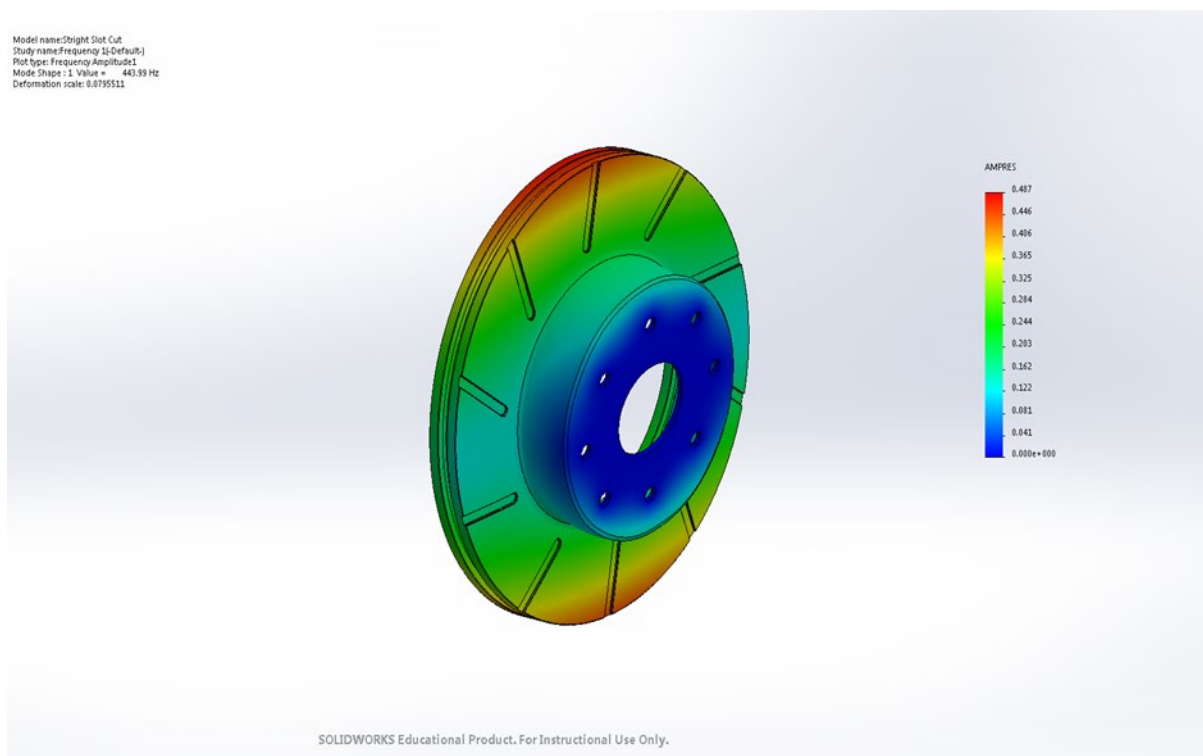


Figure 49. Frequency Analysis Results for 5mm - Straight Slotted Cuts

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	2172.5	345.77	0.002892
2	2176.2	346.36	0.002887
3	3595.9	572.31	0.001747
4	4949.9	787.8	0.001269
5	4950.5	787.9	0.001269

Table 10. Frequency Analysis Results for 1.67mm Mesh Size - Straight Slotted Cuts

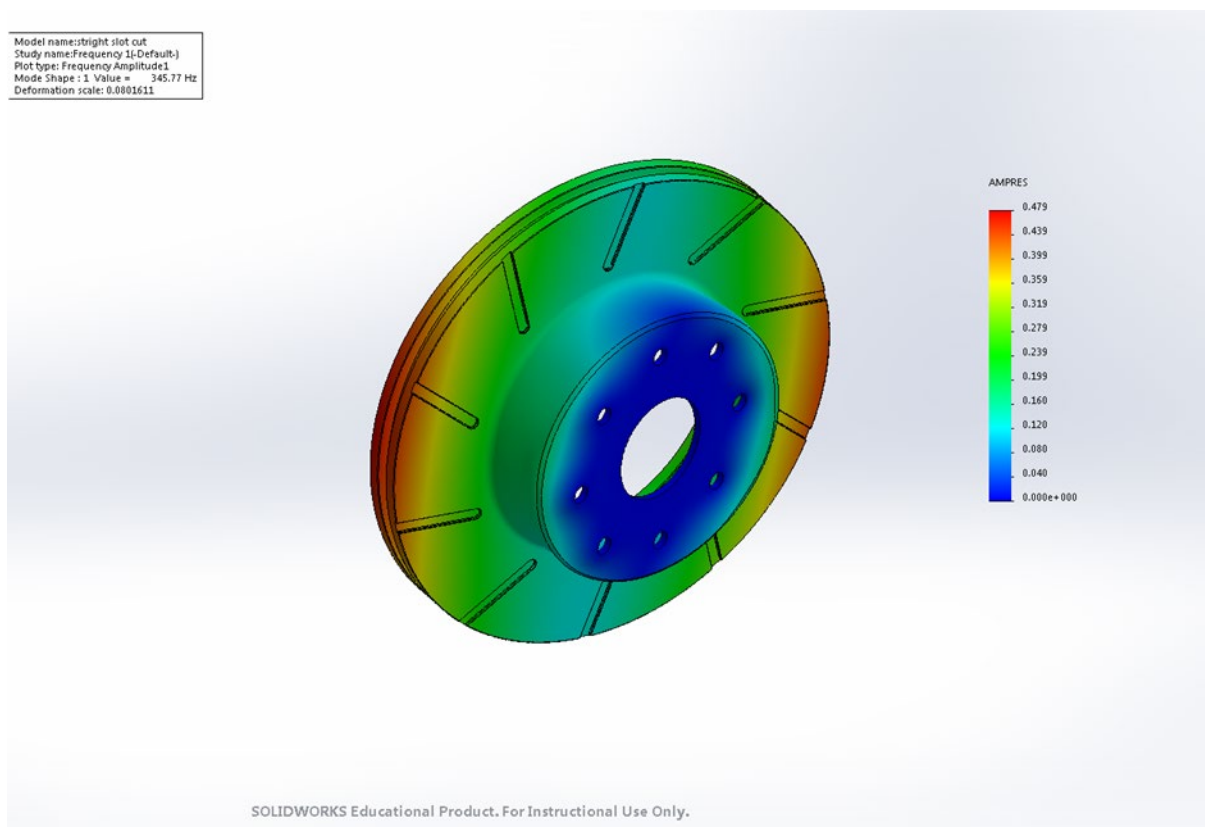


Figure 50. Frequency Analysis Results for 1.67mm Mesh Size - Straight Slotted Cuts

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	2811.4	447.45	0.002235
2	2825.1	449.63	0.002224
3	4436.7	706.12	0.001416
4	5280.3	840.39	0.00119
5	5283.2	840.85	0.001189
6	5888.4	937.17	0.001067
7	6564.7	1044.8	0.000957
8	6565.8	1045	0.000957
9	9308.8	1481.5	0.000675
10	9315.9	1482.7	0.000674

Table 11. Frequency Analysis Results for 5mm Mesh Size - Drilled Holes and Slotted Curved Cuts

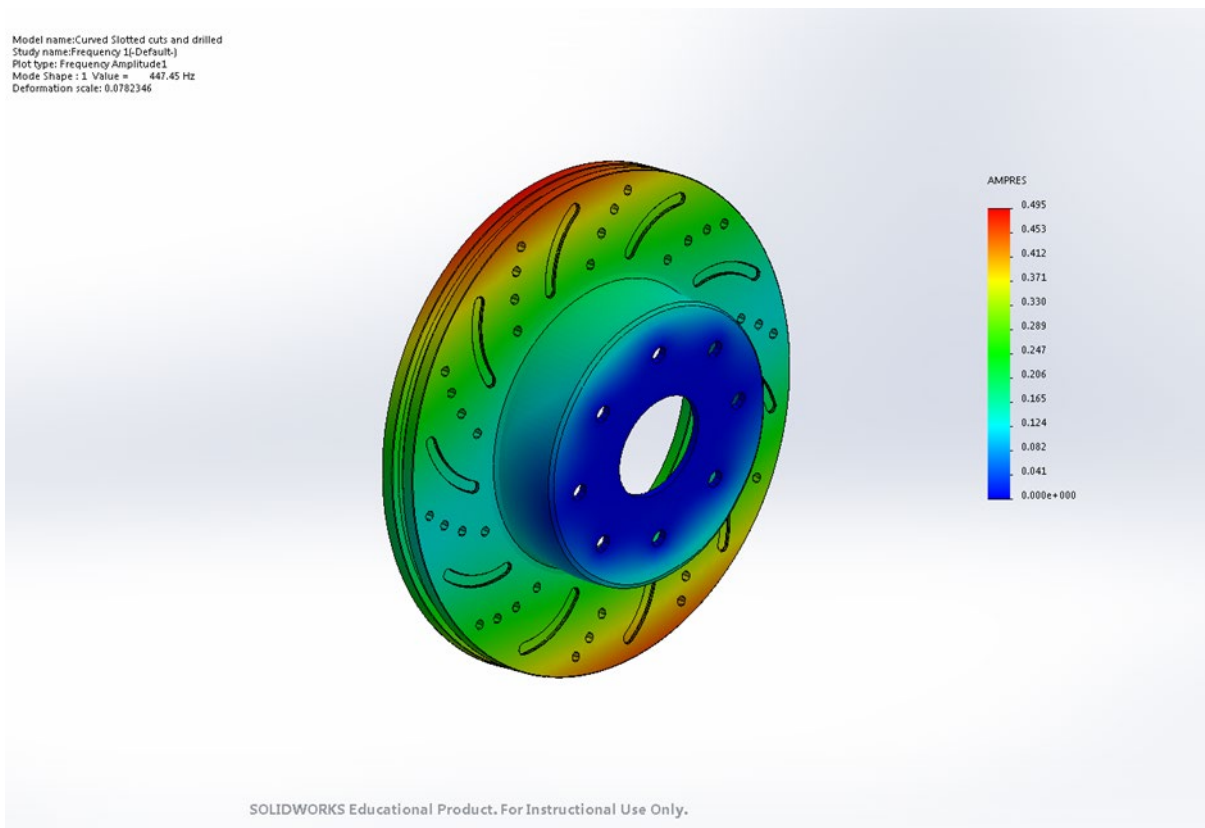


Figure 51. Frequency Analysis results for 5mm Mesh Size - Drilled Holes and Curved Slotted cuts

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	2192.7	348.97	0.002866
2	2195.9	349.49	0.002861
3	3607.4	574.13	0.001742
4	4897	779.38	0.001283
5	4897.1	779.4	0.001283
6	5811.5	924.93	0.001081
7	6137.8	976.86	0.001024
8	6139.3	977.11	0.001023
9	8568	1363.6	0.000733
10	8568.7	1363.7	0.000733

Table 12. Frequency Analysis Results for 1.67mm Mesh Size - Drilled Holes and Curved Slotted Cuts

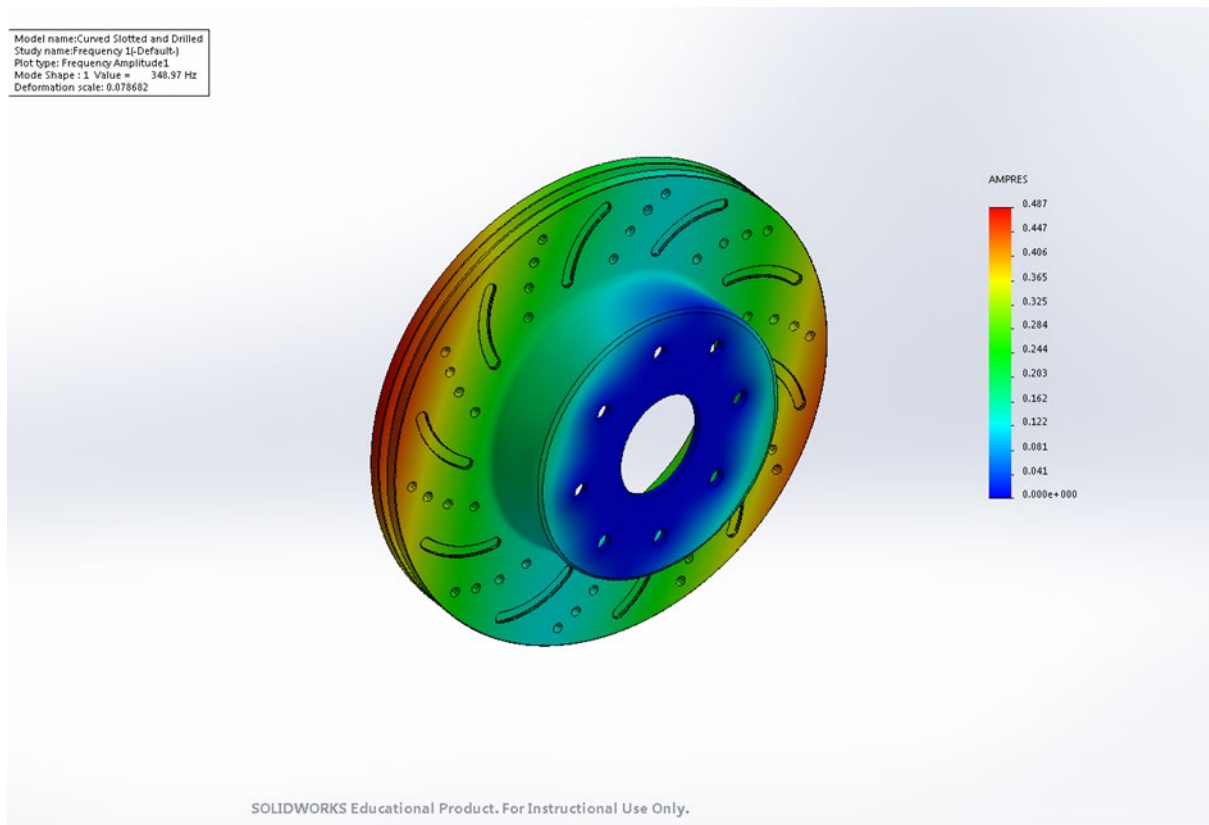


Figure 52. Frequency Analysis results for 1.67mm Mesh Size - Drilled Holes and Curved Slotted Cuts

Difference in mesh size (1.67mm and 5mm) has showed variation in the frequency as per the below above. Results for the rest of the designs are shown in Table 13.

Brake Rotor Description	Frequency At 5mm (Hertz)	Frequency At 1.67mm (Hertz)
Straight Slotted Cuts	443.9	345.77
Drilled holes	445.76	348.52
Curved Slot	444.52	346.32
Drilled Holes and Slotted Cuts	447.45	348.97
Plain Rotor	441.95	345.3

Table 13. Frequency Analysis Results for 1.67mm and 5mm Mesh Sizes

Note that the curved slotted cuts had an error in the 1.67 mm meshing results. Therefore, from the other design results and the 5mm result, the result of 1.67 mm was assumed.

From the results, it is seen that the model with fine mesh is stiff and will oscillate less compared to the coarse size. The graph of overlap between two mesh sizes is shown in the below Figure 53 and have significant differences.

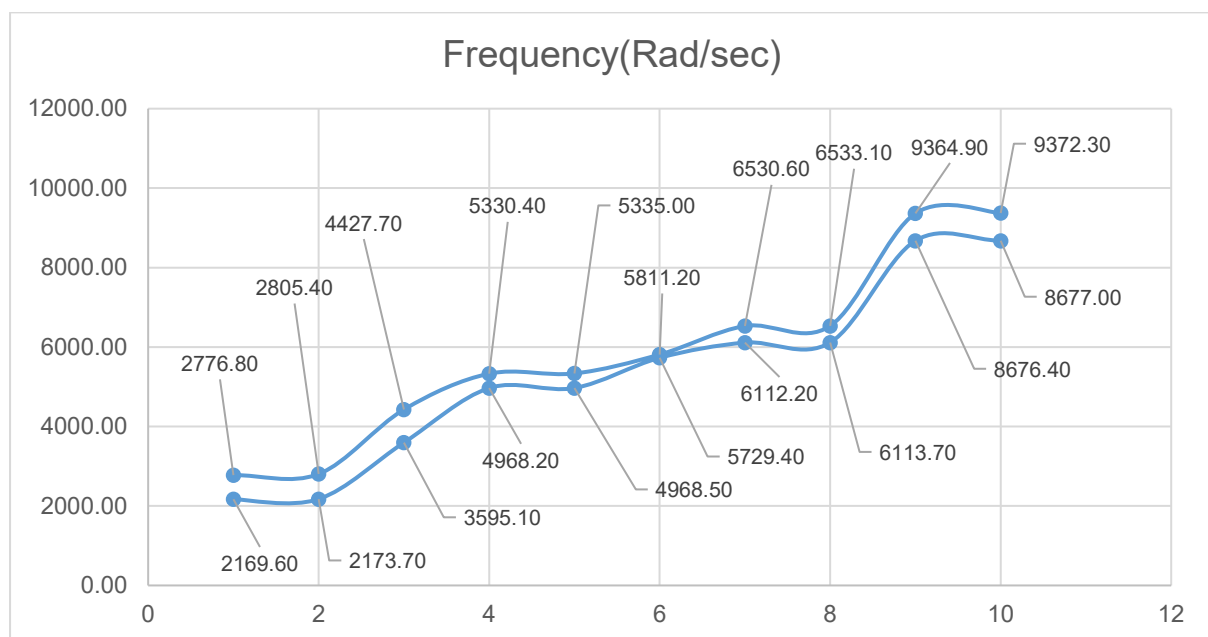


Figure 53. Variation in Frequency results between 1.67mm and 5mm mesh size

This suggests that using the right size mesh will have significant impact on the overall design. Hence experimental results are inevitable along with comparison of results before the final design. Researchers indicated the CAE modelling reliability should not only be the means to finalise a design as seen from literature review.

% difference between mesh sizes
22%
23%
19%
7%
7%
1%
6%
6%
7%
7%

Table 14. Percentage Difference Between 1.67mm and 5mm Mesh size

4.12 Observations and discussions – Frequency analysis:

1. Two different mesh sizes showed variation in results varies between 1% as minimum and 23% maximum.
2. There is a combination of both close correlation and no correlation between two mesh sizes, further investigation is required in between 1.67mm and 5mm mesh sizes. This will allow to make a better correlation and obtain mean value for improvement in frequency results.

Chapter 5 – Results and Discussions:

5.1 Literature review analysis:

Results for two types of analysis is presented in the earlier sections. Frequency and Thermal analysis for the brake rotor is performed. The project was approached via a literature review focusing on some of the critical aspects of the brake rotor design. Previous work showed the Cast Iron brake rotors reached peak temperatures as high as 410°C under transient conditions.

Researchers underpinned the Brake Squeal as one of the critical issues the industry is facing due to the double modes it can create, which will result in undesirable noise and that it falls in the frequency that is audible to human ears.

The double modes in the brake system will result in higher amplitudes that will lead to the vibration of the full brake system components. Experimental results should be carried out in conjunction with theoretical/CAE in order to ensure there is a close correlation. One of the experimental results showed the brake pad and rotor created double mode as shown in Figure 54.

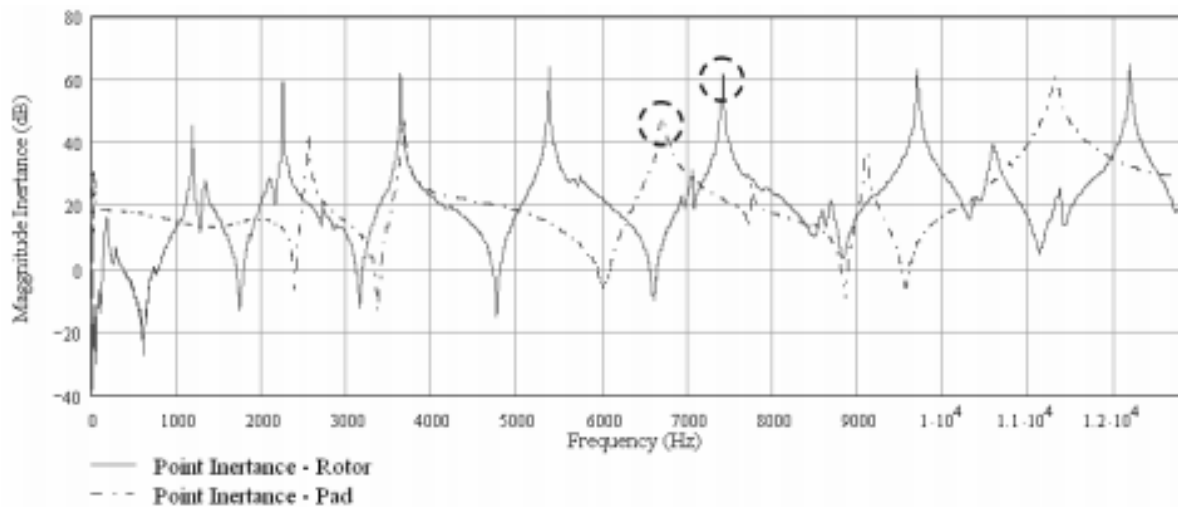


Figure 54. Point of Interference - Brake Rotor and pad

The third bending mode of pad and the 60th bending mode of disc shows the point of close interference. This, however, should be avoided and was able to identify via the theoretical analysis.

5.2 Frequency analysis review:

Fine mesh size showed high stiffness for any given design and is well within the region that is audible for human noise. Recalling the earlier research that suggested that any parts that brake rotor operating in the range 1 to 16 kHz will be responsible for brake squeal. Results obtained will ensure there is no squeal issues for mode shapes until 8. Mode shapes 9 and 10 for 1.67mm mesh size show theoretical possibility of squeal which will need modification of the geometry to avoid such concerns. However, an appropriate mesh size is to be determined by an average method. Mesh size over 5mm will mean the frequency of brake rotor will increase and there is a tendency it may fall within the range of brake squeal, which is undesirable.

5.3 Thermal analysis review:

Five designs were considered for the thermal analysis to understand the effect of braking events. Transient analysis with 3 seconds braking time is considered. Slotted cuts design showed the lowest surface temperature at the brake pad interface. From the results obtained it was noticed more surface operations will reduce the surface area available for friction between rotor and pads and this will have an impact on increased stress.

One of the reasons for high thermal stresses is there are more number of sharp corners on each of such features, which will act as stress raisers. Hence the sharp corners should be avoided.

The results obtained are closely comparable to previous results obtained by research carried out by other authors, which confirms the design is reliable from a thermal stress point of view.

Chapter 6 – Future work:

A number of learning and observations are gathered from the analysis carried out. Detailed discussions are discussed below.

1. Error in Thermal results – Negative temperatures were seen on the rotor surface at the interface of the brake pad. To resolve the issue, a simple cylinder of Cast Iron is subjected to similar boundary conditions, which resulted in similar negative values. This is one of the major drawbacks seen from the Solid works software. Upon switching to Absolute Maximum Temperature, the values closely resemble to results obtained from previous researchers. Evidence for this study is provided with snap shots as per below.
2. Hand calculations from beginning – more detailed hand calculations need to be considered as this will enable comparison with simulation results. However, basic hand calculations are considered which will suffice the requirements. As recommended, Matlab calculations need to be considered, which will enable an in-depth understanding of the thermal behaviour. This activity should be carried out at the initial stages of the work due to the long lead time activity.
3. Fine mesh takes a long time –it is understood earlier that the size of mesh determines the frequency results. However, an associated issue with this is the high computation time that the analysis will consume when fine mesh is used. This is significantly more for complex geometries. One of the rotor design consumed over 2 hours when subjected to simulation with fine mesh option. Hence the recommendation is to decide the type of application the results are needed and then use the version that will need analysis to be run with fine mesh. This will allow to run fine mesh only for the version that is of interest. Fine mesh sometimes has crashed the computer due to high consumption of resources.
4. CFD analysis on rotor – In actual operation, brake rotor will have constant air flow around and this is needed to be considered in the analysis. The current analysis considered only the Heat Power generated due to brake pad interaction and not the air flow around it. Since the air flow around the rotor will have an effect on the cooling, the thermal performance should be better when designed with adequate cooling. Since this is one of the drawbacks to the problem, it is recommended to consider that along with Thermal analysis for more accurate and realistic results.

Chapter 7 – Conclusion:

The enclosed work used theoretical hand calculations and Solid works tool to carry out a Brake Rotor design and analysis. Two types of analysis were carried out with the use of Finite Element analysis that resulted in results that could be closely correlated with results obtained by other researchers.

The work included the use of vehicle mass 1800 Kgs travelling at 70 mph as a maximum speed. Using the hand calculations, the Kinetic Energy is determined and eventually a number of parameters were determined and is presented in Table 1.

Using the literature review, the structural response, the heat conduction and convection aspects of the brake rotor is studied following which Cambridge Engineering Selector material selection tool is used to choose the material. From the analysis, Gray Cast Iron offered the best fit.

For the considered load case (1800 kg vehicle mass), thermal study and frequency analysis is carried out. Thermal study showed a peak temperature of 401.19°C for a drilled hole design and 389.96 °C for slotted cuts. The results closely match the previously carried out research. Hence the results are highly reliable and the recommended finite element analysis can produce acceptable results.

However, big differences were seen in the frequency analysis for 1.67mm and 5mm mesh size. From the results obtained, it is concluded that a large mesh size will lead to high frequency response and the target to avoid brake squeal is to keep the frequency below 1 kHz.

A list of recommendations is provided based on the experience that is gained during the analysis and is presented in the earlier section. For more accurate and reliable results, it is recommended to follow them in the future.

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