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Harmonic and Modal Analysis of Brake Drum with Different Grades of Cast Iron by using Finite Element Analysis

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ABSTRACT. Brake drums are critical components in vehicle braking systems, responsible for converting kinetic energy into thermal energy through friction. However, their operation is often accompanied by undesirable vibrations and noise, commonly known as brake squeal. These phenomena degrade performance, reduce component lifespan, and negatively impact passenger comfort. The dynamic behavior of a brake drum, particularly its susceptibility to vibration, is significantly influenced by its material properties and geometry. Cast iron is the predominant material for brake drums due to its favorable thermal and mechanical characteristics. However, different grades of cast iron possess varying properties that can affect their dynamic response. This study employs Finite Element Analysis (FEA) to investigate the modal and harmonic characteristics of a standard brake drum geometry when manufactured from three different grades of cast iron. Modal analysis determines the natural frequencies and corresponding mode shapes, which are intrinsic dynamic properties indicative of resonance potential. Harmonic analysis assesses the frequency response of the drum under typical braking excitation forces across a relevant frequency range, revealing its susceptibility to forced vibrations. By comparing the natural frequencies, mode shapes, and frequency response curves obtained for each cast iron grade, this research provides insights into how material selection influences brake drum dynamic performance. The findings contribute to a better understanding of the relationship between cast iron microstructure, mechanical properties, and vibrational behavior, offering valuable guidance for material selection and design modifications aimed at mitigating brake drum noise and vibration issues.

I. INTRODUCTION

Brake systems are essential for vehicle safety, facilitating deceleration and stopping. Drum brakes, a common type, achieve braking by pressing shoes lined with friction material against the inner surface of a rotating drum [3]. While effective, this friction-based mechanism is inherently prone to generating vibrations and noise.

The dynamic characteristics of each component, particularly the brake drum, play a substantial role in whether unstable vibrations manifest. The structural dynamics, including natural frequencies and damping capacity, dictate how the drum responds to the excitation forces generated during braking. Understanding and controlling these dynamic characteristics are crucial steps toward reducing or eliminating brake noise and vibration problems.

Brake squeal is a high-frequency noise caused by friction-induced vibrations, often linked to the coupling of natural frequencies between the drum and lining. Brake noise has been divided into three categories [6]

The three categories of brake noise based on frequency are:

1.Low-frequency noise (below 1 kHz)
2.Mid-frequency noise (between 1 kHz and 5 kHz)
3.High-frequency noise (above 5 kHz)
This classification helps in understanding the nature of the noise and its potential causes, which is crucial for developing effective solutions to mitigate brake noise issues.
Natural frequencies and mode shapes of drum will be determined by using ANSYS.
The material properties of the brake drum-such as vibration damping, strength, and wear resistance-play a critical role in its dynamic behavior and noise characteristics.
This project aims to analyze and compare the modal and harmonic responses of brake drums made from three different grades of cast iron: Grey Cast Iron, Nodular Cast Iron, and Ductile Cast Iron.
The goal is to identify which material offers the best performance in terms of vibration damping, structural integrity, and noise reduction
The findings will help engineers and researchers design quieter, safer, and more reliable braking systems for heavy-duty vehicles, ultimately contributing to better urban environments and improved vehicle performance.

II. LITERATURE REVIEW

Spurr (1961) stated that the primary cause of drum brake squealing is the state of the linings. Additionally, he noted that the temperature differential in the linings during operation, particularly with repeated use [1].

Johan Hultén's research on drum brakes identifies four mechanisms generating unstable waves in different directions. Their superposition tends toward a stable standing wave, which is always stable. Every step toward a standing wave is a step toward stability. This suggests that encouraging the formation of standing waves can help eliminate brake squeal at the source.

Day and Kim (1996) used finite element modal analysis on a drum brake with a S-cam shaft in heavy commercial vehicles to address noise issues. They found that drum asymmetry has a greater impact on natural frequencies and noise than the stiffness of the parts or contacts [2].

Phatak and Kulkarni (2017) presented a drum brake noise problem solution in passenger cars by using finite element vibration analysis [4].

2.1 Conclusions/Findings from literature review
Cast iron, nodular cast iron, and ductile cast iron are commonly used materials for brake drums due to their good casting properties, vibration damping, wear resistance, and machinability. The choice of material affects the dynamic response of the brake drum, including its natural frequencies and vibration damping capability. Lighter materials with higher natural frequencies are generally preferable for reducing noise and improving performance. Structural modifications, such as the addition of stiffeners or changes in drum geometry, can shift natural frequencies and alter mode shapes, helping to avoid resonance with excitation frequencies. The contact stiffness between drum and lining is important for brake squeal. Brake squeal is proportional to friction coefficient between drum and lining. Squeals generally arise if the modal characteristics of drum and shoes are near to the coupled vibration frequency. Brake spider is critical for noise reduction.Phatak and Kulkarni shifted the natural frequency from high natural frequency to low natural frequency by modifying the geometries of the spider.

III. OBJECTIVES

1. To evaluate and compare the natural frequencies, vibration behavior, and dynamic stability of the brake drum for three different materials
2. To enhance safety, improve braking performance, extend component lifespan, reduce repair costs, and meet regulatory standards
3. To obtain free vibration characteristic of non-simplified drum and Lining by using finite element analysis.
4. To present parametric studies of vibration analysis by using finite element analysis.

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IV. METHODOLOGY

4.1 Preprocessing (Preparation)
Import the STEP File from Creo 9.0 to Ansys 2019. Select the drum material - From Engineering - Gray Cast Iron, Nodular Cast Iron and Ductile Cast Iron to Drum. Then From Toolbox Select - Static Structural Analysis. Provide Meshing to the Geometry. After that Applying the Boundary Conditions Fix the drum supports of the Bolting Plate of the Drum. Apply appropriate Pressure. Selecting Modal Analysis Form the Toolbox. Creating 6 Modes For in a gradual Increasing Frequencies for the Drum Analysis. Selecting Harmonic Analysis Form Toolbox. Applying Min. and Max. Rage of the Frequency. Selecting Random Vibration Analysis from Toolbox.

4.2 Processing (Solution)
In Static Structural Solution Insert: -Total Deformation, and Equivalent Stress to get the Deformation Results. In Modal Analysis Solution According to 6 Modes Frequencies Insert the Total Deformation 1- 6 to analyze Drum Walls Displacements in Different Frequency. In Harmonic analysis Solution Insert the Frequency Response Graph to check The Total Deformation of Drum in Amplitude and Frequency & Phase Angle and Frequency Chart.

Modal Analysis:
Analyze to identify unstable modes that can lead to squeal. Assess the effectiveness of damping measures like shims in reducing squeal through modal analysis.

Harmonic Analysis:
Analyze the steady-state response of the drum brake to sinusoidal excitation at different frequencies. Identify the frequencies at which maximum vibrations and noise occur. Evaluate the Results from the Tests Report. After this analysis, you will get the precise and Optimum Design for Drum of three different materials.

V. MODELING AND ANALYSIS/FABRICATION OF SYSTEM

5.1 Drum CAD Model & Drawing

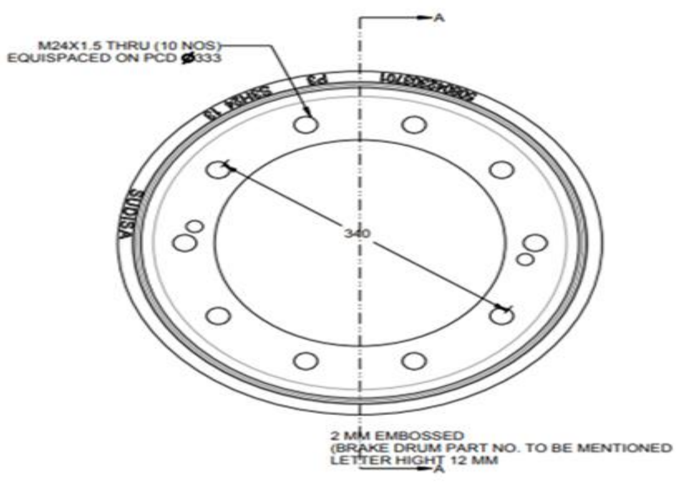

Figure1. Drawing of the brake drum with dimensions

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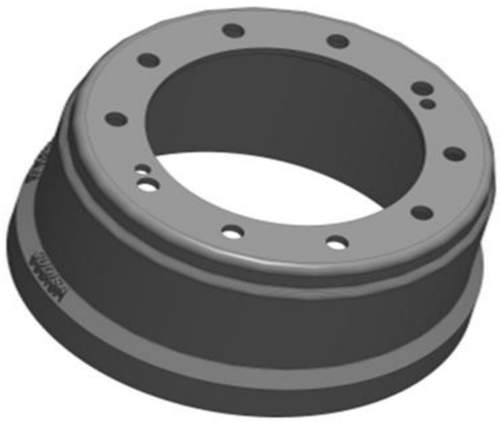

Figure 2. Brake drum CAD model

Made a CAD Modeling and Manufacturing Drawing according to the drum dimensions. Import the model in the ANSYS 2019 version select the geometry in Modal Analysis and the Harmonic Analysis from the analysis tree and regenerate.

5.2.1 Material Selection of the Brake Drum: -
Before the finite element analysis of the brake drum, its material parameters need to be defined.
The first material used for the brake drum is Gray cast iron. Gray Cast iron has good casting properties, good vibration damping, good wear resistance, good machinability, and low notch sensitivity.

5.2.2 Material Selection of the Brake Drum: -

Properties of Outline Row 4: Gray Cast Iron

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	7200	kg m^-3		
4	Isotropic Secant Coefficient of Thermal Expansion				
6	Isotropic Elasticity				
7	Derive from	Young's Modulus and Poisson...			
8	Young's Modulus	1.1E+11	Pa		
9	Poisson's Ratio	0.28			
10	Bulk Modulus	8.3333E+10	Pa		
11	Shear Modulus	4.2969E+10	Pa		
12	Tensile Yield Strength	0	Pa		
13	Compressive Yield Strength	0	Pa		
14	Tensile Ultimate Strength	2.4E+08	Pa		
15	Compressive Ultimate Strength	8.2E+08	Pa		

Figure 3. Materials Details

The Second material used for the brake drum is Nodular iron. Nodular iron has good casting properties, good vibration damping, good wear resistance, good machinability, and low notch sensitivity.

The material properties of nodular iron are

Properties of Outline Row 4: Cast iron, nodular

	A	B	C
1	Property	Value	Unit
2	Density	7370	kg m^-3
3	Isotropic Secant Coefficient of Thermal Expansion		
5	Isotropic Elasticity		
6	Derive from	Young's Modulus and Poisson's Ratio	
7	Young's Modulus	1.22E+11	Pa
8	Poisson's Ratio	0.275	
9	Bulk Modulus	9.037E+10	Pa
10	Shear Modulus	4.7843E+10	Pa
11	Tensile Yield Strength	2.34E+08	Pa
12	Tensile Ultimate Strength	4.26E+08	Pa

Figure 4. Material Properties

5.2.3 Material Selection of the Brake Drum: -

The third material used for the brake drum is Ductile Cast Iron. Ductile Cast Iron has good casting properties, good vibration damping, good wear resistance, good machinability, and low notch sensitivity.

The material properties of Ductile Cast Iron are

Properties of Outline Row 3: Cast iron, ductile

	A	B	C	D	E
1	Property	Value	Unit		
2	Density	7130	kg m^-3		
3	Isotropic Secant Coefficient of Thermal Expansion				
5	Isotropic Elasticity				
6	Derive from	Young's Modulus and Poisson's Ratio			
7	Young's Modulus	1.71E+11	Pa		
8	Poisson's Ratio	0.275			
9	Bulk Modulus	1.2667E+11	Pa		
10	Shear Modulus	6.7059E+10	Pa		
11	Tensile Yield Strength	3.44E+08	Pa		
12	Tensile Ultimate Strength	5.48E+08	Pa		

Figure 5. Materials Details

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5..3 Static Structural Analysis of Brake Drum

The default meshing method is used to mesh the brake drum. After meshing, the finite element model is obtained. The brake drum has 136018 nodes and 83051 elements

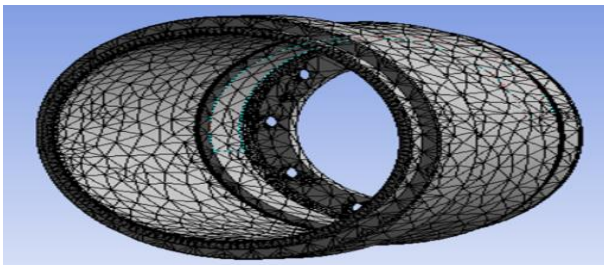


Figure 6. Meshing of brake drum

Fixed Support: -During the braking process, the bolt holes of the brake drum are fixed, so the ten bolt holes are fixed.

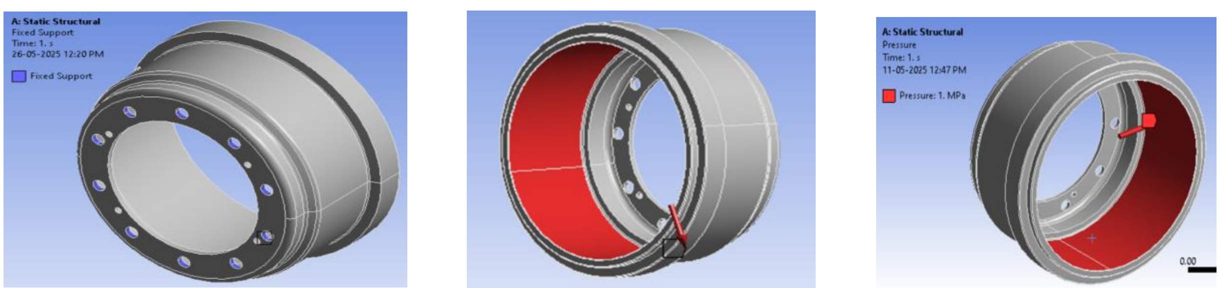
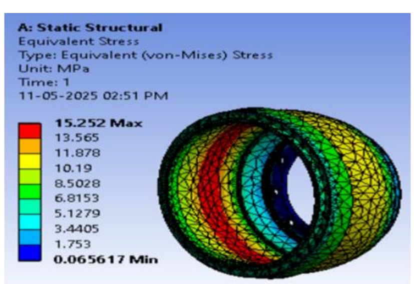


Figure 7. Applying Boundary Conditions on Fixing of bolt holes

In the process of braking, the pressure from the brake shoe is applied around the brake drum, so a pressure of 1 MPa is applied around the brake drum. The static analysis of the brake drum is carried out, and the equivalent stress and deformation are obtained for three different materials

5.4.1 For Grey Cast Iron



Tabular Data

	Time [s]	Minimum [MPa]	Maximum [MPa]	Average [MPa]
1	1.	6.5617e-002	15.252	6.583

Figure 8. Equivalent stress of the grey cast iron brake drum

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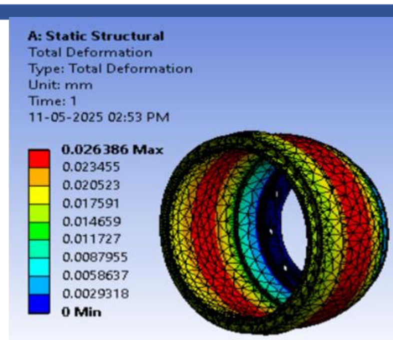
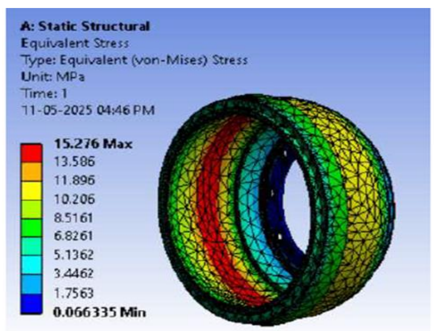


Tabular Data

	Time [s]	Minimum [mm]	Maximum [mm]	Average [mm]
1	1.	0.	2.6386e-002	1.4237e-002

Figure 9. Deformation of the grey cast iron brake drum

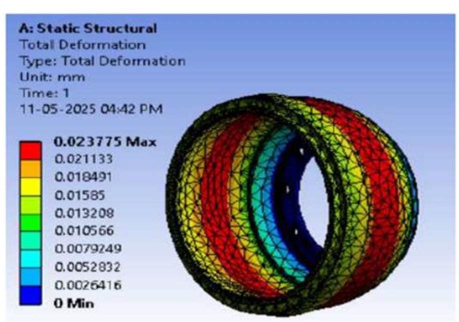
5.4.2 For Nodular Cast Iron



Tabular Data

	Time [s]	Minimum [MPa]	Maximum [MPa]	Average [MPa]
1	1.	6.6335e-002	15.276	6.5806

Figure 10. Equivalent stress of the nodular cast iron brake drum

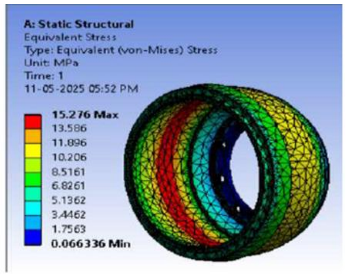


Tabular Data

	Time [s]	Minimum [mm]	Maximum [mm]	Average [mm]
1	1.	0.	2.3775e-002	1.2817e-002

Figure 11. Deformation of the nodular cast iron brake drum

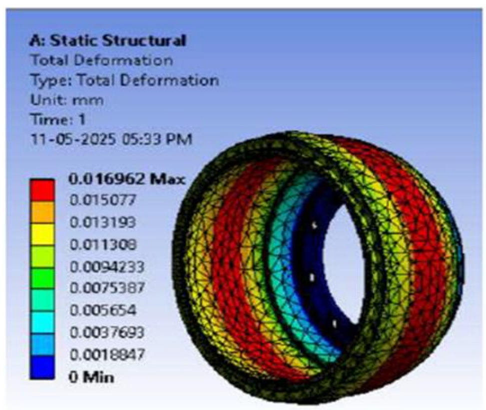
5.4.3 For Ductile Cast Iron



Tabular Data

	Time [s]	Minimum [MPa]	Maximum [MPa]	Average [MPa]
1	1.	6.6336e-002	15.276	6.5806

Figure 12. Equivalent stress of the ductile cast iron brake drum



Tabular Data

	Time [s]	Minimum [mm]	Maximum [mm]	Average [mm]
1	1.	0.	1.6962e-002	9.144e-003

Figure 13. Deformation of the ductile cast iron brake drum

It can be seen from the equivalent stress of the brake drum that the maximum equivalent stress appears on the friction surface between the brake drum and the friction plate, and the stress concentration on the brake drum conforms to the actual situation

For gray cast iron the maximum stress is 15.252 MPa, and the ultimate tensile strength is 240 MPa, so the brake drum fully meets the strength requirements.

For nodular cast iron the maximum stress is 15.276 MPa, and the ultimate tensile strength is 234 MPa, so the brake drum fully meets the strength requirements.

For ductile cast iron the maximum stress is 15.276MPa, and the ultimate tensile strength is 344 MPa, so the brake drum fully meets the strength requirements.

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It can be seen from the deformation of the brake drum in figure 4 that the deformation of the bolt hole is small. The maximum deformation occurs at the outermost side of the contact surface between the brake drum and the friction plate,
The maximum deformation of grey cast iron is 0.026386 mm.
The maximum deformation of nodule cast iron is 0.023775 mm.
The maximum deformation of ductile cast iron is 0.016962 mm.

5.5 Modal Analysis of the Drum Brake

In the modal analysis of drum brake, fixed constraints are imposed on the brake drum according to the actual working conditions to simulate the actual working conditions.
The rotating element is the brake drum, and the inner surfaces of the ten bolt holes of the brake drum need to be fixed to make the simulation results more realistic.
We created 6 mode shapes of each material, showing how the drum vibrates at each natural frequency of each material.
For grey cast iron, the mode shapes help identify potential resonance conditions that could cause brake squeal. Lower natural frequencies and higher amplitudes suggest a higher tendency for noise issues compared to other materials.
Mode shape images for nodular cast iron will generally show higher natural frequencies and lower vibration amplitudes than grey cast iron. This means nodular cast iron is less likely to resonate within the typical excitation frequency range, reducing the risk of brake squeal.
The mode shape images for ductile cast iron will show the highest natural frequencies and the lowest vibration amplitudes. This material is the most resistant to resonance and vibration-induced noise, making it optimal for minimizing brake squeal and improving durability.

5.6.1 Mode shapes of gray cast iron

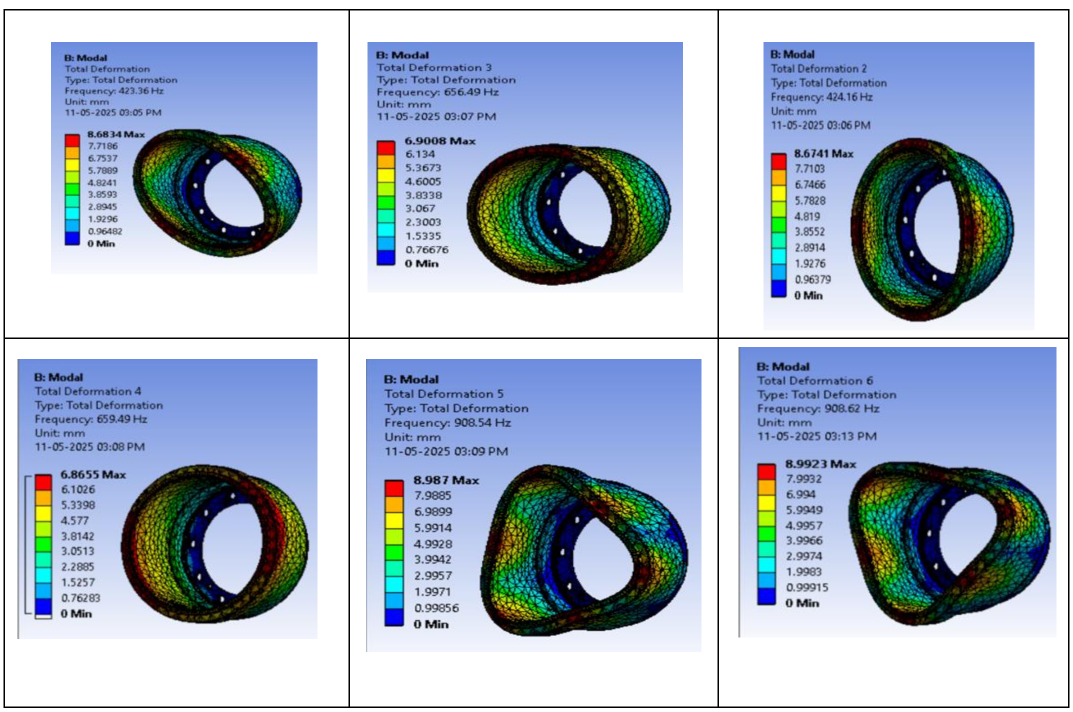

Figure 14. The result of modal analysis of grey cast iron

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5.6.2 Mode shapes of nodular cast iron

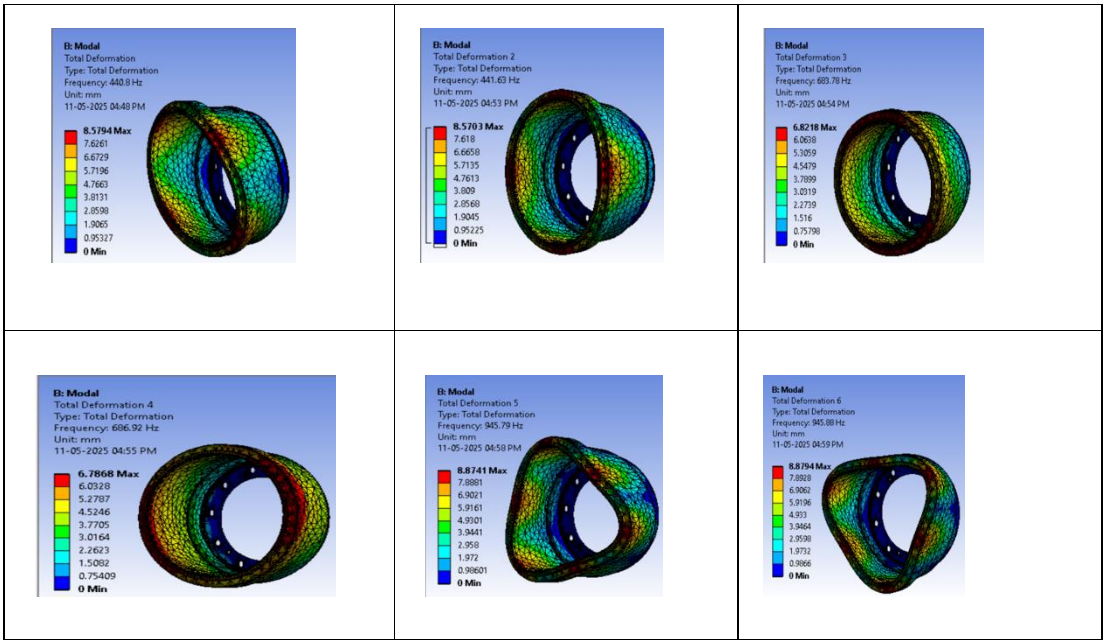

Figure 15. The result of modal analysis of nodular cast iron

5.6.3 Mode shapes of Ductile cast iron

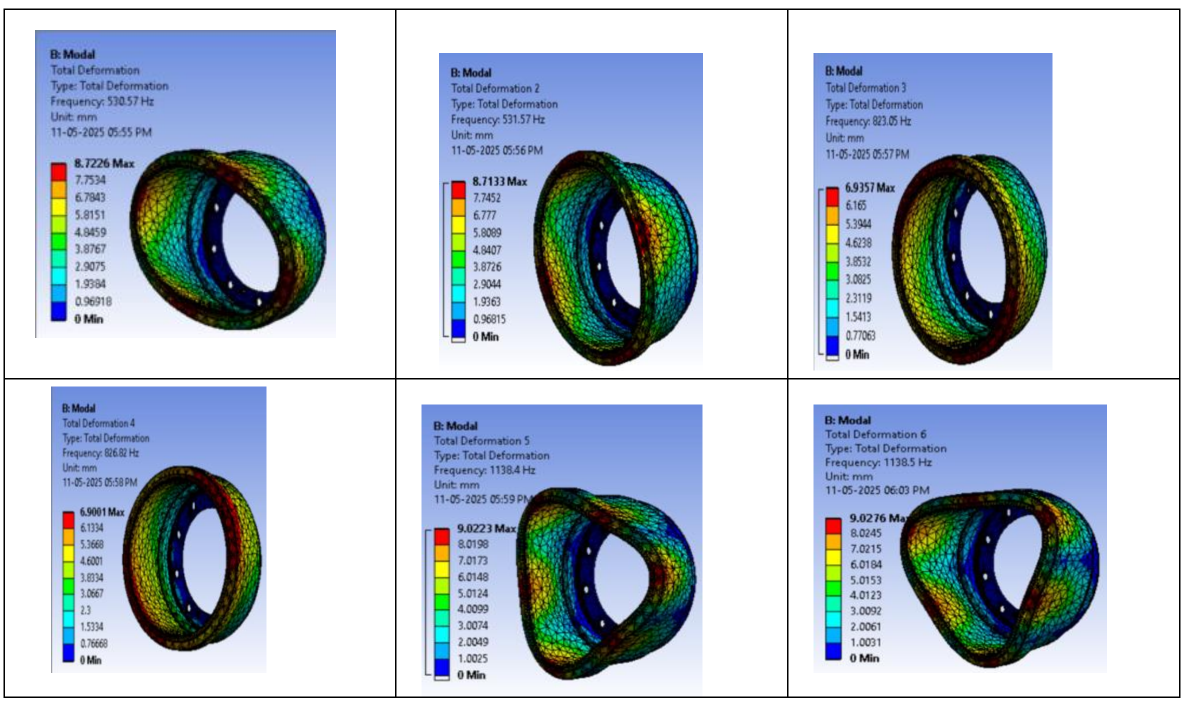

Figure 16. The result of modal analysis of ductile cast iron

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5.8 Harmonic Response Analysis of Brake Drum

In the Harmonic analysis of drum brake, fixed constraints are imposed on the brake drum according to the actual working conditions to simulate the actual working conditions

Maximum amplitude shows forced vibration which causes this much amplitude at respective frequency.

We should make sure that our natural frequency never matches with this forced vibration otherwise it will create resonance

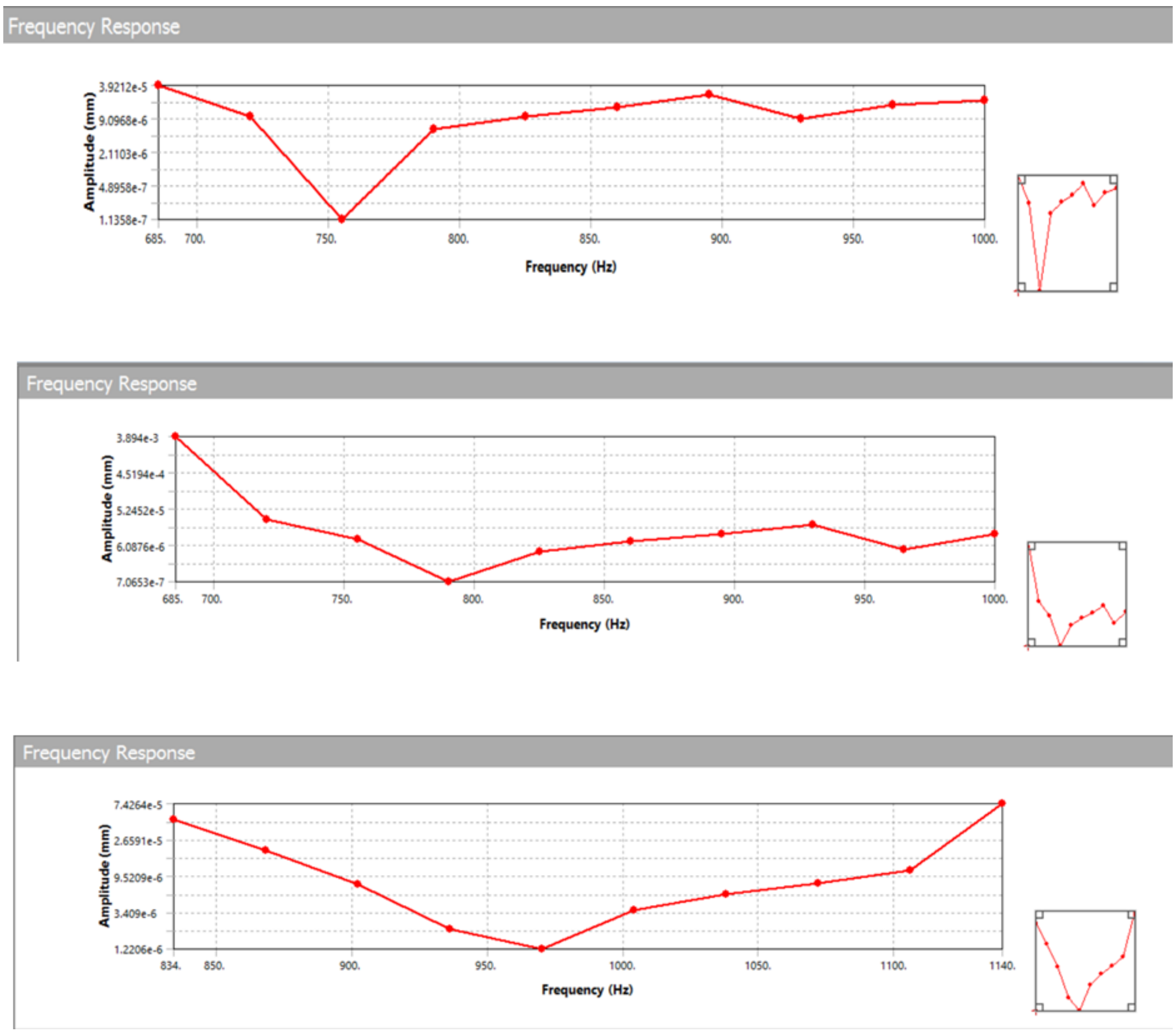

Figure 17. frequency response curve a) gray cast iron b) nodular cast iron c)ductile cast iron

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VI. RESULTS AND DISCUSSION OF RESULTS

6.1.1 Natural frequencies of gray cast iron brake drum

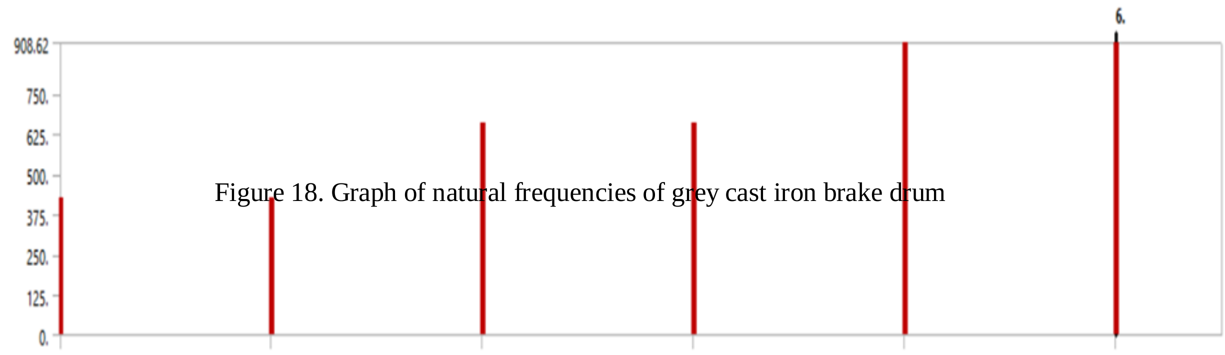

Figure 18. Graph of natural frequencies of grey cast iron brake drum

Figure 19. Analysis settings

Details of "Analysis Settings"

Options	
Frequency Spacing	Linear
Range Minimum	650. Hz
Range Maximum	1000. Hz
Solution Intervals	10
User Defined Frequencies	Off
Solution Method	Mode Superposition
Include Residual Vector	No
Cluster Results	No
Modal Frequency Range	Program Controlled
Store Results At All Frequencies	Yes

Figure 20. Frequency vs Amplitude tabular data

Tabular Data

	Frequency [Hz]	Amplitude [mm]	Phase Angle [°]
1	834.	1.5816e-005	0.
2	868.	2.062e-005	0.
3	902.	4.4983e-005	0.
4	936.	1.5754e-005	0.
5	970.	2.2006e-005	0.
6	1004.	2.6221e-005	0.
7	1038.	3.053e-005	0.
8	1072.	3.5602e-005	0.
9	1106.	4.2116e-005	0.
10	1140.	5.1193e-005	0.

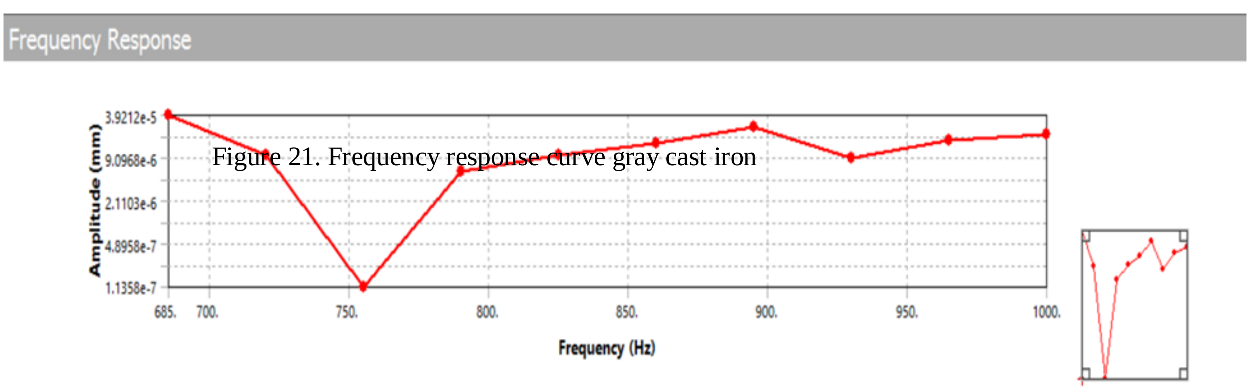

Figure 21. Frequency response curve gray cast iron

A sharp peak at a relatively lower frequency range indicates a high amplitude of forced vibration. Gray cast iron is more prone to resonance due to its lower damping and lower natural frequencies. This makes it less ideal for noise control. The

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resonance lies close to operational vibration ranges, making gray cast iron more likely to produce brake squeal under certain conditions.

The curve shows higher amplitudes at resonance compared to other materials, reflecting its lower damping capacity and higher tendency to vibrate. This means grey cast iron drums are more susceptible to brake squeal if the operating frequencies of the brake system coincide with these resonance peaks

Figure 22. Phase angle vs frequency

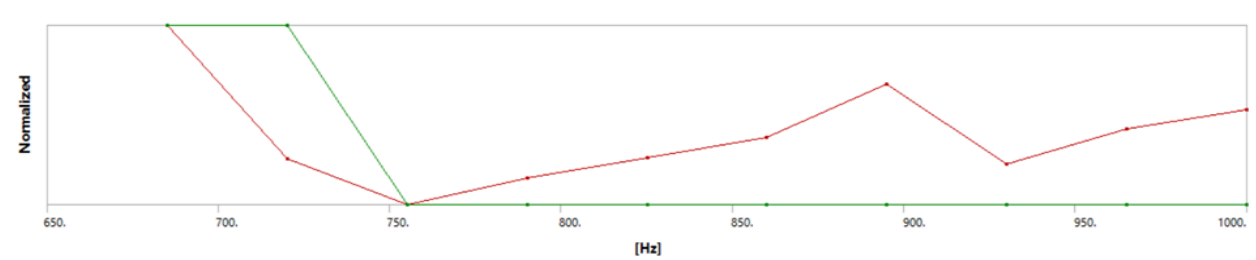

Figure 23. Normalized graph

7.1.2 Natural frequencies of nodular cast iron brake drum

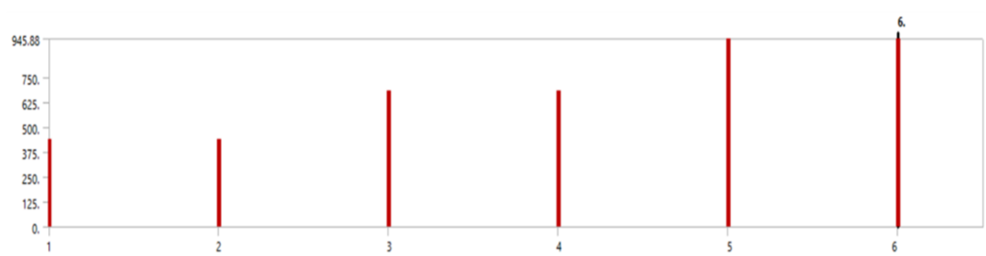

Figure 24. Graph of natural frequencies of nodular cast iron brake drum

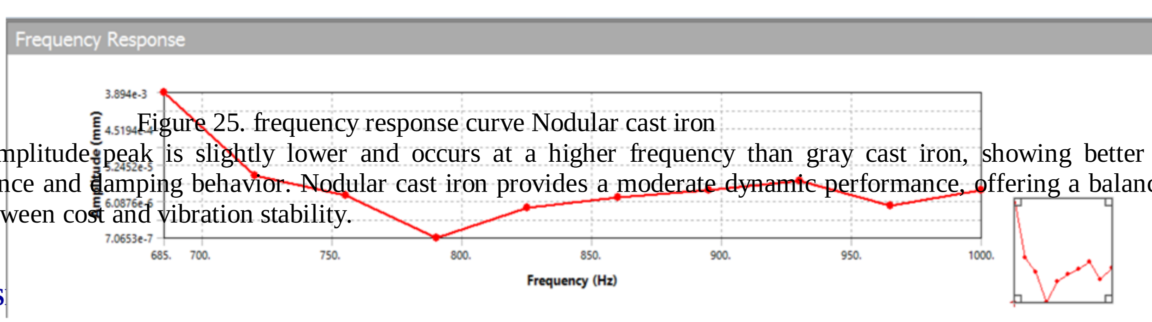

Figure 25. frequency response curve Nodular cast iron

The amplitude peak is slightly lower and occurs at a higher frequency than gray cast iron, showing better vibration resistance and damping behavior. Nodular cast iron provides a moderate dynamic performance, offering a balanced trade-off between cost and vibration stability.

Compared to grey cast iron, the resonance peaks are lower, indicating improved damping and a reduced tendency for excessive vibration. This is due to the spherical (nodular) graphite structure in the material, which interrupts crack propagation and enhances both strength and vibration damping. As a result, nodular cast iron brake drums are less likely to experience problematic resonance and brake squeal within the typical operating frequency range.

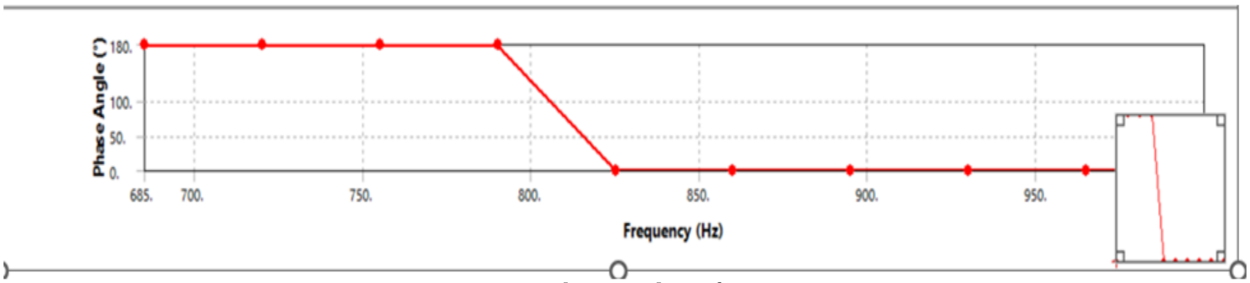

Figure 26. Phase angle vs frequency

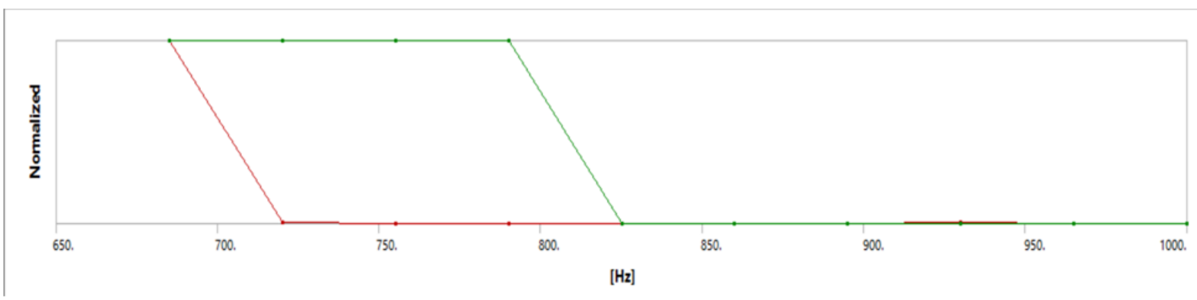

Figure 27. Normalized graph

6.1.3 Natural frequencies of ductile cast iron brake drum

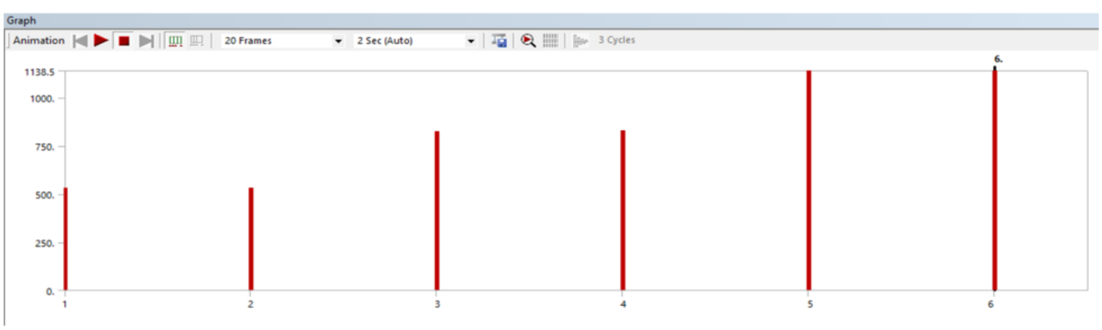

Figure 28. Graph of natural frequencies of ductile cast iron brake drum

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Details of "Analysis Settings"

Options	
Frequency Spacing	Linear
Range Minimum	800. Hz
Range Maximum	1140. Hz
Solution Intervals	10
User Defined Frequencies	Off
Solution Method	Mode Superposition
Include Residual Vector	No
Cluster Results	No
Modal Frequency Range	Program Controlled
Store Results At All Frequencies	Yes

Figure 29. Analysis settings

Tabular Data

	Frequency [Hz]	Amplitude [mm]	Phase Angle [°]
1	834.	4.7194e-005	180.
2	868.	1.9911e-005	180.
3	902.	7.6993e-006	180.
4	936.	2.1451e-006	180.
5	970.	1.2206e-006	0.
6	1004.	3.6669e-006	0.
7	1038.	5.7458e-006	0.
8	1072.	7.8995e-006	0.
9	1106.	1.1354e-005	0.
10	1140.	7.4264e-005	180.

Figure 30. Frequency vs Amplitude tabular data

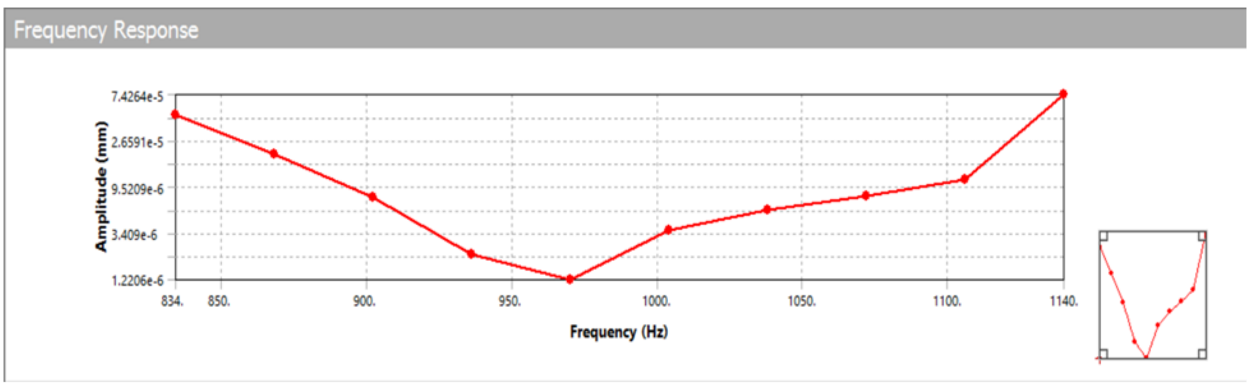

Figure 31. frequency response curve ductile cast iron

The ductile cast iron curve displays the lowest resonance peaks among the three materials. This indicates the highest damping capacity and the best resistance to vibration-induced resonance. Ductile cast iron's microstructure, with a high percentage of spheroidal graphite nodules, provides superior mechanical properties and vibration damping. Therefore, drums made from ductile cast iron are least likely to experience high vibration amplitudes, making them optimal for noise reduction and durability in high-performance or heavy-duty applications.

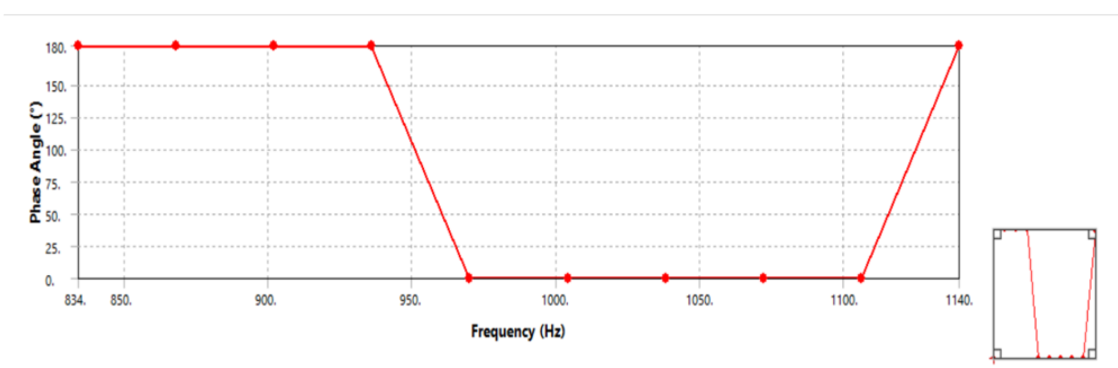

Figure 32. Phase angle vs frequency

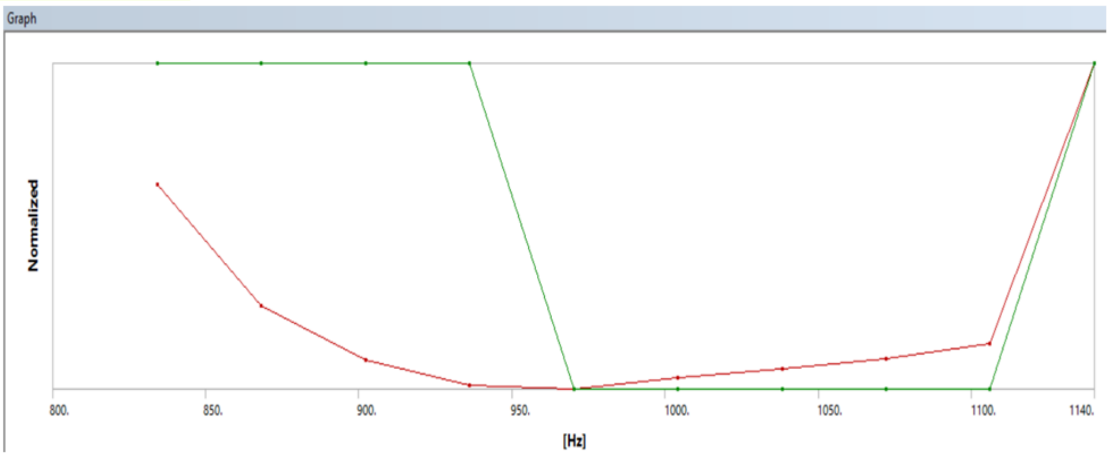

Figure33. Normalized graph

Table 1. Key mechanical properties influencing load-bearing capacity, deformation resistance, and vibration damping in brake drums

Property	Gray Cast Iron	Nodular Cast Iron	Ductile Cast Iron
Ultimate Tensile Strength (MPa)	240 Mpa	234 Mpa	344 MPa
Max. Equivalent Stress (MPa)	15.252 Mpa	15.276 Mpa	15.276 Mpa
Max. Deformation (mm)	0.026386 mm	0.023775 mm	0.016962 mm
Vibration Damping	Good	Good	Good
Dynamic Performance	Lowest	Moderate	Highest
Cost	Lowest	Moderate	Highest

Table 2. Comparative analysis of material properties to assess suitability for heavy-duty brake drum applications

Grey Cast Iron	Harmonic Response	Higher resonance peaks, more vibration, higher risk of squeal due to lower damping.
Nodular Cast Iron	Harmonic Response	Lower resonance peaks than grey cast iron, improved damping, reduced risk of squeal.
Ductile Cast Iron	Harmonic Response	Lowest resonance peaks, best damping, minimal vibration and squeal risk, best for heavy-duty and high-performance use.

VII. CONCLUSION

In this project, we performed harmonic and modal analysis of a brake drum using three different materials to investigate their dynamic behavior under vibrational loading conditions. The study revealed key differences in natural frequencies, mode shapes, and vibrational responses depending on the material properties.Ductile Cast Iron exhibited the highest natural frequencies among the three materials, indicating better resistance to vibration-induced resonance and superior dynamic performance.

Nodular Cast Iron: showed improved vibration behavior compared to Gray Cast Iron, due to its enhanced toughness and ductility, but slightly lower performance than Ductile Cast Iron.Gray Cast Iron: while still acceptable, showed lower natural frequencies and higher vibrational amplitudes, making it less ideal for high-performance or heavy-duty applications.

Ductile Cast Iron is the most suitable material for brake drum applications where higher vibrational stability and durability are required. However, considering manufacturing cost and traditional use, Gray Cast Iron remains a practical choice for standard vehicles where extreme dynamic performance is not critical.This project also investigates the hypothesis that optimizing brake drum design and material properties can reduce brake squeal in heavy-duty vehicles. Brake squeal is a key source of environmental noise.

Harmonic and modal analysis using FEA helps determine natural frequencies and vibration modes responsible for brake squeal. When these natural frequencies align with forced vibrations, resonance occurs, amplifying the noise and vibrations. The study identifies effective strategies to mitigate squeal, including modifying brake geometry and materials and introducing damping measures like vibration dampers to absorb excessive vibrations.

Enhanced brake designs improve vehicle safety, reduce noise pollution, lower maintenance costs, and comply with environmental standards, making them both economically and ecologically beneficial.This study highlights the importance of selecting the right material based on the intended operational requirements of the brake system to enhance safety, reliability, and service life.
Future research can focus on testing innovative materials, conducting field tests under real-world conditions.

IX. SCOPE FOR FUTURE WORK

The detailed modal and harmonic analysis results for three different grades of cast iron provide a valuable reference for future studies. Researchers can use this data as a baseline when exploring new materials or design modifications for brake drums.

The step-by-step methodology-from data collection and CAD modeling to simulation setup in ANSYS-serves as a practical guide for researchers aiming to conduct similar finite element analyses. This can help others replicate, validate, or extend this work with different parameters or materials.
By comparing grey cast iron, nodular cast iron, and ductile cast iron, this project highlights the strengths and weaknesses of each material in terms of vibration damping, stress distribution, and suitability for heavy-duty applications. This information is crucial for material selection in both academic research and industry projects.

By categorizing noises, researchers and engineers can analyze the contributing factors for each type and implement targeted strategies for noise reduction.

Implement various damping measures to reduce squealing.
By knowing natural frequency, we can control it by adding vibration dampers to absorb vibrations at high speed.
Research can focus on the material properties of brake drum, particularly how different materials respond to thermal and mechanical stresses during braking.

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Current studies are conducted using ANSYS simulations. Future work could focus on Field testing that examines the performance of drum brakes in varying environmental conditions and driving scenarios.

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