Design and Dynamic Analysis of Locomotive Wheel Axle

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Abstract:

A rolling component is typically pressed onto an axle and mounted directly on a locomotive or indirectly on a bogie.In this paper, in order to obtain the dynamic forces on the locomotive axle.The objective is to calculate the natural frequency and operating frequency of wheel axle of the locomotive is modulating those frequencies and avoiding resonance by using the harmonic response, thus the vibrations of wheel axle of the locomotive may reduce. Resonance [2] is a vibration phenomenon that occurs at certain rotor speeds when the wheel axle of the locomotive is on the work. The influence of wheel axle of the locomotive design resonance phenomenon is investigated by ANSYS software. In this paper, the 3D model of wheel axle of the locomotive is modelled in NX-CAD and imported into ANSYS software to perform static and dynamic analysis to analyze strength and dynamic characteristics [1]of wheel axle of the locomotive and optimize if required.

Key words: wheel axle, dynamic characteristics, harmonic response, resonance.

I. INTRODUCTION

A train wheel or rail wheel is a type of wheel specially designed for use on rail tracks. A rolling component is typically pressed onto an axle and mounted directly on a rail car or locomotive or indirectly on a bogie, called a truck. Wheels are cast or forged (wrought) and are heat-treated to have a specific hardness. New wheels are trued, using a lathe, to a specific profile before being pressed onto an axle. All wheel profiles need to be periodically monitored to insure proper wheel-rail interface. Improperly trued wheels increase rolling resistance, reduce energy efficiency and may create unsafe operation. A railroad wheel typically consists of two main parts: the wheel itself, and the tire (or tyre) around the outside. A rail tire is usually made from steel, and is typically heated and pressed onto the wheel, where it remains firmly as it shrinks and cools. Mono block wheels do not have encircling tires, while resilient rail wheels have a resilient material, such as rubber, between the wheel and tire.

1.1 Parts of rail wheel

Crank pin: A pin protruding from a wheel into a main or coupling rod.

Wheel for road –rail vehicle: Wheels used for Road-rail vehicles are normally smaller than those found on other types of rolling stock (such as locomotives or carriages). This is because the wheel has to be stored clear of the ground when the vehicle is in road-going mode - Such wheels can be as small as 245 mm (9.65 in) in diameter.

Cause of damage:

The most usual cause of damage is drag braking on severe gradients. Because the brake blocks apply directly on the tire, it is heated up, relaxing the interference fit. It is not feasible to fit the tire with such a heavy interference as to eliminate this risk entirely, and the retaining ring will ensure that the tire can only rotate on the wheel center, maintaining its alignment.

1.2. Experimental methodologies to design and verify the innovative wheel set:

With the need to optimise wheel set geometries and develop innovative materials [4] to reduce the non suspended masses and improve life cycle costs, the use of full scale test rigs has become necessary for final experimental design validation and for the product reliability guarantee

Experimental wheel homologation[3] is generally obtained by performing a static test on test rig BS500 where the same loads used in the wheel FEM calculation can be applied to half wheel set and strains can be measured by strain gauges placed on the web, from here the most damaging fatigue stress cycle can be calculated.

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1.3. Wheel Sets:

Wheel set comprises two wheels rigidly connected by a common axle. The wheel set is supported on bearings mounted on the axle journals.

The wheel set provides:

- The necessary distance between the vehicle and the track
- The guidance that determines the motion within the rail gauge, including at curves and switches
- The means of transmitting traction and braking forces to the rails to accelerate and decelerate the vehicle

The design of the wheel set depends on:

- The type of the vehicle (traction or trailing) † The type of braking system used (shoe brake, brake disc on the axle, or brake disc on the wheel)
- The construction of the wheel centre and the position of bearings on the axle (inside or outside)
- The desire to limit higher frequency forces by using resilient elements between the wheel centre and the tyre.

The main types of wheel set design are shown in Figure 1.

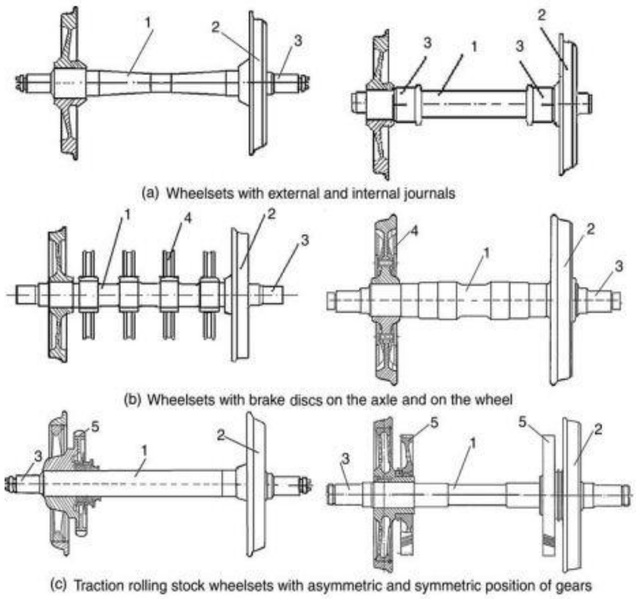

Fig.1. Main types of wheel set design: (a) with external and internal journals; (b) with brake discs on the axle and on the wheel; (c) with asymmetric and symmetric position of gears (1,axle; 2, wheel; 3, journal; 4, brake disc; 5, tooth gear).

1.4. Axle Boxes

The axle box is the device that allows the wheel set to rotate by providing the bearing housing and also the mountings for the primary suspension to attach the wheel set to the bogie or vehicle frame. The axle box transmits longitudinal, lateral, and vertical forces from the wheel set on to the other bogie elements.

Axle boxes are classified according to:

- Their position on the axle depending on whether the journals are outside or inside
- The bearing type used, either roller or plain bearings

Axle boxes[1] with plain bearing consist of the housing (1), the bearing itself (2) which is usually made of alloy with low friction coefficient (e.g., bronze or white metal), the bearing shell (3) which transmits the forces from the axle box housing to the bearing, a lubrication device (4) which lubricates the axle journal. Front and rear seals (5 and 6) prevent dirt and foreign bodies entering the axle box, while the front seal (6) can be removed to monitor the condition of the bearing and add lubricant.

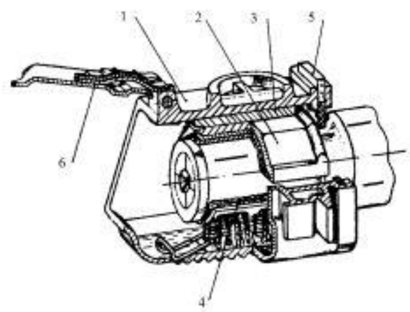

Fig.2 construction of an axle box with friction bearing.

Spherical bearings have not been widely applied due to their high cost and lower weight capacity, although they have a significant advantage is providing better distribution of load between the front and rear rows in case of axle bending.

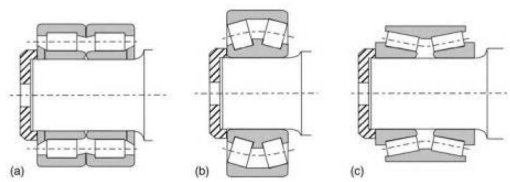

Fig.3 Constructions of roller bearings: (a) cylindrical double-row; (b) one-row self-alignment; (c) two-row conical.

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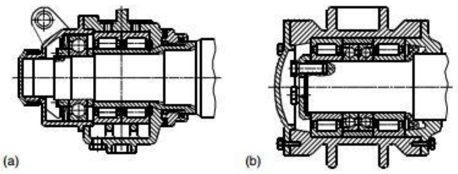

Fig.4 Use of spherical bearings: (a) triple bearing of Japanese high-speed trains; (b) triple bearing of French high-speed trains..

II PROBLEM DEFINITION AND METHODOLOGY

In this paper, main objective is to obtain the dynamic forces on the locomotive axle. It was recognized that axles suffer a great many dynamic load cycles as they rotate and in the early days many fanciful theories were proposed to explain why failures occurred after periods of successful service. The 3D model of wheel axle of the locomotive is modelled in NX-CAD and imported into ANSYS software to perform static and dynamic analysis to analyze strength and dynamic characteristics of wheel axle of the locomotive and optimize if required.

2.1. 3D modelling of rail wheel axle

The 3D model of the Rail wheel axle is created using UNIGRAPHICS NX software from the 2d drawings. UNIGRAPHICS NX is the world's leading 3D product development solution. This software enables designers and engineers to bring better products to the market faster. It takes care of the entire product definition to serviceability. NX delivers measurable value to manufacturing companies of all sizes and in all industries

2.2 2D drawing of Rail wheel axle:

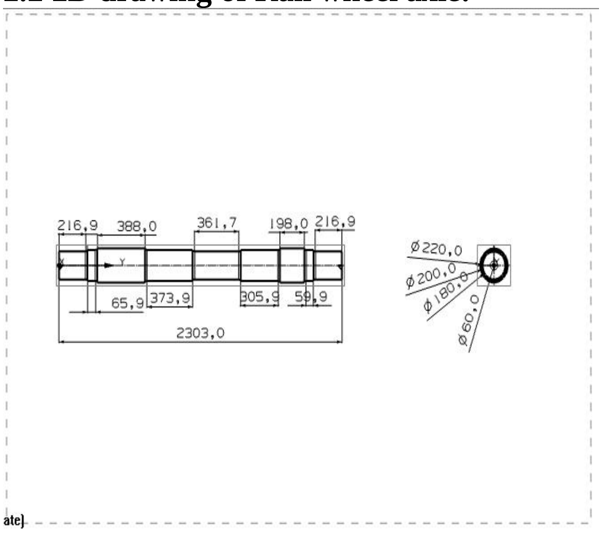

Fig.5. 2D drawing of Rail wheel axle

2.3 Methodology

The methodology followed in this project is as follows:

- Perform design calculations of rail wheel axle model.
- Create 3D model of the existing model of rail wheel axle from the 2D drawings. NX-CAD software is used to do the 3D modeling.
- Convert the 3D model into parasolid[5] format and import into ANSYS to do Finite element analysis.
- Perform Static analysis of the of rail wheel axle by applying the allowable axle load, and document the stresses and deflections.
- Perform Static analysis of the of rail wheel axle by applying the required axle load, and document the stresses and deflections.

2.4 3D Model of Rail wheel axle:

i) Side view of Rail wheel axle

Fig.6.The 3D model of Rail wheel axle (Right side view)

ii) Top view of Rail wheel axle

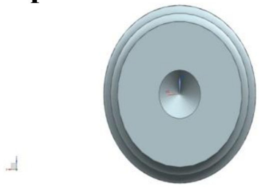

Fig.7.The 3D model of Rail wheel axle (top view)

iii) Isometric view of Rail Wheel Axle

Fig.8. The 3D model of Rail wheel axle (isometric view)

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III. FINITE ELEMENT ANALYSIS

3.1 Structural analysis of rail wheel axle

Finite Element Modelling (FEM) and Finite Element Analysis (FEA) are two most popular mechanical engineering applications offered by existing CAE systems. This is attributed to the fact that the FEM is perhaps the most popular numerical technique for solving engineering problems. The method is general enough to handle any complex shape of geometry (problem domain), any material properties, any boundary conditions and any loading conditions.

3.2 Finite element methods

The FEM is numerical analysis technique for obtaining approximate solutions to wide variety of engineering problems. The method originated in the aerospace industry as a tool to study stresses in complicated airframe structures. It grew out of what was called the matrix analysis method used in aircraft design. The method has gained popularity among both researchers and practitioners and after so many developments codes are developed for wide variety of problems.

3.3 Material properties

30 NiCrMoV12 steel properties are used to Rail wheel axle:

Young's Modulus (E) =180GPa

Poisson's Ratio = 0.3

Density = 8900Kg/mm3

Yield Strength = 490MPa

Element Type Used:

Element type: Solid92
No. of nodes: 10
Degrees of freedom: 6

3.4 Solid92 element description

SOLID92 [5] has a quadratic displacement behavior and is well suited to model irregular meshes (such as produced from various CAD/CAM systems). The element is defined by ten nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element also has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities.

3.5. Solid92 input data

The geometry, node locations, and the coordinate system for this element are shown in Figure "SOLID92 Geometry"[2]. Beside the nodes, the element input data includes the orthotropic material properties. Orthotropic material directions correspond to the element coordinate directions. The element coordinate system orientation is as described in Coordinate Systems. Element loads are described in Node and Element Loads. Pressures may be input as surface loads on the element faces as shown by the circled numbers on Figure "SOLID92 Geometry". Positive pressures act into the element. Temperatures and fluencies may be input as element body loads at the nodes. The node I temperature T(I) defaults to TUNIF. If all other temperatures are unspecified, they default to T(I). If all corner node temperatures are specified, each mid side node temperature defaults to the average temperature of its adjacent corner nodes. For any other input temperature pattern, unspecified temperatures default to TUNIF. Similar defaults occurs for fluency except that zero is used instead of TUNIF.

The Rail wheel axle component is meshed with solid 92 element type. A total of 61873elements and 80554 nodes are created. The meshed model of the Rail wheel axle component is shown in the below figure.

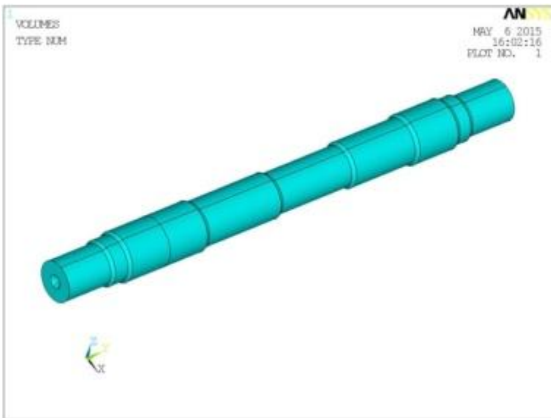

Fig.9. The 3D model of Rail wheel axle

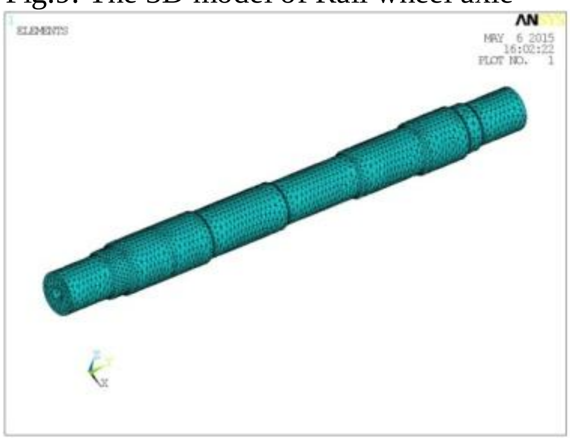

Fig.10. The Meshed body of Rail wheel axle

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3.6 Boundary conditions

3.6.1 Allowable axle load calculation

Analytical calculation of Rail wheel axle to design the Rail wheel axle firstly we choose the diameter of the axle which can bear the applied stress at a safe range.

We know that axle load formula

$$P = \frac{n\pi EI}{l*2}$$

Where,

P= Allowable Axle load
n = number of fixed points
E= Young's modulus of material
l = length between the fixed points
I= moment of inertia

$$I = \frac{\pi}{64}(D*4)$$

d =Diameter of the axle= 180mm
n = number of fixed points = 2
E= Young's modulus of material = 180000 N/mm^2
l = length between the fixed points = 1684mm
I= moment of inertia

$$I = \frac{\pi}{64}(180*4)$$

I = 51503880 mm^2

$$P = \frac{2*3.14*180000*51503880}{1684*2}$$

P=32232004 N

We know, Area of load acting location **A= 2πrL**

Where,

A = Surface area (mm2)
r = radius of axle loading area (mm)
L = length of axle loading area (mm)

A= 2*3.14*110*194

We know, Axle Force (F) = P/A

F = 587.9N/mm2

IV. BOUNDARY CONDITIONS

- Axle was arrested in all Dof[2] at the 1st end of the axle fixed with wheel.
- Allowable axial load of 587N has been applied at the 2nd end of the axle fixed with wheel.

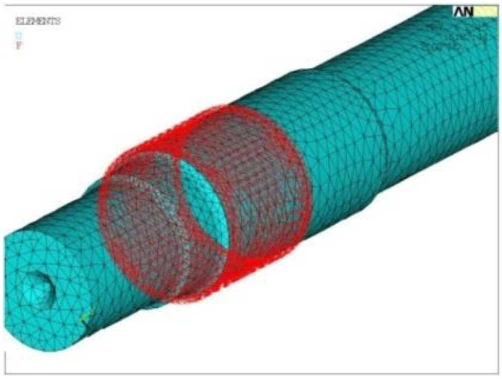

Fig. 11. The applied boundary conditions on Rail wheel axle.

V RESULTS AND DISCUSSIONS

5.1 Deflections

5.1.1 The maximum deformation observed 1.5mm on Rail wheel axle in X-dir:

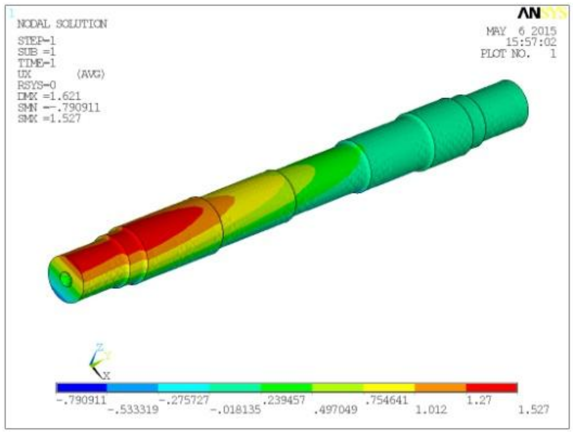

Fig.12 the deformation of Rail wheel axle in X-dir

5.1.2 The Max. Deformation observed 0.049mm on Rail wheel axle in Y-dir:

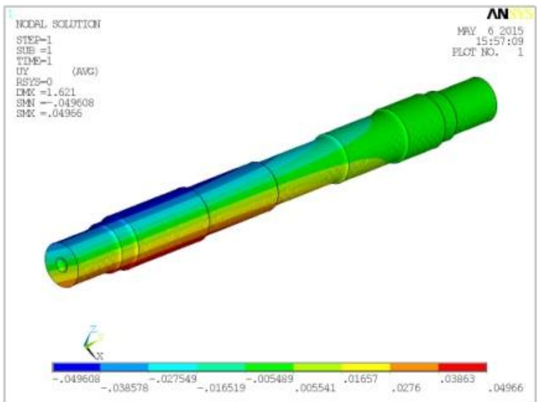

Fig.13 the deformation of Rail wheel axle in Y-dir

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5.1.3 The Max. Deformation observed 0.8mm on Rail wheel axle in Z-dir:

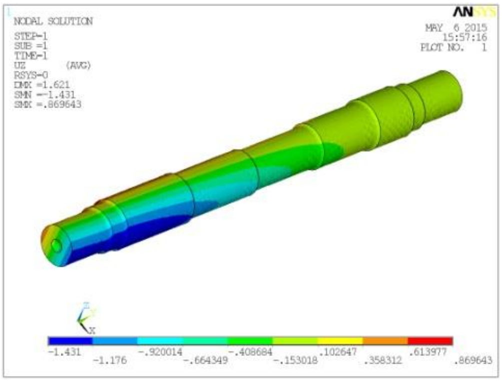

Fig.14 shows the deformation of Rail wheel axle in Z-dir

5.1.4 The Max.Displacement vector sum observed 1.6mm on Rail wheel axle:

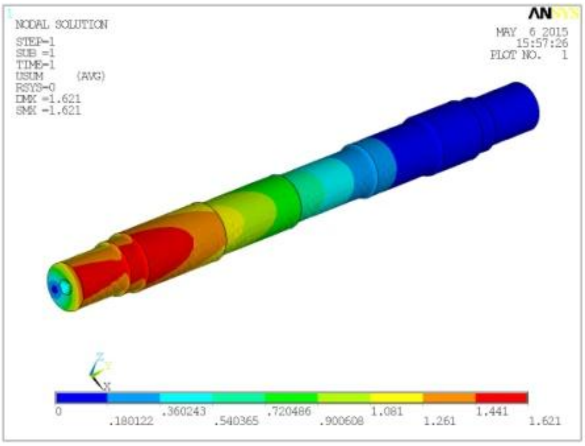

Fig.15 The Max. Deformation of Rail wheel axle

5.2 stress

5.2.1 1st principle Stress observed 97MPa on Rail wheel axle in X- Dir:

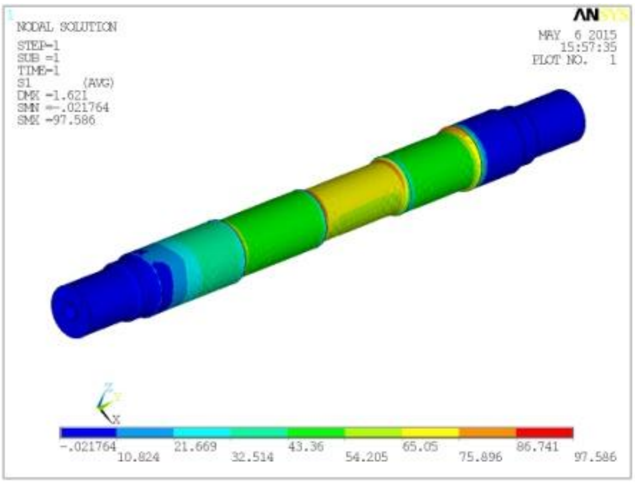

Fig.16 The 1st principle Stress of Rail wheel axle

5.2.2 2nd principle Stress observed 4.3MPa on knuckle joint in Y- Dir:

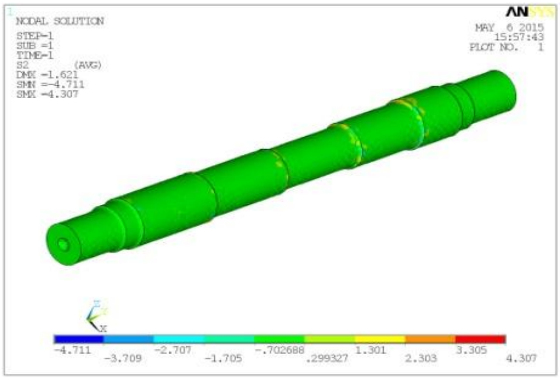

Fig.17 The 2nd principle Stress of Rail wheel axle

5.2.3 3rd principle Stress observed 0.01MPa on Rail wheel axle in Z- Dir:

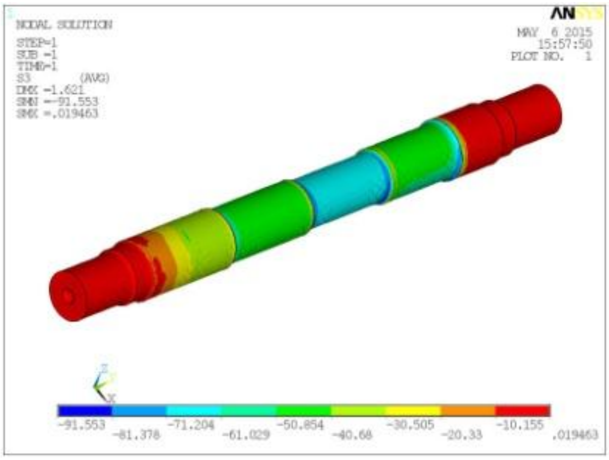

Fig.18 The 3rd principle Stress of Rail wheel axle

5.2.4 The Max. Von Mises Stress observed 163MPa on Rail wheel axle:

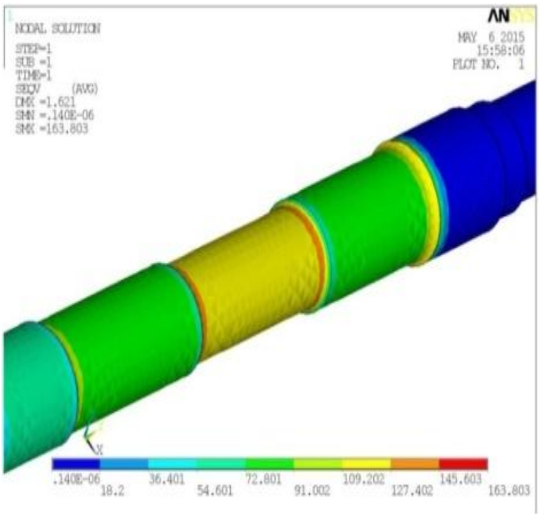

Fig.19 The Von Mises stress of Rail wheel axle

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Table.1. The Max. Deflection and Max. Stress

S. NO.	DEFLECTION (mm)				STRESS(MPa)			
	UX	UY	UZ	USUM	σ_X	σ_Y	σ_Z	Von mises
1	1.5	0.04	0.8	1.6	97	4.3	0.01	163

From the above analysis:

- The Max Deflection and the Max Avg. VonMises Stress observed on the Rail wheel axle for axial loads is 1.6mm and 163MPa with respectively. And the Yield strength of the material stainless steel is 490 MPa.
- Hence according to the Maximum Yield Stress Theory, the VonMises stress[3] is less than the yield strength of the material. The design of Rail wheel axle is safe for the above operating loads. But the factor of safety is (490/163=3).

5.3 Modal analyses

Modal analysis is used to determine the vibration characteristics (natural frequencies and mode shapes) of a structure or a machine component while it is being designed. It can also serve as a starting point for another, more detailed, dynamic analysis, such as a transient dynamic analysis, a harmonic response analysis, or a seismic analysis[4].

5.4 Natural frequency:

Natural frequency is the frequency at which a system naturally vibrates once it has been set into motion. In other words, natural frequency is the number of times a system will oscillate (move back and forth) between its original position and its displaced position, if there is no outside interference.

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$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

Fundamental Natural Frequency

The fundamental frequency, often referred to simply as the fundamental, is defined as the lowest frequency of a periodic waveform. In terms of a superposition of sinusoids (e.g. Fourier series), the fundamental frequency is the lowest frequency sinusoidal in the sum.

Resonance: In physics, resonance is the tendency of a system to oscillate with greater amplitude at some frequencies than at others. Frequencies at which the response amplitude is a relative maximum are known as the system's resonant frequencies, or resonance frequencies. The system stores vibration energy.

Mode shapes: For every natural frequency there is a corresponding vibration mode shape. Most mode shapes can generally be described as being an axial mode, torsion mode, bending mode, or general modes. A crude mesh will give accurate frequency values, but not accurate stress values.

Modal analysis was carried out on Rail wheel axle to determine the natural frequencies and mode shapes of a structure in the frequency range of 0 -1000 Hz. From the modal analysis, a total of 2 natural frequencies are observed in the frequency range of 0-1000 Hz. The total weight of the Rail wheel axle observed 559kgs. The mass participation of each of these 2 frequencies are listed in the below table 2.

Table 2 Frequency

Mode	Frequency	Partic.factor			Effective mass		
		X	Y	Z	X	Y	Z
1	468	-0.1E-01	0.8E-05	0.45	0.3E-3	0.7E-10	0.207
2	469	0.4	-0.3E-04	0.1E-01	0.207	0.1E-08	0.3E-03

The mode shapes for the above frequencies are plotted below:

A) Results –Mode1 @ 468 Hz

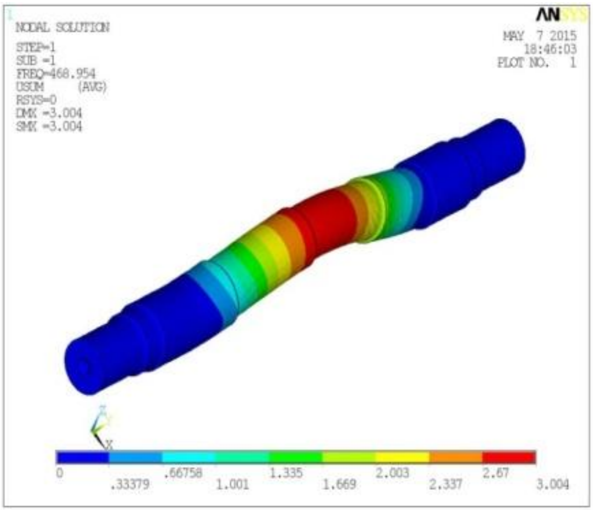

Fig.20 Mode shape 1@468 Hz for Rail wheel axle.

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B) Results –Mode2 @ 469 Hz

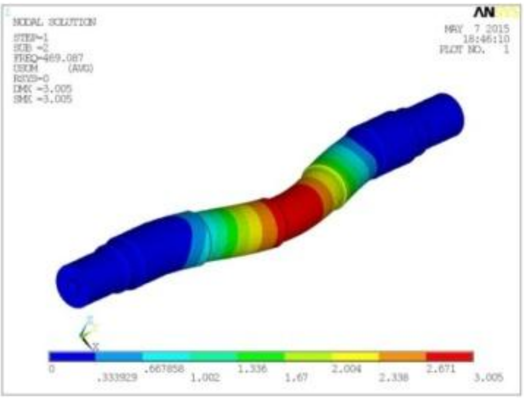


Fig.21 Mode shape 2@ 469 Hz for Rail wheel axle

From the modal analysis,

- It is observed that the maximum mass participation of 0.207Tone in X-dir for the frequency of 469 Hz.
- It is observed that the maximum mass participation of 0.14E-8Tone in Y-dir for the frequency of 469 Hz.
- It is observed that the maximum mass participation of 0.207Tone in Z-dir for the frequency of 468 Hz.

To check the structure response at the mentioned frequency due to the operating loads, harmonic analysis is carried out on the Rail wheel axle.

5.5 Harmonic analysis of rail wheel axle

Harmonic response occurs at forcing frequencies that match the natural frequencies of your structure. Before obtaining the harmonic solution, you should first determine the natural frequencies of your structure by obtaining a modal solution.

Harmonic analysis was carried out on the gear to determine the deflections and stress of a structure in the frequency range of 465 -470 Hz. The total number of sub steps defined for the analysis is 5.

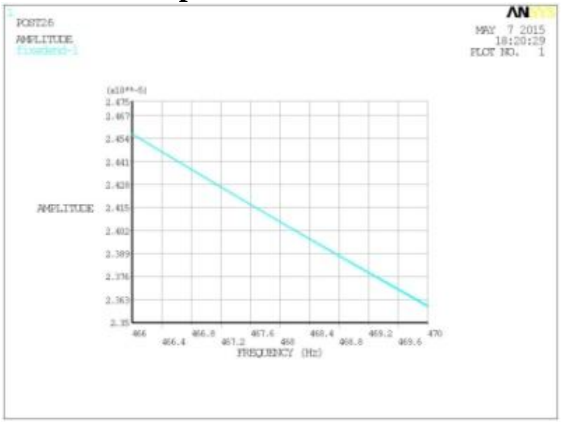
$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

Natural frequencies obtained from the modal analysis are shown in the below table. In the harmonic analysis, structure response at these natural frequencies is recorded.

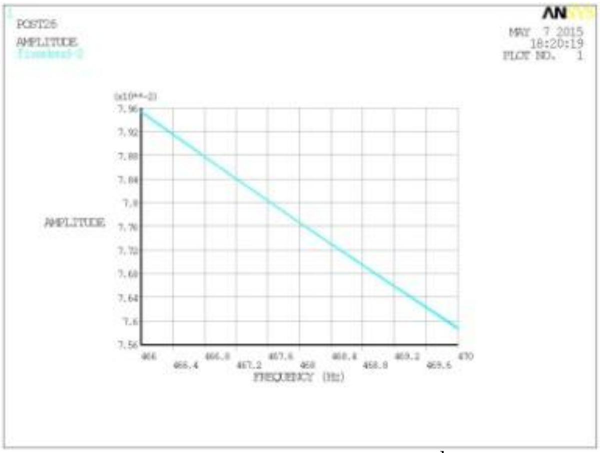
This is done to check, the structure behaviour for resonance condition. Because, resonance occurs when natural frequency coincides with operating frequency.

5.6 Graphs: Amplitude v_S forcing frequency:

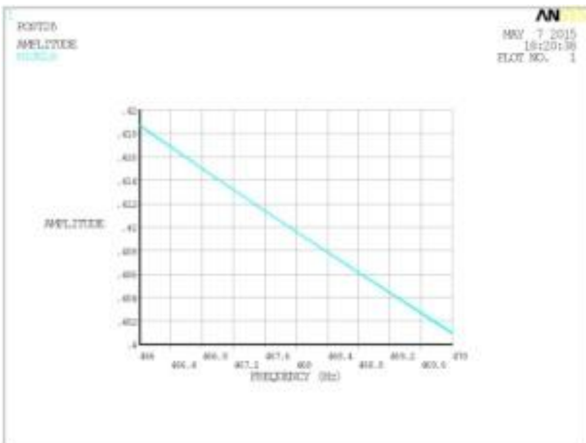
1. Harmonic response at face



Graph1 harmonic response at 1st fixed end of Rail wheel axle liner scale



Graph 2 harmonic responses at 2nd fixed end of Rail wheel axle liner scale



Graph 3 harmonic responses at mid location of Rail wheel axle liner scale

From the above graphs, the following amplitudes are observed:

- Amplitude of 0.0002mm is observed on the 1st fixed end of Rail wheel axle at a frequency of 465Hz**.**

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- Amplitude of 0.079mm is observed on the 2nd fixed end of Rail wheel axle at a frequency of 465Hz.
- Amplitude of 0.42 mm is observed on the mid location of Rail wheel axle at a frequency of 465Hz.

5.7 The deflections nearest to the above frequencies are plotted below:

A) Max. deflection and stress of frequency @ 468Hz

Max. Deflection:

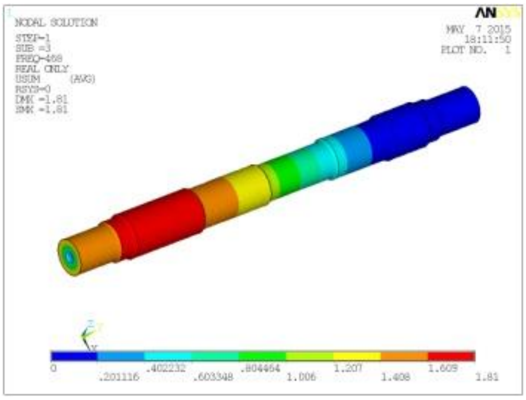

Fig.22 Tthe max. Deflection of Rail wheel axle

VonMises stress:

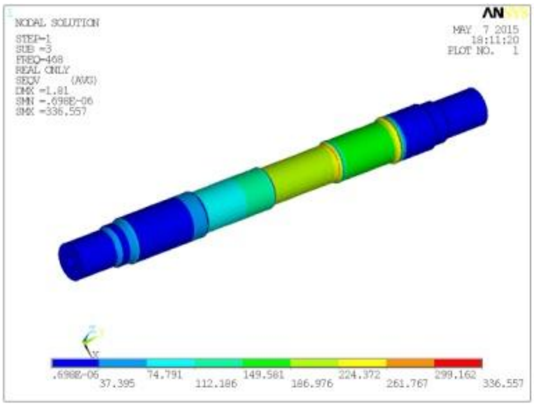

Fig.23 The VonMises stress of Rail wheel axle

B) Max. deflection and stress of frequency @ 469Hz

Max. Deflection:

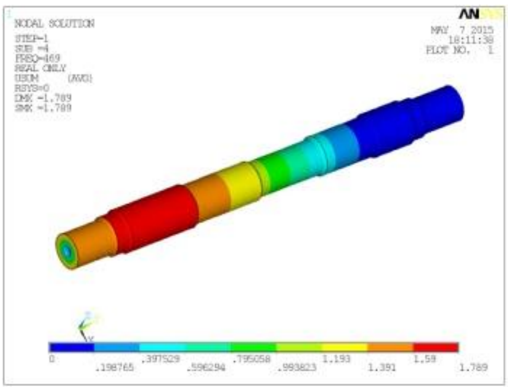

Fig.24 The max. Deflection of Rail wheel axle

VonMises stress:

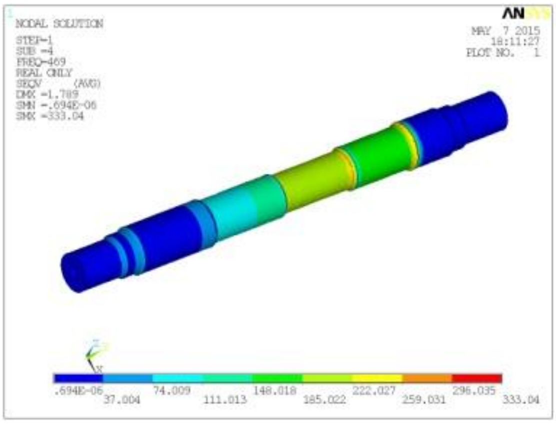

Fig.25 The VonMises stress of Rail wheel axle

Table.3 Deflections and von mises stress for critical frequencies

S.no	FREQUENCY(Hz)	DEFLECTIONS (mm)	VON MISES STRESS (mpa)
1	468	1.8	336
2	469	1.7	333

From the above results it is observed that the critical frequencies 468Hz and 469Hz are having stress 336MPa and 333MPa respectively. The yield strength of the material (stainless steel) used for gear is 490MPa.

According to the VonMises Stress Theory, the VonMises stress of gear at frequencies 468Hz and 469Hz having stresses less than the yield strength of the material.

Hence the design of Rail wheel axle is safe for the above operating loading conditions

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VI CONCLUSION

1. Maximum stress by ANSYS is lower than the yield stress of material.
2. Von-mises stresses [2] are less than ultimate strength.
3. Since the von-mises stresses are less than the ultimate strength, talking deflections into account, 30 NiCrMoV12 steel [1] is preferred as best material for designed Rail wheel axle.

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VII SCOPE FOR FUTURE WORK

1. In the above proposed work only force acting circumferentially on the wheel axle is only

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considered, this can be extended to other forces that act on the wheel rim and structural analysis is carried out, this can be extended to Transient Analysis.

2. If it is possible, damping should be added to the system. Because, it is clear that in the damping case, sudden force rise can be avoided and also, dynamic forces for other speeds can be decreased.

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