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Design of Modular Cast Axle Housing for Off-Highway Vehicles

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ABSTRACT

In the global competition, it is very important for engineering to bring up new innovative product and design solution to cater competition and produce design solution at reduced cost. As time and cost are major factors in design and innovative product is need of design. Especially this competition is slightly higher in the automotive sector. In this work, the time and cost spent on producing a new cast rear axle housing for off-highway vehicles is reduced to a greater extent. An off-highway vehicle is considered to be a type of vehicle which is capable of driving on and off paved road conditions. These robust vehicles are basically designed to work under overload and abuse conditions. The rear axle assembly is the important system of the drive train. The major function of the rear axle is to pull the load and to support the load. The axle housing is a structural component of the axle which takes the vehicle weight. Modular design approach is used in this work to design the rear axle housing, so that the same design can be used for several configurations. The concepts revolve around to make the Track length and Spring Mounting Centers modular.

Keywords: Off-highway vehicles, Rear axle housing, Track length, Spring Mounting Centers, Modular, pugh matrix, Bending stress.

1. Introduction

Figure 1: Off-Highway vehicles

An “Off-Highway Vehicle” is considered to be any type of vehicle which is capable of driving on and off paved or gravel surface (Figure 1). It is generally characterized by having large tyres with deep, open treads & a flexible suspension. In Other words, vehicles that do not travel public streets or highways are generally termed off- highway vehicles, including tractors, forklifts, cranes, backhoes, wheel loaders, bulldozers and Golf carts. These vehicles were basically designed to work under the harshest conditions, for example, deployment of these vehicles in hilly areas under worst weather conditions. Thus there is a need for robust vehicular design for sustainability of these vehicles in the worst conditions in the long run.

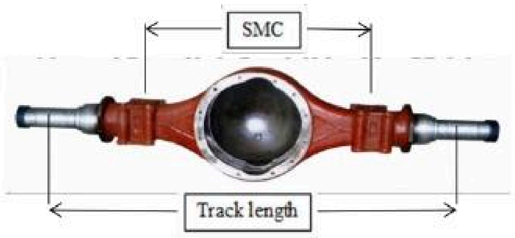

Figure 2: Rear Drive Cast Axle Housing

Meng Qinghua et al [1] in their research “Fatigue failure fault prediction of truck rear axle housing (Figure 2) excited by random road roughness” offered a comprehensive approach to predicting the fatigue failure of a truck's rear axle housing due to random road roughness. By integrating dynamic simulations, fatigue analysis, and statistical techniques, the research gave valuable insights to the potential failure mechanisms and probabilities. The findings have implications for truck design, maintenance strategies, and safety improvements, as they enable better prediction and mitigation of fatigue-related failures in rear axle housings **G. Rajesh Babu et al [2]** in their research “Static and modal analysis of rear axle housing of a truck” provided valuable insights into its mechanical behaviour and dynamic characteristics. The study's findings contributed to a comprehensive understanding of housing's strength under static loads and its response to dynamic excitations. The research has implications for optimizing the design and structural performance of rear axle housings in trucks, enhancing their reliability, safety, and overall operational efficiency. **Javad Tarighi et al [3]** carried research on “Static and dynamic analysis of front axle housing of tractor using finite element methods” using finite element methods offered valuable insights into its mechanical behavior under both static and dynamic loads. The study's findings contributed to understanding the housing's structural strength and its response to dynamic forces during agricultural operations. The research has implications for optimizing the design, performance, and durability of front axle housings in tractors, ultimately enhancing their reliability, safety, and overall operational efficiency. **Sanjay Aloni et al [4]** worked on evaluation of tractor trolley axles using finite element analysis contributed to a deeper understanding of the axles' structural behavior and performance. The study's findings had implications for optimizing tractor trolley axle designs to enhance their strength, durability, and load-bearing capacity. By utilizing advanced computational techniques, the research highlighted the potential benefits of FEA in guiding design decisions and improving the efficiency and safety of tractor trolley systems. **Guruprasad.B.S et al [5]** evaluated the Factor of Safety (FOS) for a rear axle housing using hybrid aluminum composites contributed to the assessment of the modified design's structural integrity and safety. The study's findings had implications for optimizing rear axle housing materials and designs to enhance their load-bearing capacity, durability, and overall safety. By utilizing advanced materials and computational techniques, the research highlighted the potential benefits of hybrid aluminum composites in improving the performance of critical automotive components**. I.D. Paul et al [6]** carried research on the optimization of a tractor trolley axle using finite element methods offered a systematic approach to enhancing the design's efficiency and cost-effectiveness. The study's findings had implications for optimizing axle geometry and material selection to achieve weight reduction and cost savings while maintaining structural integrity. By leveraging advanced computational techniques, the research highlighted the potential benefits of engineering optimization in improving the performance of essential automotive components. **Md Riasat Azim [7]** carried research on analytical investigation on bolt tension in a flanged steel pipe joint subjected to bending moments provided valuable insights into the behaviour of such joints under realistic loading scenarios. The study's outcomes have implications for engineering design, particularly in the field of pipeline systems, where flanged joints are commonly used. Understanding how bolt tension is influenced by bending moments and axial loads can lead to more accurate and efficient design practices, ultimately enhancing the safety and reliability of various engineering structures. Present work is carried out on rear axle housing. Axle housing is one of the significant components that lead to great performance of the vehicle. The rear axle housing is a solid structure that moves up and down as they moveover uneven profiled roads. The housing is provided with openings both at front and rear ends; the front opening is closed by the differential carrier, while the rear is closed by a spherical cover plate. The functions of axle housing is to incorporate the components of axle within it, support the vehicle weight, mount brakes and suspensions and also acts as a tank for the rear end lubricants. The axel housing is provided with a plurality of different attachment positions, adapted to hold the components like an anti-roll bar, radius arm, shock absorbers, suspension components etc., along with these the smaller components such as the differential switch, cables are provided on axle housing. Axle housing can be manufactured by casting method or fabricating method. Since the housing must carry the weight of the vehicle, the axle housing in heavy trucks and off-highway vehicles is a heavy cast unit.

2. Objective of the work

- ❖ To provide an improved axle housing which is modular and assembled from several smaller part
- ❖ To use the same housing for both single drive axle and tandem axle with different attachment
- ❖ To reduce time and cost involved in both design and manufacturing
- ❖ A further objective of the invention is to find more manufacturers.

3. Material specification

Axle housing is made of Nodular cast iron, also termed as spheroidal graphite iron, since graphite will be in the spherical shape. Nodular cast iron combine the favorable characteristics of other ductile materials such as steel, with other advantages like easy machinability (10%-16%), Design flexibility, i.e. the free selection of shape of the component and thus the ability to integrate several functions in a single part. High dimensional accuracy of the raw castings and thus resultant cost reduction in final machining. Surface treatment is done to improve the properties by cold rolling, shot peening, nitriding, and hardening. About 10% lighter. Higher damping capacity. Lower notch sensitivity.

Table 1: Mechanical properties of Nodular Cast Iron

Material	Nodular Cast Iron
Ultimate Tensile Strength	**550 Mpa**
Yield Strength	**379 Mpa**
Percentage Elongation	**6 %**
Young's Modulous	**162027 Mpa**
Poisson's Ratio	**0.25**

4. Chemical composition

The axle housing is made from nodular cast iron with the chemical composition of 3.2-4.1% C, 2.7% Si, 0.1-1.0% Mn, 0.03% P, 0.02% S, 0.1% Cr and 0.05% Tin. The graphite component of the microstructure shall consist of at least 80% spheroidal graphite i.e. the nodularity level is 80% and the graphite size is 0.030-0.050µm.

5. Boundary Conditions

5.1 Static boundary condition

The design of rear axle housing is basically based on the static loading condition. Most of the industries use the same principle to design the axle housing. The both ends of rear axle housing is connected to the spindle which in turn connected to the wheel mounting hub, hence there will not be any relative motion between the housing and wheel hub. Therefore both the ends of the rear axle housing are fixed in all degrees of freedom and the rear axle housing acts as a simply supported beam. The chassis is connected to the axle housing at two points i.e. spring mounting centres, through isolator leaf spring which transfer the total load on the axle as concentrated loads.

5.2 Dynamic boundary condition

An off-highway vehicle is considered to be any type of vehicle which is capable of driving on and off paved or gravel surface. Off-road conditions include construction sites, mining area, agricultural field surfaces etc. These vehicles travel at a moderate speed i.e. up to 70 to 100 km/hour. On full load conditions, the maximum speed is 80 km/hour. Due to this moderate speed, wavy road conditions the axle is subjected to dynamic loads which are

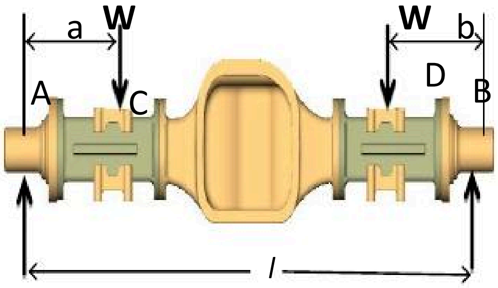

Figure 3: Loading condition to find the Bending stress

nonlinear in nature. The shocks due to sudden velocity change may cause impact loading. The worst condition of dynamic load is when the vehicle travel over a hump or dip. The load coming on axle due to these are much larger than static loads, which makes it necessary to design axle housing for dynamic loads. It is very difficult to determine the dynamic loads accurately as we don't know the exact surface on which the vehicle is travelling and other inputs like suspension rate, tire etc. hence from the past experience the dynamic load is taken as three times the static load.

i.e. Dynamic load = 3 x Static load.

In dynamic loading conditions, the vertical acceleration of lumped mass of the vehicle body due to the road surface roughness can be three times as much as the acceleration of gravity. This means that the maximum dynamic loads can be increased three times as much as the corresponding loads in static loading conditions.

6. Design Calculations

6.1 Stresses in axle housing

In engineering practice, the axle housing is subjected to both static and dynamic loads which will cause bending stress in the sections. From the past experience it is seen that the bending stress is maximum in the sections of spring mounting centres as shown in Figure 3. Therefore, it is necessary to calculate the bending stress at these sections.

The bending equation is given by,

$$\frac{M}{I} = \frac{\sigma}{y} = \frac{E}{R} \quad \text{... (1)}$$

Also, $\sigma = \frac{M}{Z}$, Where $Z = \frac{I}{y}$ (Section modulus)

M = Bending moment acting at the given section, σ = Bending stress, I = Moment of inertia of the cross-section about the neutral axis, Y = Distance from neutral axis to extreme fibre, E = Young's modulus of the material,

R = Radius of curvature of the beam. Before calculating the bending stress it is required to calculate the bending moment acting at the spring mounting centres.

The bending stress for the given load condition is calculated as follows

Specifications

W = Dynamic load = 15 ton = 147150 N l = Track length (Modular)

a = b = Distance from supports A and B respectively to the load point (Modular) (Track length – SMC distance) /2

R_A = R_B = Reactions at supports A and B respectively

Case 1: When l = 2020 mm and SMC distance = 1154 mm, then, a = b = 433 mm.

Step 1: To find reactions at the supports,

Taking moments about A,

$$R_B \times l = W \times a + W (l - b) \quad \text{... (2)}$$

$R_B \times 2020 = 147150 \times 433 + 147150 (2020 - 433)$

R_B = 147150 N

Taking moments about B,

$R_A \times l = W(l - a) + W \times b$ … (3)

$R_A \times 2020 = 147150 (2020 - 433) + 147150 \times 433$ **R_A = 147150 N**

Step 2: To find bending moment in the axle housing

Bending moment at C (SMC 1),

$M_C = R_A \times a$ … (4)

$M_C = 147150 \times 433 = 6.3715950 \times 10^7$ N-mm

Bending moment at D (SMC 2),

$M_D = R_B \times b$ … (5)

$M_D = 147150 \times 433$ **$= 6.3715950 \times 10^7$ N-mm**

The bending moment diagram is as shown in Figure 4.

Step 3: To find section modulus

I = 25690457 mm^4, y = 76 mm,

Then, $Z = \frac{I}{y} = 338032.32\ mm^3$

Step 4: To find the bending stress

M = 6.3715950×10^7 N-mm, Z = 338032.32 mm^3,

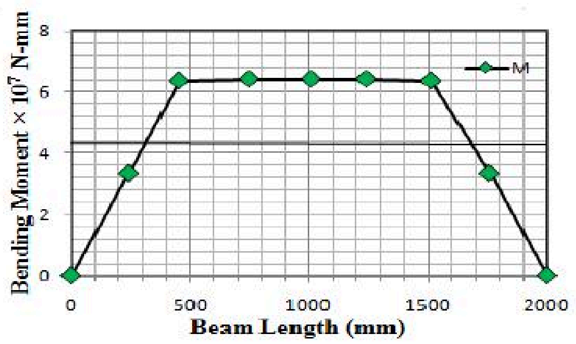

Figure 4: Bending moment diagram

Then, Bending stress $\sigma = \frac{M}{Z} = 188.49$ MPa

(This is the stress acting at the sections of each SMC). The bending stress induced in the rear axle housing is found to be 188.49 MPa, which is 54.1 % of the yielding strength of the material, hence the housing satisfies the safety conditions.

6.2 Deflection in the axle housing by Macaulay's method

This method is an improved version of double integration method. It is a very useful method for the beams subjected to a set of concentrated loads and UDL. Figure 5 shows a modular cast axle housing of track length "*l*", carrying two point loads W at C and D each.

Let R_A and R_B be the support reactions at A and B respectively.

Specifications:

W = Dynamic load = 15 ton = 147150 N,

l = Track Length (Modular)$R_A = R_B$ = 147150 N

E = young"s modulus = 162027 Mpa,

I = Area moment of inertia (X-X) = 25690457 mm^4

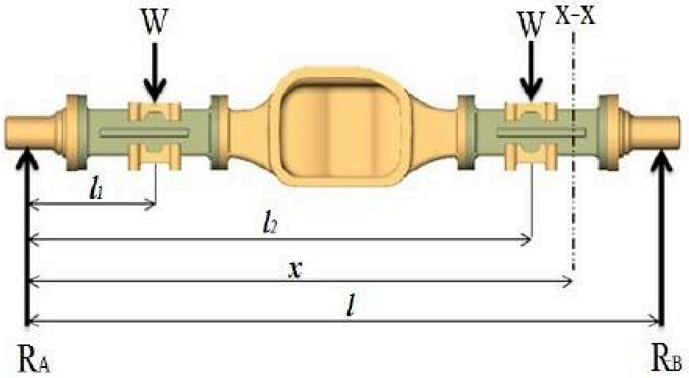

Figure 5: shows a modular cast axle housing

Case 1: $l = 2020$ mm, $l_1 = 433$ mm and $l_2 = 1587$ mm

Design procedure

Step 1: Taking bending moment

Any section between A and C at a distance x from A,

Bending moment $M_x = R_A \times x$ .. (6)

Equation (6.7) is valid between $x = 0$ to l_1

Any section between C and D at a distance x from A,

Bending moment

$M_x = R_A \times x - W(x - l_1)$ ... (7)

Equation (6.8) is valid between $x = l_1$ to l_2

Similarly any section between D and B at a distance x from A,

Bending moment

$M_x = R_A \times x - W(x - l_1) - W(x - l_2)$ ... (8)

Equation (6.9) is valid between $x = l_2$ to l

Hence the general expression for any section of the beam (housing) can be written as,

$$M_x = EI\frac{d^2y}{dx^2} = R_A\,x - W(x - l_1) - W(x - l_2) \quad \ldots(9)$$

If the value of x is between 0 and l_1, then only the first term of equation (9) should be considered.

If the value of x is between l_1 and l_2, then only the first two term of equation (9) should be considered.

If the value of x is between l_2 and l, then only the all the term of equation (9) should be considered.

Integrating the equation (9) once,

$$EI\frac{dy}{dx} = R_A\frac{x^2}{2} + C_1 - \Big|W\frac{(x-l_1)^2}{2} - \Big|W\frac{(x-l_2)^2}{2} \quad \ldots\ldots(10)$$

Equation (10) is the slope equation and the constant C_1 is valid for all the values of x.

Integrating equation (10),

$$EIy = R_A\frac{x^3}{6} + C_1x + C_2 - \Big|W\frac{(x-l_1)^3}{6} - \Big|W\frac{(x-l_2)^3}{6} \quad \ldots(11)$$

Equation (11) is the deflection equation and the constant C_2 is valid for all the values of x. Using the boundary conditions, the constants C_1 and C_2 can be calculated.

Step 2: Boundary condition

For simply supported beam, deflection y = 0 at the supports

At x = 0, y = 0 substituting these values upto the first dotted line in equation (10)

$0 = 0 + 0 + C_2$ Therefore, $C_2 = 0$

At x = 2020 mm, y = 0 Substituting these values in equation (11) by considering all the terms

$$0 = 147150\,\frac{2020^3}{6} + C_1 x\,2020147150\,\frac{(2020-433)^3}{6} - 147150\,\frac{(2020-1587)^3}{6}$$

$$\mathbf{C_1 = -5.05586 \text{ X } 10^{10}}$$

Step 3: Deflection under the loads and maximum deflection

Substituting the values of C_1 and C_2 in equation (11)

$$\text{E I y} = 147150\,\frac{x^3}{6} + (-5.0558 \times 1010)x - 147150\,\frac{(x-433)^3}{6} - 147150\,\frac{(x-1587)^3}{6} \quad \ldots \text{(12)}$$

When $x = 433$, y = y_B, substituting these values up to the first dotted line in eqn. (12)

$$\text{E I } y_B = 147150\,\frac{433^3}{6} - 5.0558 \times 10^{10} \times 4$$

$$y_B = \mathbf{2.81mm.}$$

Deflection at C, $y_C = \frac{-1.990\times10^{13}}{\text{E I}}$

On substituting the values of E and I, we get **y_c = – 4.78 mm** (– ve sign indicating the downward deflection).

When x = 1587, y = y_c Substituting these values up to the second dotted line in equation (12)

$$\text{EI } y_c = 147150\,\frac{1587^3}{6} - 5.0558 \times 10^{10} \times 1587 - 147150\,\frac{(1587-433)^3}{6}$$

Deflection at D, $y_D = \frac{-1.990\times10^{13}}{E\,I}$

On substituting the values of E and I, we get **y_D= – 6.14 mm** (– ve sign indicates downward deflection). From this it is concluded that the maximum deflection will occur in between B and C.

Also for maximum deflection $\frac{dy}{dx} = 0,$

Hence considering upto second dotted line in equation (10)

$$0 = 147150\,\frac{x^2}{2} - 5.0558 \times 10^{10} - 147150\,\frac{x^2}{2} - 63715950\,x - 1.39 \times 10^{10}$$

x = 1010 mm.

When x = 1010 mm, y = y_{max} Substituting these values upto the second dotted line in equation (12)

$$\text{E I } y_{max} = 147150\,\frac{1010^3}{6} - 5.0558 \times 10^{10} \times 1010 - 147150\,\frac{(1010-433)^3}{6}$$

$$y_{max} = \frac{-3.0506 \times 10^{13}}{\text{E I}}$$

On substituting the values of E and I, Therefore, Maximum deflection is found to be **y_{max} = -7.32 mm** (– ve sign is indicating the downward deflection)

Some of the important observations in Macaulay's method are

- ❖ Always take the origin on the extreme left of the beam.
- ❖ The constants C1 and C2 should be written after the first term, since it is validfor all the points.
- ❖ The section X-X is to be taken in the last portion of the beam. The bracket values are to be integrated as a whole and hence integration of whole and hence integration of

Table 2: Results for different Track length and SMC

Sl. No	**Specification**	**Case 1**	**Case 2**	**Case 3**
1	Load	147150 N	147150 N	147150 N
2	Track length	2020 mm	1876 mm	1804 mm
3	SMC distance	1154 mm	1036 mm	930 mm
Sl. No	**Results**	**Case 1**	**Case 2**	**Case 3**
1	Bending stress	188.49 Mpa	182.83 Mpa	190.23 MPa
2	Maximum deflection	-7.32 mm	- 6.09 mm	- 5.79 mm
3	No. of bolts	8	8	8
	Bolt size	M12	M12	M12

$$(x - l_1)\ is\ \frac{(x-l_1)^2}{2}\ not\ \frac{x^2}{2} - l_1 x$$

6.3 To determine the bolt size and number of bolts required in flange.

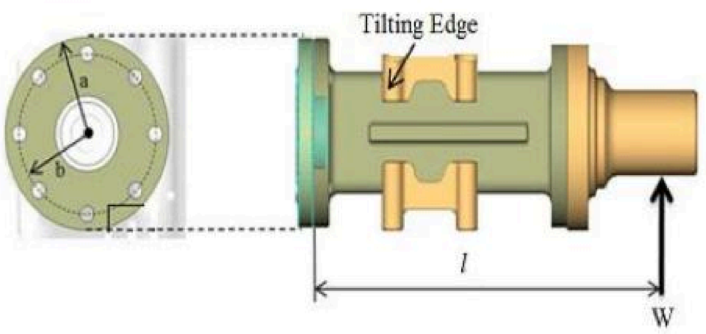

Figure 6: Loading condition to determine the Bolt size

Figure 6 shows a flange having circular base bolted to another similar flange with aid of support by means of bolts. The load is eccentric and acting perpendicularly to the bolt. The flange dimensions are same as that of spindle

Specifications:

W = Dynamic load = 15 ton = 147150 N, l = Length at which load is acting (changes with track length), a = Flange radius = 117.5 mm, b = Pitch circle radius of bolt = 104 mm, n = No. of bolts = 8 (Assume), τ = Minimum proof strength = 830 MPa (Class 10.9).

Case 1: When l = 560 mm

Design procedure:

Direct shear load on each bolt,

$$F_b = \frac{W}{n} = \frac{147150}{8} = 18393.75\ N\ ....\ (13)$$

The maximum load occurs on bolt 1 since it is farthest from the tilting edge.

Therefore, Normal load on bolt 1,

$$F_n = \frac{2\ F\ l\ (a+b)}{(2a^2 + b^2)n}$$

$$= \frac{2 \times 147150 \times \ 560\,(117.5 + 104)}{(2\ \times 117.5^2 + \ 104^2)8}$$

$$\mathrm{F}_{\mathrm{n}} = 118743.15\ \mathrm{N} \qquad ..\ (14)$$

According to maximum shear stress theory,

Maximum shear load on Bolt 1,

$$\mathrm{F}_{\tau} = \frac{1}{2}\sqrt{\mathrm{F}_{\mathrm{n}}^2 + 4\,\mathrm{F}_{\mathrm{b}}^2}$$

$$= \frac{1}{2}\sqrt{118743.15^2 + 4\,(18393.75)^2} \quad ...\ (15)$$

F_{τ} = 62155.56 N.

Also, Shear stress area of the bolt,

$$\mathrm{A}_{\mathrm{c}} = \frac{\mathrm{F}_{\tau}}{\tau} = \frac{62155.56}{830} = 74.88\ \mathrm{mm}^2.$$

According to metric standards the nearest standard stress area is, Ac = 84.30 mm² and the corresponding bolt size is **M12.** Therefore **Eight M12** bolts are required. In this design approach the effect of flange thickness cannot be incorporated in the equation. But flange thickness has significant effect on bolt tension. There is an upward shift in the bolt tension against the number of bolts with increase in flange thickness. That is, the bolt tension increases with the increase in flange thickness.

6.4 Results for different Track length and SMC

The main aim of Modular cast axle housing is to adjust to the different Track length and SMC distance. Hence it is necessary to design the housing for different conditions. In the present work the housing is tested for three different Track length and SMC distance. The results obtained are are as shown in Table 2. From the above Table 2 it is evident that the housing is safe in all the three cases.

7. Conclusion

Modular cast axle housing for Off-highway vehicles have been designed in this project. This concept reduces the time and cost in development of new axle housing. By using the modular design approach several configurations of Track length can be achieved easily by keeping the centre portion common across all configurations and changing the two axle tubes as per requirement, as the shape of the axle tubes are simple they can be easily manufactured. In this project, Spring Mounting Centres are also designed for modularity to suit the requirement. By using this design SMC can be varied in the range of 300 mm in a housing having a Track length of 2020 mm, i.e. from 1140 mm to 1440 mm. The same design for three configurations of Track length and SMC is evaluated for strength under dynamic condition using theoretical approach. Hence the modular cast axle housing can be used as a basis for new design development, prototyping and testing at industry.

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