International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 07 Issue: 07 | July 2020 www.irjet.net p-ISSN: 2395-0072

Design and Parametric Evaluation of a Staircase Climbing Forklift

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Abstract - *The sole objective of a forklift is lifting off heavy objects and transporting them from one location to another. These criteria were considered while designing and fabricating the model. A modified forklift has been presented that is capable of climbing staircases and lifting a certain amount of load to a certain height simultaneously. The designed forklift uses a low speed motor, which is cost-efficient, with a reduction gearbox and a pulley to lift the weight instead of using a hydraulic set up which is traditionally used in industrial forklifts. This increases the load capacity of the forklift in comparison to the industrial forklifts. Efforts have been made for coupled construction of the forklift and the climbing trolley. This has been achieved by introducing two tri-star-wheels at the rear of the forklift for enhancing the parametric evaluation of the newly proposed concept. Overall, the concept turned out to be usable for manoeuvrability and durability and also proves the usage of staircase climbing mechanism in a normal forklift.*

Key Words: **Forklift, Staircase, Tri-star-wheels, Manoeuvrability, Durability**

1. INTRODUCTION

In the early 20th century, there has been a great hype in the usage of modern machines for the efficient use in transmission and manufacturing sectors. Back in the days of World War II, the concept of the forklift truck has greatly expanded worldwide. The use of forklifts has become an indispensable thing in manufacturing and warehousing. Mechanisation reduces human efforts and manpower, but needs closer and complex human supervision. If consistency and close supervision are not provided, there might be a costly process error. So, the automation process will eliminate the error and human interface by taking full control over the operations of the mechanised equipment and provide consistency through the process control system and strengthen the instrumentation built in the system.

1.1 Forklift

A forklift is a machine that is used to lift heavy objects/products and move them from one place to another over a short distance. Products vary in size and shape and have different packaging; loading and unloading has always been a heavy process during transportation. Forklifts makes the process easier and reliable and hence become a solution to this problem saving time and space. If cargos are organised properly for the use of forklifts with a right attachment, it would be the best way to load and unload which would make the whole process less time consuming and less labour-intensive. Also, forklifts optimize the use of storage space by eliminating the need for many people to handle the loading and unloading operation and enabling the stacks up to a good stacking height of 4-5m or even more than that.

1.2 Staircase Mechanism

It is a mechanism developed to move or transfer an object/product from one floor to another through the stairway provided in the infrastructure. It is well known that any linear motion over a staircase is not that smooth. If required, a proper mechanism can be developed for achieving better performance of a machine. There is a continuous inflow of ideas in the field of development of suitable staircase mechanism. The general methodology for this mechanism mostly includes different modifications and design of the wheels.

1.3 Tri-star-wheel

Robert and John Forsyth of the Lockheed Aircraft Corporation designed the tri-star-wheel. The wheel works as an ordinary wheel on flat ground but can climb automatically when an impediment to rolling is encountered. This wheel consists of three tires each mounted to a separate shaft. These shafts are connected to the vertices of an equilateral triangular set of wheels with the three shafts geared to the fourth central shaft. When geared in this quasi planetary fashion, these triangular set of wheels can negotiate many types of terrain. The wheel may be gear driven with two wheels in rolling contact with the ground. The third wheel rests at the top until the lower front wheel marks the obstruction preventing the lower front wheel from moving forward not affecting the motion of the driving axle. This causes the top wheel to roll forward into positions as the new front wheel. This wheel lands on the top of obstruction and allows the rest of the assembly to vault over.

2.FEASIBILITY OF THE STAIRCASE CLIMBING MECHANISM

Regarding the utility and the practical viability of the two-wheel-drive forklift with staircase climbing mechanism being an alternative to the conventional one, a good amount of intensive and extensive study by individual scholars and organisations have been conducted at globally. Raundal et al. [2] showed that the project had some limitations regarding the strength and built of the structure. It can be considered as

a small step forward, as far as stair climbing vehicles are concerned. During the test run of the work, it was realised that it would be a good idea to consider the design for carrying heavy loads up the stairs. This product will be well-acclaimed if it can be commercialised to suit the needs. Though the initial cost of the project seemed to be higher but more accurate manufacturing would minimise this. As far as the commercial aspect of this product are a concern, if this product can be fully automated and produced at a lower cost the acceptance will be unimaginable. Kaithwas et al. [3] in the article "Two Wheel Aisle Forklift" has studied about analysis of forklift. The test result shows that the vehicle is a forklift conveyer. It is completely eco- friendly as it is battery operated. To have a smooth movement of the fork of the vehicle from top to bottom and vice versa, it is mounted with a lead screw mechanism. This consumption of forklift conveyor is less as compared to other transport vehicles within industries. As it is compact it requires much less area. The components can be loaded and unloaded easily in forklift conveyer. The working efficiency of the forklift is more as compared to other transport vehicles. Meanwhile, Panara et al.[4] has discussed the control of the forklift through wired communication. The main advantage of using this technology is to increase the safety of the operator by operating the forklift from a certain distance. This increases the efficiency because human errors due to poor visibility can be minimised. The system is designed and developed successfully, for the demonstration purpose a prototype model is constructed. Marissa L. Jacobich [9] has explained a stair climbing hand truck using the Blanco mechanism which proves to be a feasible design. However, it is not the simplest design for a tool whose goal is to climb stairs bearing an important payload. Although, preliminary analysis suggested that both tri-star and dynamic ramp designs could potentially be incorporated into hand trucks. There were insufficient resources and time available to develop all the three designs. To produce a successful product, other design options must be examined more closely. Future work on this product should involve design and construction of other prototypes using different stair climbing strategies.

3. TWO -WHEEL -DRIVE FORKLIFT

Factories, industries and storage godowns need forklifts and cranes for storage and moving large goods. Also, there are several goods that are comparatively lighter but cannot be moved around easily by human labour. To obviate this difficulty, a two-wheel-drive forklift is introduced to lift and transport such medium weight goods across factories & industrial warehouses. The two-wheel-drive may be a fast, efficient and low power consumption vehicle that doesn't require much space to manoeuvre around.

3.1 Components

(a) Frame: A frame may be a rigid structure which supports something thereon. A typical forklift is defined by a little rectangular frame with a front-facing mast assembly that's liable for raising and lowering the carrier load.

(b) Wheels: Wheels are meant to manoeuvre the forklift around. Here we are using the rear-wheel-drive system where the rear wheels are powered by a DC motor.

(c) Chain: The chain attached to the pulley at one end and a DC motor at the opposite end helps to lift the forks.

(d) Sprocket: A sprocket or sprocket-wheel may be a profiled wheel with teeth or cogs that mesh with a sequence, drag or other perforated or indented materials. The name (sprocket) applies generally to any wheel upon which radial projection engages a sequence passing over it. It is distinguished from a gear therein sprockets are never meshed together directly, and differs from a pulley that sprockets have teeth and pulleys are smooth.

(e) DC motor: Two DC motors are going to be used; one is going to be engaged in driving the rear wheels and the other in lifting the forks.

(f) Battery: A battery is employed to power the 2 DC motors.

(g) Forks: Two forks are used at the front which will slide under heavy loads and then raised for moving and stacking materials in warehouses, shipping depots, etc.

3.2 Mechanism

The whole design is mechanized into two basic functions:

(i) Forklift
The mini forklift will run on dc motors and can drive small weight with pickup arrangement across small distances easily. For this, a mini wheel chassis is designed having a platform and motorised wheel mounts. It has a perpendicular handle ahead to carry on as an alternate. The lifting mechanism comprises a rotating chain connected to a high power motor via pulley.

(ii) Staircase Climber
The staircase climber is implemented to reduce liability rather than increasing it. Conventional hand trucks work well on flat ground but their usefulness decreases when it is necessary to carry an object over the stairs. The entire concept of using the conventional wheel is to avoid lifting heavy objects using less or negligible manpower. A small survey was done on small scale industries to collect information about its utility. Also, a market survey was carried out to see the cost of the raw materials and the finished products required to fabricate the unit. The tri-star-wheel is the chosen concept which can reduce the burden of staircase climbing.

4. SYSTEM MODELLING

The system mainly consists of a forklift coupled with various components required to fulfil the objective concerned. The system has been reconceptualised with the methodology proposed below.

4.1 Concepts and Objectives

The main objective of this study is to prepare a two-wheel-drive forklift mounting tri-star-wheels which will be able to move from one floor to another with minimal human effort possible.

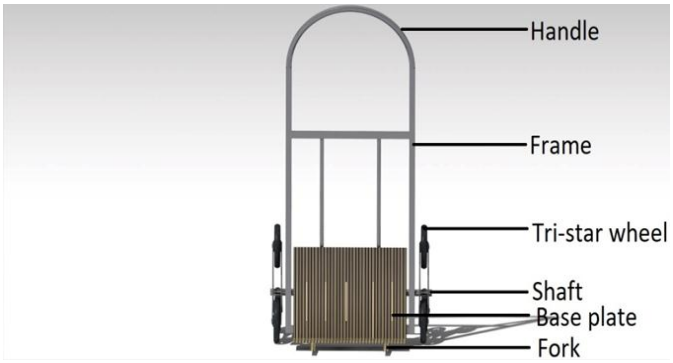

Fig -1: Top view of the Prototype

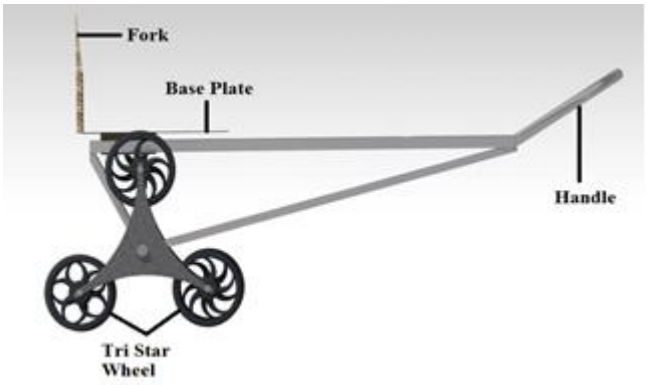

Fig -2: Side view of the Prototype

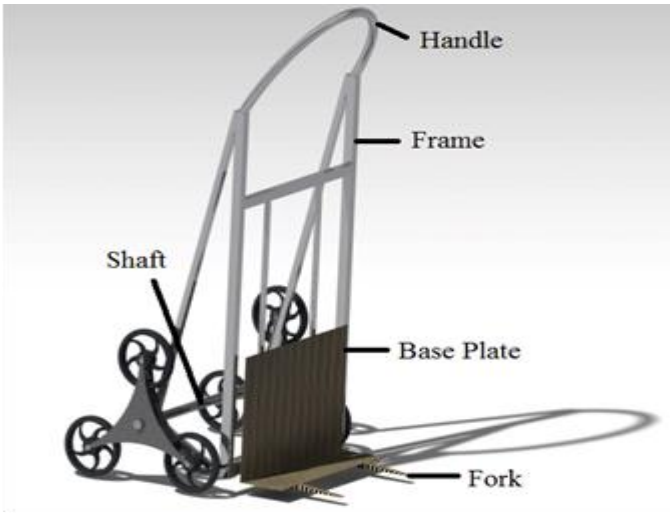

Fig -3: Isometric view of the Prototype

4.2 Equation For Tri-star-wheel Design

(i) Wheels

The wheels are arranged in a triangular array such that centres of each of the wheels coincide with the vertices of an equilateral triangle. Now the side of an equilateral triangle(R) and radius of the wheel(r) is calculated using equations described as follows:

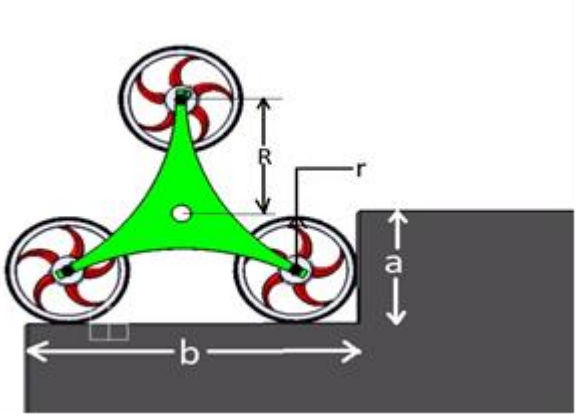

Fig -4: Formation of Tri-Star-Wheel

$$R = \sqrt{\frac{(a^2 + b^2)}{3}} \quad \text{..... (1)}$$

The maximum value of the thickness of the holder (Tmax) to avoid the collision between the holder and stairs

$$T_{max} = \frac{a*r(3-\sqrt{3}) + b*r(3+\sqrt{3}) + a(\sqrt{3a} - \sqrt{3b})}{6R} \quad \text{..... (2)}$$

(ii) Radii of a regular wheel

The minimum radius of regular wheel (r_{min}) to prevent collision of the wheels together as shown in Fig -5 is expressed as

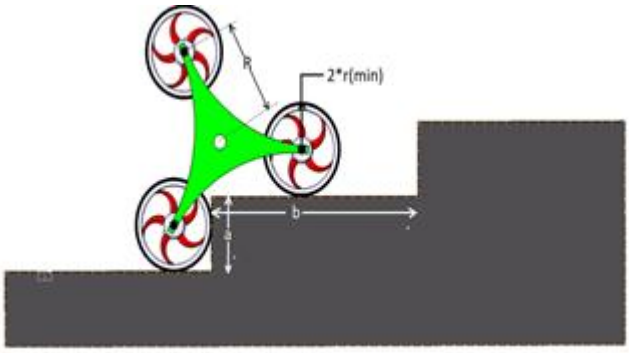

Fig -5: Minimum radius of a regular wheel

$$r_{\min} = \frac{6Rt + a(3b - \sqrt{3}a)}{(3-\sqrt{3})a + (3+\sqrt{3})b} \quad \text{..... (3)}$$

The maximum radius of regular wheel (r_{max}) to prevent collision of the wheels together is expressed as

$$r_{\max} = \frac{\sqrt{a^2 + b^2}}{2} \quad \text{..... (4)}$$

(iii) Force necessary to pull the Trolley

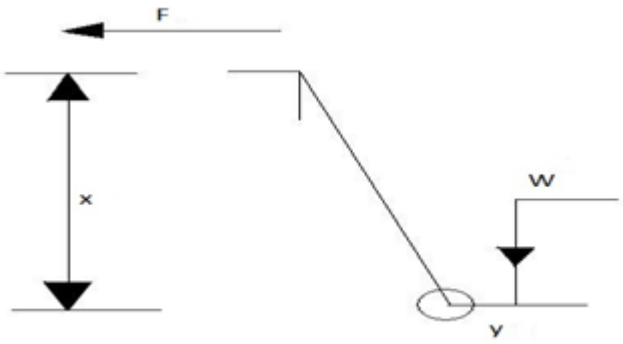

Fig -6: Maximum Load Determination

$$F = y / x.\, W \quad \text{..... (5)}$$

(iv) Force analysis of wheel frame

$$(\frac{W_1 + W_2}{2} - F\sin\theta).k = F\cos\theta\sqrt{R^2 - k^2}$$

.....(6)

$$R_e \cos\phi = F\cos\theta \quad \text{.....(7)}$$

$$R_e \sin\phi + F\cos\theta = \frac{W_1 + W_2}{2} \quad \text{..... (8)}$$

$$R_e = \sqrt{(F\cos\theta)^2 + (\frac{W_1 + W_2}{2} - F\sin\theta)^2}$$

..... (9)

$$\tan\phi = \frac{W_1 + W_2 - 2F\sin\theta}{2F\cos\theta} \quad \text{..... (10)}$$

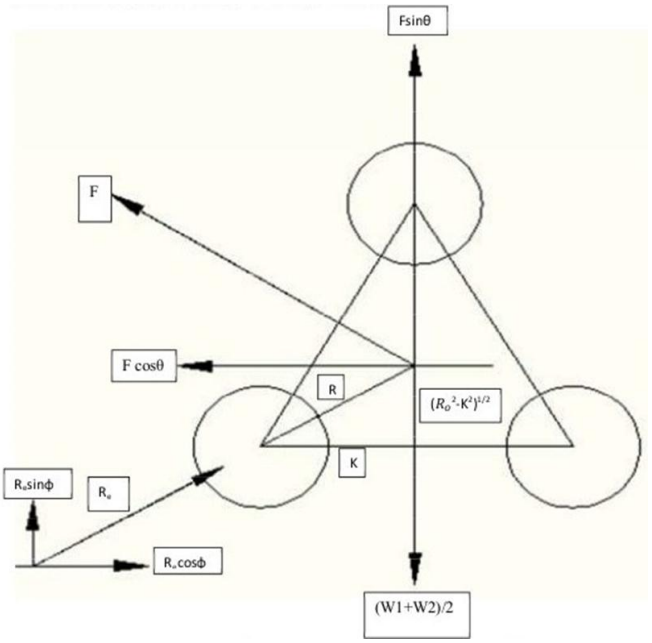

Fig -7: Tri-star wheel force analysis

4.3 Specifications

Material selection may be a step within the process of designing any object. In the context of product design, the goal of fabric selection is to attenuate the cost while meeting product performance goals. Systematic selection of the simplest material for a given application begins with properties and costs of candidate materials.

a. Frame Material

The main issue regarding the selection of frame material was the type of material used to construct the frame which not only affects the weight of the frame but also the overall weight of the forklift. The type of frame material also affects the forklift's overall strength to uphold the overall external load whether it is tensile or compressive. Cast Iron has more compressive strength whereas steel is more tensile. After analysing the forces, it is evident that the forklift design is going to experience more compressive force than tensile force. Grey cast iron is characterized by its graphitic microstructure, which causes fracture of the fabric to possess a grey appearance. It is the foremost commonly used forged iron and therefore the most generally used cast material. Grey cast iron has more shock resistance than steel but its compressive strength is of the grade of low and medium carbon steel. These mechanical properties are controlled by the size and shape of the graphite flakes present in the microstructure and can be characterized according to the guidelines given by the ASTM [9].

b. Shaft

The placement of the shaft in the forklift design has played a crucial role in the selection of suitable material. After Analyzing the forces and the

structure, it is clear that that the shaft will experience more tensile force than compressive force. Mild steel is a low carbon steel and it contains approximately 0.05–0.25% carbon making it malleable and ductile. The density of mild steel is approximately 7.85 g/cm^3 (7850 kg/m^3 or 0.284 lb/in^3) [10] and Young's modulus is 200 GPa[11]. Also compared to other steels, mild steel has a relatively low tensile strength; cheap and easy to form. Considering the strength of the mild steel being used, it is enough to withstand the tensile strength acting on it.

c. Bearing

As the Tri-Star-wheel mechanism is implemented in the model, a perfect bearing material in terms of size and load capacity to provide smooth motion of forklift over staircase is needed. Hence, keeping in mind the maximum load for the designed forklift and considering the dimensions of Tri-Star-wheel, a suitable bearing i.e. bearing 6205 and 6002 are used. Steel is mostly used in manufacturing bearings [12] because of the tensile force experienced by it.

d. Sprocket

Fig -8: Sprocket

Sprockets are meant to transmit the rotary motion between two shafts into a linear motion of forks through chains that are attached to it. Sprockets are used rather than gears or pulleys because unlike gears, sprockets never mesh together directly and can easily transmit power from one shaft to the other placed at some distance with the help of a chain. And unlike pulley, sprockets have teeth at its circumference. Also in the case of pulleys, the percentage of slip is higher due to the presence of a belt or rope. Hence, it is found that the use of sprocket is reasonable and suitable for the forklift mechanism. The material used in manufacturing sprocket is cast iron [12] because of the compressive force experienced by it.

e. Motor

The Square Gearbox Motor is a mechanically commutated DC electric motor , these motors are equipped with gearboxes for providing a great balance between torque and speed as per requirement. A square Gearbox motor is a simple DC motor of 6000 rpm (base motor rpm)which features a heavy-duty metal Gearbox. This square gear-box DC motor is a very high torque motor which should be used to make big robots or robotized platform. The motor will run at 10 rpm when powered with 12V DC supply. It produces a massive torque of 22kg-cm @10 rpm. The motor shaft is made up of good quality engineering steel with nickel plating to handle high torsion stress. The shaft of the motor equips metal bushes which make these DC geared motors shafts more wear resistant.

Fig -9: Gearbox Motor

Table -1: Motor Specification(Used)

Base motor rpm	6000
Rated voltage	12 V
Rated torque	16kg-cm
Rated current	220mA-1.3A
Stall torque	66kg-cm
Shaft diameter	8mm
Shaft length	25.6mm
Gearbox shape	Rectangular

Gear material	Mild steel
Operating temperature	(-10-85)°C
Weight	446gm

4.4 Machining Operations

1. **Cutting**
   The cutting technique uses the method of fabric removal. Cutting consists of processing continuously small parts coming from an ingot to possess high productivity. Cutting provides a high precision workout to the hundredth of a millimetre, for diameters starting from 0.1 mm to 40 mm. Once cut, these products may undergo thermal, mechanical or chemical treatments before being made to use. The material removal process allows getting end products like chrome steel, aluminium, steel, titanium. The oblong frame of the forklift is fabricated by cutting hollow rectangular rods into dimensions of 115cmx65cm followed by the cutting of handle of the forklift into102cm length rod. For tri-star-wheels, 12 pieces of the forged iron sheet of length 22cm are cut. 12 Support pieces are fabricated and attached to the wheels. The platform of the fork is fabricated with dimensions of 35cm. The forks are then dug 13 inches length. Then 2 pipes each of dimension 80cm length is provided as support for the movement of the fork.
2. **Pipe Bending**
   Pipe bending is a technique used in various metal forming processes to increase the fabrication capabilities of plumbing fixtures. The pipe is often bent at varying angles and in several directions. The simplest curve turns the tube at an angle of 90 degrees forming an elbow. Besides, pipe bending often wipes out several other geometries that include 2D and 3D dimensions. In the fabrication of the forklift, only the handle has been bent into a semi-circle of radius 32.5cm.
3. **Welding**
   The frame of the forklift is welded together using the metal rod welding process. The rods are then attached to the frame. After the rods are placed in their correct location, the platform is welded on to it. The forks are fixed under the platform and the shaft is welded to the wheels to provide movement to the machine. The motor is then welded on to the frame.
4. **Lathe Operation**
   A hollow shaft of length 65cm undergoes 5cm insertion of two rods on both ends,each of length 10cm and dia 3cm, thus giving a complete dimension of 75 cm in length. Since the motor shaft is of length 2.5 cm only, a little rod is operated on the lathe to supply support to the most shaft and therefore the bearing to lift the load.

Fig -10: Turning Operation of Sprocket

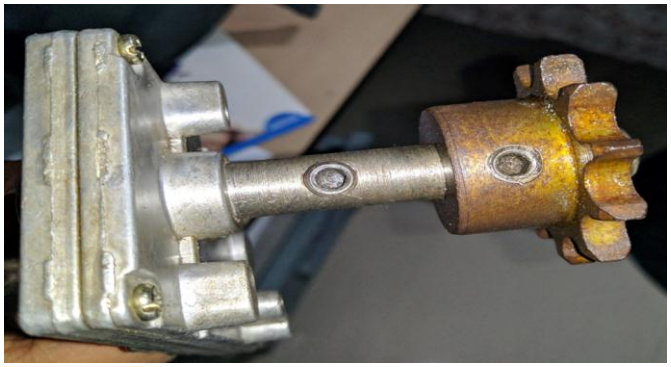

Fig -11: Sprocket and Shaft Assembly

5. **Drilling**
   The tri-star wheels are drilled into a hole of radius 2.5cm. Then 6 holes are drilled on each assails of both the edges. Drilling is also applied for making the shaft. Two rods of 10 cm are drilled inside a hollow shaft and welded to supply rigid support to the applied weight.

5. PARAMETRIC CALCULATIONS

a) Radius of Wheel

From Equation (1)

$$R = \sqrt{\frac{(a^2 + b^2)}{3}}$$

$$= \sqrt{\frac{(150^2 + 350^2)}{3}}$$

$$= 219.8$$

$$\approx 220mm$$

b) Radius of tri-star wheel

From Equation (3) and calculating the value of T_{max} from Equation (2)

$$r_{min} = \frac{6Rt + a(3b - \sqrt{3}a)}{(3-\sqrt{3})a + (3+\sqrt{3})b}$$

$$r_{min} = \frac{6\times 220\times 250 + 150\times(3\times 350 - \sqrt{3}\times 150)}{(3-\sqrt{3})\times 150 + (3+\sqrt{3})\times 350}$$

$=820mm$

$=8.2\text{cm}$

Fig -12: Tri-star-Wheel Setup

c) Bearing Load Calculation

(Pure radial force for lifting)

Considering total weight to be 40 kg

$$F_r = W \times g$$

$$=40\times 9.81 \quad \text{.....(11)}$$

$=392.4\ \text{N}$

Speed of rotation, n=10rpm

Diameter of supporting rod,d=15mm

Equivalent dynamic load(P):

$P = F_r = 392.4\ \text{N}$

For trolley type cars life,

L_{10} = 500 million revolution[13]

Dynamic load capacity of bearing (C):

$$C = P\times (L_{10})^{\frac{1}{3}}$$

$$= 392.4\times (500)^{\frac{1}{3}} \quad \text{..... (12)}$$

$=3114.5N$

- *Selection of bearing :*

For d=15mm, 4 different bearings are available [13]

Bearing 6002 with dynamic load capacity of 5590 has been selected.

d) Analysis of axle load

$$\frac{M}{I} = \frac{\sigma}{Y} = \frac{E}{R}$$

$$\therefore \frac{M}{I} = \frac{\sigma}{Y}$$

$$\Rightarrow \sigma = \frac{M}{I}\times Y$$

Now,

$$I = \frac{\pi\times r^4}{4} = \frac{\pi\times 0.016^4}{4} = 3.21\times 10^{-9} m^4$$

$$Y = \frac{D}{2} = 0.008m$$

$$M = \frac{\omega l^2}{8} = \frac{245.25\times (0.65)^2}{8} = 12.95Nm$$

Considering factor of safety(f.o.s)=1.5

$$M = \frac{12.95}{1.5} = 8.63Nm$$

$$\therefore \sigma = \frac{M\times y}{I} = \frac{8.63\times 0.008}{3.21\times 10^{-9}} = 2.15\times 10^7\ N/m^2 = 21.5N/mm^2$$

Fig -13: Shaft Assembly

6. CONCLUSION

In this model, grey forged iron is used instead of steel to make it cost efficient. The planning is improvised by using two tri-star-wheels and shaft assembly, resulting in compactness of the model.In previous work, motor and gear were installed separately but here the idea of square geared motor is being used. Balancing of the downward force of the weight is feasible with this new design as the frame isn't rigidly welded to the shaft. The bearings are used to provide movement to the frame to supply user advantage. Thus the aim of the work to minimize the human effort i.e. transportation of heavyweight objects over irregular surfaces and at low cost is accomplished.

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