

Design and development of steering mechanism for hydraulically driven firefighting trailer

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ABSTRACT

Firefighting is the act of extinguishing destructive fires. Hydraulic fire fighting trailers are specially designed trailers equipped with modern firefighting equipments used in fire fighting. In general practice fire fighting is done with the help of traditional water gun or nozzle which is controlled by manually by fire fighters. For fire coming under low temperature range, extinguishing is easy because water monitor can be taken closer to the fire source, but in case of destructive fire, a heat zone is created around the heat source. The temperature of this heat zone is very high and hence fire fighters cannot enter the heat zone. In such cases the act of firefighting is done from a distance. If the act of fire extinguishing is done from a distance with the help of water gun only 20-30% of water reaches the source as a major part of it evaporates due to high temperature. In such condition a remote operated vehicle is required which can easily enter the heat zone and extinguish the fire. The only limitation of these kind of trailers is that, we cannot use Electric motors, batteries because of chances of explosion or melting of the other circuitry. To eliminate this problem a hydraulic fire fighting trailer was developed by Mr. Amit Bhende under the guidance of Prof. Prashant.S Kadu. Using the properties of hose pipe such as straightening, elongation and buckling a hydraulically driven vehicle was fabricated which can easily enter the heat zone without human assistance. The trailer travels with the help of hydraulic pressure developed by the firefighting pump. As the flow of water is continuous within the hose pipe, it can easily bear the high temperature of the heat zone.

Key words: Water monitor trailer, fire, Finite element model, stress distribution, deformation pattern, fire resistant steel.

INTRODUCTION

The present design of the trailer lacks a steering mechanism which makes it difficult to move and position it to required location in case of fire extinguishing. The objective is to design and develop an effective steering mechanism for the trailer so that we can easily position our trailer to required location in the heat zone and can target the source.

Temperature is the major factor in design and development of any attachments for fire fighting trailer. As the temperature of the heat zone is much high every design should have temperature consideration. If a temperature resistant, remote operated automatic control system is developed for the trailer which will propel the trailer to the heat source and adjust the water gun and all the other controls, this fire fighting trailer can easily fight destructive fire without causing any damage to fire fighters.

Working of Proposed Design

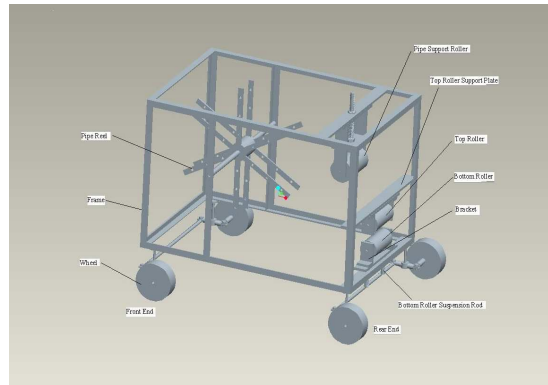


Fig 1 Proposed Design of Trailer

The trailer consists of a steel frame with a pulley over which the hose pipe is wound. One end of the pipe is fixed to the pulley and other is passed through the rollers and is connected to the pump. The lower roller is spring loaded and the upper one is fixed. When pressurized fluid passes through the pipe, due to sudden contraction near the roller, pressure rise takes place which results in development of thrust which pulls the hose pipe wound on the pulley, which in turn propels the trailer in forward direction. Because of this the trailer can easily enter the heat zone without any human assistance and we can easily attack the fire source. Once it reaches the required location we can divert the fluid flow to the water gun and spraying action takes place.

2 FORCE CALCULATIONS CONSIDERING ACTUAL WORKING CONDITION

The pumps generally used in fire fighting are in the range of 800-1000 lpm (Liter per minute). It means that the discharge of the pump is around 0.015 cubic meters per sec.

Loss of kinetic energy of water = [gain of strain energy in water + strain energy stored in pipe material]

$$\frac{1}{2} AL = \frac{1}{2} \frac{p^2}{K} \times AL + \frac{p^2}{2} \frac{ADL}{Et}$$

From the above equation,
Increase in pressure in pipe

$$p = V \times \sqrt{\frac{\rho}{\left(\frac{1}{K} + \frac{D}{Et}\right)}}$$

Where,

ρ = Density of water = $1000 / 9.81 \text{ kgf} / \text{m}^3 = 101.936 \text{ kgf} / \text{m}^3$

k = Bulk modulus of the hose pipe material = $2 \times 10^8 \text{ kgf} / \text{m}^2$

E = Modulus of elasticity of pipe hose material = $2 \times 10^{10} \text{ kgf} / \text{m}^2$

$1/m$ = poisson's ratio for pipe material

p = increase of pressure due to water

t = thickness of pipe wall = 2 mm

D = diameter of the pipe = 50 mm

Calculation of Increase in Pressure in the Pipe

Velocity of water in pipe 'V'

$$V = \frac{Q}{A}$$

Where,

*Q = Discharge of pump = 0.015 m³/s

A= Area of hose pipe = $1.96 \times 10^{-3} \text{ m}^2$

$V = Q/A$

$V = 7.63 \text{ m/sec.}$

Hence,

Increase in pressure in pipe

$$P = 7.63 \times \sqrt{\frac{101.936}{\left(\frac{1}{2 \times 10^8} + \frac{0.05}{2 \times 10^{10} \times 0.002}\right)}}$$

$$= 9.55 \text{ N/mm}^2$$

Forces Acting on the Roller Surface

The force exerted by the increase in pressure just before the rollers, is calculated as follows

Force exerted by water in hose = pressure x area

$$F_t = 9.55 \times 3.14/4 \times 50^2$$

$$= 19634.9 \text{ N}$$

This total force exerted by water is utilized in tractive force required to drive trailer, overcoming the roller bearing rolling friction, pull force for drawing the hose pipe, force exerted on roller and some transmission losses. So we calculate these forces one by one

Total force exerted by water on roller = tractive force required to drive trailer + overcoming the roller bearing rolling friction + pull force for drawing the hose pipe + exerted on roller + nozzle reaction -----
------(A)

i) Tractive force required to drive trailer = Frictional force + Rolling wheel resistance + Grade resistance

$$= ma + R_{rl} + R_g$$

$$a) ma = 85 \times 3 = 255 \text{ N}$$

$$\therefore a = \left(\frac{(3-0)}{1} = 3\right)$$

$$b) R_{rl} = f_{rl} \times W$$

$$f_{rl} = 0.01 \left(1 + \frac{3}{147}\right) = 0.0102$$

$$= 0.0102 \times 85 \times 9.81 = 8.5 \text{ N}$$

$$c) R_g = m \cdot g = 85 \times 9.81 = 833.85$$

$$\text{Tractive Force} = 255 + 0 + 8.5 + 833.85$$

$$= \mathbf{1097.35 \text{ N}}$$

ii) Roller bearing rolling friction

$$= 4 [0.01022 \times \text{mass of roller} \times 9.81]$$

$$= 4 [0.01022 \times 4.4 \times$$

$$= \mathbf{1.76 \text{ N}}$$

iii) Power required to pull the hose pipe between the rollers is given by

$$P = r_s \{V_u \cdot g \cdot 3.14 \cdot d_u \cdot N_u + 2 [V_l \cdot g \cdot 3.14 \cdot d_l \cdot N_l]\}$$

Where,

$$R_s = \text{Density of steel} = 7861.093 \text{ kg/m}^3$$

$$V_u, V_l = \text{Volume of upper and lower roller}$$

$$G = \text{acceleration due to gravity} = 9.81 \text{ m/s}^2$$

D_u, d_l = diameter of upper and lower roller
 P = Power required to pull

$$P = 7861.093 \{0.000576 \times 9.81 \times 3.14 \times 0.07 \times 458.6 + 2 [0.000576 \times 9.81 \times 3.14 \times 0.07 \times 458.6]\}$$

$$= 4485.03 \text{ W}$$

Now torque required to pull the hose between rollers is given by
 $T = (P \times 60) / 2 \times 3.14 \times 458.6$
 $= 93.44 \text{ N-m}$

Force required to pull the hose between the rollers is given by
 $F = \text{Torque} / \text{Radius of roller}$
 $= 93.44 / 0.035$
 $= 2669.65 \text{ N}$

Frictional force between hose pipe and roller = $(\mu \times \text{force at roller}) \times 2$
 $= 0.002 \times 2669.65 \times 2$
 $= 10.67 \text{ N}$

Hence total force required to pull the pipe = $2669.65 + 10.67 = 2680.32 \text{ N}$

Nozzle Reaction

$$NR = 1.57 \times d_2 \times \text{Nozzle Pressure}$$

The nozzle reaction on a 2½" hose line flowing through a 1" nozzle tip at nozzle pressure of 70 psi considering smooth bore nozzle is given by

$$NR = 1.57 \times 1^2 \times 70$$

$$= 109.9 \text{ Pound}$$

$$= 488.86 \text{ N} \sim 500 \text{ N}$$

Putting all the values in equation (A)

We have

$$19634.9 = 1097.35 + 1.76 + 2680.32 + 500 + \text{force on rollers}$$

$$\text{Force exerted on roller} = 15355.5 \text{ N}$$

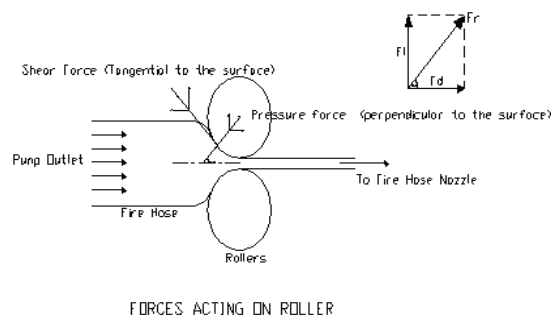


Fig 2 Force Acting on Rollers

From the above fig
 Lift and drag force acting on the rollers are

$$F_d = 15355.5 \times \cos \phi = 15355.5 \times \cos 45 = 10857.9 \text{ N} \quad (\phi = 45)$$

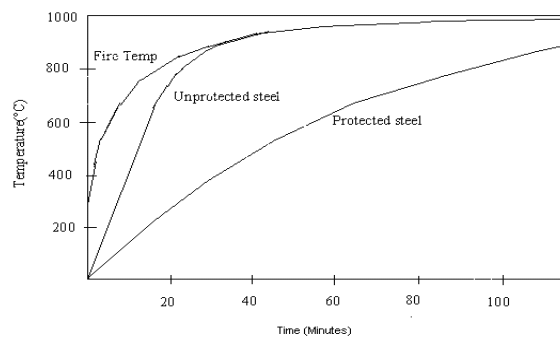
$$F_l = 15355.5 \times \sin \phi = 15355.5 \times \sin 45 = 10857.9 \text{ N}$$

MATERIAL SELECTION

The effect of temperature on metals

Generally, unprotected steel in a high temperature environment does not perform well as a structural material due to the fact that steel has a high thermal conductivity and the members made of steel usually have thin cross sections.

Figure 1 shows the rise in temperature of the protected and unprotected steel exposed to the fire with respect to the rise in temperature of the fire. From the figure 3.5 it is clear that the time required by unprotected steel to attend the particular temperature is quite less than that of protected steel. Hence time required to reach the temperature of 500°C (temperature up to which the property of the steel remains unchanged) by unprotected steel is approximately 15 minutes while that of protected steel is 35 minutes. Hence the use of fire protected steel for the manufacturing of the trailer gives 20 minutes extra that of trailer manufactured by unprotected steel. These 20 extra minutes are extremely crucial during the fire fighting and reduce the further damage due to fire.



Considering the above mentioned behavior of the materials in case of high temperature an alloy which can withstand high temperature of destructive fire can be used as a trailer material. The material selected for the trailer and all its components is high temperature alloy steel of grade SAE40. The alloy contains 1% Carbon, Molybdenum, Vanadium. This reduces the creep rate of steel at high temperature and increases its resistance to high temperature. The properties are as follows

Table 1. Material properties

Sr. No.	Name of Property	Value
1	Comp Ultimat Strength	0.0 Pa
2	Comp Yield Strength	2.5 x 10 ⁸ Pa
3	Density	7850.0 kg/m ³
4	Ductility	0.2
5	Poisson's Ratio	0.3
6	Tensile Yield Strength	2.5 x 10 ⁸ Pa
7	Tensile Ult Strength	4.6 x 10 ⁸ Pa
8	Young's Modulus	2.0 x 10 ¹¹ Pa
9	Thermal Expansion	1.2 x 10 ⁻⁵ 1/°C
10	Specific Heat	434.0 J/kg °C
11	Relative Permeability	10,000.0
12	Resistivity	1.7 x 10 ⁻⁷ Ohm-m

4 Finite element model.

The water monitor trailer was modeled by 10 node tetrahedral (Tet-10) solid92 element. Linear static analysis is carried on the model to find out the stress distribution and deformation pattern of the trailer under static loading. The trailer model was meshed with 8035 Tet-10 elements with 21175 nodes were used. For static analysis, the trailer was treated as a fixed member. While applying boundary conditions the frame was made fixed and then the analysis was carried out. The frame was treated as simply supported beam to find its stability which was determined by finding out the normal reactions at various supports. The bottom spring loaded roller is allowed to have one degree of freedom in downward direction for compensating the compression of the spring. Loading conditions are defined by

applying surface forces of magnitude 7677.8 N each on top and bottom rollers. Solution contains calculated response for the model under given loading condition at 600 degree temperatures defined in environment.

5 Results of static thermal analysis

The static analysis results are based on the assumptions made where the trailer is treated as stationary member. The frame was treated as a simply supported beam and force exerted by the pressurized water due to sudden contraction in the hose pipe just before the rollers and the weight of the component applied to the beam were treated as the loading conditions for the trailer.

Figure 4 shows the result of von mises stress distribution contour of the trailer under loading condition. The stress distribution is almost uniform, with highest stressed area at the bottom roller suspension springs, where the maximum stress is about 150 MPa.

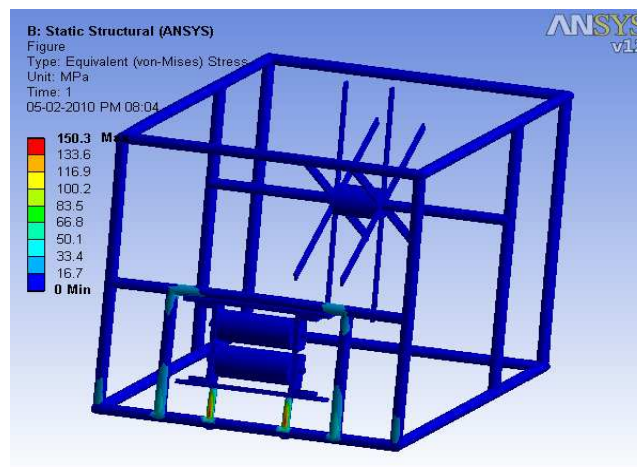


Figure 3 . Vonmises stress contour

Figure 5 shows the deformation contour and deformation pattern of the trailer under static load. The highest deformation happens at the top surface of the bottom roller where the hydraulic pressure is being applied

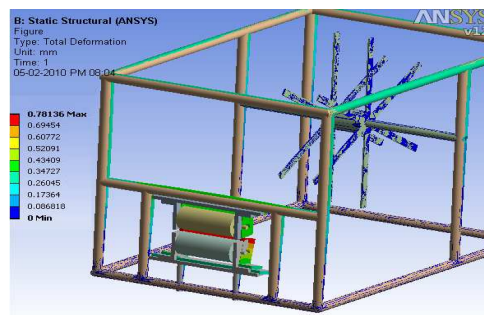


Figure 4. Deformation contour

6 STEERING DESIGN FOR TRAILER.

Study of various types of mechanism shows that the ultimate aim in all the steering systems is to control the tie rod motion to achieve the desired motion of the wheels. The steering mechanism, gears and linkages are used just to reduce the effort required to steer the vehicle and to control the tie rod motion.

For this particular trailer, a steering mechanism, working on Ackerman's principle was proposed.

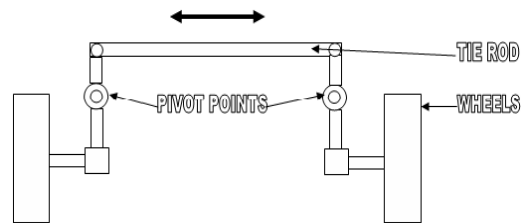


Fig 5 Proposed Steering Mechanism

The dimensions of the proposed design of the steering mechanism were selected arbitrarily based on the dimensions of the trailer. The mechanism consist a tie rod and a bearing housing type member which is provided with pivot joints which will be attached to the trailer frame. An elevated arm will be provided on the tie rod and the actuator will be attached to that arm which will actuate the steering mechanism. The actuations of the steering tie rod will be done with the help of a linear hydraulic or pneumatic actuator. The actuator was selected considering following points

- A Degree of turn required
- B Force required for steering the trailer.

7 STEERING CALCULATIONS

7.1 CALCULATION FOR TIE ROD TRAVEL

The trailer is assumed to take a 60 degree turn with respect to its initial straight position. Considering this assumption the stroke length of the hydraulic actuator can be determined.

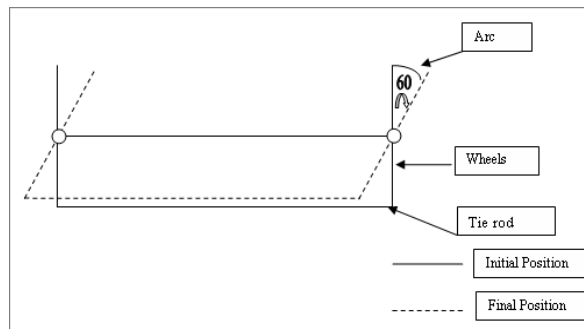


Fig 7 Line Diagram for Steering

Distance traveled by the steering tie rod for the required 60 degree turn of the vehicle is same as the length of the arc traced out by the tip of the steering linkages or wheel.

$$\text{Length of Arc} = (\Theta/360) \times 2 \times \pi \times r$$

Where r is the radius or the wheel.

$$= (60/360) \times 2 \times \pi \times 125$$

$$= 130 \text{ mm.}$$

This means that if we move the tie rod of the steering mechanism by 130 mm it will turn the wheel by 60 degree in right or left direction respectively.

So the hydraulic actuator to be used for actuation of the steering mechanism should have a stroke of around 130 mm.

7.2 CALCULATION FOR FORCE REQUIREMENT FOR STEERING.

A manual testing was done on the trailer steering mechanism to find the force required to steer the trailer. The test was based on the practical industrial approach generally used to find the force required for any process.

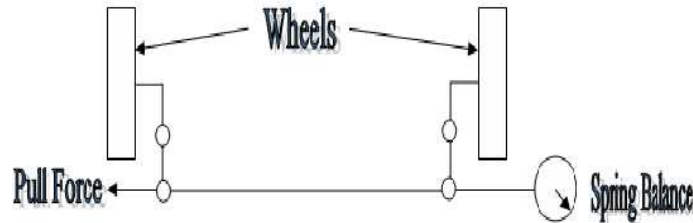


Fig 6 Force Requirement

A spring balance was attached to one end of the tie rod of the steering and then the other end of the steering rod was pulled manually to find what force in Kg is required to turn the wheels of the trailer. 3-4 trials were done on various conditions such as on plain

Cement surface and on marshy surface, and the average value of all the readings was considered as the required actuation force for the steering.

The force required to turn the wheels came to be around 27kg. Considering it to be 30 kg which is around 300 N.

So now the selection of the actuator depends on two things it should develop a force of around 300 N and must have a stroke length of around 130mm.

Considering the above requirement and availability of standard rating actuators a double acting, 150 mm stroke cylinder with 90 mm bore diameter and 25 mm rod diameter was selected. The force generated by this actuator will be much higher than required but with the use of pressure regulating valve this pressure can easily be controlled.

7.3 CALCULATION FOR FORCE EXERTED BY CYLINDER.

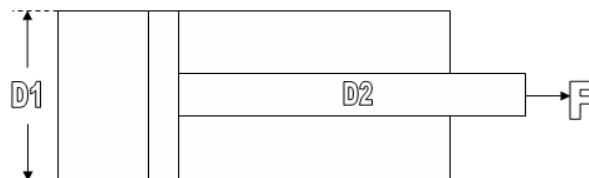


Fig 8 Double Acting Cylinder

The force exerted by double acting pneumatic cylinder on outstroke can be expressed as

$$\text{Force} = p \times \pi \times (D1^2 - D2^2) / 4$$

Where D1= Piston Diameter (m)

D2= Rod Diameter (m)

P= pressure

$$\text{Therefore Force exerted} = 200 \text{ KPa} \times \pi \times (90^2 - 25^2) / 4$$

$$= 1200 \text{ N.}$$

This force is acting on the steering assembly while steering mechanism is actuated.

The steering mechanism is to be analyzed for the above calculated force and its stability and reliability is to be checked. Analysis of the steering system was done with the same approach followed during the analysis of trailer.

7.4 ANALYSIS OF STEERING MECHANISM

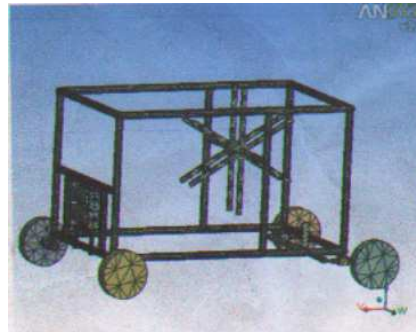


Fig 4.13 Meshed Steering Assembly

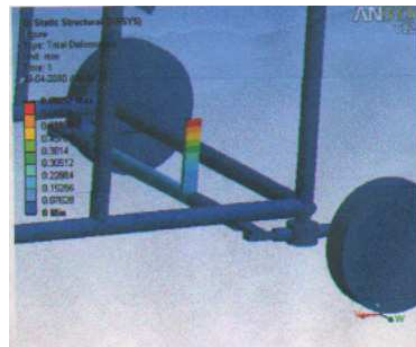


Fig 4.14 Deformation in Steering Assembly

Fig 4.14 shows the deformation occurred in the circular section trailer. And maximum deformation is found to be 0.6865 mm.

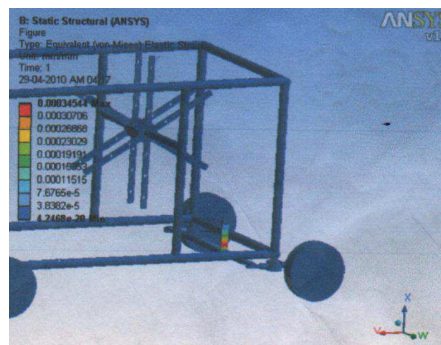


Fig 4.15 Stress Distribution in Steering Assembly

Fig 4.15 shows the maximum induced stress in the trailer which is found to be 150.3 MPa.



STEERING MECHANISM

8 EXPERIMENTAL SET-UP AND TESTING

Validation of the results is very important in case of any designing or analysis. This dissertation was not limited only to the designing of the system, but also the actual development ie fabrication of trailer is also done. To validate the results few test were carried out on the trailer. For this purpose an experimental setup was established with all the necessary equipments, where we can actually run the trailer and see the response of trailer for different pressure, its steering mechanism etc.

8.1 Hydraulic circuit for the setup

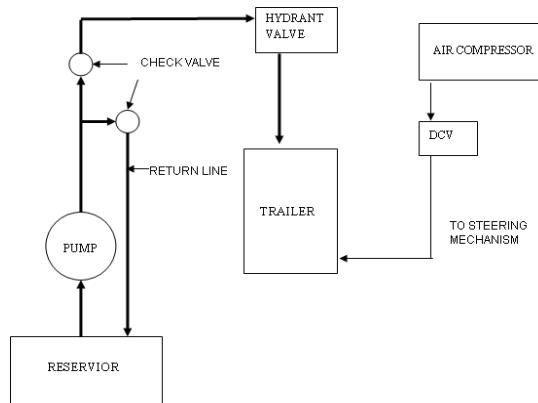


Fig 6.1 Experimental Set-up



8.11 TESTING

For testing purpose a track was prepared for the trailer where we can actually drive the trailer and record its response for different pressure and the response of steering mechanism for corresponding pressure.

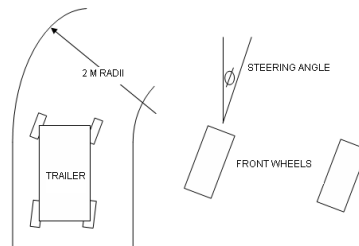


Fig. 6.2 Testing of Steering

At the start of experimentation we keep the return line full open so that the water is re circulated and no pressure rise is observed at the hydrant valve end. When the return check valve is closed slowly the pressure starts building at the hydrant valve end and then this pressurized water is diverted towards the roller of the trailer. The trailer moves forward and when it reaches the prepared turn the steering mechanism is actuated and then the steering angle of the wheels is measured, by making the trailer stop at that particular position.

The trailer was tested for different water pressure and the observations are as follows.

Table 6.1 Observation during Testing

WATER PRESSURE	TRAVEL TIME FOR 3METER	STEERING ANGLE AT TURN	STEERING PRESSURE
2 KG/CM ²	7.11 SEC	20 ⁰	2 KG/CM ²
3 KG/CM ²	6.85 SEC	25 ⁰	2 KG/CM ²
4 KG/CM ²	4.44 SEC	20 ⁰	2 KG/CM ²
5 KG/CM ²	3.94 SEC	33 ⁰	2 KG/CM ²

From the observations it is found that the steering pressure required to steer the trailer at various water pressure is same. The only change which is observed is in the velocity of the trailer and the steering angle at that particular velocity. As the steering is manually remote operated the steering system the angle may vary with person to person because it depends on the response of the operator while turning the trailer at a particular velocity.

Table 6.2 Calculated Velocity of Trailer

WATER PRESSURE	VELOCITY OF TRAILER
2 KG/CM ²	0.417 M/SEC
3 KG/CM ²	0.437 M/SEC
4 KG/CM ²	0.675 M/SEC
5 KG/CM ²	0.761 M/SEC

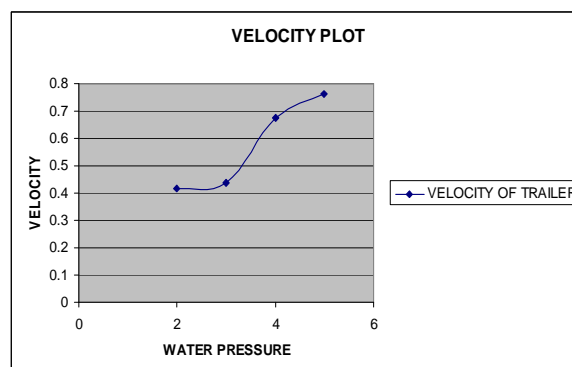


Fig 6.3 Trailer Velocity Graph

Table 6.3 Steering Parameters

WATER PRESSURE	STEERING PRESSURE	STEERING ANGLE
2 KG/CM ²	2 KG/CM ²	20 ⁰
3 KG/CM ²	2 KG/CM ²	25 ⁰
4 KG/CM ²	2 KG/CM ²	20 ⁰
5 KG/CM ²	2 KG/CM ²	33 ⁰

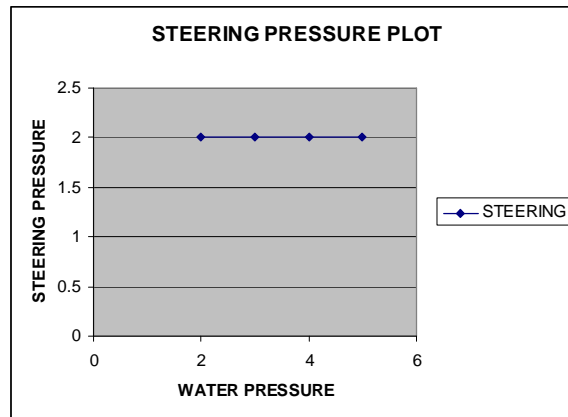


Fig 6.4 Water pressure v/s steering Pressure graph

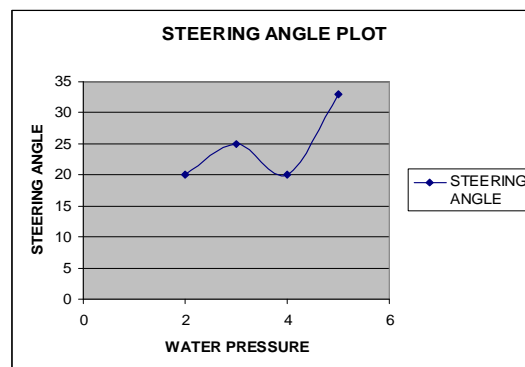


Fig 6.5 Steering Angle Graph

CONCLUSION

The objective of this dissertation was to design and develop a steering and water gun lifting mechanism for a hydraulically driven fire fighting trailer. The objective is achieved in *three* stages.

Stage1.

Here we have analyzed the proposed design of the trailer considering it to be working under actual fire fighting condition. We have calculated the forces acting on the trailer under actual condition and then analyzed the trailer using analysis software ANSYS Workbench. Forces, temperature and boundary conditions were defined assuming all the actual parameters that the trailer may face in case of fire fighting.

When the results of the analysis were studied it is found that the trailer is safe the maximum induced stress is well below the allowable stress limit of the material used for the trailer, and hence the dimensions of the proposed model are finalized as the final dimension of the trailer.

Stage2.

After finalizing the trailer dimensions, a steering mechanism working on Ackerman's principle was proposed. The dimension of the steering mechanism linkages are selected on the basis of the trailer dimensions. Steering force and

tie rod travel was calculated so that proper actuator can be selected for actuating the steering mechanism. After selecting the actuator, the force exerted by the steering actuator on the steering assembly was calculated and the system was then analyzed for the exerted force.

The results show that the steering assembly is safe under given working conditions or working forces. The induced stress is below the allowable stress limit of the material.

Considering the effect of nozzle back pressure and reactions developed because of the nozzle at wheel end a mechanism for water gun lifting is also proposed.

Stage 3.

As it is a development project actual trailer with steering mechanism is fabricated. To validate the results obtained from the software few testes were carried out on the trailer at different water pressures. The velocity, steering pressure and steering angle were found out for different pressure conditions.

The results shows that

- As the pressure of water directed towards the rollers of the trailer increases, the velocity of the trailer increases.
- The steering pressure, or the air pressure required to actuate the steering mechanism is constant for all the different water pressure ranges.
- The steering angle shows a non linear behavior with change in water pressure. But the results can lead to the conclusion that as the speed or velocity of the trailer increases the steering angle, for taking a particular turn, increases.

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