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Design Analysis of 5 Tonne Hydraulic Jack

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Abstract: This paper present detailed parts design analysis for production of 5 tonne hydraulic jack. The study focuses its attention on the design of the hydraulic jack parts that are involved in production of the jack.Such as piston, cylinder, jack base etc. the main objective of the study is to came-up with production line of the equipment with locally available materials that could be used as a milestone for mass production of the jack.
Keywords: Hydraulic machines, Hydraulic jack, Piston, Cylinder

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I. INTRODUCTION

Hydraulic machineries are machines and tools which use fluid power to do work. In this type of machine, high pressure liquid called hydraulic fluid is transmitted throughout the machine to various channels where it will be converted to work that will overcome a load. The fluid is controlled directly or automatically by control values and distributed through hoses or tubes.

The popularity of hydraulic machineries is due to the very large amount of power that can be transferred through small tubes, and the high power density and wide array of actuators that can make use of this power. In hydraulics, the powering medium is liquid while gas is the powering medium for pneumatics. A very good example of this equipment is a hydraulic jack.

II. MATERIAL AND METHODS

Hydraulic jack is a fluid processed device which is used to lift heavy load(s) by the application of much smaller force. This device works on the principle of "Pascal law of pressure" which states that "intensity of pressure is transmitted equally in all directions through a mass of fluid at rest [5].
The working mechanism of a hydraulic jack may be explained with the help of diagram below:

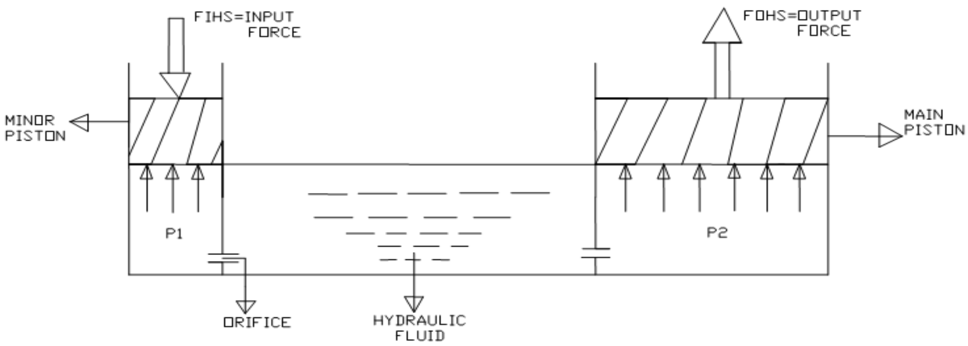

Fig 1.0: Schematic Diagram of Hydraulic jack

In the diagram above, the system comprises of a main piston and minor piston operating in two cylinders of different diameters that are inter-connected at the base, through a chamber which is filled with incompressible fluid. As force is supplied externally, on the minor piston, pressure P_1 is exerted at the minor cylinder. Based on the principle of Pascal's law of pressure, the pressure P_1 is transmitted through the channel to the main cylinder which has a bigger cross sectional area. Here, the pressure P_2 is exerted on the bigger piston to produce the work which could be used to overcome the load.

It should be noted that high pressure is generated and care must be taken to prevent pressure loss which might adversely affect the efficiency of the machine [10].

2.1DESIGN ANALYSIS(MAIN PISTON)
2.1.0 DESIGN CRITARIA

1. The element is taken as a column because of the operating condition.
2. To reduce failure due to buckling and ensure convenience lift to carry out minor repair or maintenance on the part of automobile, a lift of distance 100mm is selected.
3. Base on the operating condition, steel AISI1020 Hot rolled with $\sigma_y =$ 207 Mpa is selected.
4. By virtue of the operating condition, “fixed – free” fixity ends with stress factor k = 2 are selected.

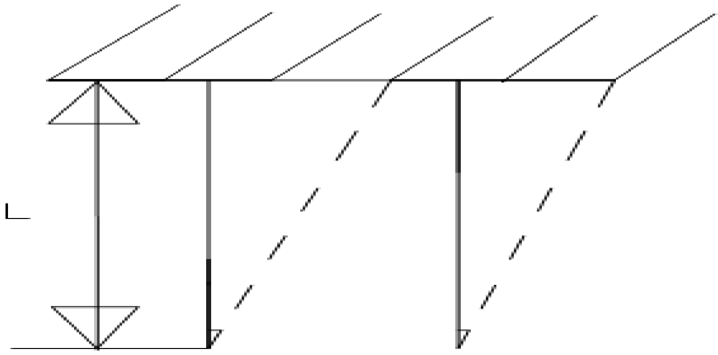

Fig 4.0: A fixed – free ends column

2.1.1 TO DETERMINE TYPE OF COLUMN,

$$D = \left\{\frac{64nP\,(KL)^2}{\pi^3 E}\right\}^{1/4} \text{………………(VII)}$$

Where: D = Column diameter (mm)
n = Design factor
P = Load (49050N is given)
K = Stress factor
L = Distance of lift
(100mm is selected to ensure safety of the operator)
E = Modulus of elasticity for steel is 207 GPa

Let n = 4 (shock and impact energy is required on the column)

$$D = \left\{\frac{64 \text{ X } 4 \text{ X } 49050 \text{ X}(2 \text{ X } 0.1)^2}{\pi^3 \text{ X } 207 \text{ X } 10^9}\right\}^{1/4}$$

D = 0.0167m
≈ 16.7mm

$$r = \frac{D}{4} \text{…………….(VIII)}$$

where: r = Radius of gyration (mm)

$$r = \frac{0.0167}{4}$$
$$= 0.00418\text{m}$$

$$\text{S.R.} = \frac{KL}{r} \text{…………………..(IX)}$$

where : S.R. is Slenderness Ratio

$$\text{S.R.} = \frac{2 \text{ x } 0.1}{0.00418}$$

S.R. = 47.85

$$\text{T.R.} = \left\{\frac{2\pi^2 E}{\sigma_y}\right\}^{1/2} \text{…………(X)}$$

where : T.R is Transmission Ration

$$\text{T.R} = \left\{\frac{2 \text{ x } \pi^2 \text{ x } 207 \text{ x } 10^9}{207 \text{ x } 10^6}\right\}^{1/2}$$

T.R. = 140.5

Note: Slender Ratio (S.R) is less than Transition Ratio (T.R), and then the column is short. Therefore the column is re-designed as short column using J.B. Johnson equation [13].

$$D = \left\{\frac{4NP}{\pi\sigma_y} + \frac{4\sigma_y\,(KL)^2}{\pi^2 E}\right\}^{\frac{1}{2}} \text{…………..(XI)}$$

D = $\left\{\frac{4 \text{ X } 4 \text{ X } 49050}{\pi \text{X } 207 \text{ X} 10^6} + \frac{4 \text{ X } 207 \text{ X } 10^6}{\pi^2 \text{ X } 207 \text{ } 10^9}\right\}^{1/2}$

D = 0.03497

≈ 35mm

2.1.2 MAIN PISTON LENGTH

Consider the relation below:

$$\frac{D_1}{L_1} = \frac{D_2}{L_2} \text{ ……………..(XII)}$$

Source: [2].

where: D_1 and L_1 = Diameter and length of minor piston (mm)

D_2 and SL_2 = Diameter and length of minor piston (mm)

$$\frac{10}{52} = \frac{35}{L_2}$$

. L2= 182mm

Average length of minor piston adapted is 180mm

2.1.3 PRESSURE EXACTED BY THE MAIN PISTON

$$P = \frac{F_2}{A_2} \text{ …………………………. (XIII)}$$

Where: P = Working pressure (N/m^2)

A_2 = Area of main piston (m^2)

F_2 = Output load acting on the jack is 49050N (Given)

Because design factor (n) is 4 in the design of main piston diameter, the pressure is considered as the working pressure and not maximum pressure, therefore the working pressure P is;

$$P = \frac{49050}{[\pi \text{ x } (0.035)^2/4]}$$

$$P = \frac{49050}{9.621 \text{ x } 10^{-4}}$$

$$P = 50.98 \text{ x } 10^6 \text{ N/m}^2$$

However, to determine the maximum pressure,

P_{max} = nP …………………..(XIV)

n = 4 was earlier selected

Where:P_{max}= Maximum pressure (N/m^2)

P_{maxS}= 4 x 50.98 x 10^6

= 203.6 x 10^6 N/m^2

= 203.6 MPa

2.1.4 MAIN CYLINDER (DESIGN CRITARIA)

1. Base on the operating condition of the element, a thin cylindrical shell is assumed.
2. Because the piston reciprocates up and down in the cylinder, only internal pressure is taken to be exerted.
3. Because the element in thin cylindrical shell, circumferential stress is adapted [8].
4. Base on operating condition, steel AISI1144 Hot rolled, with σ_T = 640 MPa is selected.
5.

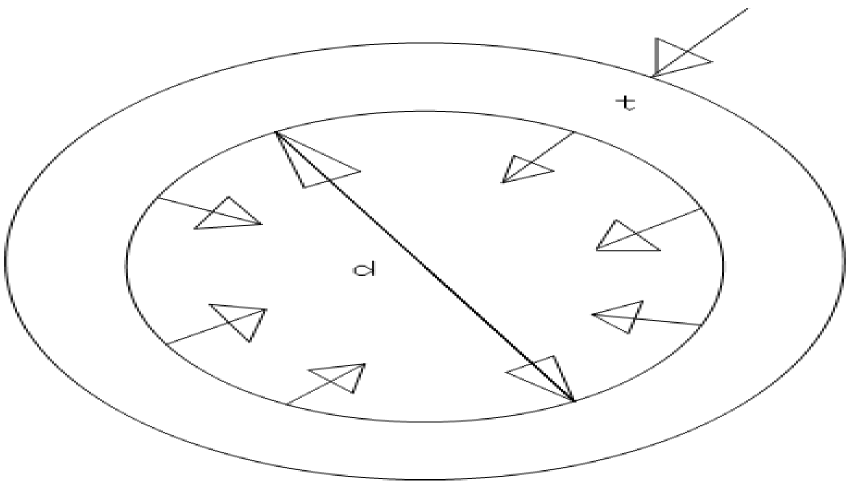

Fig 5.0: A Thin Cylindrical Shell Subjected to Internal Pressure.

$\sigma_C = \frac{\sigma_T}{n}$ …………………… (XV)

Where: σ_C = Circumferential stress (N/m^2)
σ_T = Tensile strength (N/m^2)
n = Design factor 3 (material and load ascertained)

$\sigma_C = \frac{640}{3}$

σ_C = 213.3 x 106 N/m^2

Take internal diameter of cylinder to be diameter of the piston + clearance 0.5 is recommended by [9].

d = 35 + 0.5
= 35.5mm

$t = \frac{Pd}{2\sigma_c}$ …………………(XVI)

Source: (Khurmi, 2006)

Where: t = Thickness of the wall of thin cylindrical shell (m)
P = Intensity of internal pressure
= 50.9 x 106 N/m^2 i.e. working pressure calculated.

$t = \frac{50.98 \text{ x } 10^6 \text{ x } 0.035}{2 \text{ x } 213.3 \text{ x } 10^6}$

t = 0.0042m
= 4.2mm
≈ 4mm

When the value of $\frac{t}{d}$ is less than 1/10th, then it is assumed a thin cylindrical shell [9]. Therefore, $\frac{4}{35.5}$ = 0.11
This value is around 1/10th, therefore thin cylindrical shell adapted earlier is appropriate.

1. Based on hardness and fair ductility properties required, steel AISI1050 cold drawn with σ_y = 579mpa is selected [11].

Where: Z = Sectionmodulus rectangular cross section (N/m)
b = Thickness of Number of threads subjected to load and constraint.

$Z = \frac{0.003 b^2}{6}$

Z = 0.0005b^2 N/m^3

$\sigma_{ALL} = \frac{M}{Z}$ ………………(XXV)

$193 \text{ x } 10^6 = \frac{22.992}{0.0005 b^2}$

b = 0.0154m

Take $b_T = \frac{b}{N}$ ……………(XXVI)

Whereb_T = Thickness of a thread (mm)
N = Number of threads subjected to load and constraint.

$b_T = \frac{0.015}{N}$

$\sigma_b = \frac{3Wh}{2\pi N r_i (b_T)^2}$ ……………..(XXVII)

Where: σ_b = Bending stress (N/m^2) acting on per thread.
Substitute b_T in above equation

$\sigma_b = \frac{3WhN}{2\pi r_i (0.0154)^2}$

Let $\sigma_b = \sigma_{ALL}$

$193 \text{ x } 10^6 = \frac{3 \text{ x } 49050 \text{ x } 0.003 \text{ x } N}{2 \text{ X } \pi \text{ X}0.00899 \text{ X } 0.0154^2}$

N = 5.9
≈ 6

If the number of threads subjected to load and constraint is 6, thickness per thread;

$b_T = \frac{0.0154}{6}$

b_T = 0.0026mm
= 2.6mm

P_d = D - Sin θ P………………..(XXVIII)

Where P_d= Pitch diameter (mm)
P = Pitch

θ = Included angle of the thread, (For a square thread $\theta = 5^{o}$), Source: [16].

$P_d = 23 - 6\sin 5^{o}$

$= 22.47$ mm

2.1.5 MINOR PISTON (DESIGN CRITERIA)

1. Consider that the material selected is having same properties with material selected for main piston.
2. Take the design factor N to be same i.e. 4.
3. Assume that there is no pressure loss

From Pascal's law of pressure

$$\frac{F_1}{A_1} = \frac{F_2}{A_2} = 50.9 \times 10^6$$

Where: F_1 = Input force on hydraulic system

= 3750 N (determined)

A_1 = Area of minor piston (m^2)

$$50.9 \times 10^6 = \frac{3750}{A_1}$$

$A_1 = 7.353 \times 10^{-5}\ m^2$

$$d_1 = \left[\frac{4A_1}{\pi}\right]^{1/2} \ldots\ldots\ldots\ldots\ldots \text{(XXIX)}$$

Where: d_1 = Minor piston diameter (mm)

$$d_1 = \left[\frac{4 \times 7.353 \times 10^{-5}}{\pi}\right]^{1/2}$$

$d_1 = 9.61 \times 10^{-3}$ m

$d_1 = 9.6$

≈ 10mm

2.1.6 MINOR PISTON LENGTH

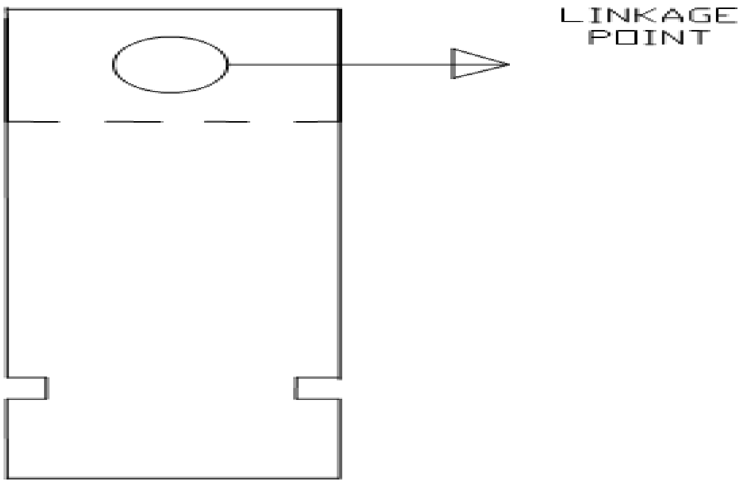

Fig 8.0: Linkage Point of Minor Piston

However, note that the piston conveniently fills the cylinder at the downward stroke. The length of the piston is considered to be length of cylinder plus linkage clearance (10mm) with lever system to ensure adequate movement of the minor piston.

$L_1 = C_L + C$

$= 52.0 + 10$

$= 62.0$mm

≈ 62mm

2.1.8MINOR CYLINDER (DESIGN CRITERIA)

1. Based on the operating condition, thick wall cylindrical shell is assumed.
2. Because the piston reciprocates up and down in the cylinder, only internal pressure is considered to be exerted.
3. Based on the working condition, steel AISI1020 Hot rolled with σ_T= 392mpa is selected.

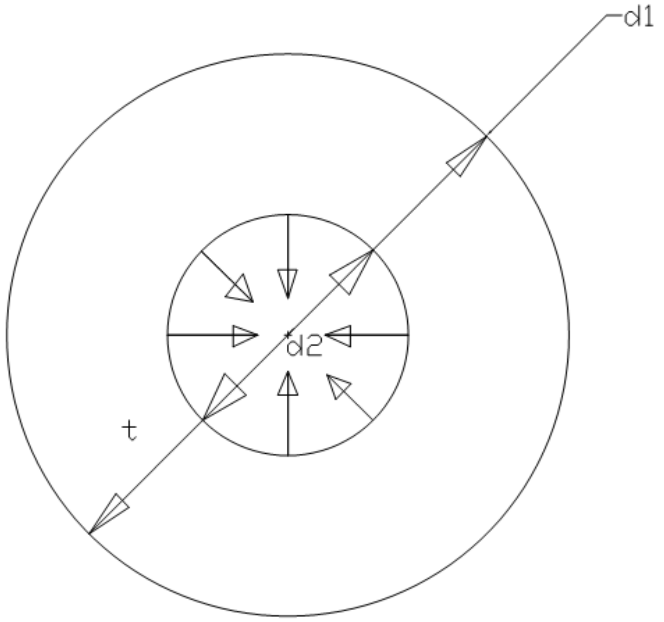

Fig 9.0: A Thick Cylindrical Shell Subjected to Internal Pressure.

Apply Lame's equation:

$$P = \frac{b}{(r_2)^2} - a \ldots\ldots\ldots\ldots\ldots(XXX)$$

Source: [6].

Where: P = Intensity of internal pressure = 50.9 x 10^6 N/m^2

r_2 = Radius of internal wall of the cylinder (mm)

a and b = constants.

Take d_2 = diameter of minor piston + clearance 0.5 [6].

$$= 10 + 0.5$$

$$= 10.5mm$$

$$r_2 = \frac{10.5}{2}$$

$$= 5.25mm$$

Therefore;

$$50.9 \times 10^6 = \frac{b}{(5.25 \ x \ 10^{-3})^2} - a$$

$$a = \frac{b}{2.76 \ x \ 10^{-5}} - 50.9 \ x \ 10^6 \ldots\ldots(XXXI)$$

$$n = \frac{\sigma_T}{\sigma_{T(ALL)}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(XXXII)$$

Where: σ_T = Tensile strength = 392 x 106 N/m^2

$\sigma_{T(ALL)}$ = Allowable tensile stress (N/m^2)

n = Design factor is 4 (shock and impact energy required)

$$4 = \frac{392 \ x \ 10^6}{\sigma_{T(ALL)}}$$

$\sigma_{T(ALL)}$ = 98 x 10^6 N/m^2

$$\sigma_{T(ALL)} = \frac{b}{(r_2)^2} + a \ldots\ldots\ldots\ldots(XXXIII)$$

$$98 \times 10^6 = \frac{b}{2.76 \ x \ 10^{-5}} + a$$

$$a = 98 \times 10^6 - \frac{b}{2.76 \ x \ 10^{-5}} \ldots\ldots\ldots\ldots(XXXIV)$$

Equate equations (XXXI) and (XXXIV)

$$\frac{b}{2.76 \ x \ 10^{-5}} - 50.9 \ x \ 10^6 = 98 \times 10^6 - \frac{b}{2.76 \ x \ 10^{-5}}$$

$$\frac{2b}{2.76 \ x \ 10^{-5}} = 148.9 \ x \ 10^6$$

b = 2054.82

Substitute b = 2054.82 in equation (XXXI)

$$a = \frac{2054.82}{2.76 \ x \ 10^{-5}} - 50.98 \ x \ 10^6$$

a = 23.47×10^6

If only internal pressure is assumed to be exerted, external pressure is zero

$P_2 = \frac{b}{(r_1)^2} - a$………..(XXXV)

Where: P_2 = External pressure intensity = 0

r_1 = External radius of the cylinder (mm)

$0 = \frac{2054.82}{{r_1}^2} - 23.55 \times 10^6$

$r_1 = 9.34mm$

Wall thickness t = $r_1 - r_2$

= 9.34 – 5.25

= 4.09

≈ 4mm

Note: $\frac{t}{d} = \frac{4}{10.5} = 0.38$

The value 0.38 is greater than 1/10th, therefore the thick cylindrical wall shell selected earlier is appropriate.

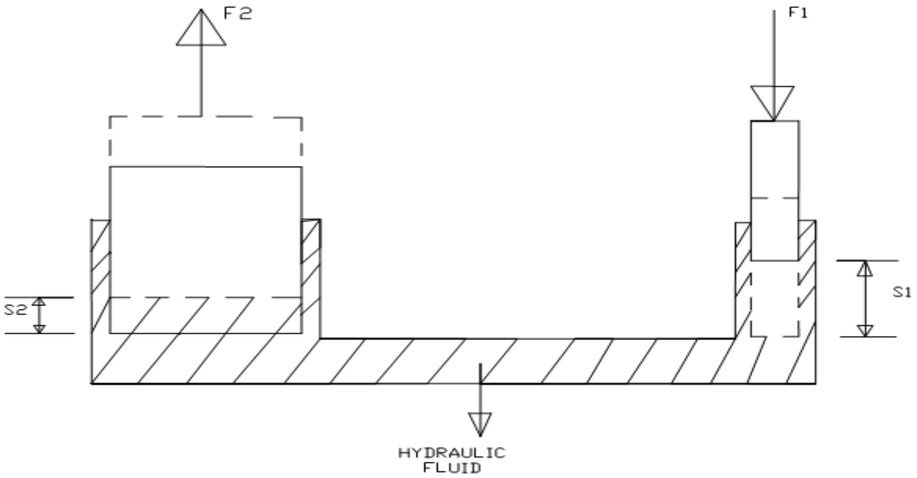

Fig 10.0: Schematic Diagram of Hydraulic Jack Operation System

F_1 = Hydraulic system input force

F_2 = Hydraulic system output force

S_1 = Fluid displacement in minor cylinder

S_2 = Fluid displacement in main cylinder

The volume of fluid displaced in the minor cylinder equals the volume of fluid that raised the main piston in the main cylinder

Source: [12].

$V_1 = V_2$

Take the area of minor and main pistons as the area of fluid displaced in minor cylinder and the fluid that raised the main piston respectively

$A_1S_1 = A_2S_2$…………(XXXVI)

By experiment, total number of strokes to conveniently raise the load to 100mm is averagely 50.

Distance of lift/stroke = $\frac{100}{50}$

= 2mm

: S_2 = 2mm

$7.353 \times 10^{-5} S_1 = 9.621 \times 10^{-4} \times 0.002$

S_1 = Distance of fluid displace = 26.17×10^{-3}m

S_1 ≈ 26mm.

At the return stroke of the piston when the inlet is opened to release another set of fluid into the chamber, a factor 2 is selected to conveniently trap the fluid in the system thus avoid pressure loss and fluid loss. Therefore minor cylinder is taken to be twice the distance of fluid displaced.

Therefore,

: $C_L = 2S_1$ …………………..(XXXVII)

Where: C_L= Length of minor cylinder

C_L = 2 x 26

= 52mm.

2.1.9MAIN CYLINDER LENGTH

If the main piston length is taken as 180mm and the required distance of lift of the load is 100mm (earlier recommended).

Note: at the start of the operation, the whole of the main piston is inside the main cylinder. So clearance is required.

Therefore, to allow some part of the piston to remain in the cylinder at the maximum lift distance, and also to ensure that there is no pressure or fluid loss, the main cylinder length selected is 150mm.

III. CONCLUSION AND FUTURE WORK

This report has presented a detailed design analysis for production of 5 tonnehydraulic jack, the engineering drawings of all the parts were developed using two approaches namely conventional and reverse engineering.

Conventional engineering team were able to design the jack by producing the design calculations, detailed drawings and cost of producing each component involve for the development of the prototype. While reverse engineering team were able to produce the jack through reverse engineering approach, material of the jack parts were identified through spark test and some other tests.

The base of the jack was successfully produced, tested and its performance was very good. Some of the components that were locally produced includes:Main cylinder, main cylinder, minor piston and jack base etc.

Henceforth, this paper recommend on the increase in the tonnage from 5 to 20 tonne in the future and attention should also focus on elemental analysis and hardness test of each part

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