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Under pressure

This month is a second look at pressure, force and area, here with particular reference to hydraulics in specialized transport equipment. MARCO VAN DAAL reports

Every hydraulic cylinder or jack (see Figure 1) follows the principle of Pascal, not because they want to but because it is a law of Nature. The principle of Pascal can be expressed in a formula:

$$F = p * A$$

Where: F is a force in Newton (N)

p is a pressure in Pascal (Pa or N/m^2)

A is an area in square metres (m^2)

NOTE: *Blaise Pascal was a French mathematician and physicist who lived from 1623 to 1662. Pascal's impact on the world of science should not be underestimated. Apart from the hydrostatic principle he delivered contributions binomial calculations, he invented the syringe and a computer programming language is named after him.*

If we consider a few average numbers a simple calculation can be performed. Let's assume that a given hydraulic cylinder has a 13 cm diameter (5.1 inch) and needs to lift a 15 metric ton load.

A diameter of 13 cm equates to an area "A" of 132.7 cm^2 or 0.01327 m^2.

A load of 15 metric tons equated to a force of approximately 147,000 Newton following F=m*g.

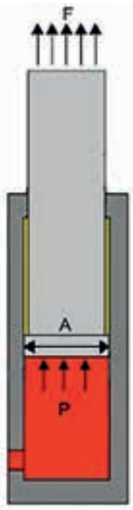

FIGURE 1

$$F = p * A \quad \text{or} \quad p = \frac{F}{A} = \frac{147{,}000}{0.01327}$$

$$= 11{,}077{,}618 \text{ Pa} = 110.7 \text{ bar} = 1{,}607 \text{ PSI}$$

NOTE: *1 bar = 100,000 Pa*

The hydraulic cylinder in the axle of a transporter is no different. As a matter of fact many hydraulic cylinders in transporter axles are close to 13 cm in diameter and many hydraulic transporters have an axle capacity close to 15 metric ton/axle. Therefore, the above sample calculation could have been for a hydraulic axle cylinder.

NOTE: *15 metric ton/axle = 30 metric ton/axle line. There are two axles in each axle line.*

There is, however, a question that arises now. If the axle capacity is indeed close to 15 tons and if the pressure in a hydraulic cylinder with a 13 cm diameter is indeed 110 bar, why do the pressure gauges on a transporter show pressures of (sometimes) 400 bar, see Figure 2. At first glance this seems like quite a bit of overkill.

In reality it is not overkill, the geometry of the hydraulic axle and the angle of the hydraulic cylinder inside the axle cause the pressure in the hydraulic cylinder to increase.

Component arrangement

First let's review the geometry of the hydraulic axle. See Figure 3. The first thing we see is that the upper connection of the hydraulic cylinder is not situated at the centre of the turntable (on the underside of the transporter), it is offset towards the knee joint. Similarly, the lower connection of the cylinder is also not connected to the lower arm at the centre of the axle, again, it is offset towards the knee joint. This offset distance at the top and bottom of the hydraulic cylinder makes the hydraulic axle a "type 2 or class 2 lever". In popular terms, the hydraulic cylinder is squeezed between the upper and lower arm of the axle.

The second thing we see is that the offset distances (towards the knee joint) are not equal, causing the cylinder to sit not perfectly at 90 degrees from horizontal but slightly less.

FIGURE 2

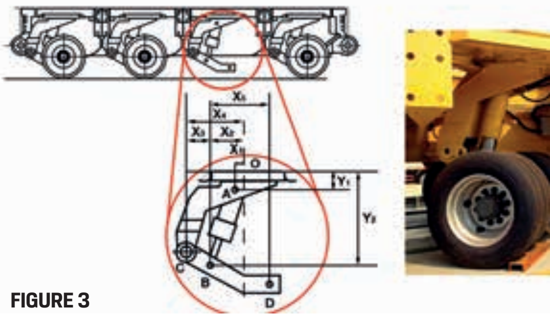

FIGURE 3

NOTE: *As the transporter deck raises the angle of the hydraulic cylinder changes because of the circular motion that the lower arm makes about the knee joint.*

Levers (see Figure 4)

Every lever consists of three components:

- an input force or effort that is applied
- an output force or load that is exercised on an object
- a fulcrum that determines if the lever is of class 1, 2 or 3.

CLASS 1 LEVER is a lever in which the fulcrum is situated between the input force (or effort) and the output force (or load). Examples are scissors, pliers, claw hammer, crowbar, see-saw, crane boom, etc.

CLASS 2 LEVER is a lever in which the output force (or load) is situated between the input force (or effort) and the fulcrum. Examples are staplers, nut crackers, wheel barrow, bottle opener and the hydraulic axle.

CLASS 3 LEVER is a lever in which the input force (or effort) is situated between the fulcrum and output force (or load). Examples are sugar or ice cube tongs, staple remover, tweezers.

For all lever classes the distance from the effort to the fulcrum is called the "effort arm" and the distance from the load to the fulcrum is called the "load arm".

Figure 3 shows the geometry of a typical hydraulic axle where the following points can be identified on the sketch:

O centre of the turntable at transporter deck level (let's call this the origin "O")

A upper connection of the hydraulic cylinder

B lower connection of the hydraulic cylinder

ABOUT THE AUTHOR

MARCO VAN DAAL has been in the heavy lift and transport industry since 1993. He started at Mammoet and later with Fagioli from Italy, both leading companies in the industry. His 20-year-plus experience extends to five continents and more than 55 countries. His book *The Art of Heavy Transport*, available at: www.khl-infostore.com/books Van Daal has a real passion for sharing knowledge and experience and holds training seminars around the world.

C knee or axle pivot point (class 2 fulcrum)
D center of the tyre.

In addition, with the following X and Y dimensions are indicated on the sketch:

X_1 = 109 mm Y_1 = 74 mm
X_2 = 245 mm Y_2 = 643 mm
X_3 = 290 mm
X_4 = 535 mm
X_5 = 225 mm

The horizontal distances X3 and X5 change as the hydraulic cylinder extends and retracts. The ratio, however, remains the same and therefore the mechanical advantage (MA) also remains the same.

Mechanical advantage = MA

$= \text{effort arm} / \text{load arm} = (X_3 + X_5) / X_3$

$= (290 + 225) / 290 = 1.776$

With the above dimensional information we can write the upper and lower connection points of the hydraulic cylinder as (X, Y) co-ordinates;

Upper co-ordinate (X_1, Y_1) or (109, 74)

Lower co-ordinate (X_2, Y_2) or (245, 643)

These two co-ordinates allow us to calculate the angle (alpha or at which the cylinder is acting (compared to horizontal).

$$\tan\alpha = \frac{(Y_2 - Y_1)}{(X_2 - X_1)} \qquad \alpha = \tan^{-1}\frac{(Y_2 - Y_1)}{(X_2 - X_1)}$$

$$\alpha = \tan^{-1}\frac{(643 - 74)}{(245 - 109)} = \tan^{-1}\frac{569}{136} = 76.5 \text{ deg}$$

The load placed on the axle in the centre of the turntable is 15 metric tons, as mentioned before. This means that the loads onto the soil or road surface is also 15 metric tons. As shown earlier, a 15 metric ton load (m) equals a 147,000 Newton force (F_L) following F_L=m*g. The force that the cylinder experiences can now be determined as follows:

$$F_{cyl} = \frac{F_L * M.A.}{\sin\alpha} = \frac{147{,}000 * 1.776}{\sin(76.5)}$$

$= 268{,}490 \text{ N} = 268.5 \text{ kN}$

Again, following F=m*g, we can state that 268.5 kN roughly equals 27.4 metric tons.

From this force F_{cyl} we can, using the principle of Pascal, calculate the pressure inside the hydraulic cylinder.

An axle load of 15 metric tons causes a pressure of 202 bar inside the hydraulic axle cylinder.

$$F = p * A \quad \text{or} \quad p = \frac{F}{A} = \frac{268{,}490}{0.01327}$$

$= 20{,}232{,}856 \text{ Pa} = 202 \text{ bar}$

In this case the cylinder angle was 76.5 degrees but could be as little as 60 degrees on some brands and models. Also, the self weight of the transporter which can easily be 3 to 4 ton per axle line or 2 ton per axle has not been taken into account in the above approach. And, last but not least, a 15 to 20 % margin for impact loads and overload testing. The formula now look like this:

A load of 15 metric tons + a self weight of 2 metric tons + 20 % impact/overload = 20.4 metric tons. Following F_L=m*g this equals 199,920 Newton (F_L).

The force on the hydraulic cylinder is now:

$$F_{cyl} = \frac{F_L * M.A.}{\sin\alpha} = \frac{199{,}920 * 1.776}{\sin(60)}$$

$= 409{,}985 \text{ N} = 410 \text{ kN}$

The pressure in the hydraulic cylinder is now:

$$F = p * A \quad \text{or} \quad p = \frac{F}{A} = \frac{409{,}985}{0.01327}$$

$= 30{,}895{,}672 \text{ Pa} = 309 \text{ bar}$

Hydraulic pressure gauges as installed on hydraulic transporters are subject to all kinds of environmental issues such as extreme heat and cold, constant vibration, shock loads, etc. The accuracy of such gauges at best is 5 % but can be as little as 10 %.

Taking this into account, a calculated pressure of 309 bar can show up on the gauge as 325 bar.

Hence the gauges have a full scale reading of 400 bar. ■

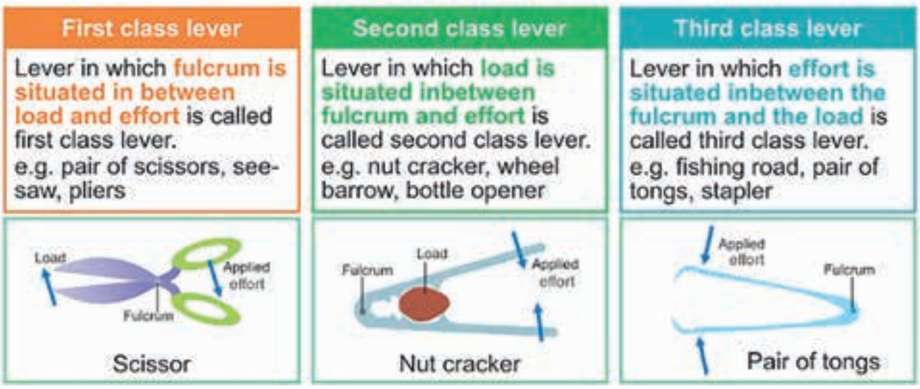

FIGURE 4