Geometric Modeling and Optimized Design of an Hydraulic System for Concrete Batching Plant

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Abstract - The present paper describes the geometric modeling and design and the feasibility study of an innovative hydraulic system that would allows a mobile batching plant to improve the safety, to increase the reliability and to reduce the concrete working process time. In particular, the present paper outlines the dynamic behavior of a telescopic hydraulic cylinder in order to replace the current lift system (skip). Mechanical theory, principles of hydraulics, geometric modelling and design, using cad software, were used in developing the model of the telescopic cylinder. Using the spreadsheet software Excel it was possible to compare dynamic movements of some types of actuators. An approach to a hydraulic batching plant lift systems is presented, where the results are compared with those obtained from the existing skip.

Keywords - Hydraulic cylinder; Batching plant; 3D modeling; Reliability; Safety.

I. Introduction

In a mobile batching plant, the skip is a type of loading system that provides the requirement of small dimensions in the construction site. The skip is a conveyor lift system operated by ropes. Given the issues related to: the operation of the lifting device, the reliability of limit switch sensors, the probability of breaking the ropes and other issues involving the use of the skip, it was considered essential to investigate the behaviour of a hydraulic system. Due to the plant's requirement of small dimensions in the transport configuration, suitable for container – transport trucks, the idea is to replace the skip system with a single-acting telescopic hydraulic system.

Fig. 1. Transport configuration of mobile batching plant.

In this configuration, the skip rails and the main frame are turned over 180°. The inside height of the open top 40″ container is about 2 m. The minimum closed length of the telescopic cylinder needs to be of 1 m to suit the container transport truck dimension. Assuming a rails inclination of 70° from the horizontal plane, the stroke of the cylinder must be of 7 m to permit the skip to travel from the bottom to the top along the rails. The table below presents the technical features of a suitable telescopic cylinder:

Table. 1. Technical features of telescopic cylinder

Technical features	Values and units
Load capacity	3000 kg
Operating pressure	160 [bar]
Stroke speed	34 [m/min]
Stroke length	7000 [mm]
Closed length	1000 [mm]
Open length	7000 [mm]
Load capacity (Retraction)	1000 [kg]
Mounting configuration	Pivot mounts
Mounting condition: incline angle	70°
Environmental condition	Dusty
System operating temperature	-10°C < T < +40°C

II. A Brief Overview Of the hydraulic System

The main elements of the hydraulic system are:

1. 3 phase 4 pole asynchronous electric motor (15 kW) 1450 rpm
2. Internal gear pump (160 bar)
3. Pressure gauge and shut-off valve
4. 4/3- way directional control valve
5. Throttle adjustable valve
6. Pressure relief valve (safety valve)
7. Cooler
8. Exhaust filter
9. Intake filter
10. Oil reservoir tank
11. Pipes
12. Single- acting telescopic cylinder (4 stages)

The schematically circuit of single-acting telescopic cylinder is shown in figure 3.

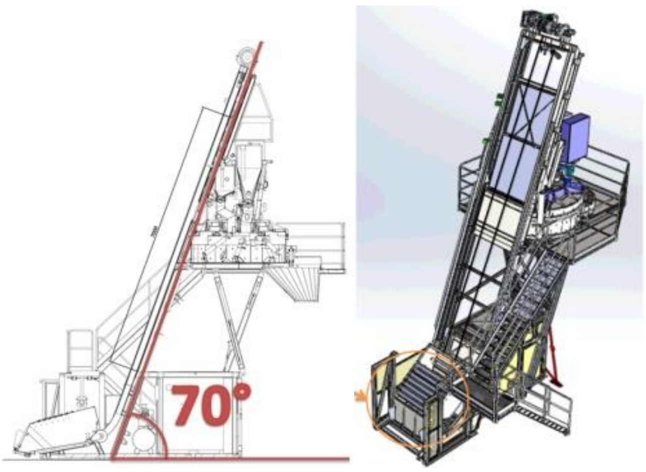

Fig. 2. Operative configuration of mobile batching plant.

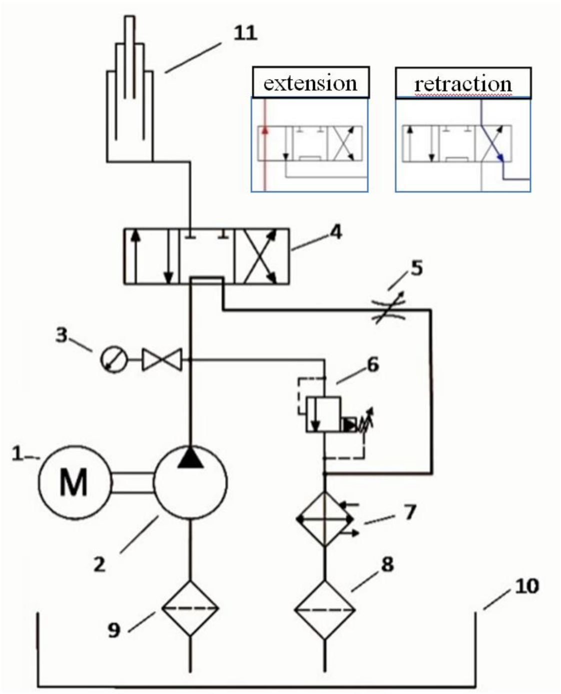

Fig. 3. Schematically circuit of single-acting telescopic cylinder.

A pump, driven by an electrical motor, takes oil from reservoir and the fluid passes through a filter (9), before to enter in the circuit.

When the 4/3 control valve (4) is in its neutral position, the telescopic cylinder (11) is hydraulically locked and the pump (2) is unloaded back to the tank (10). Oil filters (8-9), situated in the return line to the tank and before the pump, trap solid particles while allowing fluid to pass trough [1, 2].

When the 4/3 way valve is actuated, the discharged line is under pressure because the pump must overcome the force of load (3000 kg) to be moved [3]. The oil, passing from the 4/3 way valve, feeds the ascent of the cylinder.

When the control valve is moved in the opposite direction, connecting the chamber of the cylinder with the tank, oil is forced to pass by the throttle valve (5), that it regulates the speed of descent. The telescopic cylinder returns to its initial retracted configuration, thanks to the gravity, because the hopper discharges the inert into the mixer and it remains only the empty hopper of 1000 kg of weight.

The pressure relief valve(6) is placed immediately after the pump. The spring is adjusted to the maximum working pressure, in such a way that in case of overpressures, the fluid is discharged into the reservoir tank.

One of the most important components of the hydraulic drive system is the telescopic hydraulic cylinder, that is an actuator which gets its power from pressurized hydraulic fluid (oil, in this case) and it is used to convert fluid power in mechanical motion. A single-acting cylinder transfers a hydraulic force in one direction only and it must be retracted by gravity (in this specific case).

III. The Telescopic Hydraulic Cylinder

Telescopic cylinder is a special design of hydraulic cylinder which provide an exceptionally long output travel from a very compact retracted length. It consists of nested multiple cylinders called sleeves, which slide inside each other.

A telescopic cylinder is used when a long stroke length and short retracted length are required.

It normally extends from the largest stage to the smallest.

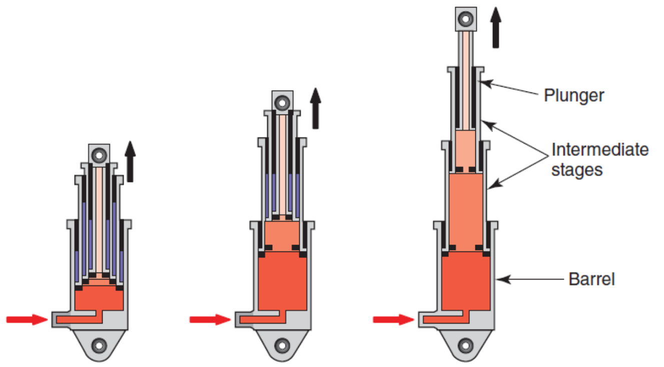

Fig. 4. Functionality of telescopic cylinder.

This means the largest stage, with all the smaller stages nested inside it, will move first and complete its stroke before that the next stage begins to move. This procedure will continue for each stage until the smallest diameter stage (plunger) will be fully extended. Conversely, when retracting, the smallest-diameter stage will retract fully before the next stage starts to move. This continues until all stages are nested back in the main. During the initial extension, the cylinder extends at the slowest speed and with most force. A smaller diameter stage will extend next, the cylinder extends faster with less force.

The cylinder load capacity is calculated considering the smallest sleeve diameter in the assembly.

Gravity return type single-acting cylinder is where the cylinder extends to lift a weight [4] against the force of gravity by applying oil pressure at the blank end. To retract the cylinder, the pressure is simply removed from the piston by connecting the pressure port to the tank.

Table. 2. Technical features of telescopic cylinder

N° of stages of telescopic cylinder	10 stages	9 stages	6 stages	5 stages
Closed length [mm]	910	1000	1550	1528
Open length [mm]	7055	8000	7800	7073
Working max pressure [bar]	200	160	200	200
Stroke length [mm]	6315	7000	6250	5620
Load Capacity [ton]	6.5 - 28	3	34 - 63	10 - 45
Stroke speed [m/min]	30	30	30	30
Amount of oil [l]	149	-	77.5	80
Φ minimum stage [mm]	68	30	80	88
Φ maximum stage [mm]	265	220	192	190
Total weight [kg]	391	-	215	253

IV. Numerical Model of Hydraulic Cylinder

The continuity equation about oil, which after introduction into the cylinder end runs down the opposite site, can be so formulated [5]:

$$\begin{cases} Q_1 = A_{1i} v_{1i} + V_{1i} \dot{p}_1 / \beta_e \\ Q_2 = A_{2i} v_{2i} + V_{2i} \dot{p}_2 / \beta_e \end{cases} \qquad (1)$$

With:

- i=1, 2, ..., 10 stages

-A_1, A_2 useful thrust surfaces in the cylinder [m^2]

- v_1, v_2 opening and closing speed of the extensions

- V_1, V_2 volume of fluid entering / leaving the cylinder [m^3]

- p_1, p_2 pressures in the cylinder inlet / outlet chamber [Pa]

- β_e Compressing equivalent modulus (thus considering the fluid, the air contained in it, etc)

Supposing that the oil mass in the hydraulic cylinder can be omitted and act as a rigid body, Newton's second law of motion finds out that:

$$p_1 A_1 - p_2 A_2 = $$
$$= ma + Bv + sgn(x) F_a(p_1, v) + F_c = F_r + F_c \qquad (2)$$

With:

- a acceleration of the extensions

- x extension direction

- B coefficiente di smorzamento viscoso [Ns/m]

- F_a coulomb friction force [N]

- F_c external force [N]

- m equivalent mass of moving parts [kg]

- F_r force that includes all the resistive forces [N]

From the above-mentioned equations it appears clear that the parameters of the simplified model refer to the properties of rigid body, kinematic and geometric data; moreover, many of these parameters are changing in time. A consequent difficulty in obtaining an accurate valuation derives; the valuation of the single force component identified by the eq (2) was not possible as during the experimental tests the displacement signal was not recorded. However, it was looking for identifying the static component of the resistance forces by referring to the time intervals where the signals in pressure were constant or slowly changed. As these intervals concerns, a regression of the external force signal F_c was fulfilled as experimentally measured with respect to theoretic signal F_t which was calculated by considering the pressures in the chambers of the cylinder ($p_1 A_1 - p_2 A_2$), using different models.

I Modello: $F_c = F_t - A$; da cui: $F_r = A$; (3)

II Modello: $F_c = mF_t$; da cui: $F_r = (1 - m)F_t$ (4)

The first model assumes the presence of a resistance force as costant and indipendent from the force levels exerted by the cylinder.

The second model assumes instead that the resistance forces are proportional to the applied force.

The dynamic behaviour of the system was simulated assuming the theoretic force F_t as input variable and the force exerted by the cylinder F_c, experimentally measured, as signal in output. The same problem of a missing recording of the displacement signal occured again. Therefore the choice to realize an empiric model trying to minimize the number of freedom degrees was taken. After repeated numerical simulations,it was noticed that a model with a unique pole and zero was the most effective: only with three degrees of freedom (the static benefit and the position of the pole and zero), it is indeed able to interpolate effectively the experimental data, always provided an index of correlation r^2 superior to 0.85 Analysis of telescopic cylinder dynamic movements

By comparing cylinder features it was selected the 10-stages cylinder to examine in depth its dynamic movements.

Table. 3. Stages diameter of 10-stages cylinder

N° of stages	Diameter [mm]
1	68
2	88
3	107
4	126
5	145
6	165
7	187
8	210
9	236
10	265

Table. 4. Areas, volumes and speeds of each stage.

N° of stages	Sleeve cross section area [mm²]	Sleeve volume [mm³]	Speed sleeve [mm/s]
1	3632	0.002	3590
2	6082	0.004	2144
3	8992	0.006	1450
4	12469	0.008	1046
5	16513	0.011	790
6	21383	0.014	610
7	27465	0.019	475
8	34636	0.024	376
9	43744	0.030	298
10	55155	0.038	236
Total		0.161	

An Excel table was created to find relationships between different variables related to cylinder movements. It was used to calculate each stage velocities and then the results were analyzed creating different graphs.

The extension speed shows a slowly increasing trend as a function of the extension time, while, when the cylinder extends to the last stage (the plunger- Ø minimum stage), it reaches the highest speed.

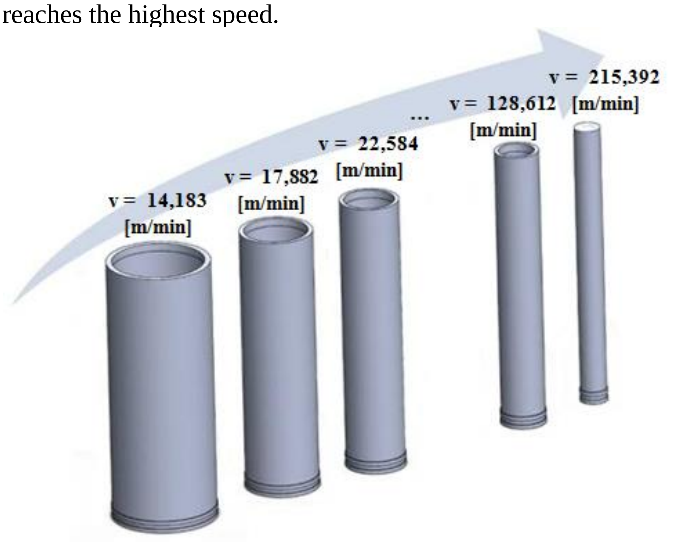

Fig. 5. Sleeves Speeds - 10-stages telescopic cylinder.

It was possible to create a chart from the worksheet data to show the telescopic cylinder performance.

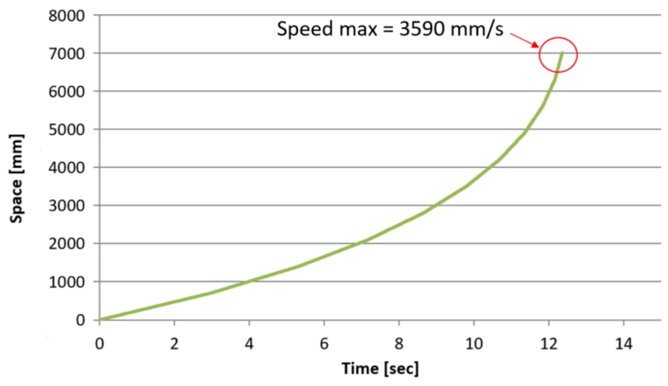

Fig. 6. Space-time chart 10-stage cylinder.

From the analysis of the above performance chart the research was focused on finding a more linear extension of the cylinder, reducing the difference between the initial and the final extension speed.

The figure 7 was analyzed the space-time chart trend of the ropes lifting system (skip). The next step was to find a cylinder with a similar space-time chart.

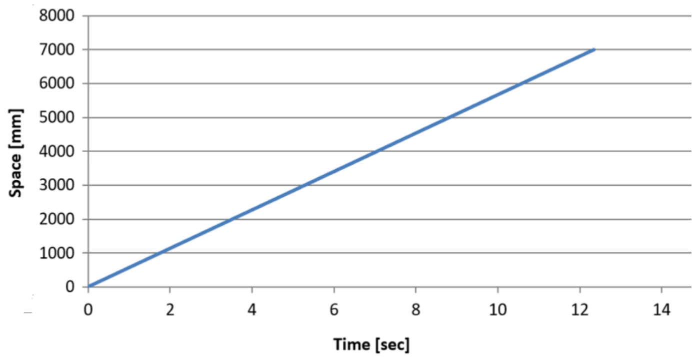

Fig. 7. Space-time chart rope lifting.

Using SolidWorks ver. 2016, it was created a 3D design of the 10-stages telescopic cylinder, in order to analyze movements and to check its dimensions such as retracted length, stroke, etc. The design started by modeling every single part, then the final 3D assembly model was created.

In Fig. 8 you can see cut view and front view of 10 stage cylinder. Fig. 9 show axonometric view of 10 stage cylinder in maximum extension.

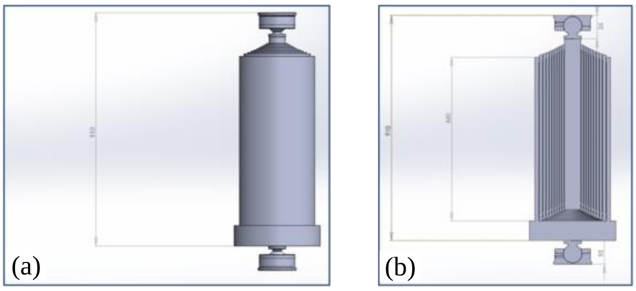

Fig. 8. (a) 10-stages cylinder; (b) Section view.

Fig. 9. Maximum extension10-stages cylinder.

The 3D ball joint model is created using technical design and data from a company that produces hydraulic cylinders and components. We have chosen this type of interface to reduce the problem of misalignment and transversal force that they can reduce the lifting force and increase the friction coefficient t [6 - 9].

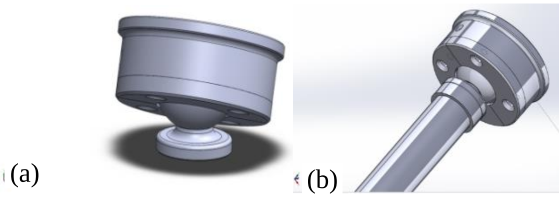

Fig. 10. (a) Ball joint; (b) Ball joint assembled on last stage.

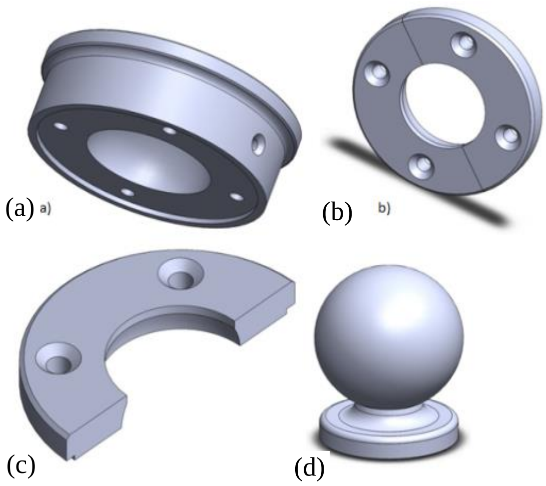

Fig. 11. (a) ball seat; (b) ring, (c) ball.

Using Excel a new space-time chart was obtained considering a cylinder with a fewer number of stages.

Table. 5. Diameter and sleeve length of 4- stage cylinder

Numbers of stages	Diameter [mm]	Sleeve length [mm]
1	107	1750
2	126	1750
3	145	1750
4	165	1750

Table. 6. Areas, volumes and speeds of four stage

N° of stages	Sleeve Cross section area [mm²]	Sleeve Volume [m³]	Sleeve Speed [mm/s]
1	8992	0.015	935
2	12469	0.021	674
3	16513	0.028	509
4	21383	0.037	393
Total		0.161	

From the space-time chart it was possible to analyze the theoretical performance of this 4-stages telescopic cylinder. Then it was made a comparison graph between the skip and the cylinder space-time charts.

It was created a design of a 4-stages telescopic cylinder take into account the effect of friction and functional Tolerancing [10, 11]. It was found that the latter space-time cylinder chart is more similar to the linear skip's chart.

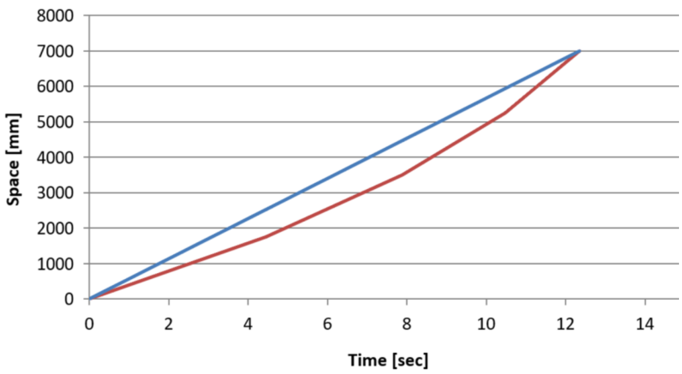

Fig. 12. Comparison chart between rope lifting and 4-stages cylinder.

Figures below show the design of the 4-stages telescopic cylinder with some details views.

In order to find the perfect cylinder features to realize a space-time trend chart as linear as possible, it was chosen a plunger's diameter of 107 mm, that can lift up to 3000 kg.

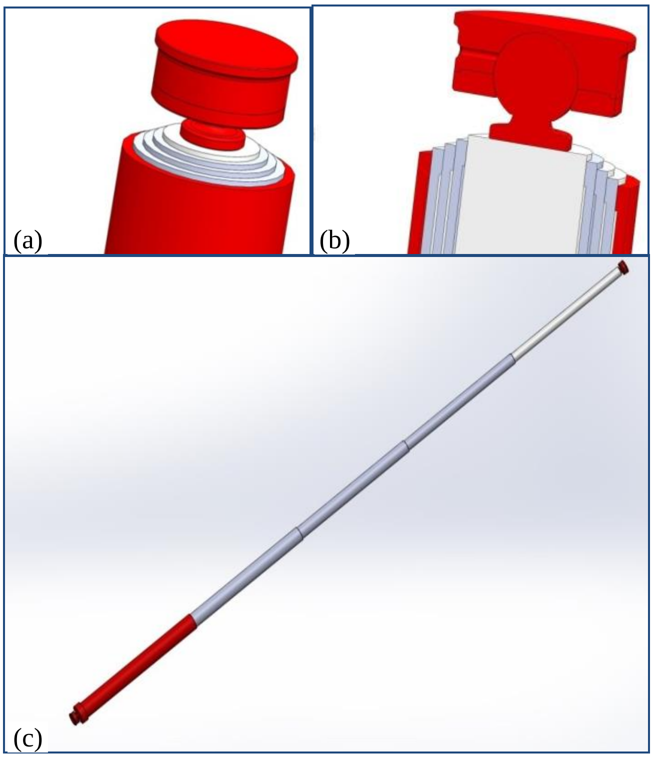

Fig. 13. (a) Detail of the top; (b) Detail of a cut view of the top; (c) 4-stages telescopic cylinder - fully extended.

In order to find the perfect cylinder features to realize a space-time trend chart as linear as possible, it was chosen a plunger's diameter of 107 mm, that can lift up to 3000 kg.

Using Excel it was created a comparison space-time chart between two different trends: 4 and 10 stages cylinders. The next figure shows a comparison chart between the skip and the other two types of cylinders trends.

By comparing the above charts is possible to observe that dynamic motions of 4-stages cylinder are better than a 10-stages type because the former has a less accentuated speed trend, the line has a reduced slope, and the trend chart is more similar to the skip's chart. For the above reasons the 4-stages cylinder was selected to be fitted in the hydraulic system while the 10-stage configuration was rejected.

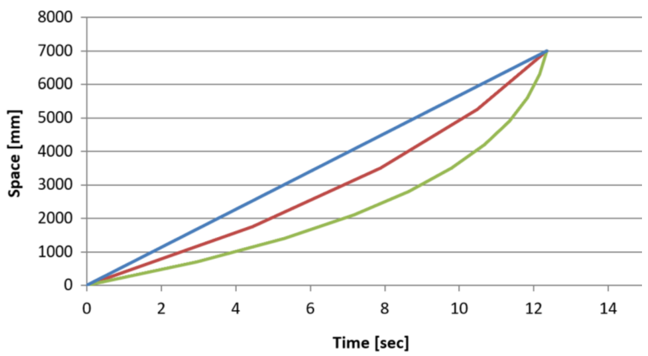

Fig. 14. 10 Stage cylinder speed; 4 Stage cylinder speed and Skip speed.

V. Hydraulic drive system layout

A hydraulic drive system is a drive or transmission system that uses pressurized hydraulic fluid to power hydraulic machinery. A hydraulic drive system consists of three parts:

- Power supply section: a hydraulic pump driven by an electric motor;
- Power control section : valves, filters, piping, etc using to guide and control the system;
- Drive section : a hydraulic actuator using to drive the machinery.

This system is used where the telescopic cylinder piston is returned by the gravity force. With the 4/3-way directional control valve in neutral position (5), pump flow passes though the valve and back to the storage/fluid tank (1) also known as reservoir. The liquid, is generally high density incompressible oil. It is filtered to remove dust or any other unwanted particles and then pumped by the hydraulic pump.

The oil filtration unit is also often contained in the power supply section. Impurities can be introduced into the system as a result of mechanical wear, too hot or too cold oil or external environmental influences. For this reason, filters are installed in the hydraulic circuit to remove dirt particles from the hydraulic fluid. Water and gases in the oil are also disruptive factors and special measures must be taken to remove them. Valves are devices for controlling the energy flow.

They can control and regulate the flow direction of the hydraulic fluid, the pressure, the flow rate and, consequently, the flow velocity.

With the 4-stages telescopic cylinder, it is possible to have lower speed at the end of the stroke with a minimum stage diameter (d) of 107 mm. The piston surface is:

$$A = \pi \frac{d^2}{4} = 8990 \ [mm] \tag{5}$$

The cylinder total load capacity is 3000 kg. However to increase the plant safety an higher weight is considered to select the correct pump. Considering a safety weight of 4000 kg the max operating pressure is:

$$p = \frac{F}{A} = \frac{4000 \ kg}{8990 \ [mm]} = 45 \ bar \tag{6}$$

Due to the possible oil leakages and other leaks in the system, system operating pressure is increased up to the safety value of **60 bar**. The stroke time of the telescopic cylinder is given by the stroke of the cylinder per the cylinder speed (t= 34 m/min):

$$t = \frac{stroke}{speed} \tag{7}$$

The flow rate is:

$$Q = \frac{Volume}{time} \tag{8}$$

Q = 504,53 [l/min].

If the pump couples with an asynchronous 4 pole three-phase self-braking electric motor operating at 1450 rpm, the capacity of the pumps is:

$$Capacity = \frac{Q*1000}{1450} = 350 \ [cm^3/rev] \tag{9}$$

The choice of the pump is approached by researching Companies producing internal hydraulic gear pump, which is the best option to be fitted in the hydraulic system.

VI. Conclusions

In the paper was described geometric optimized design of an hydraulic system that would allows a mobile batching plant to improve the safety, to increase the reliability and to reduce the concrete working process time. In particular, the present paper outlines the dynamic behavior of a telescopic hydraulic cylinder in order to replace the current lift system (skip).

Due to troubleshooting and maintenance issues regarding the hydraulic system and difficulties in controlling the cylinder's retraction speed, a double acting cylinder could be an option to solve technical problems. However, even with the application of this device, there is a need of continue maintenance program to make the cylinder operable and safe for a long period of time without dangerous sudden failure [12], in particular way for sealing gaskets, subjected to sliding contact force, infact is extremely important to maintance the optimal operating tolerance standard [13], and contact with the metal surface of the extensions and therefore the seal [14].

Possible future developments for the present work could be oriented in researching new applications of telescopic hydraulic systems to be applied in other concrete plants with different technical requirements.

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