Modelling and evolution of designing the hydraulic circuit for a cable pulling winch machine

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Abstract. The hydraulic circuit, the heart of the fluid powered winch machine, is the sequential arrangement of the major components to smoothly maintain the working mechanism of the machine to achieve its functions. This logical setup is the driving force to convert flow and pressure to speed and torque required to maintain the operation. As it is a congregation of elements like motors, valves and pumps, optimization is a priority to efficiently execute the operation with least losses and more power output. The research is undertaken in view of the drawbacks in the machine manufactured by Efit Arabia Ltd, Ajman. The drawbacks noticed were backlash, less pulling speed, mechanical imbalance and losses. Hereby with the means of commercial software called Automation Studio, this research focuses on using the mechanical advantages of newly suggested features this circuit to divide the work load thus gaining more control and speed to pull in and pull out the winch rope. This paper ascertains the optimized advantages incurred by replacing with a double capstan motor integrated with a single directional control solenoid valve to shift between the series and parallel modes, an inbuilt motor-braking system for the balance of the movement of the drum motor and the addition of the sequence valve for flow control with experimental analysis, observations and results.

Key words: Hydraulic Circuit, Cable Pulling Winch, Cable Laying, Evolution, Manifold, Hydraulics.

1. Introduction

Cable laying is the process of carefully burying or suspending large capacity, high voltage telecommunication, fiber optical and electrical cables in order to achieve a connection between two areas. Two major types of cable laying consist of Underground and Overhead Laying. It is carried out by two different methods namely Direct Burial or Trenching and Draw-In System or Duct Cable Laying. Trenching shown in Fig 1 is a cheaper technique wherein the ground is exhumed to create a channel or a ditch. This channel is prepared immaculately which is then followed by cautiously placing the cable load using various accessories to smoothly drag from one end of the channel to another. These accessories will protect the armoured cable against friction and damage. Duct cable laying or draw-in system is a similar process for un-armoured cables where the bare cable is enclosed by an underground cast iron pipe which is then linked and dragged underground between two manholes along the desired cable route. Underground laying is more prevalent than overhead or aerial laying and is susceptible to be seen in densely populated regions that require establishing intercity connections. This method considers the aesthetics of the city, improved environmental safety and lowered cost of installation. It does not involve the risks and detriments that could be caused by natural calamities. Maintenance and reparations aren’t tedious due to the advancements in fault detections.

Let us consider the direct process of trenching and burying the cable loads for this matter. Here, the cable needs to be pulled or laid across the cable route from one end to another. For this purpose, a cable puller aka a cable winch is entrenched on one side of the channel and simultaneously a cable
drum supported and transported by its trailer is positioned on the other extreme end. The rope from the winch machine is unwound and pulled across the trench to be attached to cable coiled on its storage drum via cable grips and swivel links. Once all the appropriate accessories such as rollers and lubricants are used and placed, the stationary winch commences to pull in and wind its rope thus unwinding the cable load from the drum onto the trench. These accessories aid in avoiding friction between the cable and surface, therefore, protecting the cable during the burial process. In this research, the primary objective is focussed on the cable pulling winch and its internal hydraulic circuit configuration. With multiple iterations, the evolution of the hydraulic circuit is subdivided into cases, each explaining the improvement of an additional feature.

![Figure 1. Simple Layout for Underground Cable laying process](image)

2. Cable Pulling Winch Machine

From the above discussion, the crucial component of the laying process constitutes of the Cable Pulling Winch (Fig 2). This fluid powered machine is specifically manufactured to abridge and mitigate traditional manual labour entailed for this process. With its basic idea of a pulley system, it assists in unwinding the load from its storage drum. This is simply achieved by attaching the winch rope to the cable load and then providing flow and pressure from the hydraulic system to produce sufficient speed and torque to drive the load bearing modules of the winch.

![Figure 2. Winch Machine](image)

2.1. Main Components in a Cable Pulling Winch

A description of the internal configuration of the winch consists of multiple electrical and mechanical elements. It includes an internal combustion diesel powered engine, variable hydraulic pump, three bi-directional hydraulic motors, twin-capstans and a storage drum. Additional features like sensors, solenoid valves, and linear actuators, also comprise the interior model of the winch. The logical sequence of the working principle of the operation of the winch is reinforced by a hydraulic circuit. The structure of this circuit determines the amount of losses and holistic efficiency of the machine. A two-dimensional hydraulic circuit diagram is drawn and transformed into a three-dimensional
hydraulic manifold which is the backbone of the system. The diesel engine converts the input fuel into mechanical energy to drive the pump which is mechanically coupled to the engine. This pump uses this mechanical energy to energize the fluid of the system to generate pressure and flow. As a variable pump is used, the pump displacement parallely with the engine power controls the pressure and flow of the fluid. This produces hydraulic energy to drive the motors that are mechanically coupled to the drum and capstans. The motors output sufficient speed and torque that aids in rotating the drum and capstans. Therefore, the function of pulling the rope in and out the winch is achieved (Fig 3). Since a pressurized hydraulic fluid is used as the working fluid for this closed loop system, the components are equipped with a reservoir in case of drainages. Feedback from the motors regulates the amount of flow and pressure required from the hydraulic pump.

Figure 3. Internal Configuration for cable pulling winch machine

It is observed that the tonnage capacity of the winch or the necessary pulling tension is mainly experienced by the capstans making them the load bearing element in the system. Moreover, the numbers of motors coupled to the capstans also play a vital role on the amount of speed and torque required to wind and unwind the drum rope. Incorporating valves such as directional control, pressure relief, check and sequence valves monitors and measures the level of pressure and flow.

2.2. The Winding Mechanism

There are two main operations of the winch namely Pull-IN and Pull-OUT operation. In the pull-IN operation, the winch rope is pulled into the system. The twin-capstans and drum move in the clockwise direction (Fig 4). This allows the cable load to be laid down into the trench. The pull-OUT operation pulls the rope out of the system making the capstans and drum rotate in the anti-clockwise direction allowing the winch rope to be attached to the cable load. This function is supervised by an internal mechanism called the Level Winding Mechanism (Fig 4(a)) which consecutively controls the working of both the capstans and drum.

Figure 4.(a) Level winding machine (b) Capstan (c) Drum (d) Drum motor (e) Capstan Motor

Both the double capstans and the drum system encounter varying loads i.e. mainly depended on factors like external resistance. Two relations are deduced stating that, as the load on capstans are more than load on drum \( (Lc > Ld) \) then the capstans produce more resistance \( (R_c > R_d) \) and vice versa. Since the flow of the pressurized hydraulic fluid regulated by the pump is inversely proportional
to the resistance offered by the capstans and drum, the flow rate into the component is lowered as the resistance produced by the component increases. These relations are analysed during the Pull-In and Pull-Out processes to concur modifications in the hydraulic circuit.

**Figure 5.** Pull in process

In the PULL-IN process (Fig 5), when \( L_c > L_d \), the flow into the drum is increased compared to that of the capstan. However, it is observed in Fig 3 that as the capstans and drum are mechanically coupled through the level winding mechanism, eventually the pressure on the drum must increase to a point wherein the resistances of both capstans and drum are equal. This will then initiate the rotation of the capstans and the pull-in process commences. Now, when \( L_c < L_d \), the flow input to the capstans increases which initiates its rotation. This makes the capstans spin uncontrollably. For the proper functionality of the capstans, there must be tension offered on either side. As there isn’t enough flow into the drum to generate resistance, the capstans fail.

**Figure 6.** Pull out process

In the PULL-OUT process (Fig 6), when \( L_c > L_d \), the flow into the drum increases making the drum rotate to unwind the winch rope. But when \( L_c < L_d \), the drum remains stationary which makes the capstans fail and loosely spin. As in both cases of \( L_c < L_d \), a problem is encountered. Irrespective of the conditions, the fluid must initially flow into the drum motor which is then followed by the capstan motors for synchronized rotation to achieve the processes. This problem is cause for the evolution of the hydraulic circuit.

3. **Cause of Evolution of the Hydraulic Circuit**

Over the years, the logical sequence mechanism has proved to be cumbersome for engineers due to the numerous losses incurred in the hydraulic circuit. This closed loop circuit determines the overall efficiency of the winch. The hydraulic circuit regulates the pressure and flow of the fluid flowing into the motors coupled with the capstans and drum. The series and placement of the components in the circuit can drastically vary the amount of speed and torque produced. Once this circuit is mastered, a hydraulic manifold can be construed and fabricated to be placed as the central node of the machine. This research concentrates on the evolution of the hydraulic circuit with different iterations, each one introducing an additional element and is upgraded to create an optimized compact manifold to increase system efficiency and reduce pressure losses.

3.1. **Case 1**

This hydraulic circuit consists of the hydraulic pump sequence and the hydraulic motor sequence algorithm (Fig 7). The dotted red lines represent the direction of fluid flow from the pump into the respective capstan motor and drum motor. The solid green lines represent the drains of fluid into the reservoir. Initially, only two bi-directional motors were utilized. The pump is attached with pressure-
relief valves to regulate the pressure needed by the motors. The arrows depict a clockwise direction showing the Pull-In operation. While designing, the motors are considered to have the same capacity. The fluid flows in both the motors of the capstan and drum.

![Case 1 circuit with a single capstan motor, drum motor and a pressure relief valve](image)

Figure 7. Case 1 circuit with a single capstan motor, drum motor and a pressure relief valve

But during the operation, it is possible that the capacities or loads on these motors do not remain constant. From the above internal configuration block design (Fig 3), it is shown that the capstan and drum are mechanically coupled. As the load on the capstan motor increases, the resistance of the capstan increases. This forces an increase in the flow rate into the drum due to the inverse relationship of both the parameters of load and resistance. Therefore, the capstans fail to rotate. Similarly, when the load on the drum motor increases, the flow rate into the capstan also increases (Fig 8(a, b)). This hinders the rotation of the drum.
For the initiation of a smooth pull-in operation, it is mandatory that the fluid must flow initially into the drum motor. The drum then rotates and generates a resistance which triggers the rotation of the capstans. To follow this sequence of fluid flow without stalling of either of the components, a sequence valve is integrated right before the capstan motor. This sequence valve regulates and controls the direction of fluid into the motors. The significance of this valve is to direct the flow to enter the drum motor followed by capstan motor irrespective of the influence of resistance. It mitigates the flow to enter the drum motor when the weight on the drum motor is more than capstan motor. Once equipped, the pull-in operation proved to be successful (Fig 9).

**Figure 8(a, b).** Pull In process in the hydraulic circuit and the problems encountered

**Figure 9.** Successful Pull In operation with sequence valve placed before capstan motor
3.2. Case 2
The previous iteration must also be considered for the Pull-out operation of the winch. The arrows in this hydraulic circuit depict an anti-clockwise direction which states the Pull-out operation (Fig 10). When this operation is initiated, the load on the capstan is higher than that of the drum which increases the flow rate into the drum. A problem is encountered at the drum motor as the drum begins to loosely unwind. Since there isn’t any flow into the capstans, the pull-out operation fails. To avoid this, an additional sequence valve is fixed next to the drum motor (Fig 10(a)). However, in doing so, the drum motor still starts to rotate slowly as the fluid flowed out of the drain and the input side of the motor doesn’t receive any fluid (Fig 10(b)).

![Figure 10 (a, b). Pull Out process in the hydraulic circuit and problems encountered](image)

This problem of unwanted rotation of the drum was tackled by adding a bypass between the motor input and motor output. This forced the fluid to move to either sides of the drum motor thus locking the rotation of the drum. Therefore, the drum unwound only when necessary (Fig 11).

3.3. Case 3
The previous iteration is now considered for the Pull-In operation. During that operation, it is observed that the fluid is restricted to flow through the drum motor due to the bypass. This constricts the rotation of the drum and the pull-in operation fails (Fig 12(a)). To eliminate this, a check valve is introduced at the bypass. This check valve acts like an obstacle to stop the flow of fluid directly into bypass and allows the fluid to flow into the drum motor during pull-in operation (Fig 12(b)).
Figure 11. Modified circuit for pull out process by adding a sequence valve and a bypass line to avoid unnecessary rotation of drum

Figure 12(a, b). Introduction of check valve in the bypass line to achieve Pull-In process
3.4. Case 4: Final

Finally, the last iteration has incorporated all the additional components for the smooth operation of both pull-in and pull-out processes from the previous cases. To balance out the load, another hydraulic motor is added to the capstan system. The sequence valve of the capstan motor is shifted to the output side in order to reduce the pressure drop. This completely altered hydraulic circuit is the final evolution to be used as reference to manufacture the hydraulic manifold (Fig 13).

![Figure 13. Addition of a 2nd motor for the capstan and shifting sides of sequence valve to balance out load and reduce pressure loss](image)

4. Results

From the above presented evolution of the hydraulic circuit with multiple iterations and designs performed, it is observed that this logical sequence with the appropriate addition of components has proved to produce an optimized closed loop hydraulic circuit to reduce the losses incurred in the system. Elucidating all the cases presented with different problems encountered, the careful engineering of this circuit controls the fluid flow and the pressure entailing to the drum and capstan motors. Controlling these parameters allows the machine to toggle between its two fundamental operations that are Pull-In & Pull-Out. These parameters are vital in order to avoid damage and stalling of components present in the machine. The resistance offered by the load bearing components (Capstans and Motors) are analyzed to upgrade the hydraulic circuit. Keeping in mind to achieve synchronized rotation, the fluid must initially flow into the drum motor which is followed by the
capstan motors. With this pertinent integrated system, the cable laying procedure is performed with minimized losses generated. Thus, this efficient circuit is used to manufacture the hydraulic manifold which is placed as the central node of the hydraulic system in the fluid powered machine.

5. References

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