Recovery of Potential Energy by Using a Digital Hydraulic Cylinder

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Abstract: *The recovery of energy in hydraulic systems is becoming increasingly essential not only to reduce energy consumption but also to lower carbon emissions into the atmosphere. A significant portion of the articles and studies published address the recovery of potential energy in hydraulic accumulators and its use to compensate for consumption peaks. This article presents a solution for recovering potential energy in a lifting/lowering device equipped with a digital hydraulic cylinder, converting this energy into electrical energy, which is stored in a battery and can later supply power during the operational cycle.*

Keywords: *Digital hydraulic cylinders, energy recovery, potential energy*

1. Introduction

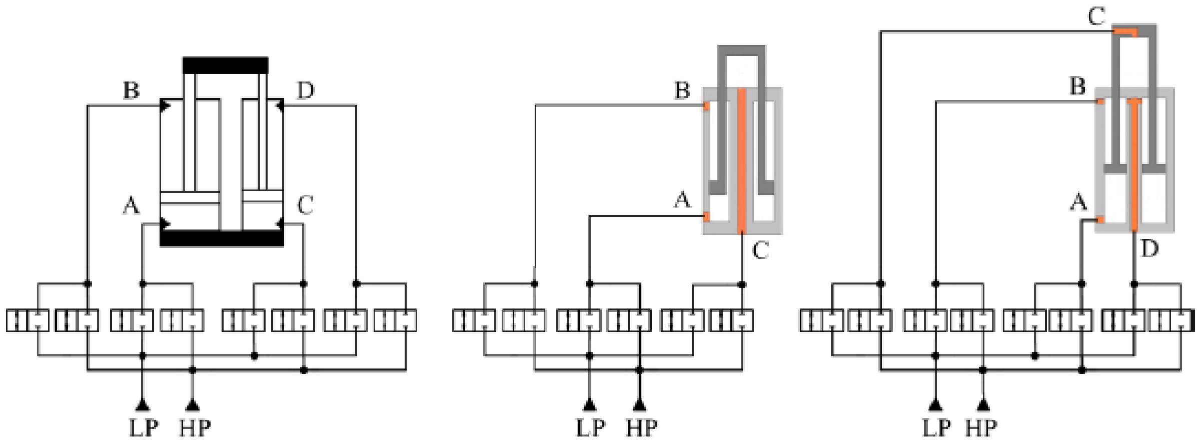
In the current context, marked by a new scientific and technological revolution, we are witnessing a rapid transformation of technologies, the expansion of automation, and the accelerated processing and transmission of information. The development of science and technology is occurring exponentially, significantly impacting daily life, the environment, and space exploration. In this new era, competitiveness no longer depends solely on primary production factors such as cheap labor, access to natural resources, or investments. The modern economy is rooted in innovation, which has become the primary source of competitive advantage, involving the ability to develop innovative products and services by utilizing cutting-edge technologies and the most advanced methods available globally.

Thus, energy losses associated with inefficient hydraulic systems contribute to increased production costs and overheating of hydraulic fluid, which can lead to premature equipment failures. This phenomenon is also accompanied by additional greenhouse gas emissions and increased energy consumption for cooling. Hydraulic actuators, which convert pressure into force, play a crucial role in hydraulic systems, where force variation is typically achieved by varying pressure and speed by adjusting the flow rate. However, a more energy-efficient alternative is to vary the actuator's cross-sectional area, as in the case of the digital cylinder. According to theoretical principles, this method of control reduces energy losses compared to traditional pressure or flow rate control.

Regarding digital hydraulic cylinders, it has been demonstrated that varying the surface area is more efficient than adjusting pressure or speed for active cylinder control. The concept of digital hydraulics is based on the discretization of the nominal opening or working surface in the case of cylinders, with each variable defined by binary on/off states. By combining these sections and states, active control of speed or force at the actuator level is achieved.

Recently, multi-area hydraulic cylinders have garnered increasing interest in research on the application of digital hydraulics. These cylinders are used in systems requiring variable forces and speeds during the work process. An example of the application of multi-area cylinders is found in pressing and stamping machines, where rapid advance is achieved using the smaller piston surface, while high pressing pressure is obtained with the larger surface area.

One approach to varying the piston's active surface involves dividing it into multiple concentric, annular zones with binary-multiplied areas (fig. 1c or 1d). These zones are supplied either separately or cumulatively, with constant flow and pressure, following well-defined rules. This method allows for various combinations of zones to be supplied, facilitating linear motion with variable speeds and loads, thereby providing additional control options. As a result, the hydraulic system's energy requirements are met efficiently.



a. b. c.

Fig. 1. Digital hydraulic cylinder solutions

The parallel connection of the chambers of multiple hydraulic cylinders (Fig. 1a) has been previously investigated [1,2] and involves the use of several independent cylinders of varying sizes on the same axis, which can be selected based on the system requirements. The literature includes a study on the use of multi-chamber cylinders [3], equipped with discretely controlled start/stop devices that allow for three pressure levels. This study includes relevant examples for improving efficiency in hydraulic installations and describes a highly efficient hydraulic hybrid system for excavators [4] that utilizes multi-chamber cylinders and secondary control. Additionally, a switching control system for hydraulic cylinders with multiple chambers has been investigated [5], enabling the control of force and speed by combining the supplied active areas.

Energy recovery in hydraulic systems is becoming increasingly important for reducing energy consumption and carbon emissions. Recent studies focus on recovering potential energy in lifting and lowering equipment equipped with hydraulic cylinders, using hydraulic accumulators to compensate for consumption peaks. The simplest solution for energy management is the parallel connection of cylinders (Fig. 1a). However, a more compact design can be achieved by integrating multiple chambers into a single cylinder, as shown in Fig. 1(b) and (c). In this case, four integrated chambers are used, generating 16 discrete force values depending on the combination of valve states. An additional increase in the number of force values can be obtained by adding extra supply pressures. The total number of force values is given by the formula \(N_S\), where \(N\) represents the number of supply pressures and \(S\) represents the number of chambers.

Another solution for minimizing or completely eliminating the need for proportional valves is the use of hydraulic transformers, which are supplied from a pressure line that powers both the working mechanisms and the rotational drive of a front loader system [6,7].

A team from the Tampere University of Technology and Aalto University in Espoo, Finland, has developed, simulated, and tested a multi-pressure digital hydraulic actuator that shows a high potential for energy savings [8]. This system includes a hydraulic accumulator and four pressure converters, allowing the connection of six supply pressures to the chambers of the cylinders through on/off valves.

2. The solution for recovering potential energy and converting it into electrical energy

The solution presented in this article for converting potential energy into electrical energy has been evaluated through simulations conducted on a testing stand for digital hydraulic cylinders (Fig. 2). This testing stand is equipped with a force transducer, a displacement transducer, and a cylinder designed to simulate potential energy.

The recovery of potential energy occurs during the return stroke by connecting the exhaust ports of the digital cylinder to a hydraulic motor that drives an electric generator. The produced electrical energy is subsequently stored in a battery via a charger.

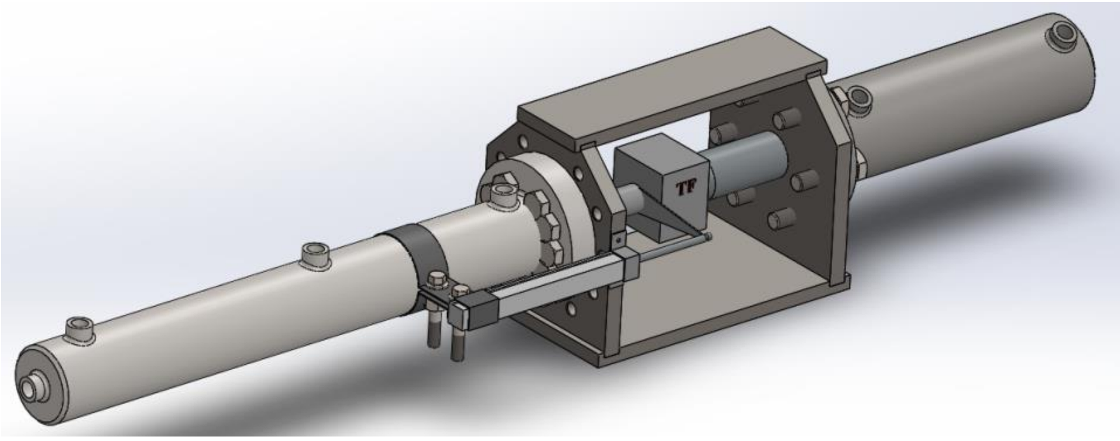


Fig. 2. Testing stand for digital cylinders

For testing, a simplified version of a digital hydraulic cylinder was chosen, featuring two concentric surfaces of 13.5 cm² and 19.6 cm². For the return stroke, the surface area is 20.6 cm² (fig 3)

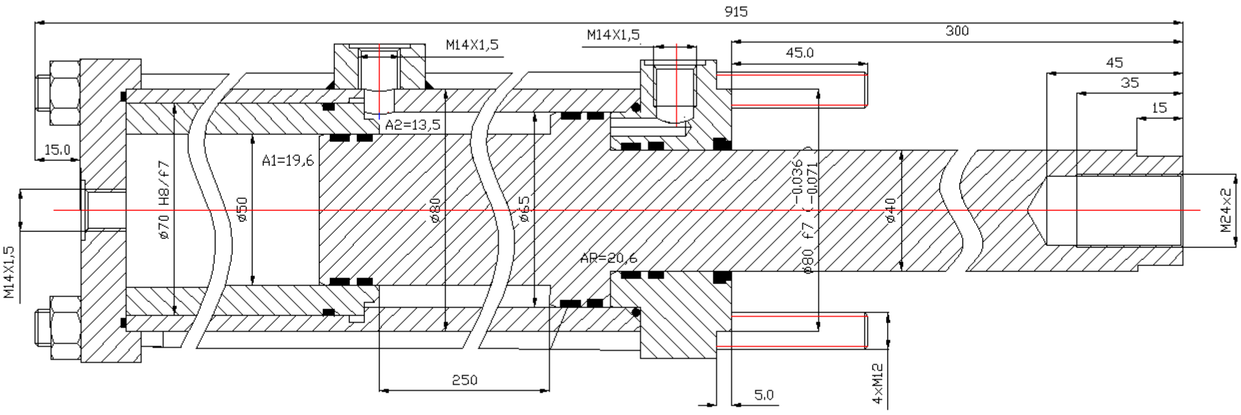


Fig. 3. Digital hydraulic cylinder with two surfaces

Technical characteristics of a digital hydraulic cylinder with two active surfaces S1 = 13.5 cm².

S2 = 19.6 cm²

S1+S2 = 33.1 cm²

S ret = 20.6 cm²

Race = 250 mm

Calculation of the maximum advance speed (constant flow rate supplied by SP1 and minimum area of the digital cylinder), equation (1).

$$V = \frac{Q}{S} \tag{1}$$

Where:
V = speed
Q = flow rate
S = section
Calculation of the maximum feed rate, equation (2).

$$V_{max} = \frac{Q}{S} = \frac{16\ l/min}{13.5\ cm^2} = \frac{16\ dm^3}{0.135\ dm^2 \cdot 60\ sec} = \frac{16\ dm}{8.1\ sec} = \frac{1.6\ m}{8.1\ sec} = 0.197 m/sec \tag{2}$$

The maximum speed of the hydraulic motor MH is 3500 rpm, exceeding the nominal speed of the generator GE, which is 3000 rpm. To rotate MH at 3000 rpm, the speed of the piston rod during the return stroke must be 74.3 dm/min. This speed ensures the necessary flow is discharged from the chambers C1 and C2 of the digital hydraulic cylinder to rotate the hydraulic motor at the optimal speed for the electric generator.
The calculation of the optimal flow rate for SP2 (the retraction speed) during the simulation of potential energy is as follows, equation (3):

$$Q_{nec} = V_g \cdot n \tag{3}$$

V_g= Geometric volume of the hydraulic motor

n = speed of the generator (hydraulic motor)

$$Q_{nec} = 0.0082 \frac{dm^3}{\cancel{rot}} \cdot 3000 \frac{\cancel{rot}}{min} = 24{,}6 \frac{l}{min} \tag{4}$$

Calculation of the rod displacement speed during retraction, equation (5)

$$V = \frac{Q}{S} \tag{5}$$

V = speed of the cylinder rod
Q = required flow rate for discharging chambers C1 and C2
S = moving section (S1 + S2)

$$V = \frac{24.6\ l/min}{0.331 dm^3} = 74.3\ \frac{dm}{min} \tag{6}$$

The flow rate provided by station SP2 to ensure a speed of 74.3 dm/min must be:

$$Q_{SP2} = v \cdot S = 74.3\ \frac{dm}{min} \cdot 1.13\ dm^2 = 83.96\ \frac{l}{min} \tag{7}$$

The pressure supplied by SP2 must be at least equal to the load created by GE plus the pressure losses along the fluid path.

3. Methodology for converting potential energy into electrical energy in a system equipped with a digital cylinder

In Figure 4, the hydraulic schematic of the system for converting potential energy into electrical energy is presented. The digital cylinder is supplied during the advance phase by the pumping station SP1 through the combination of states of the distributors E1 and E2, while retraction is achieved with the help of distributor E3, located on the distribution block BD. The simulation of potential energy is performed using the pumping station SP2. The recovery of simulated potential energy in the EP chamber of the load cylinder occurs during the return stroke of the digital cylinder, with the flow discharged from chambers C1 and C2 directed towards a hydraulic motor (MH). This drives an electric generator (GE), which produces electrical energy, subsequently stored in a battery (BAT). The recovered energy is measured using an electric meter (CE) and transmitted to the BAT battery via a charger (IN). Additionally, the flow and pressure values resulting from the recovery of potential energy are recorded by a hydraulic monitoring system (SHM).

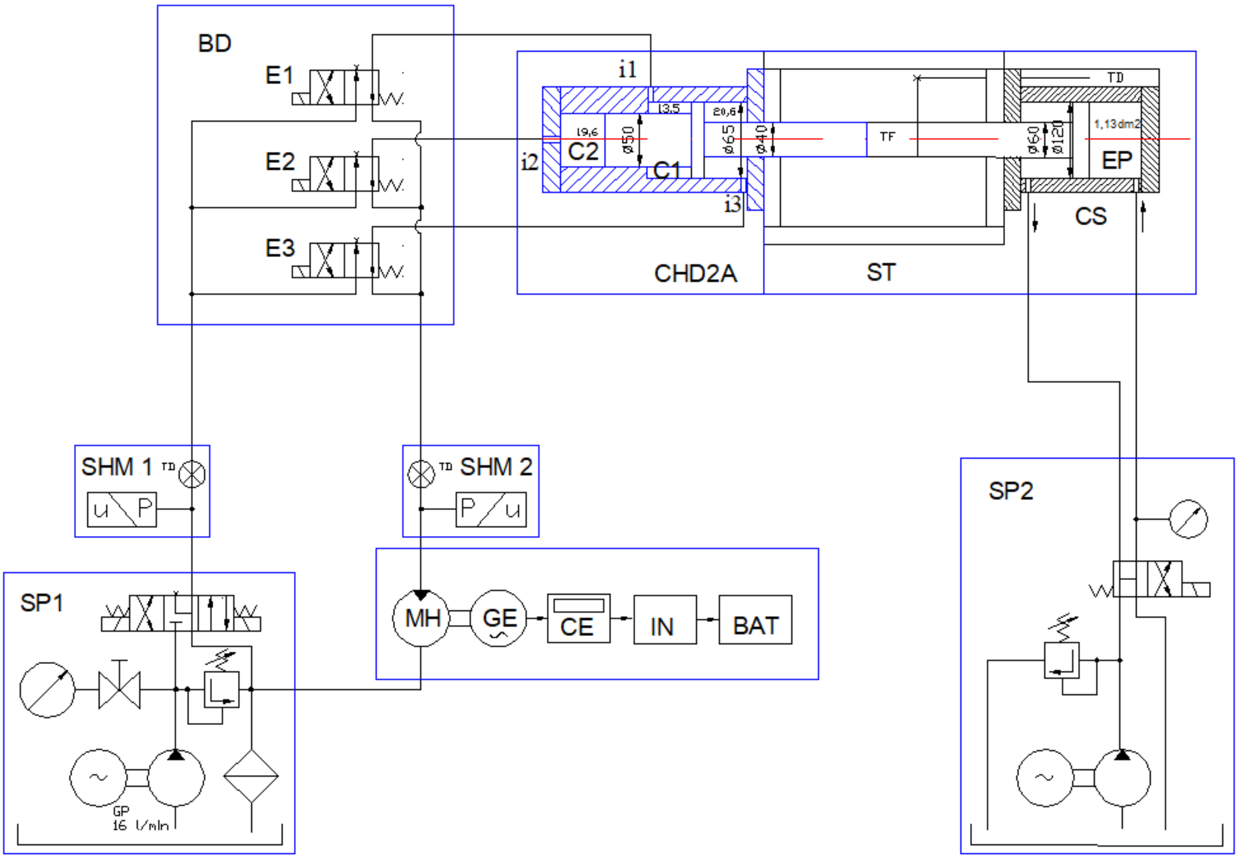


Fig. 4. Hydraulic diagram of potential energy to electricity conversion stand

4. Conclusions

To achieve a speed of 3000 rpm for the hydraulic motor (electric generator), a retraction speed of the cylinder rod of 74.3 dm/min is necessary, thus ensuring a discharged flow from chambers C1 and C2 of 24.6 l/min. To support this retraction speed, the pumping station SP2 must provide a flow rate of 84 l/min.

The need for precise adjustment of force and speed in modern hydraulic systems, in the context of energy efficiency requirements and the simplification of design solutions, highlights the necessity for research and development of cylinders with multiple areas. These cylinders allow for variation in working area, and consequently in operating force and speed, offering innovative solutions for machinery. The hydraulic cylinder, being the most widely used equipment in hydraulic drives, represents an essential starting point in the design of hydraulic installations. The introduction of digital technologies in this field can pave the way for new applications in modernized or newly designed installations.

Digital hydraulics represents an emerging research field that is attracting the attention of numerous prestigious institutes and international companies. This technology offers innovative solutions for implementing more efficient hydraulic systems. Although they may seem more complex, digital systems consist of a reduced number of standardized components capable of replacing a large portion of traditional hydraulic equipment.

The main obstacle to the widespread application of digital hydraulic solutions is the lack of specific equipment available on the market. There is a need to develop a range of cylinders with multiple areas, rapid distributors, digital actuating elements, and control electronic components, all integrated into a configurable and user-friendly package.

The simulation of the digital hydraulic cylinder's operation confirms the possibility of effective adjustment of force and speed by selecting active sections and using constant flow rates and pressures. This work represents a first step in the development of the digital hydraulics concept, opening up perspectives for in-depth research in this field.

In the near future, reducing costs and increasing energy efficiency will become determining factors in the success of any industry. Currently, the hydraulic industry is not yet fully prepared to meet these requirements, as traditional systems are costly and energy inefficient. The correct choice of technical and economic solutions can transform hydraulic systems into the fastest and most efficient methods of power transmission. The energy savings resulting from modeling and simulating suitable solutions can improve the technical and economic performance of production lines, thereby contributing to cost reduction and supporting sustainable development.

Acknowledgments

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