Conceptual solutions for digital hydraulic pumps

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Abstract. One of the methods by which specialists in the field of hydraulic drives try to increase the efficiency of the systems is the use of digital hydraulics. Digital hydraulics is a system with one or more digital components that actively controls the output of the system. One of the basic elements of such a system is the digital hydraulic pump. The first proposed and recognized variant was the one with digital pumping element; from this solution, it was possible to produce digital hydraulic pumps on an industrial scale. In this article we present some solutions regarding the creation of digital hydraulic pumps starting from several fixed flow hydraulic pumps that can ensure the variation of the flow through a special selection of them. The displacement of each pump is different and chosen taking into account the binary criterion. The article gives an overview of several such systems developed within the institute.

1. Introduction

1.1. Introduction to hydraulic drives

Hydraulics have existed for a very long time, since antiquity, when the first technical books were written, with chapters related to water or air-based drive, such as Archimedes' work "On floating bodies". And yet there was a long, blurry period, in which almost 1000 years seem to have been without important, known technical-scientific achievements. However, interesting ideas reappeared in the early Middle Ages, so that Leonardo da Vinci's work "On the movement and measurement of water" is a benchmark. A real technical boom occurred in the 16th and 17th centuries when in countries (or regions of these countries) such as Italy, France, Germany, England or Russia, research has been developed, books have been written and many equipment and machines have been developed, which over time have entered the history of the field of hydraulic drives, for example the writings of Galileo and Newton. Starting with the 18th century, the basic technical-scientific elements of hydraulics were created by personalities such as Leonhard Euler, Daniel Bernoulli, Chezy, Darcy, Stokes, Reynolds, Jukovski, Prandtl, and so on.

In Romania, the first achievements in hydraulics belonged to professors such as D. Pavel, A. Barglan, George Constantinescu, Dionisie Gherman, Caius Iacob, D. Dumitrescu, E. Carafoli, C. Mateescu in the mid-20th century. However, one could not talk still about achievements in the field of hydrostatic or pneumatic drives. The first specialists in the field appeared in the 60s and 70s of the last century, such as Marin Virgil, Theodor Demetrescu, N. Oprescu, S. Dobrescu, I. Mazilu, A. Popov, G. Radulescu, G. Tarlescu, R. Visan, D. Teneslav, D. Lazar, R. Moscovici, N. Arama, D.C. Popescu, M. Popescu, S. Medar designed and put into production the first hydraulic and pneumatic equipment. During that period, the first specialized factories appeared, such as those in Sibiu, Plopeni, Bucharest, Focsani, Ramnicu Valcea, Bistrita, Sinaia, Cluj-Napoca, Stei, Braila, Galati.
Nowadays the field is preserved by several production units in Bucharest, Iasi, Ramnicu-Valcea, Sibiu and several research centers, such as INOE 2000-IHP Bucharest and research centers of technical universities in Iasi, Cluj-Napoca, Bucharest, Timisoara, Galati and Brasov.

1.2. The concept of digital hydraulics

Hydraulic drives have become, since the interwar years of the last century, some of the basic drives in technology, along with mechanical and electrical drives. The main steps in modernizing hydraulics, over time, were those related to the development of high-quality pumps, advances in servotechnics and computerization of hydraulic systems and equipment. One of the great novelties of the last years, starting with 1990, is the emergence of digital hydraulics, which is intended to be a replacement (probably a partner) of hydraulic servosystems. The idea is part of the intention and mostly of the desire of specialists that the energy (be it electrical or mechanical) consumed by the hydraulic system be as close as possible to the value of useful energy, conveyed to the machine by the hydraulic installation. A solution prior to the novelties of the last years is the one in which the pumping group consists of 3 pumps that are introduced into the hydraulic circuit depending on the flow required at a given time; Dr. Heinrich Theissen of Aachen calls them digital pumps [1]. The selection of pumps with the help of simple on/off distributors can be done by several methods, of which the German specialist considered that it would be of interest to use the binary system or even better the ternary system. If a brief analysis is made, it is possible that this variant fall, roughly speaking, in the field of digital hydraulics with parallel-connected components.

The solution, although old, is still used in many applications, significantly improved, but there are specialists who do not think of it as modern digital hydraulics. What is being blamed on this solution is the low response time and the complexity of the pumping group, which we should probably discuss more, considering that in fact these elements do not give the quality of being “digital”.

|                   | On-Off methods | Switching methods | Parallel-technologies |
|-------------------|----------------|-------------------|-----------------------|
| Valves            |                |                   |                       |
| Pumps             |                |                   |                       |
| Cylinders         |                |                   |                       |
| Accumul.          |                |                   |                       |

**Figure 1.** Graphical synthesis of traditional hydraulics vs. digital (switching technology and parallel connection) hydraulics [2].
It should be noted that digital hydraulics does not mean traditional, classic or modern hydraulics with analog type elements that we drive with digital electronics. As a result, a computer-driven servo-hydraulic system is not digital hydraulics, although in the opinion of the authors when it comes to an electro-hydraulic device, hence mechatronic device, the optics may change. Digital hydraulics means hydraulic systems that have in their structure at least one hydraulic element able to ensure precisely and actively controlled discrete values at the output. This involves, in addition to digital hydraulic elements, proper electronic control and therefore a good computerization of the system. The main advantages of digital hydraulics, more hoped for than achieved, are related to the speed, robustness, simplicity, reliability and energy efficiency of the products. Although worldwide there is an important development, unfortunately chaotic, often specific to a piece of equipment, it seems that the idea that digital hydraulic systems can be grouped on two main directions has been accepted quite widely, namely the first direction is based on parallel connection and the second is based on switching technology. Both directions are in their early stages, even if some achievements from the production of important companies are attached to them. An interesting synthesis is made by Prof. Scheidl starting from an article written by Prof. Linjama, and it is shown in this material in the table in figure 1 [2, 3, 4].

2. Digital hydraulic rotary pumps and motors
The arguments that make digital hydraulics a technology of great interest seem to be best supported by the obvious advantages of digital hydraulic pumps and motors, which are high-impact innovative equipment. The major differences between conventional and digital pumps are, according to Luke Wadsley at Sauer Danfoss, related to the way in which the displacement is achieved and the cylinder piston makes the switch from suction to discharge [5]. The permanently variable stroke of the classic pumps made by a special plate is replaced by a cylinder which has a fixed stroke and two valves, one inlet and one discharge valve, electronically controlled. The simplified diagram in figure 2 shows the basic functional element, which is actually equivalent to that of classic in-line piston pumps. In this way, both the suction-to-discharge switching and the adjustment of the displacement are performed electronically.

![Element of a digital hydraulic pump](image)

**Figure 2.** Element of a digital hydraulic pump [5].

Several very interesting solutions for digital hydraulic pumps and motors belong to the ARTEMIS company; they are controlled directly by means of fast directional control valves driven with embedded microprocessor.

It should be noted that most of the vehicles and mobile machines that exist on the market are based on very old technologies, which control the stroke of the pump piston with the help of the distribution plate (swash plate), a mechanism patented since 1893 and introduced industrially since the 30s of last century. The mechanism has several disadvantages (friction, leakage, etc.), highlighted in recent years when energy efficiency has become extremely important.
The fact that in the Artemis project the cylinders are individually controlled led to the reduction of energy losses, to the increase of the response time and to the reduction of the noise level.

The specialist Dan Helgerson considers it extremely important that Stephen Salter (co-founder of Artemis) patented the Digital Displacement Pumps (DDP) and Motors (DDPM) in 1994. The implementation of this equipment on the transmission of excavators has led to a reduction in fuel consumption by 20% and especially an increase in productivity by 30%.

The industrial variant is the one shown in figure 3, which clearly shows that the active pistons are radial and the fact that the distribution and control equipment is compactly placed in the system; practically one can reckon that there is a technological grouping of several piston pumps under a central logical control.

Figure 3. Digital hydraulic pump - industrial variant [6].

3. The situation of digital hydraulics in Romania
In Romania, there are few researches in the field of digital hydraulics, and the great achievements are even fewer. The only theoretical attempts and achievement of some components belong to the research group at INOE 2000 – IHP, which has developed a hydraulic directional control valve, currently at the stage of a functional model, for which a patent application was filed, 2 variants of digital hydraulic cylinders and a variant of digital hydraulic pump [7, 8, 9]. It is worth noting the existence of two stands (shown in figure 4 and figure 5) specialized for digital hydraulic equipment, the one for cylinders being extremely interesting and useful.

A small group led by the professor I. Bordeas from Politehnica University in Timisoara and another group led by the professors Vaida and Opruta from Technical University in Cluj-Napoca joined the first group of researchers from INOE 2000 – IHP. The version addressed by the specialists from IHP Bucharest is that of digital switched hydraulics, represented on an international scale by the professor Scheidl from the University of Leinz, Austria. The group of specialists from IHP, consisting of PhD. eng. Petrin Drumea, PhD. eng. M. Blejan, PhD. eng. R. Radoi, and four PhD. eng. students – M. Al. Hristea, B. Tudor, I. Pavel and St. M. Sefu - have research interests in digital hydraulic valves, digital hydraulic cylinders and digital hydraulic pumps [10].
4. The digital pumping unit
Most variants of digital hydraulic pumps are similar to in-line (triplex) pumps, to which selection, intake and discharge blocks have been added and which, through a suitable construction, can deliver different flow rates depending on the number of cylinders which are part of its structure, such as the solutions of American specialists Luke Wadsley and Elton Bishop [11]. Also, the solutions of pumping groups with fixed gear pumps or water transfer pumps have been known for a long time; they allow a primary adjustment of the flow in only a few steps. All these solutions have the disadvantage of the small number of flow steps, the complexity of the flow selection system and most of the time the large number of drive motors, usually equal to the number of driven pumps. Such groups are found in hydraulic drives for presses, for hydraulic installations in metallurgy and for mobile equipment in which multi-stage speed hence multi-stage flow is required, as shown by the German specialist H. Theissen at the HERVEX 2011 conference [1]. The complexity of these types of pumping units has

Figure 4. Servo equipment test stand and digital switching distribution.

Figure 5. Digital hydraulic cylinder test stand and parallel distribution.
led to the increase in the price of hydraulic installations and, as a result, of the entire industrial equipment that includes them.

The solution presented by the authors, which, among other elements, is the subject of a patent application, eliminates all these disadvantages having in its structure a single drive motor, only 2 double pumps with different displacement observing the increase of the size in the terms of the binary numbers, a simple pump selection system by introducing on/off valves, controlled by the digital electronic block, which selects according to the indications in table 1 which pumps are connected to the mains and which pumps remain directed to the tank.

The advantages of the digital pumping system, according to the elements presented in figure 6 and table 1, are as follows:

- The mechanical block is simplified.
- With a number of 4 fixed pumps, a range of 15 flow rates is easily accessible through an extremely simple digital electronic control. The 15 flow rates finally ensure a flow adjustment accuracy of approximately 7%, which is sufficient in the vast majority of industrial applications.
- The fixed pumps not involved in achieving the chosen flow are driven, but they are discharged to the tank by means of on/off valves, and as a result the energy consumption is reduced to the level of the useful one and also the wear is reduced.
- The efficiency of the group (over 80%) is quite high, all components being simple, with good efficiency and easy (without additional consumption) to operate.
- This solution eliminates the disadvantage of starting and stopping the pumps from time to time, in connection with the selection according to table 1.

Returning to the diagram in figure 6 and table 1, we mention that they are a hydraulic diagram of the digital group, and respectively a table for selecting the size of the pumps and for choosing the actuation of the on/off valves by the electronic control block (8). The digital pumping group, as shown in figure 6 and table 1, is based on a group of 4 fixed gear pumps (2, 3, 4 and 5), grouped two by two in double pumps, which are driven by an electric drive motor (1) through the two output ends. The speed of the electric motor and consequently of the pumps (2, 3, 4 and 5) is 1500 rpm. In accordance with the information displayed in table 1, 15 combinations of pumps hence 15 flow sizes can be selected. The pumps included in the system are differentiated by their displacement volume (Vg), as shown in table 1. The numbering of the pumps (displacement volumes) is also kept for the on/off valves (2, 3, 4 and 5). The pressure level taken into account is 210 bar, provided by a drive motor of about 30 kW.

![Figure 6. Digital pumping system with selection of fixed pumps by means of on/off hydraulic directional control valves.](image-url)
Table 1. Possible combinations of pumps.

| Item no. | Combination of pumps | Displacement [cm³/rev] | Total displacement [cm³/rev] | System flow [l/min] | Power required [kW] | Pump torque [daNm] |
|---------|----------------------|------------------------|-----------------------------|---------------------|---------------------|-------------------|
| 1       | Vg1                  | Vg4 4                  | 4                           | 6                   | 2                   | 1.27              |
| 2       | Vg2                  | Vg2 8                  | 8                           | 12                  | 4                   | 2.54              |
| 3       | Vg1 + Vg2            | Vg3 8                  | 4                           | 12                  | 6                   | 3.81              |
| 4       | Vg3                  | Vg3 16                 | 16                          | 24                  | 8                   | 5.08              |
| 5       | Vg3 + Vg1            | Vg4 16                 | 16                          | 30                  | 10                  | 6.34              |
| 6       | Vg3 + Vg2            | Vg2 16                 | 16                          | 36                  | 12                  | 7.61              |
| 7       | Vg3 + Vg2 + Vg1      | Vg4 16                 | 16                          | 42                  | 14                  | 8.88              |
| 8       | Vg4                  | Vg4 32                 | 32                          | 48                  | 16                  | 10.15             |
| 9       | Vg4 + Vg1            | Vg4 32                 | 32                          | 54                  | 18                  | 11.42             |
| 10      | Vg4 + Vg2            | Vg4 32                 | 32                          | 60                  | 20                  | 12.69             |
| 11      | Vg4 + Vg2 + Vg1      | Vg4 32                 | 32                          | 66                  | 22                  | 13.96             |
| 12      | Vg4 + Vg3            | Vg4 32                 | 32                          | 72                  | 24                  | 15.23             |
| 13      | Vg4 + Vg1 + Vg2      | Vg4 32                 | 32                          | 86                  | 28                  | 16.49             |
| 14      | Vg4 + Vg3 + Vg2      | Vg4 32                 | 32                          | 90                  | 30                  | 18.76             |
| 15      | Vg4 + Vg1 + Vg2      | Vg4 32                 | 32                          | 90                  | 30                  | 19.03             |

5. Conclusions

5.1. Digital hydraulics is one of the ways to modernize hydraulic drives in order to improve the energy efficiency of systems.

5.2. The main element of the hydraulic system, the pump, is also the most important in the technical process of lining up the level of energy consumed to that of the energy actually required. Therefore, specialists need to focus mainly on modernizing the pumping units.

5.3. The solution presented in this article is known in principle, but it is new in terms of technology and structure; the authors join those specialists who consider this type of aggregate as being a digital hydraulic pump.

5.4. Digital hydraulics can be a high-efficiency research niche for specialists in our country.

6. References

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