

FUNDAMENTAL CONCEPTS OF DIGITAL HYDRAULICS - DIGITAL FLOW CONTROL UNIT (DFCU)

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Abstract: *Classic hydrostatic systems, based on continuous control using proportional or servo-valves, are characterized by high precision but also significant energy losses, mainly related to flow throttling. Digital hydraulics represents an alternative concept for controlling hydrostatic systems, replacing continuous modulation with discrete, binary states of hydraulic valves (ON/OFF type). This approach is, in many cases, associated with improving the system's energy efficiency, increasing system reliability, and lowering its construction costs. The core of digital hydraulic systems is the Digital Flow Control Unit (DFCU). This article presents the basic operational features of the DFCU and compares its key characteristics with traditional analog solutions. Key engineering challenges, such as pressure pulsations and shock loads identified during experimental research, are also discussed.*

Keywords: *Digital Hydraulics, DFCU, discrete control, energy efficiency, ON/OFF control, hydrostatic systems*

1. Introduction- The Digital Hydraulics Paradigm

Classic hydraulic systems use continuously variable components (e.g., variable displacement pumps, proportional valves) for precise control of force and speed. Despite their precision, systems based on throttling control are primarily characterized by relatively low energy efficiency. Energy is lost in the form of heat during flow throttling, which is an inherent feature of continuous regulation [6]. Digital Fluid Power (DFP) represents a proposed paradigm shift. Instead of smooth modulation, DFP utilizes discrete control based on the binary states of "on/off" (ON/OFF) type valves. This concept can be compared to the digital revolution brought about by electronics, where analog signals were replaced by digital ones, leading to an increase in the efficiency and reliability of control systems [5]. The key advantages of digital hydraulics compared to classic "analog" hydraulics (Table 1) are:

- Higher energy efficiency: Elimination of throttling losses by operating components only in fully open or fully closed states.
- Greater reliability and fault tolerance: Digital systems often use multiple parallel, simpler components. The failure of one element does not stop the entire system's operation, but only degrades its operating parameters (e.g., resolution).
- Contamination resistance: Simple ON/OFF valves are much less sensitive to oil contamination than the precise spools of proportional or servo-valves [12].
- Lower system construction costs: The use of standard, mass-produced components (e.g., gear pumps, 2/2 valves) instead of complex and consequently expensive axial-piston units or proportional valves.

Table 1: Comparison: Digital vs. Analog Hydraulics [7]

Feature	Classic Hydraulics	Digital Hydraulics
Signal Type	(with proportional valves)	Discrete (On/Off)
Energy Losses	Continuous (Proportional)	Minimal
Fault Tolerance	High due to throttling	High – redundant components
Precision	Low – susceptible to minor failures	Depends on valve resolution
Contamination Sensitivity	Very High	Low

2. Digital Flow Control Unit (DFCU)

2.1 Principle of Operation

A Digital Flow Control Unit (DFCU) is, by definition, a device that performs the regulation of hydraulic flow rate in a discrete (stepped) manner. Instead of a single element with continuous regulation, the DFCU consists of multiple parallel-connected switching elements (valves) (Fig. 1). The total flow rate at the output of the DFCU (Q_{total}) is the arithmetic sum of the flow rates of all units that are currently in the "ON" state (are active). By digitally controlling the appropriate combinations of valves, the required, stepped output flow characteristic can be achieved [11], [12].

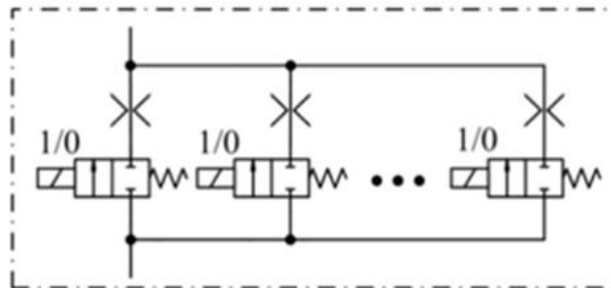


Fig. 1. Schematic diagram of a DFCU based on parallel switching valves [7]

2.2 Architecture and Encoding

The DFCU architecture can be implemented in two main ways, both consistent with the digital concept:

- Valve-based DFCU: Consists of a bank of parallel ON/OFF valves, where each valve has a specific (usually different) flow capacity (e.g., Q , $2Q$, $4Q$, $8Q$).
- Pump-based DFCU: The architecture that forms the basis of the research in co-author Ahmed Jan's doctoral dissertation. In this setup, a single variable displacement pump is replaced by a set of several fixed displacement pumps (e.g., gear pumps). These pumps are typically mounted on a common shaft, driven by a single motor. Each pump is connected to a simple ON/OFF valve (e.g., $2/2$), which decides whether the flow from that pump is directed to the working circuit or pressure-free to the tank.

Regardless of the architecture, the method of flow "encoding" is key. Binary encoding is most commonly used, where the capacities of successive units (valves or pumps) are selected in a 1:2:4:8:... ratio.

For a system with N units (e.g., 4 pumps with displacements of 2, 4, 8, and 16 cm^3/rev), the number of discrete, non-zero flow levels is $(2^N - 1)$. For $N=4$, this yields 15 different flow levels. As shown in Fig. 2, the greater the number of units (the more bits), the higher the system's resolution, and the

more the "stepped" digital characteristic approaches the ideally smooth characteristic of a proportional valve.

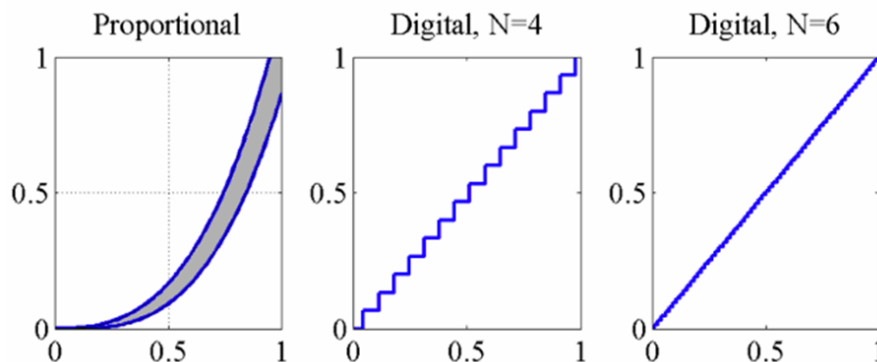


Fig. 2. Comparison of the flow characteristic of a proportional valve (left) with the stepped characteristic of a DFCU for $N=4$ (middle) and $N=6$ (right) [7]

3. Key Advantages and Challenges of DFCU

The application of the DFCU concept, whether in the form of valves or pumps, brings benefits, but also specific engineering challenges.

3.1. Advantages

- **Relatively High Energy Efficiency:** Compared to throttling control, this is the primary advantage of DFCU. By eliminating throttling control, the main source of losses in classic hydrostatic systems is removed. The pumps either operate at optimal efficiency, delivering fluid to the system, or they operate with minimal load caused by flow resistance through the pipeline (flow directed freely to the tank), thereby minimizing energy consumption.
- **Low Costs and High Reliability:** As mentioned, DFCU is based on standard, mass-produced components (gear pumps, ON/OFF valves). They are significantly cheaper and more resistant to harsh operating conditions (e.g., contamination) than precision axial-piston units or proportional valves.
- **Modularity and Fault Tolerance:** The failure of a single pump or valve in an $N=4$ DFCU system does not cause the machine to stop. The system can continue to operate with limited (but often sufficient to complete the task) performance.

3.2. Challenges: Dynamic Characteristics

The main engineering challenge and the trade-off for higher efficiency is the different dynamic characteristic of the DFCU system [7]. The discrete (stepped) nature of the control inevitably generates undesirable dynamic phenomena in the system. Experimental research conducted as part of the doctoral dissertation (Fig. 3, Fig. 4, Fig. 5) clearly demonstrated the existence of these phenomena, which were not visible in simplified simulation models:

- **Pressure and Torque Pulsations:** Even in a steady state, the "noisy" torque profile (Fig. 3) is a physical signature of DFCU operation. It results from the summation of flow pulsations from multiple gear pumps and pressure fluctuations.

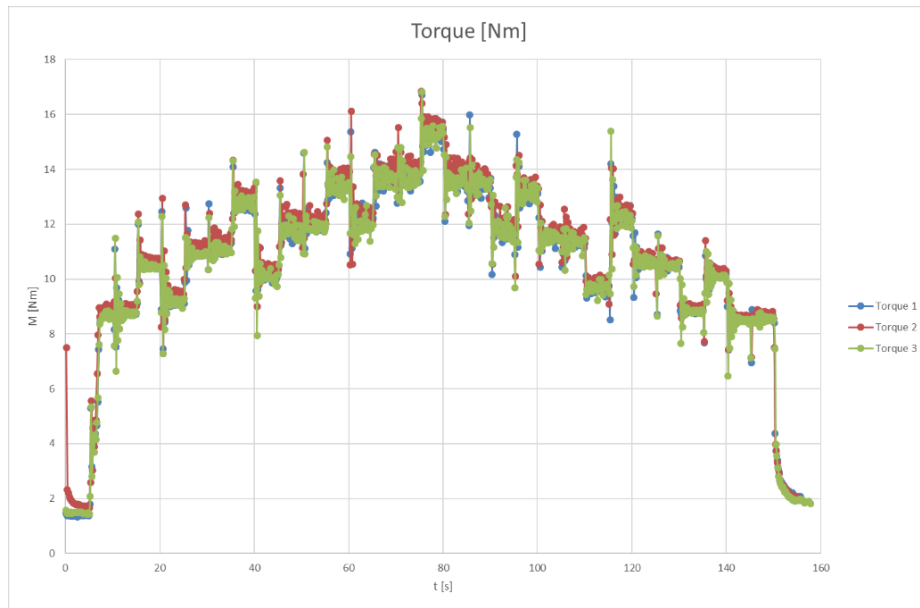


Fig. 3. Torque of 1st experimental test [7]

- Shock Loads (Hydraulic Shocks): At the moment of switching (engaging or disengaging) subsequent units to the common pressure line, hydraulic and mechanical shocks are generated. Experimental research in intermittent operation scenarios (Fig. 4 and Fig. 5) revealed the occurrence of sharp, short-term torque peaks, multiply exceeding the nominal value. The amplitude of these shock loads intensifies with the increase in operating pressure.

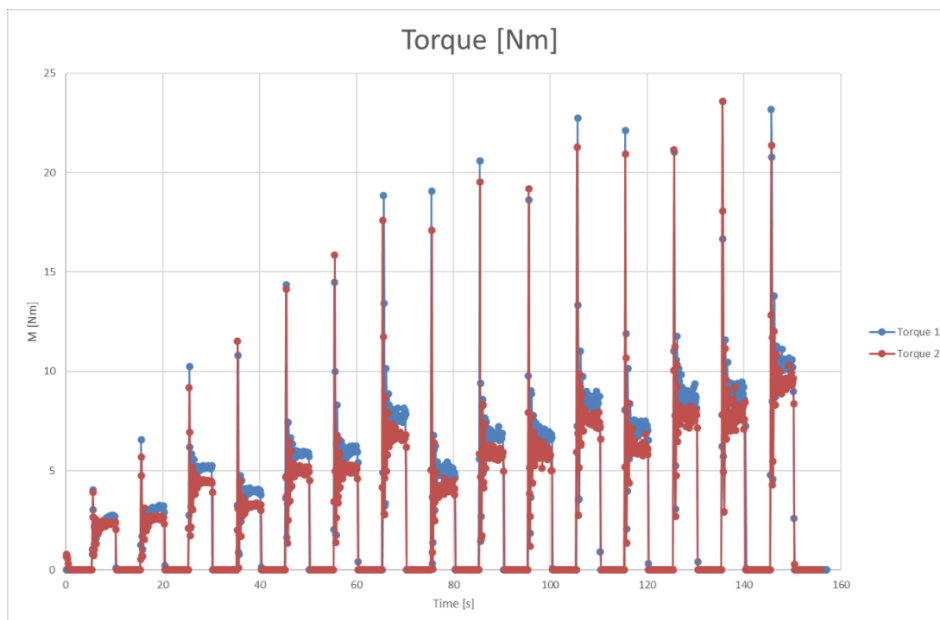


Fig. 4. Torque of 2nd experimental tests 1,2 MPa [7]

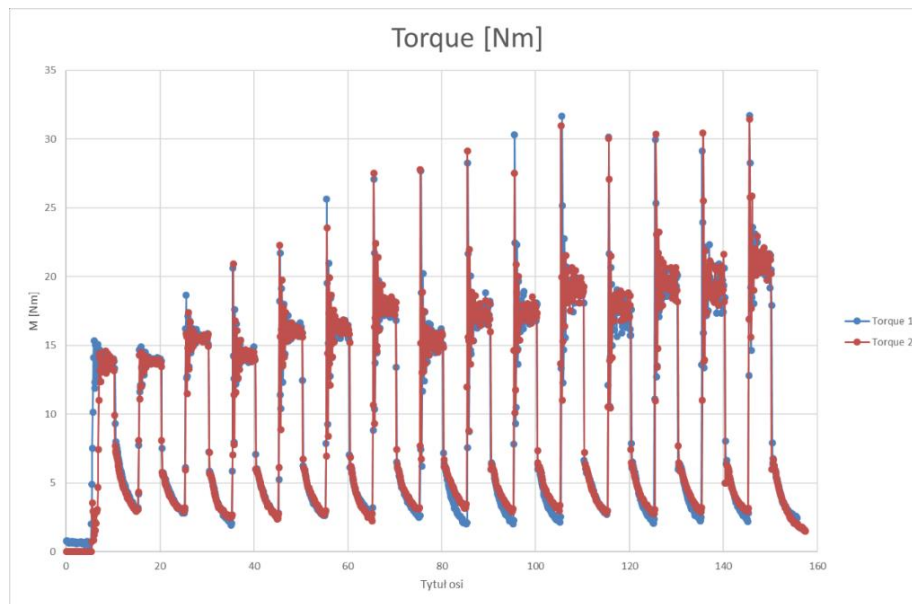


Fig. 5. Torque of 2nd experimental tests 6 MPa [7]

Managing these dynamics – ensuring operational stability, low noise levels, and the fatigue life of components – is a key aspect of designing and implementing DFCU systems.

4. Conclusion

The Digital Flow Control Unit (DFCU) is an interesting element of modern digital hydraulics, offering significant benefits in terms of energy efficiency, system construction costs, and increased reliability compared to classic analog systems. Both architectures based on valve manifolds and on sets of fixed displacement pumps appear to be an interesting alternative, allowing for the replacement of classic throttling regulation with effective discrete control.

Simulation and experimental research have confirmed that these systems can approximate the kinematic characteristics of classic drive systems with high fidelity. At the same time, this research has revealed that the main engineering challenge remains managing the inherent features of DFCU: pressure pulsations and shock loads arising during valve switching. Further work on advanced control strategies that minimize these adverse phenomena is key to fully harnessing the potential of DFCU technology.

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