FLOW SPIKE ATTENUATION FOR ELECTROHYDRAULIC UNIT WITH MIXED ANALOG AND DIGITAL CONTROL

Marian BLEJAN[1], Robert BLEJAN[1], Carmen-Anca SAFTA[2], Alexandru IONESCU[3]

[1] National Institute of Research & Development for Optoelectronics/ INOE 2000 – Subsidiary Hydraulics and Pneumatics Research Institute / IHP, Bucharest, Romania

[2] National University of Science and Technology POLITEHNICA Bucharest, Romania

[3] The National Institute of Research – Development for Machines and Installations Designed for Agriculture and Food Industry – INMA Bucharest, Romania

blejan.ihp@fluidas.ro, robertblejan@yahoo.com, carmen.safta@upb.ro, alex.alex12alx@gmail.com

Abstract *Recent advances in digital hydraulics, direct-drive hydraulics (DDH), and pump-controlled architectures have opened new possibilities for energy-efficient solutions. In this work, we present a hybrid approach for converting electrical energy into hydraulic energy with superior efficiency. The method combines Digital Flow Control (DFC) — through valve switching with predefined flow rates—with induction motor speed regulation via a frequency converter. Simulation results confirm the benefits of this strategy, showing reduced hydraulic shocks and highly flexible flow control.*

Keywords: *Asynchronous motor, digital hydraulics, DDH, electrohydraulic, mixed actuation, MATLAB/Simulink*

1. Introduction

Variable-flow hydraulic power units are traditionally based on variable-displacement pumps driven by constant-speed motors. While widely used, these systems face challenges such as structural complexity, reduced reliability, high costs, and the need for specialized adjustments. Recent research proposes several strategies to improve efficiency and flexibility in electrohydraulic systems, including digital pumps with multi-valve switching [1], fast-switching valves for discrete flow control [2], induction motors with frequency converters [3], and hybrid control methods [4–7].

Digital hydraulics has evolved to meet modern industrial demands, prioritizing energy efficiency in drive systems [1, 9–12]. A notable milestone was achieved in 1984 with the development of a 1.5 MW hydrostatic wind-turbine transmission using a Digital Displacement (DD) ring-cam pump and two DD generator drive motors [8]. These advancements highlight the potential of combining digital control concepts with conventional hydraulics to achieve superior performance.

Digital hydraulics is defined as a system that controls fluid flow using modulated, discrete digital signals to achieve active and intelligent output control [13]. It offers key advantages such as improved energy efficiency, linearity, control flexibility, robustness, and reduced sensitivity to oil contamination [14]. Digital hydraulic technology is generally categorized into three types:

(i) **Parallel digital hydraulics** – components connected in parallel;
(ii) (ii) **High-speed switching hydraulics –** on/off valves controlled by PWM signals;
(iii) (iii) **Stepping digital hydraulics –** stepping motors driven by discrete digital signals [1, 13].

New hydraulic devices based on digital hydraulics are increasingly replacing conventional components. For example, the Digital Flow Control Unit (DFCU) is a parallel valve assembly with a full response time of only 2 ms [13–15]. In addition to pulse-based modulation techniques—such as PWM, PCM, and PFC—for discrete flow control via parallel on/off valves, digital hydraulics employs intelligent algorithms (e.g., reinforcement learning) to improve motion accuracy and energy efficiency [12, 16–22].

Digital Displacement Pumps and Motors (DDPMs) represent another major innovation, replacing traditional displacement machines. This technology uses high-speed digital on/off valves to control the displacement of cam-piston pumps and motors [22]. Reported efficiencies reach 97% at full displacement and 80% at 20% displacement [22].

Direct-Driven Hydraulics (DDH) offers an efficient solution for flow regulation in hydraulic systems. This technology leverages advancements in permanent magnet synchronous motors (PMSMs), enabling precise speed control and supporting hydrostatic transmission architectures where pump flow is continuously modulated by motor speed. DDH systems stand out for their high energy efficiency, superior dynamic response, broad applicability, and seamless integration with PLCs [23–26].

This paper presents a hybrid control strategy that segments the flow range of a hydraulic power unit using digital switching of fixed-displacement pumps. Within each segment, flow is continuously regulated by adjusting the induction motor speed. This approach ensures proportional flow control while reducing mechanical complexity and minimizing hydraulic shocks.

2. Control actuation strategy

This paper continues to analyse the two methods proposed in paper [27] for generating flow proportional to a given command in a hydraulic power unit. Both approaches segment the flow range using digital switching of fixed-displacement pumps, while proportionality within each segment is achieved by varying the induction motor speed, based on direct-drive principles. The motor operates between 50% and 100% of its nominal speed, ensuring optimal efficiency and torque characteristics (93–100% of nominal torque, see Fig. 1).

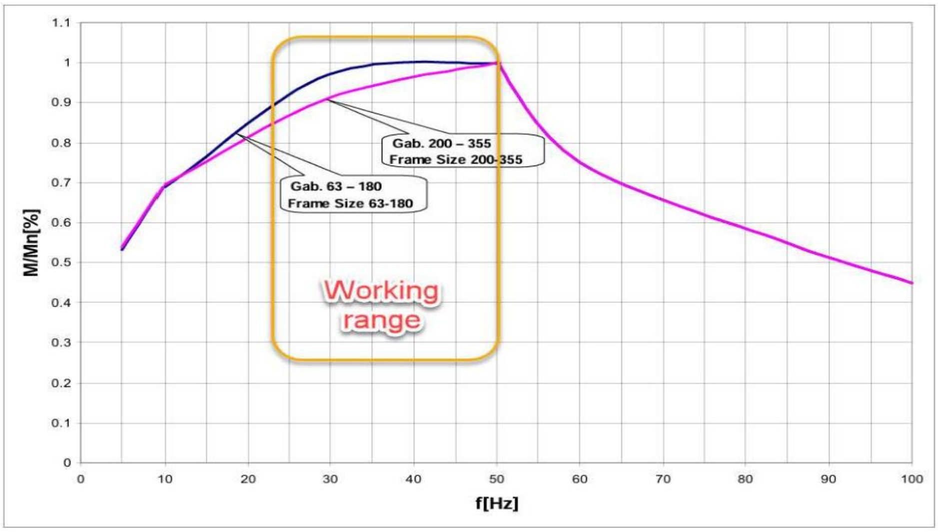

Fig. 1. Load capacity graph with frequency converter (data from UMEB – General-purpose three-phase induction motors catalogue) [27]

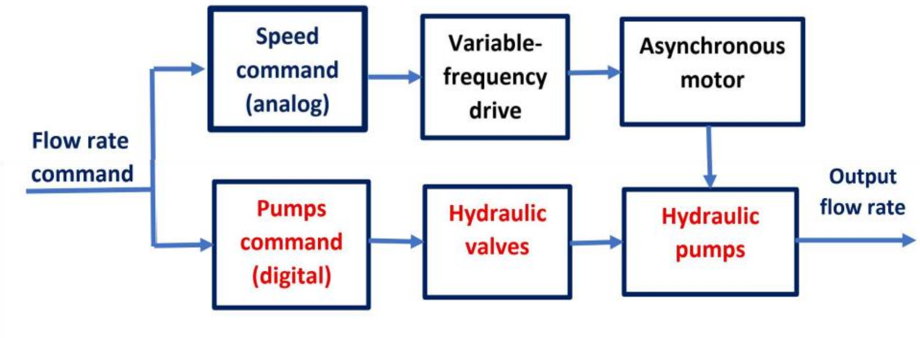

Fig. 2. Block diagram of the electro-hydraulic unit with mixed control [27]

To reduce the amplitude of hydraulic shocks, a hydraulic inductance is proposed to be connected in series with the load of the hydraulic unit.

The bloc diagram of the two proposed control methods for hydraulic drive systems is presented in Figure 2, highlighting the integration between electronic and hydraulic components for optimized performance. Thus, the coarse flow adjustment is performed through digital control, while the fine adjustment is achieved by varying the rotational speed of the electric motor by DDH control [27].

So, by employing N fixed-displacement pumps, with displacements arranged in a geometric progression of ratio 2 and driven by an asynchronous motor operating within a speed range from half the nominal speed to the nominal speed, a continuous flow regulation range from $V_g \cdot \frac{n}{2}$ to $V_g \cdot n \cdot (2^N - 1)$ can be achieved.

Here, V_g denotes the smallest displacement among the fixed pumps, and n represents the nominal rotational speed of the electric motor.

Thus, the flow range is divided into $2 \cdot (2^N - 1)$ equal intervals. For each interval, the two control signals required for the mixed control of the flow rate will be computed: the digital control of the active/inactive hydraulic pumps and the analog control of the asynchronous motor speed [27].

In Figures 3 and 4 are given the algorithms of the control in the C language implementations for both methods of the control for computing the digital and analog control signals based on the desired flow rate value. The case of using four hydraulic pumps is presented, where represents the flow control input, defined over the range [1, 30]. The values of *p0*, *p1*, *p2* and *p3* represent the hydraulic pumps control, where a value of 0 indicates an inactive pump and a value non-zero indicates an active pump. The value of *n* is asynchronous motor speed.

```
//C language implementation

float u;//desired flow rate in the range [1,30) float n;//
motor speed in percent [50%,100%] int
p0,p1,p2,p3;//pumps control

// analog control

// asynchronous motor speed

n= ((u>=1)&&(u<2))?( 50*u):

     ((u>=2)&&(u<4))?( 50*u/2):

     ((u>=4)&&(u<8))?( 50*u/4):

     ((u>=8)&&(u<16))?( 50*u/8):

     ((u>=16)&&(u<30))?( 50*u/15);

//digital control

//hydraulic pumps control
p0=((u>=1)&&(u<2)||(u>=16)&&(u<30));
p1=((u>=2)&&(u<4)||(u>=16)&&(u<30));
p2=((u>=4)&&(u<8)||(u>=16)&&(u<30));
p3=((u>=8)&&(u<16)||(u>=16)&&(u<30));
```

Fig. 3. Algorithm for Method 1

```
// C language implementation

#include <math.h>

float u;//desired flow rate in the range [1,30) float n;//
motor speed in percent [50%,100%] int
p0,p1,p2,p3;//pumps control

// analog control

// asynchronous motor speed

n= (u<16)?( 50*u/floor(u)):(50*u/15);

//digital control

// hydraulic pumps control p0=(floor(u)&1);
p1=((floor(u)&2)>>1); p2=((floor(u)&4)>>2);
p3=((floor(u)&8)>>3);
(u>=16)?(p0=p1=p2=p3=1):(1);
```

Fig. 4. Algorithm for Method 2

3. Flow spike attenuation

Spike reduction will be achieved by implementing a hydraulic inductance in series with the output of the hydraulic unit.

Hydraulic inductance or hydraulic inertance is the resistance to changes in fluid flow rate, analogous to electrical inductance. It is caused by the inertia of the fluid and is quantified by the mass of the fluid in motion and the geometry of the passageway. Just as an electrical inductor resists changes in current, a hydraulic inductor resists changes in fluid flow, requiring a pressure difference to accelerate the fluid.

In fluid mechanics [28], **inertance** is a measure of the pressure difference in a fluid required to cause a unit change in the rate of change of volumetric flowrate with time. The base SI units of inertance are (kg m^{-4}) or (Pa s^2 m^{-3}) and the usual symbol is *I*. The inertance of a pipe is given by:

$$I = \frac{\rho \ell}{A} \tag{1}$$

where: ρ (kg/m^3) the density of the fluid, ℓ (m) is the length of the pipe, A (m^2) is the cross-sectional area of the pipe.

The pressure difference is related to the change in flowrate by the equation:

$$\Delta p = I\dot{Q} = I\frac{\mathrm{d}Q}{\mathrm{d}t} \tag{2}$$

where: Δp (Pa) is the pressure of the fluid, Q (m^3/s) is the volumetric flowrate.
This equation assumes constant density, that the acceleration is uniform, and that the flow is fully developed "plug flow". This precludes sharp bends, water hammer, and so on.
To some, it may appear counterintuitive that an increase in cross-sectional surface of a pipe reduces the inertance of the pipe. However, for the same mass flowrate, a lower cross-sectional area implies a higher fluid velocity and therefore a higher pressure difference to accelerate the fluid.

4. Numerical simulation and results.

Numerical simulations of the proposed algorithms were carried out in MATLAB using Simulink and the Simscape library, which enables modeling of hydraulic drive systems. The simulation scheme of the hydraulic unit is shown in Figure 5. For dynamic behavior, Simscape models were applied; according to MATLAB documentation, these models neglect fluid inertia and spool loading. The electric motor was represented as a first-order system with the transfer function:

$$H(s) = \frac{1}{0.0002s+1} \tag{3}$$

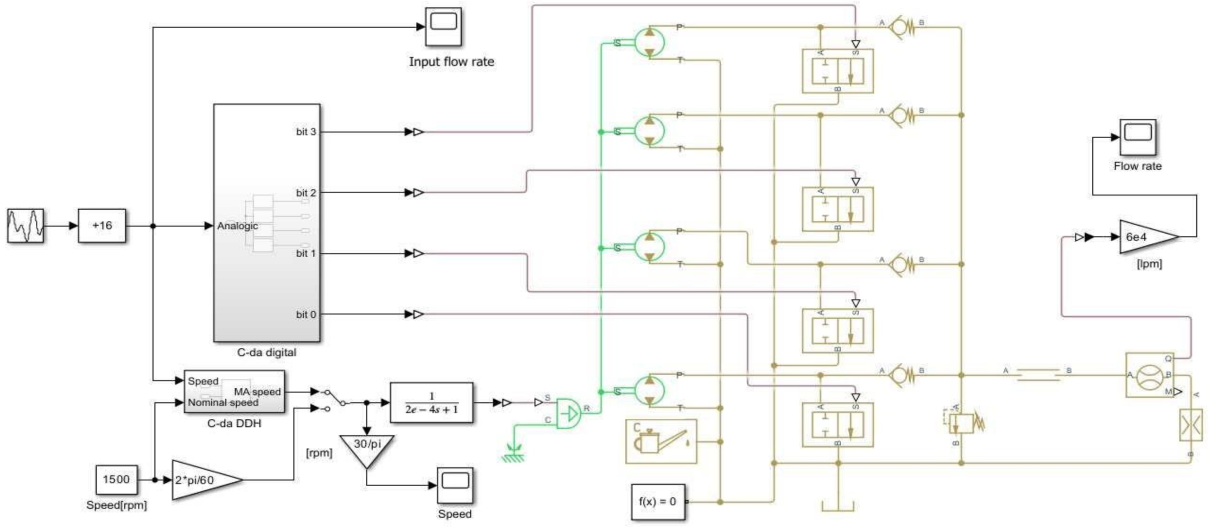

Fig. 5. MATLAB/Simulink/Simscape simulation diagram of the hydraulic unit [27]

The scheme includes a 'C-da digital' block that receives the flow command from a generator and generates control signals for the distributors activating or deactivating four fixed-displacement pumps. The algorithm for 'C-da digital,' implemented in MATLAB/Simulink, is shown in Figure 3 for Method 1 and Figure 4 for Method 2 [27].

The pumps used in the simulation have displacements in geometric progression: 2, 4, 8, and 16 cm³/rev. Driven by an asynchronous motor at a nominal speed of 1500 rpm, their nominal flow rates are 3, 6, 12, and 24 L/min. The minimum flow is achieved by operating the smallest pump at half speed (≈1.5 L/min), while the maximum flow results from all pumps running at nominal speed, respectively: $(2cm^3 + 4cm^3 + 8cm^3 + 16cm^3) \cdot 1500rpm = 45$ L/min [27].

To generate the speed command for the hydraulic pumps, the flow range is divided into 30 equal intervals of 1.5 L/min. For each interval, a control configuration for active and inactive pumps is determined according to the selected method. Additionally, a linear ramp command for motor speed is applied within each interval to ensure smooth variation of total flow. These commands are computed by the ‘C-da digital’ and ‘C-da DDH’ blocks (Figure 5). Continuous flow adjustment from 1.5 to 45 L/min is achieved using two methods, each with specific advantages and limitations, assuming a quasi-static variation of the flow command (Figure 6). Method 1 operates the 2 cm³/rev, 4 cm³/rev, 8 cm³/rev, and 16cm³/rev pumps successively, with a linear increase in speed from 750 rpm to 1500 rpm. Finally, all the pumps are operated simultaneously, also with a linear speed increase from 750 rpm to 1500 rpm (see Figures 7 and 8) [27].

Method 2 activates pumps based on the binary representation of numbers from 1 to 15. Within each interval, speed varies from 750 rpm to a value that ensures a linear, continuous increase in flow according to the command. In the upper half of the range, pump control follows the same logic as Method 1 (Figures 11 and 12). The motor speed command is computed by the ‘C-da DDH’ block, using the input flow command and the algorithm shown in Figure 4.

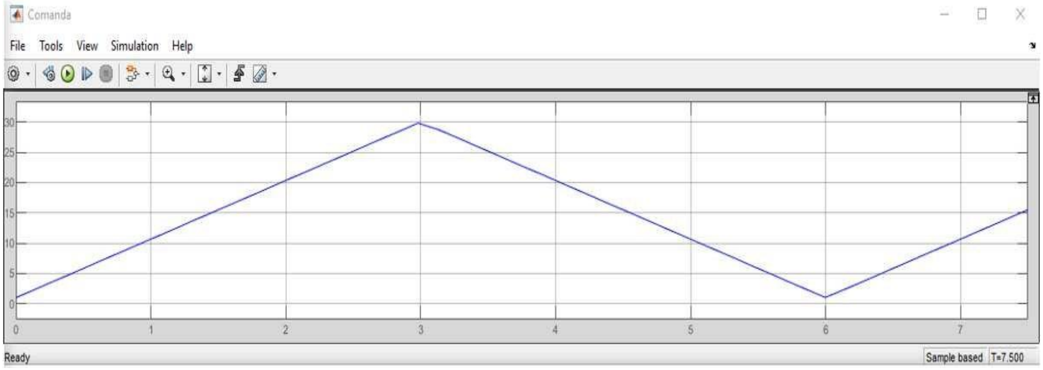

Fig. 6. Flow command: time (s) on the *X*-axis, desired flow on the *Y*-axis [27]

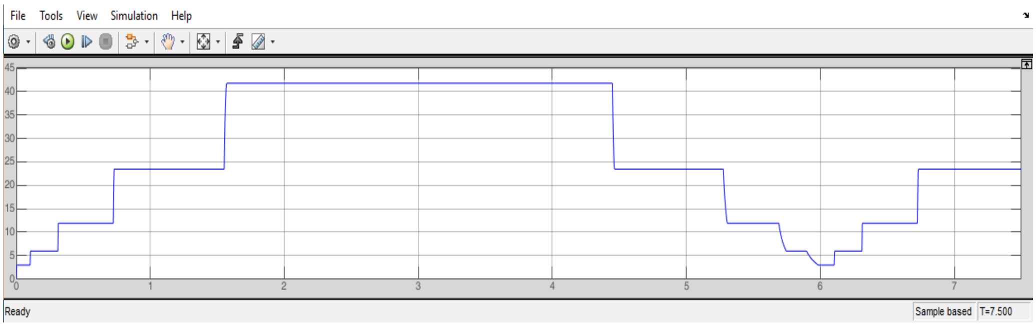

Fig. 7. Flow with digital control, Method 1 [27]

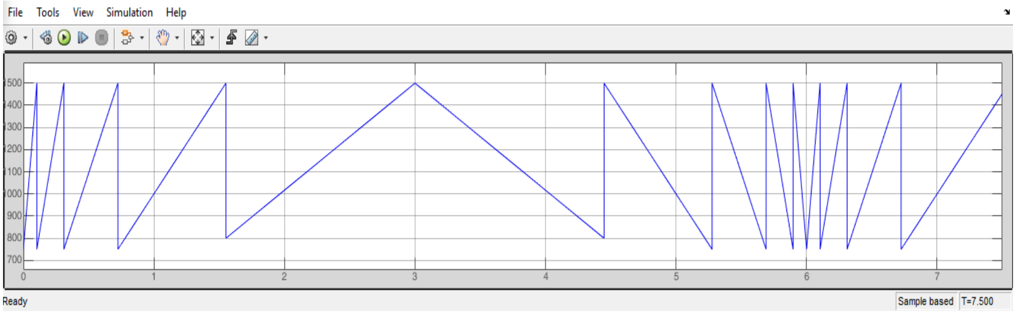

Fig. 8. Motor speed control, Method 1 [27]

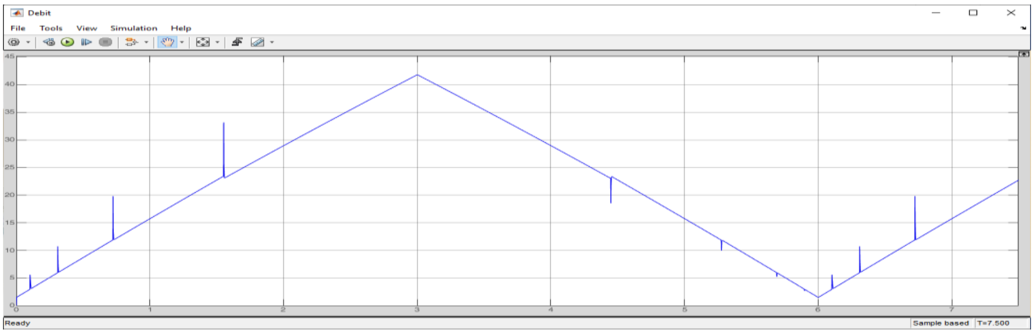

Fig. 9. Flow delivered by the hydraulic unit, Method 1 [27]

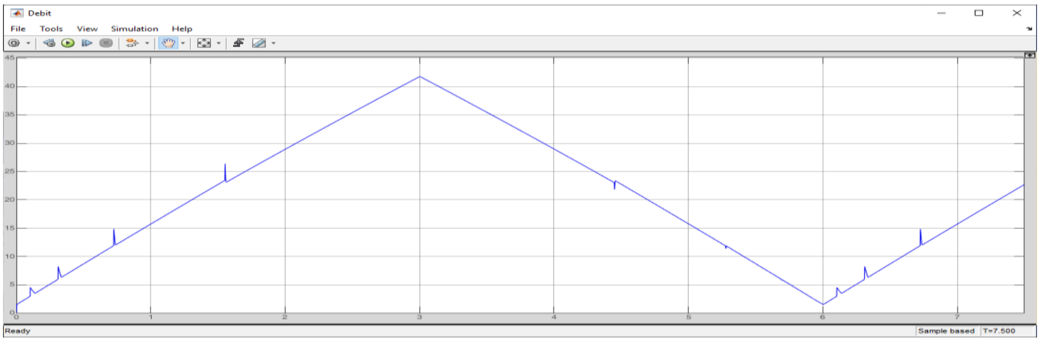

Fig. 10. Output flow with spike reduction, Method 1

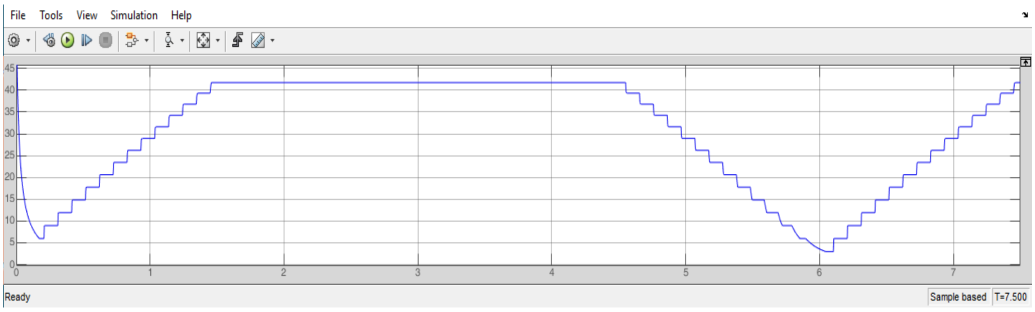

Fig. 11. Flow with digital control, Method 2 [27]

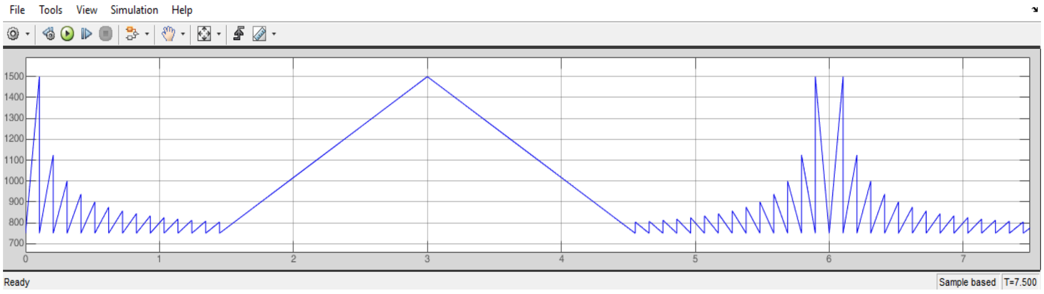

Fig. 12. Motor speed control, Method 2 [27]

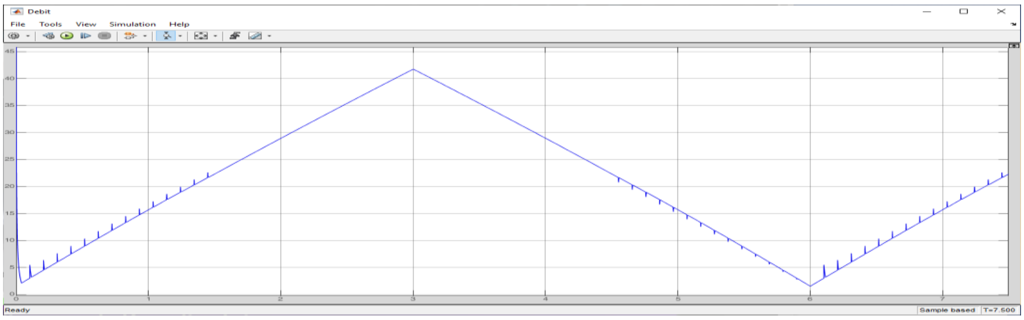

Fig. 13. Flow delivered by the hydraulic unit, Method 2 [27]

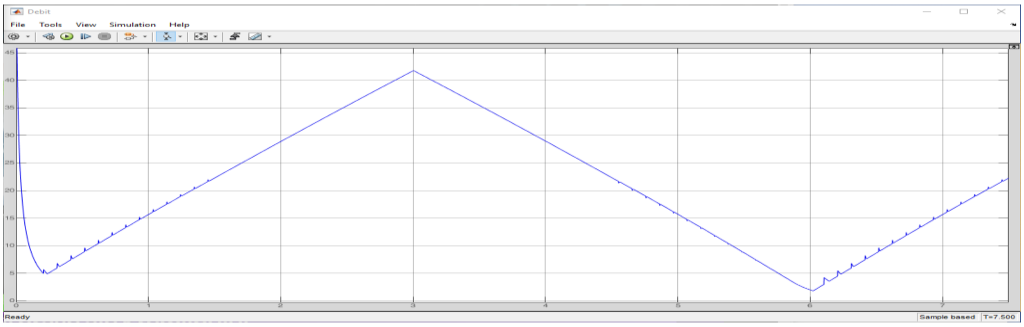

Fig. 14. Output flow with spike reduction, Method 2

In figures above, time (in seconds) is plotted along *x*-axis, and flow rate (in L/min) along *y*-axis.

When applying to both commands, digital and analog, simultaneously, the time variation of the delivered flow is shown on Fig. 9 and Fig. 13. Thus, Method 1 uses four pump switching events across the flow range (Fig. 9), while Method 2 requires fifteen switching events. (Fig. 13).

Regarding motor speed control: in Method 1, motor speed varies between 50% and 100% for each pump configuration.

In Method 2, motor speed for a given pump configuration varies within 50% and $\frac{x}{[x]}\cdot 50\%$, where x is the desired flow rate, ranging from 1 to 15.

The hydraulic inductance was implemented using a circular pipe 3 m in length and 4 mm in diameter. The results obtained using the hydraulic inductance to filter flow spikes are shown in Fig. 10 for Method 1 and in Fig. 14 for Method 2.

Depending on the application of the electro-hydraulic unit, Method 1 or Method 2 can be chosen: the first method provides fewer pump switching but larger hydraulic shocks, whereas the second method involves more frequent switching with lower-amplitude shocks.

Regarding the selection of the hydraulic unit control method based on the application: Method 1, which generates significant amplitude shocks, is suitable for driving high-inertia loads, as load's inertia helps dampen the spikes – for example, hydraulic traction system for locomotives. Method 2 is more appropriate for low-inertia loads, such as hydraulic positioning systems or servomotors.

4. Conclusions

This paper is the development of paper [27] regarding the reducing amplitude of hydraulic shocks generated by the dynamic behavior of a controlled hydraulic drive system.

Two solutions for generating hydraulic flow proportional to a commanded input are proposed, combining digital and direct-drive hydraulics. Mathematical models were developed and validated through numerical simulations to assess performance, including:

- operating flow range (Q…30Q, i.e., 3.33%–100%);
- magnitude of shocks from pump switching;
- methods to reduce shock amplitude using hydraulic inertance.

To further reduce hydraulic shocks, a series hydraulic inductance was introduced.

Algorithms were designed to convert flow commands into pump activation signals and motor speed control, implemented via a dedicated software application. Future work will include dynamic analysis and experimental validation under static and dynamic conditions.

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