DIGITAL PUMPING UNIT WITH GEAR PUMPS USE TO PROVIDE THE FLOW REQUIRED FOR MOBILE EQUIPMENT WITH HIGH ENERGY EFFICIENCY

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UNITATE DIGITALĂ DE POMPARE CU POMPE CU ROŢI DINŢATE UTILIZATĂ PENTRU FURNIZAREA DEBITULUI NECESAR ECHIPAMENTELOR MOBILE CU EFICIENŢĂ ENERGETICĂ MARE

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ABSTRACT

In this article, the authors want to present the benefits of digital hydraulics, by presenting a Digital Hydraulic Pumping System (DHPS), consisting of 4 fixed flow pumps, driven by a biaxial electric motor, 4 3/2 on/off electrohydraulic directional valve, 4/2 types electrohydraulic directional valve and a bidirectional hydraulic motor. With the help of a micro-controller, the 4 3/2 electrohydraulic directional valve, which independently control the output of each pump, are operated in a certain sequence, so that a regulation of the flow provided in the system in 15 discrete points is obtained. Due to the construction of the 3/2 electrohydraulic directional valve (electrohydraulic directional valve with port P to T), but also of the microcontroller, a variation of the flow supplied in the system with low energy losses is obtained. This system is designed within the digital hydraulics laboratory of the INOE 2000-IHP Research Institute, in order to obtain preliminary results, which will also lead to its physical realization. The article contains the results obtained by numerical simulation of using Digital fluid power technology in the field of hydraulic drives, systems which have advantages such as: the use of simple, robust components with a high degree of flexibility and programmability.

REZUMAT

În acest articol, autorii prezintă avantajele hidraulicii digitale, prin prezentarea unui sistem hidraulic de pompare, format din 4 pompe de capacitate fixa, antrenate de un motor electric biaxial cu turație constantă, 4 electrodistribuitoare 3/2 de tip on/off, un electrodistribuitoare de tip 4/2 și un motor hidraulic bidirecțional. Cu ajutorul unui micro-controler, cele 4 electrodistribuitoare 3/2, care controlează independent refularea fiecărei pompe, sunt acționate într-o anumită secvență, astfel încât se obține o reglare a debitului furnizat în sistem cu 15 valori discrete. Datorită construcției electrodistribuitoarelor 3/2 (distribuitoare cu portul P la T), dar și a microcontrolerului, se obține o modificare a debitului furnizat în sistem cu pierderi mici de energie. Acest sistem este proiectat în cadrul Laboratorului de hidraulică digitală al Institutului de cercetare INOE 2000-IHP, în vederea obținerii unor rezultate preliminarii, care vor conduce și la realizarea fizică a acestuia. Articolul cuprinde rezultatele obținute prin simulare numerică privind sistemele de pompare digitale în domeniul acționărilor hidraulice, sisteme care prezintă avantaje precum: utilizarea unor componente simple, robuste și cu un grad mare de flexibilitate și programabilitate.

INTRODUCTION

The development of electro-hydraulic servo-control components was based on a continuous improvement of their technical performances. The next stage of the hydraulics development process came with the introduction of microelectronics, making microprocessors and sensors integration in the hydraulic equipment, thus increasing the accuracy of dynamic control, feedback and reliability of the control unit *(Ioan et al. 2017).* At the beginning of the 21st century, increased production costs and the global context of reducing energy losses have forced industry and research teams to develop energy-efficient and reliable hydraulic components.

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In recent years, the main problem in the field of hydraulics has been how to reduce energy losses and reduce CO_2 emissions. Numerous studies conducted in recent years have shown that hydraulic systems are high energy consumers, resulting in almost 30% of its energy is dissipated in the form of heat *(Scheidl et al., 2013).* Generally, more than half of the output power of hydraulic pumps or motors is dissipated to spool valve or the pressure release valve.

With the introduction of "Industry 4.0" according to *Brandstetter et al., (2017),* the industrial system has put forward higher requirements for intelligent hydraulic systems and their applications. So, it can be said that if it is desired that the hydraulics survive after this market competition, the direction towards a high efficiency and low prices will be an inevitable direction to follow. Here digital hydraulics comes to provide a feasible way to achieve this goal (*Heitzig et al*, *2012).* An approach with a high potential for success has proven to use the concept of digital *hydraulics.*

The concept of digital hydraulics was theoretically presented many years in a row by renowned researchers such as Rudolf Scheidl, Matti Lindjama and others, but applied research could have begun a few years ago with the emergence of advances in electronics *(Qiwei et al., 2020, Viktor et al, 2020).*

According to *Scheidl et al*., (2012*)* the digital hydraulics it is superior over analog technology in areas as efficiency and standardization of components.

The concept of digital hydraulics is based on several principles *(Drumea et al, 2016):*

- Active control of system outputs;
- Use of on/off type directional valve;
- Smart control.

Digital hydraulics has a considerable advantage over the classic one in directions such as efficiency, redundancy, but also the standardization of components. Studies have shown that digital hydraulics can reduce energy loss compared to servo-control systems.

The authors simulated a drive diagram of a digital hydraulic pumping system for driving a rotary hydraulic motor. Having as possible applications: driving the drum of an elevator, a winch or a crane. The simulated scheme is composed of usual devices, unpretentious regarding the quality of the oil, these not needing a high degree of filtration unlike the proportional hydraulic devices. The system has a good energy efficiency due to the on / off valves that do not create hydraulic resistance when actuated. Reducing in this way the loss of energy transformed into heat (*Merill et al., 2011).*

The authors *Locateli et.al.*, *(2014)* approached a solution of this type for a hydraulic system with linear motor are presenting three operation methods (pump mode, motor mode and idle mode), which allows discrete valves to replace continuous or flow control valves in order to control the actuator. A variable displacement pump with large displacement is replaced by several small, fixed displacement units.

There are two independent methods for implementing DHPS, one of them is based on direct control of the pistons (in the case of radial hydraulic pumps or motors) or, as in our case, on a flow variation using the output control of fixed flow pumps *(Luke Wadsley, 2011).*

In this paper we approached the version with 4 pumps from which we can obtain 15 flow variations which was simulated with the help of the AMESim program, obtaining tables of flows, pressures and speeds of the hydraulic motor, showing in this way that the variable flow can be achieved with fixed pumps and low energy consumption.

MATERIALS AND METHODS

Parallel digital hydraulics involves the parallel connection of two or more hydraulic equipment and is based on a coding system, Pulse Code Modulation (PCM). PCM refers to the coding of equipment using either binary series, 2, 4, 8, 16… etc. practical 2^n, where "n" is the number of components that make up the system. *(Mantovani et al., 2020)*

Presentation of the system sketch

The hydraulic diagram of the DHPS (**D**igital **H**ydraulic **P**umping **S**ystem) is presented in figure 1, which is based of 4 pumps with fixed geometric displacement driven by an electric motor with constant speed of 1500 rpm. The pump geometric displacement is chosen in binary progression resulting as follows: P1 = 2 cm^3/rev, P2 = 4 cm^3/rev, P3 = 8 cm^3/rev, P4 = 16 cm^3/rev.

The total flow control can be performed for the version with 4 pumps in 15 stages, according to the binary progression. The total displacement of the pumps varies in multiples of 2 cm^3/rev and their capacity from 2 to 30 cm³/rev. With the help of a controller, we can get 15 steps of flow values between 3 and 45 l/min with one step of 3 l/min. The flow in l/min results at a speed of the electric motor of 1500 rpm.

In the composition of the hydraulic diagram of DHPS we have: 4 pumps with fixed geometric displacement P1-P4, binary coded, DV1-DV4 on/off type electrohydraulic directional valves that control the output of each pump and which have the hydraulic scheme P to T on idle position, CV1-CV4 check valves, FM flow meter to be able to measure the flow resulting from DHPS, a PT pressure transducer, the HM hydraulic motor, a torque and speed transducer attached to the HM hydraulic motor shaft, the return filter F and the tank of hydraulic oil T. The command logic of the electrohydraulic directional valves for binary flow progression is performed by a controller. For such a pumping unit a PLC can be used or a dedicated controller can be developed with the help of a microcontroller.

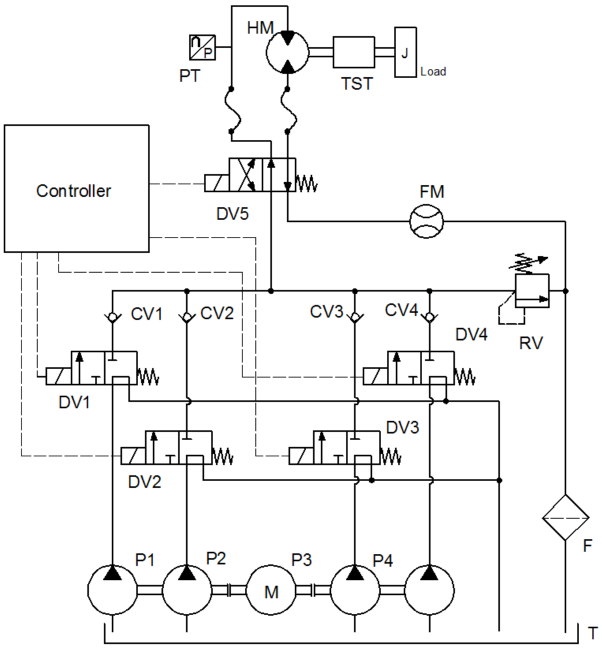

Fig. 1 - The hydraulic diagram of the pumping unit with 4 gear pumps

Modeling the drive system

The hydraulic circuit was modeled in AMESim. The hydraulic components have the sub-models in table 1 and the parameters value are shown in table 2.

Table 1

Component	Sub-model
Pump	PU001
Directional valve 3/2	HSV23_01
Directional valve 4/2	HSV24_01
Dynamic time table	SIGUDA01
Hydraulic motor	MO001
Pressure control	RV010

Table 2

Parametres		
Hydraulic Hose	**Directional valve (2/3)**	**Relief valve**
Pressure 1.013 bar	Flow rate 20 l/min	Cracking Pressure 250 bar
Diameter 10 mm	Pressure drop (ΔP) 5 bar	
Length 2,5 mm		
Hydraulic pipe	**Directional valve (2/4)**	**Hydraulic Motor**
Diameter 10 mm	Flow rate 50 l/min	Motor Displacement 30 cm³/rev
Length 0.1 m	Pressure drop (ΔP) 5 bar	Coefficient of viscos friction 0.035 Nm/(rev/min)

The hydraulic pipes are modeled with the HL0000 sub-models, and the hoses are modeled with the HL0001R sub-model. The configured parameters for pipes and hoses are the nominal diameter and length. The system simulation sketch is presented in figure 2.

There are 4 directional valve 3/2 type that control the output of each pump and 4/2 types directional valve that controls the direction of rotation of the hydraulic motor. The electrohydraulic directional valves in the simulation have proportional valve sub-models, but in this case, they are controlled with maximum ON/OFF signal. Static models have been adopted for electrohydraulic directional valves. The system safety valve has been set to 250 bar.

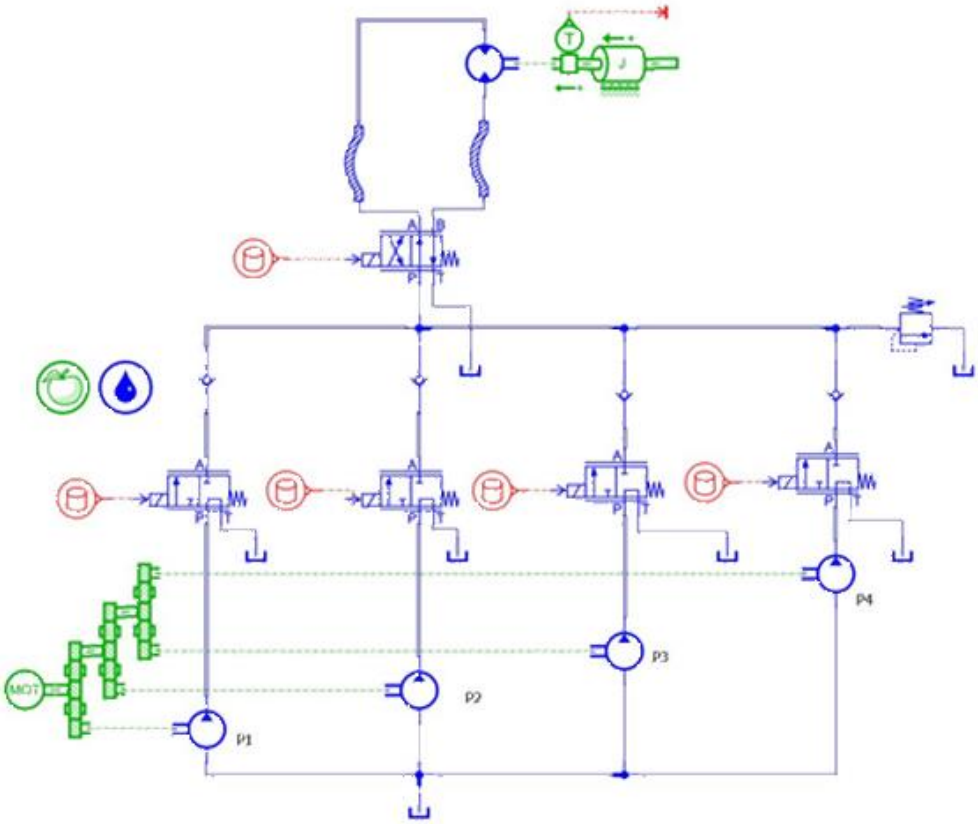

Fig. 2 - Simulation sketch

The bidirectional hydraulic motor with a geometric displacement of 30 cm^3/rev is connected with a friction centrifugal load. The sub-model for centrifugal friction load has as parameters the moment of inertia and a viscous friction coefficient.

Figure 3 shows the flows obtained and how they are obtained. The black hatched boxes represent the active pumps that send hydraulic fluid to the main line and the white boxes represent the pumps that send the hydraulic fluid to the tank with low energy losses. In the figure can be seen the status of the actuation signal for each directional valve connected one by one to the 4 pumps of the system.

Command step		OFF	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
P1	2 cc		■		■		■		■		■		■		■		■
P2	4 cc			■	■			■	■			■	■			■	■
P3	8 cc					■	■	■	■					■	■	■	■
P4	16 cc									■	■	■	■	■	■	■	■
Total Vg (cc)		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30

Fig. 3 - Variation of the total capacity of the pumps (Vg) for the 15 stages

Table 3 contains the parameters for dynamic time table used to control the valves during the simulation.

Table 3

	Dynamic time table for P1 valve command		**Dynamic time table for P2 valve command**		**Dynamic time table for P3 valve command**		**Dynamic time table for P4 valve command**		**Dynamic time table for motor valve command**	
	X	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**
1	0	0	0	0	0	0	0	0	0	0
2	1	0	5	0	13	0	29	0	65	0
3	1.01	40	5.01	40	13.01	40	29.01	40	65.01	40
4	5	40	13	40	29	40	65	40	70	40
5	5.01	0	13.01	0	29.01	0	65.01	40		
6	9	0	21	0	45	0				
7	9.01	40	21.01	40	45.01	40				
8	13	40	29	40	65	40				
9	13.01	0	29.01	0						
10	17	0	37	0						
11	17.01	40	37.01	40						
12	21	40	45	40						
13	21.01	0	45.01	0						
14	25	0	53	0						
15	25.01	40	53.01	40						
16	29	40	65	40						
17	29.01	0								
18	33	0								
19	33.01	40								
20	37	40								
21	37.01	0								
22	41	0								
23	41.01	40								
24	45	40								
25	45.01	0								
26	49	0								
27	49.01	40								
28	53	40								
29	53.01	0								
30	57	0								
31	57.01	40								
32	61	40								
33	65	40								

Figure 4 shows the chart of time dynamics table for the control of the electrohydraulic directional valves that introduces in the circuit the P1 pump. The step of the control is at 4 s, and the total simulation time is 70 s. Each 3/2 directional valve is controlled by a dynamic time table sub-model according to the binary combination shown in figure 3.

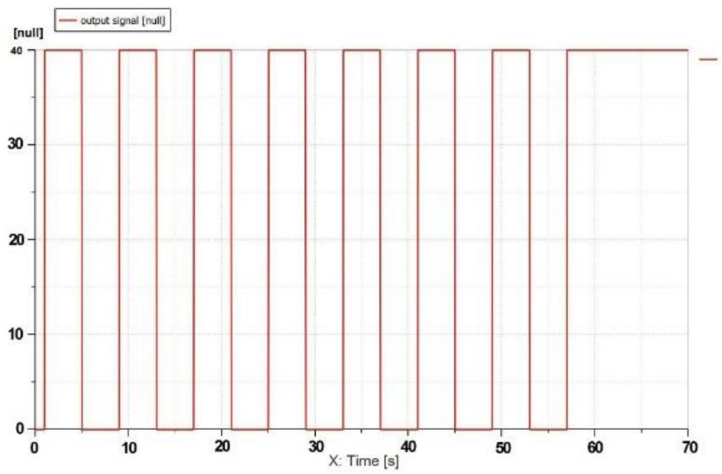

Fig. 4 - Command signal for directional valve of pump 1

In table 4 we can see the pumps that are operated, the resulting displacement, the flow provided in the system and the necessary power of the electric motor for each combination of pumps. For calculating the system flow and power in the table, the speed of the electric motor driving the pumps is 1500 rpm and the operating pressure is 315 bar.

Table 4

No.	Pump combination	Displacement [cm^3/rev]				Total displacement [cm^3/rev]	System flow [l/min]	Max power [kW]
		Vg4	Vg3	Vg2	Vg1			
1	Vg1				2	2	3	2
2	Vg2			4		4	6	4
3	Vg1+Vg2			4	2	6	9	6
4	Vg3		8			8	12	8
5	Vg3+Vg1		8		2	10	15	10
6	Vg3+Vg2		8	4		12	18	12
7	Vg3+Vg2+Vg1		8	4	2	14	21	14
8	Vg4	16				16	24	16
9	Vg4+Vg1	16			2	18	27	18
10	Vg4+Vg2	16		4		20	30	20
11	Vg4+Vg2+Vg1	16		4	2	22	33	22
12	Vg4+Vg3	16	8			24	36	24
13	Vg4+Vg3+Vg1	16	8		2	26	39	26
14	Vg4+Vg3+Vg2	16	8	4		28	42	28
15	Vg4+Vg3+Vg2+Vg1	16	8	4	2	30	45	30

RESULTS

The simulation results for the 4-pump digital system can be found in the following figures. The simulation consisted in obtaining the response for flow, pressure, motor speed and torque at the motor shaft by generating control signals so as to obtain the 15 combinations of pump displacement. The control steps occur at an interval of 4 sec. After reaching the maximum capacity, a reversal of the motor through the 4/2 electrohydraulic directional valve is also ordered.

Each command step is followed by pressure oscillations that are damped in ~ 2 sec, and the flow response oscillations are damped in about 1 sec. (fig. 5).

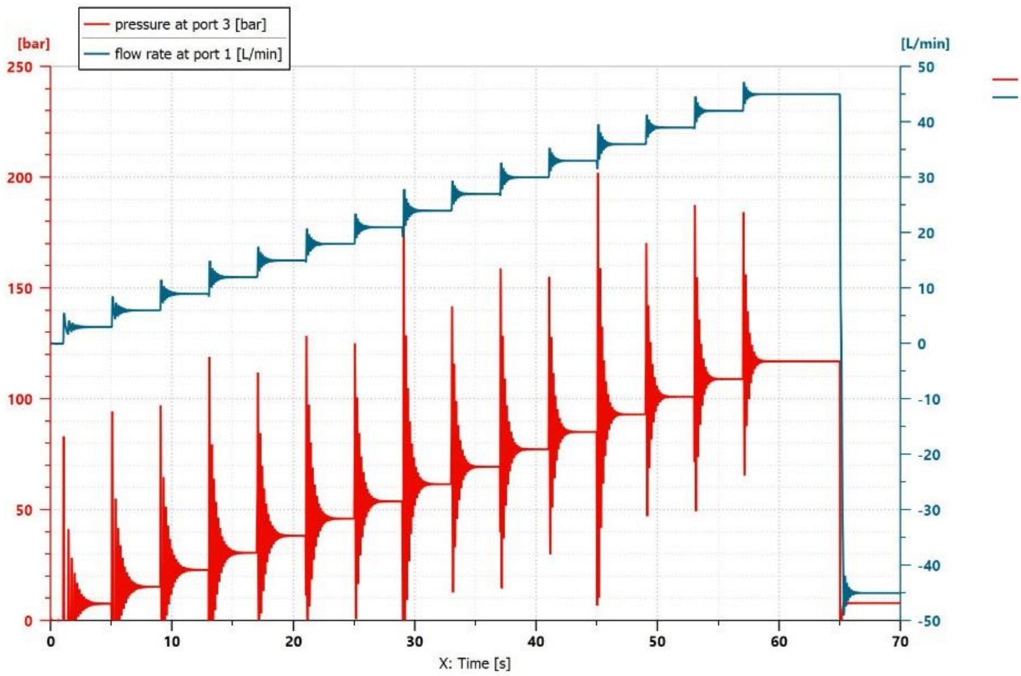

Fig. 5 - Pressure and flow rate at input port of the hydraulic motor

The speed and torque answers in fig. 6 follow the allure of the response diagrams for flow and pressure.

At the preliminary simulations the oscillations were even bigger, and for their reduction the length of the hoses to the hydraulic motor was increased from 1 m to 2.5 m.

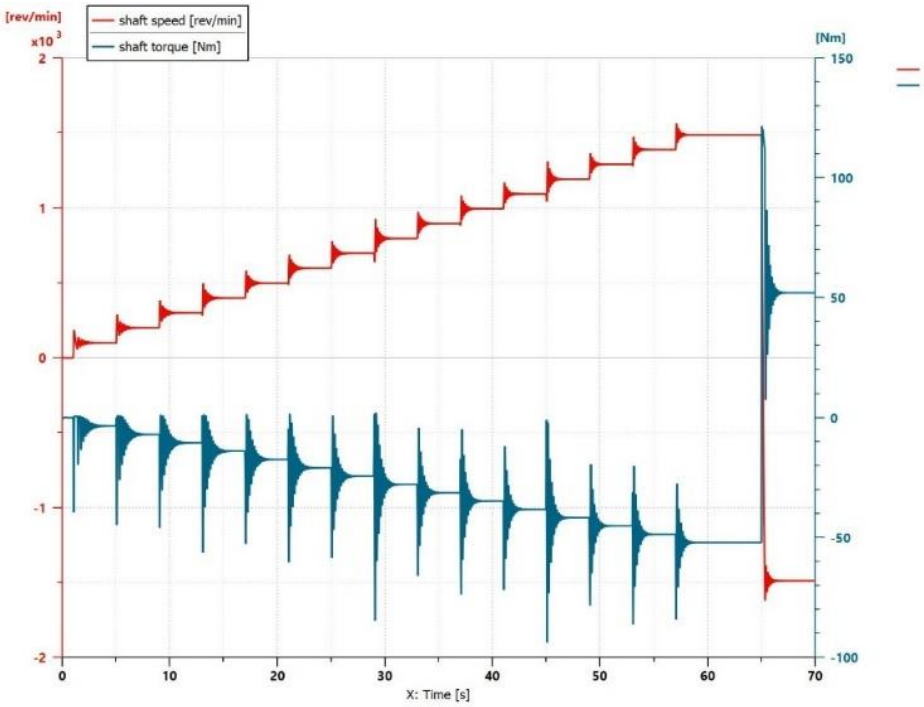

Fig. 6 - Hydraulic motor shaft speed and torque

CONCLUSIONS

- Following numerical simulations, a pressure variation could be observed at the moment of opening the electrohydraulic directional valve. In pressurized networks, static or dynamic events at a certain point affect all components of the system. Consequently, numerical simulation models must consider each pipe that is connected to a pressurized system.
- This pumping unit can be used to gradually adjust the speed of a linear or rotary hydraulic motor using a controller made with a microcontroller or an industrial PLC can be used.
- The DHPS cand be sucessfully used in aplications, where the flow control is needed.
- In a future work will be tried strategies to minimize or eliminate the amplitude and damping period of the pressure peaks, produced by switching the electrohydraulic directional valves.
- Based on the results obtained from these simulations, an experimental test stand for such equipment will be built.

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