Research on the assessment of flow and pressure pulses in oscillating hydraulic intensifiers

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Abstract:

Some mining activities, such as interventions in the event of accidents, are carried out in narrow spaces, using small (single- or double-acting) hydraulic cylinders to obtain high static (press and squeeze) or dynamic (push and pull) forces. The opposite load of these forces can occur: at the end of the advance stroke; on the entire advance stroke; on both directions. There are two types of pumping units for these cylinders: units with positive displacement pumps and high-pressure hydraulic components, units with positive displacement pumps and low-pressure hydraulic components, plus oscillating pressure intensifiers (miniboosters). The second type, which generates high pressures with low-pressure systems, has the following advantages: lower price, higher energy efficiency and operational safety. The manufacturers of miniboosters do not specify the amplitude and frequency of pulses of pressure oscillators. In order to use these hydraulic pressure intensifiers in dynamic applications specific to mining activities, under conditions of maximum safety, the authors propose a solution for a test stand on which one can determine: flow and pressure pulse characteristics, their influence on the uniform displacement of the load of hydraulic cylinders supplied by pumping units equipped with miniboosters, functional characteristics, in dynamic and stationary modes, of pumping units with embedded miniboosters.

Streszczenie:

Niektóre prace górnicze, takie jak akcja ratunkowa, są wykonywane w wąskich przestrzeniach, przy użyciu małych siłowników hydraulicznych (jednostronnego lub dwustronnego działania), w celu uzyskania dużych sił statycznych (naciskających i ściskających) lub dynamicznych (pchających i ciągnących). Przeciwny zwrot tych sił może wystąpić: po całkowitym wysunięciu tłoczyska; przy dowolnym wysunięciu tłoczyska przy przemieszczaniu tłoczyska w obu kierunkach. Istnieją dwa typy zespołów pompujących dla tych siłowników: z pompami wyporowymi i wysokociśnieniowymi elementami hydraulicznymi, z pompami wyporowymi i niskociśnieniowymi komponentami hydraulicznymi oraz oscylacyjnymi wzmacniaczami ciśnienia (miniboostery). Drugi typ, który generuje wysokie ciśnienia za pomocą systemów niskociśnieniowych, ma następujące zalety: niższa cena, wyższa efektywność energetyczna i bezpieczeństwo eksploatacji. Producenci minibosterów nie określają amplitudy i częstotliwości impulsów oscylatorów ciśnienia. Aby zastosować te hydrauliczne wzmacniacze ciśnienia w dynamicznych zastosowaniach specyficznych dla działalności górniczej, w warunkach maksymalnego bezpieczeństwa, autorzy proponują koncepcję stanowiska badawczego, na którym można określić: charakterystyki pulsacji przepływu i ciśnienia, ich wpływ na równomierny rozkład obciążenia siłowników hydraulicznych zasilanych przez agregaty pompowe wyposażone w minibostery, charakterystykę funkcjonalną w trybie dynamicznym i stacjonarnym zespołów pompowych z wbudowanymi miniboosterami.

1. Introduction

The main research issues are related to experimental testing of stationary and dynamic operation of hydraulic pumping units that integrate in their structure oscillating hydraulic pressure intensifiers, minibooster type. The aim is to create a test stand that includes a test cylinder supplied by a pumping unit with embedded minibooster and a load cylinder supplied by a low-pressure pumping unit with

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proportional pressure valve, which will allow to determine: the stationary flow rate /pressure characteristic in the secondary circuit of the booster, to linear variation of the load of the hydraulic test cylinder, performed by a ramp signal applied to the proportional valve within the supply unit of the load cylinder; the booster response to a pressure step signal applied to the proportional valve within the supply unit of the load cylinder; the amplitude/frequency of flow pulses in the secondary circuit of the booster, and their impact on the uniform displacement of the test cylinder, at constant load, over the entire stroke.

The main objective of the work is to expand the technical applications of hydraulic cylinders with small dimensions and high forces to mining activity, under conditions of maximum safety.

The methodology used in solving the problems specific to this objective comprises six stages, of which the last two will be the topic of a future paper; they are: documentation on the structure and operation of minibooster type oscillating hydraulic pressure intensifiers; preliminary numerical simulation of pulses generated by a minibooster; selecting a minibooster in order to integrate it into a low-pressure pumping unit (LPPU); determining the functional hydraulic schematic diagram of the stand on which one conducts experimental tests on a LPPU; *determining the test methodology for a LPPU (future task); developing the stand, performing experimental tests on the LPPU and completing the numerical simulation model (future task).*

2. Structure and operation of oscillating hydraulic pressure intensifiers

Hydraulic pressure amplifiers with oscillating pistons [1, 2, 3, 4, 5, 6, 7, 8, 9, 10] are known in the literature under several names: oscillating hydraulic pressure amplifiers, oscillating pumping units, pressure intensifiers, boosters, miniboosters (miniBOOSTER Hydraulics).

The oscillating hydraulic pressure intensifier (OHPI) is used to generate higher pressure using a low-pressure hydraulic power source. Considering the high-pressure flow pulses, OHPIs can be single-acting, SAOHPIs (higher pulsations; they pump on a single direction of piston movement) or double-acting, DAOHPIs (lower pulsations; they pump on both directions of piston movement).
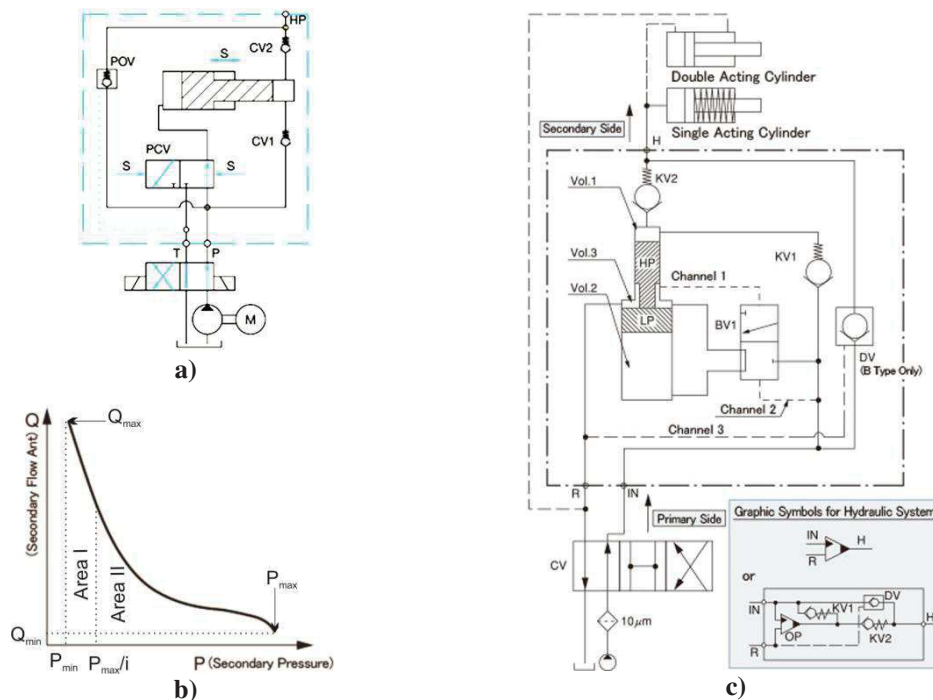
The basic structure of an SAOHPI, Fig. 1.a, includes: an assembly of two pistons of different diameters, connected by a rod; a bistable piston distribution valve (Piston Control Valve), PCV; two Check Valves, CV1 and CV2; a Pilot Operated check Valve, POV. The position of the pistons will determine, at the end of each stroke, a signal S to the PCV, which will cause a change in the direction of piston travel. This "pulsating" cycle of piston movement, with a maximum frequency of 20 Hz [11], lasts until the end pressure is reached, after which the pistons stop. Further, they will only move to maintain the end pressure.

The operating principle of an SAOHPI, Fig. 1a), is as follows: a large fluid volume and low pressure pushes a large diameter piston, which is in contact with another piston, of small diameter; as an effect of this action, the small diameter piston will push a small volume of fluid, with high pressure, HP, equal to the low pressure amplified by the ratio of piston surfaces. The high pressure, HP, will always be proportional to the supply pressure of the large piston.

The flow rate / pressure characteristic of an SAOHPI, Fig. 1b), includes two areas: area I ($p=p_{min}...p_{max}/i$; i=intensification factor), in which the fluid coming out of the pump, with high flow and low pressure, continuously supplies the consumer hydraulic motor through the secondary side of the amplifier, allowing it to operate quickly in the desired direction; area II ($p=p_{max}/i...p_{max}$), in which the consumer hydraulic motor will be supplied with low pulsating flow, by means of the high-pressure piston, until the maximum pressure of the intensifier, HP, is reached.

An SAOHPI (minibooster), embedded in a low-pressure hydraulic pumping unit, can supply a single-acting or double-acting hydraulic cylinder type consumer, Fig. 1c), or a rotary hydraulic motor (not shown in the figure). It comprises: a low-pressure piston, LP; a high-pressure piston, HP; a bistable distribution valve, BV1, with hydraulic control through the pilot channels 1 and 2, intended to change the direction of travel of the pistons; a deblockable check valve (optional), DV, controlled through the pilot channel 3, intended to discharge the high-pressure oil from the consumer chamber.

In the simplified functional diagram of the minibooster, the pistons LP and HP along with the bistable distribution valve BV1 are included in the simplified symbol of the pressure oscillator OP.

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Fig. 1. Structure and operation of the SAOHPI: a) operating principle [12]; b) flow rate / pressure characteristic [13, 14]; **c)** functional diagram of a pumping unit equipped with SAOHPI [13, 14]

In operating phase I, the low-pressure pump sends the hydraulic fluid, at system pressure, to the port IN; the liquid flows freely through the valves KV1, KV2, DV and the port H. All pump flow passes through the port H, and the cylinder supplied by the SAOHPI moves fast forward.

In phase II, the load of the hydraulic cylinder equals the force given by the pump pressure; the valves KV2 and DV close, and the fluid is directed to volume 1. The bistable valve BV1 discharges volume 2 to the tank through volume 3. As the pump pressure is applied to volume 1, the pistons move downwards.

When the pistons have completely moved downwards, the pilot channel 1 is supplied with pressure, and the bistable valve BV1 changes its position; as a result, the pump will discharge fluid under low pressure in volume 2, and the small piston, pushed by the large one, will move upwards, delivering high-pressure fluid to the consumer.

Once the high-pressure piston HP has moved upwards, the pilot channel 1 connects to the tank, and the bistable valve BV1 returns to its original position. The cycle is repeated until the maximum pressure required for the hydraulic cylinder (the supply pressure amplified by the ratio of piston surfaces) is reached at port H.

The end pressure from the consumer can be discharged through the deblockable check valve DV. To do this, one shall connect port R to the pump supply pressure and port IN to the tank; the pilot channel 3 will be pressurized, allowing the fluid from the high-pressure side of the amplifier, H, to flow back into the tank.

The directional control valve CV in Fig. 1.c, four-port three-position (4/3), controls the direction of travel of the driven cylinder (left position = advance; right position = retraction; center position = stationary).

3. Preliminary numerical simulation of pulses generated by a minibooster

The numerical simulation model in Fig. 2 has the following components:
- a low-pressure pumping unit, with 9.43 cc / rev and 1500 rev / min fixed-displacement pump, pressure-control valve, with maximum opening pressure set to 20 MPa;

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- a single-acting oscillating hydraulic pressure intensifier (SAOHPI), minibooster type, with low-pressure piston diameter of 16 mm, high-pressure piston diameter of 6.42 mm and the stroke of the assembly of the two pistons (with inertial mass) of 80 mm. The piston distribution valve (PCV) is simulated by the hydraulic component 3/2 proportional directional control valve. The intensifier also contains the two check valves, equivalent to CV1 and CV2 in Fig.1a). The deblockable check valve (POV in Fig.1a) is optional in the structure of a minibooster. For this reason and in order to simplify the simulation model, it was omitted;
- a single-acting hydraulic cylinder, represented by the hydraulic component single-acting hydraulic cylinder with spring return, stroke of 200 mm, inertial mass and ramp load.

    To measure the parameters of interest of the system - hydraulic and mechanical - the simulation model also includes six transducers: three flow transducers and one for each of the following parameters: pressure, speed and force.
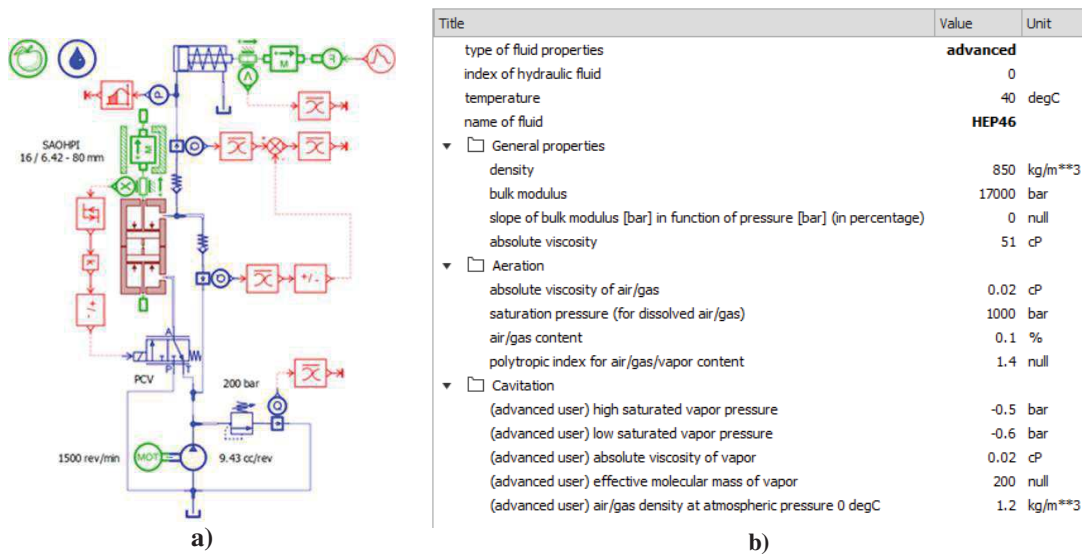

a)   b)

Fig. 2. Numerical simulation model, developed in Simcenter Amesim, for a low-pressure pumping unit equipped with SAOHPI: a) simulation model; b) fluid properties
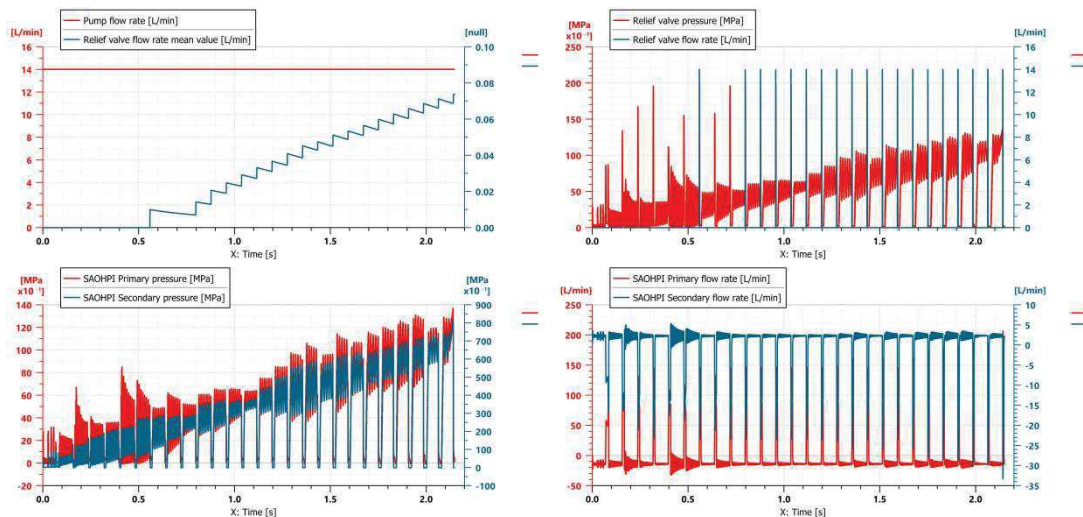

Fig. 3. Comparative time variation of: pump flow rate and valve flow rate (top left); pressure rates in the primary side and secondary side of the SAOHPI (bottom left); valve inlet pressure and valve flow (top right); flow rates in the primary side and secondary side of the SAOHPI (bottom right)

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Following the simulations performed on the model in Fig. 2, equivalent to the simplified structure and operating principle of a minibooster, we obtained the dynamic characteristics represented in Fig. 3-6, namely:

In Fig. 3, comparisons between time evolutions of the following groups of hydraulic parameters: pump flow rate (top left, in red) and average flow rate through the pressure control valve (top left, in blue); pressure in the primary side of the SAOHPI (bottom left, in red) and pressure in the secondary side of the SAOHPI (bottom left, in blue); pressure at the inlet of the pressure valve (top right, in red) and the flow rate through it (top right, in blue); flow rate in the primary side of the SAOHPI (bottom right, in red) and flow rate in the secondary side of the SAOHPI (bottom right, in blue).
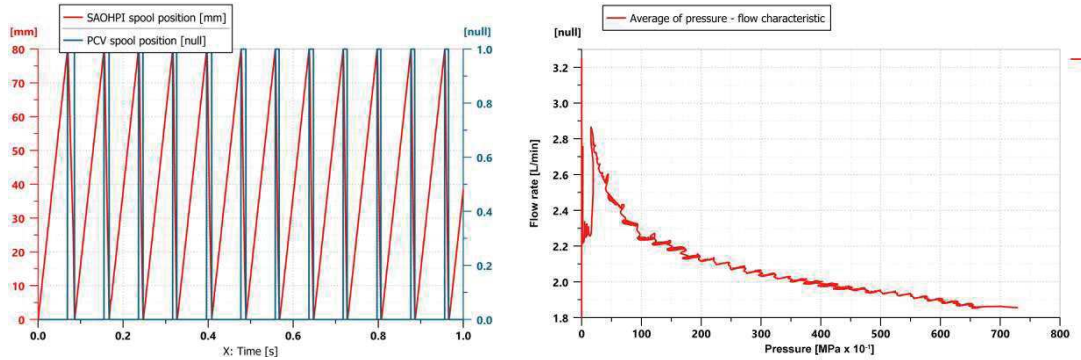
Fig. 4. Time variation of position of the pistons of the SAOHPI and the piston of the PCV (left); flow rate variation as a function of pressure in the secondary side of the SAOHPI

In Fig. 4: comparison between time evolutions of displacement of the SAOHPI pistons (left, in red) and displacement of the distribution valve PCV piston (left, in blue); variation of flow rate in the secondary side of the SAOHPI, depending on the pressure din in the secondary side of the SAOHPI (right, in red; the shape is similar to the flow / pressure characteristic in Fig. 1.b and the pressure / flow characteristic presented by miniBOOSTER Hydraulics A/S in [12]).
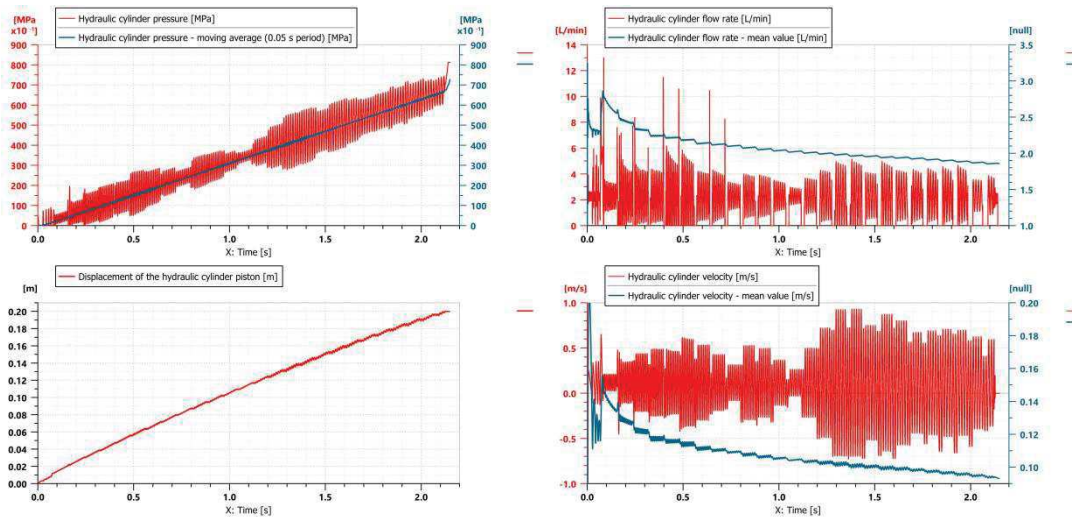
Fig. 5. Time variation of: oscillating and average pressure in the cylinder chamber (top left); cylinder displacement (bottom left); oscillating and average flow in the cylinder chamber (top right); oscillating and average cylinder speed (bottom right)

In Fig. 5: oscillating pressure variation (top left, in red) and average pressure variation (top left, in blue) in the cylinder chamber, at ramp load increase; time variation of the displacement of the

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hydraulic cylinder (bottom left, in red); oscillating flow rate variation (top right, in red) and average flow rate variation (top right, in blue) in the cylinder chamber, at ramp load increase; oscillating speed variation (bottom right, in red) and average speed variation (bottom right, in blue) of the cylinder piston, at ramp load increase.
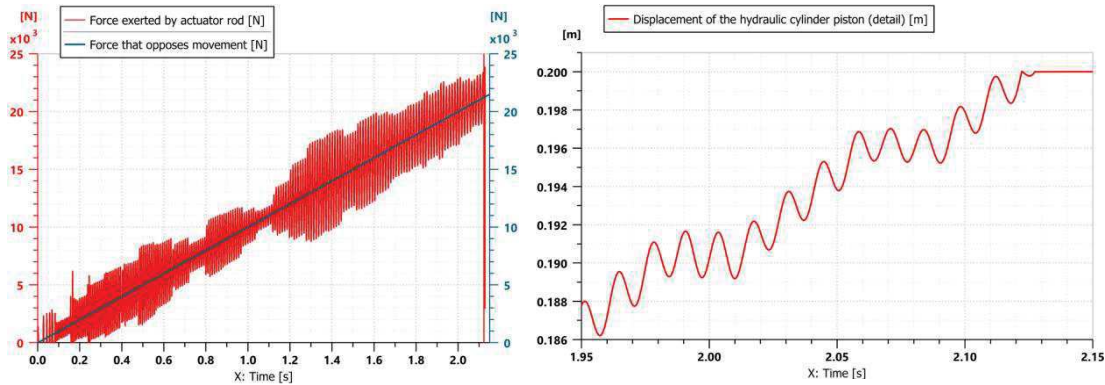

Fig. 6. Time variation of: cylinder force and load (left); oscillating displacement of the cylinder piston (right)

In Fig. 6: cylinder force variation (left, in red) and ramp load variation (left, in blue); detail of oscillating displacement of the hydraulic cylinder piston (right, in red).

After developing the test stand and conducting experimental tests, the numerical simulation model will be validated [15, 16, 17, 18].

4. Selecting a minibooster for a low-pressure pumping unit LPPU

For a 14 l/min and 20 MPa pumping unit, a minibooster from the HC7 group, code HC7-5.0-B-12, is identified; its functional diagram is shown in Fig. 7, and the main technical characteristics - in Table 1. The functional characteristics of the pump unit and the HC7 booster are similar to those in the numerical simulation model (Fig. 2) and functional diagram of the experimental stand (Fig. 8).
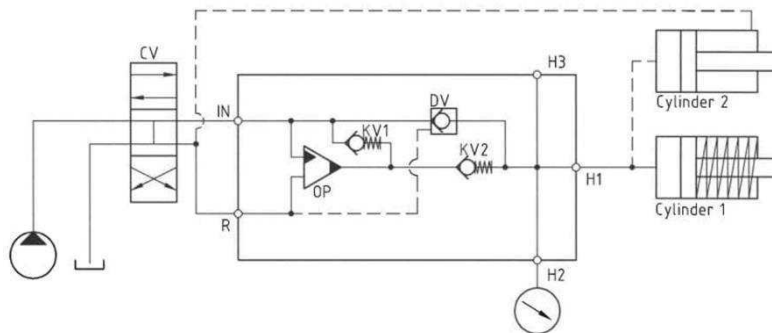
Fig. 7. Functional diagram of a pumping unit equipped with a HC7 series minibooster [19]

Table 1. Technical characteristics of the minibooster code HC7-5.0-B-12 [9]

Intensification factor i	Max. intensified outlet flow l/min	Max. inlet flow l/min	Connection types		
			IN / R	H1	H2
5.0	1.6	14.0	1/4" BSP	M22x1.5	9/16 -18 UNF

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5. The stand for conducting experimental tests on an LPPU

On the stand with the functional diagram shown in Fig. 8 one can experimentally test pumping units and hydraulic cylinders grouped in two variants, namely:

a) low-pressure pumping units equipped with one HC7 series minibooster and hydraulic cylinders, single- or double-acting, with load on the advance stroke, at the end of the stroke or on the entire stroke;

b) low-pressure pumping units equipped with two HC7 series miniboosters and hydraulic cylinders, single- or double-acting, with load on the advance stroke and the retreat stroke, at the end of the stroke or on the entire stroke.

5.1. Functional hydraulic diagram of the stand for conducting experimental tests on an LPPU
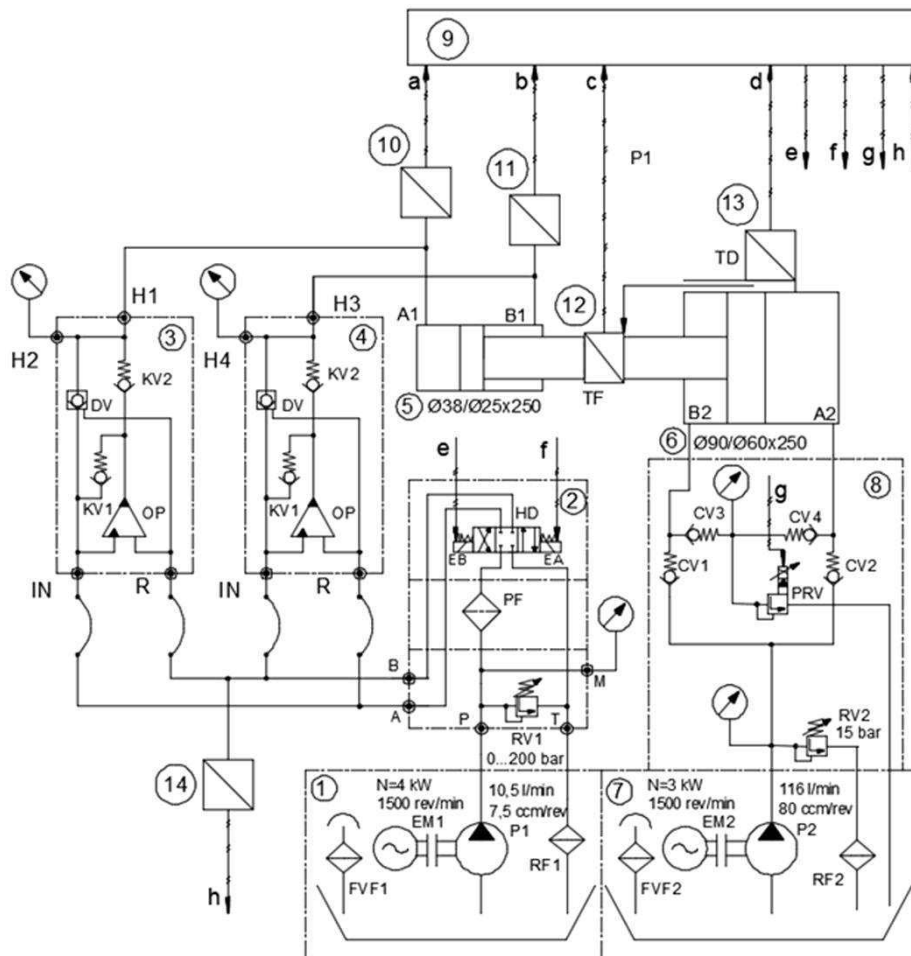

Fig. 8. Functional diagram of the stand for experimental tests on an LPPU

The stand in Fig. 8 includes nine main modules and five transducers, namely:

1- low-pressure pumping unit, which tests and supplies the test cylinder, provided with: oil tank, FVF1- filling and ventilating filter, EM- 4 kW and 1500 rev / min electric motor, P1- 7.5 ccm / rev positive displacement pump, RF1- return filter;

2- hydraulic block with four devices: RV1- 0 ... 200 bar pressure-control valve, PF- pressure filter, DH- 4/3 electrically operated hydraulic directional control valve, M- 300 bar manometer. It has an inlet port P and four outlet ports M, A, B, T;

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3, 4- HC7 series miniboosters, with four low-pressure ports (IN-inlet, R-return) and four high-pressure ports (H1, H3- for the cylinder being tested; H2, H4- for the 2000 bar manometers);

5- hydraulic test cylinder, with ports A1 / B1 and sizes Ø38 / Ø25 x 250 mm;

6- load simulation hydraulic cylinder, with ports A2 / B2 and sizes Ø90 / Ø60 x 250 mm;

7- low-pressure pumping unit, for filling the load simulation cylinder, equipped with: oil tank, FVF2- filling and ventilating filter, EM2- 3 kW and 1500 rev / min electric motor, P2- 80 ccm / rev positive displacement pump, RF2- return filter;

8- hydraulic block with six devices: RV2- 15 bar pressure valve, PRV- proportional pressure valve, CV1...CV4- check valves, M- 25 bar manometer. It has an inlet port (from P2) and four outlet ports (two to the tank and two to the cylinder 6);

9- PLC for data acquisition (from five transducers) and command signals (to the electromagnets EA, EB and the proportional pressure valve electromagnet);

10...14- transducers for: pressure (10,11), force (12), stroke (13), flow rate (14). H3-plug; B1(5)-to B(2); the rest, according to Fig. 8.

5.2. Description of the operating procedure used for the stand on which experimental tests are conducted on an LPPU

Depending on the equipment experimentally tested on the stand, grouped in the mentioned variants a) or b), the nine modules and five transducers will be coupled according to Table 2.

Table 2. Variants for coupling the stand modules

Variant no.	Cylinder 5 load simulation variants	Connections between stand components	Boosters coupled to the stand
a)	On the advance stroke and the retreat stroke	according to Fig. 8.	3 and 4
b)	On the advance stroke	H3- a plug is mounted; B1(5)- connected to B(2); the rest, according to Fig. 8	3

5.2.1. Operating procedure used for the stand; Table 2, variant a)

Step 1: Start the pump P2, with the valve PRV set to 20 MPa and the valve RV2 open, to fill the load cylinder 6 chambers. Then set the opening pressure of the valve RV2 to 15 bar.

Step 2: Start the pump P1, with the valve RV1 open and the hydraulic directional control valve HD not operating. After that, to move the cylinders to the right an electric control signal shall be sent to the electromagnet EA of the hydraulic directional control valve HD.

Step 3: Set the valve RV1 to 200 bar, then adjust the valve PRV, in the decreasing direction of the opening pressure, until the two cylinders start to move to the right.

The pump P1 supplies the port A1 of the cylinder 5 along the circuit: tank- P(block 2)- A(block 2)- IN(booster 3)-H1(booster 3)- A1. The port B1 is connected to the tank along the circuit: B1- H3(booster 4)- DV(booster 4)- IN(booster 4)- B(block 2)- T(block 2)-RF1- tank.

The pump P2 supplies the port B2 of the cylinder 6 along the circuit: tank- check valve CV1-B2. The port A2 is connected to the tank along the circuit: A2- check valve CV4- valve PRV- tank.

Step 4: Acquire the parameters measured by the transducers 10...14;

Step 5: Repeat steps 3 and 4 for other set values of the valve RV1 opening pressure (e.g. 150 bar, 100 bar, 50 bar);

Step 6: To move the cylinders to the left an electric control signal shall be sent to the electromagnet EB of the hydraulic directional control valve HD;

Step 7: Repeat steps 3, 4, 5 from moving to the right.

The pump P1 supplies the port B1 of the cylinder 5 along the circuit: tank- P(block 2)- B(block 2)-B1. The port A1 is connected to the tank along the circuit: A1- A(block 2)- T(block 2)-RF1- tank.

The pump P2 supplies the port A2 of the cylinder 6 along the circuit: tank- check valve CV2-A2. The port B2 is connected to the tank along the circuit: B2- check valve CV3- valve PRV- tank.

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5.2.2. Operating procedure used for the stand; Table 2, variant b)

To move the cylinders to the right, one shall follow **steps 1 ... 6**, identical to those of variant a).

The pump P1 supplies the port A1 of the cylinder 5 along the circuit: tank- P(block 2)- A(block 2)-IN(booster 3)-H1(booster 3)- A1. The port B1 is connected to the tank along the circuit: B1- B(block 2)- T(block 2)-RF1- tank.

The pump P2 supplies the port B2 of the cylinder 6 along the circuit: tank- check valve CV1-B2. The port A2 is connected to the tank along the circuit: A2- check valve CV4- valve PRV- tank. Steps 4,5,6 are identical to those of variant a).

Step 7: Moving of cylinders to the left is performed with no load, so with the valve PRV set to the minimum opening pressure and the electromagnet EB of the hydraulic directional control valve HD being sent an electric signal. Acquisition of the parameters measured by the transducers is no longer required.

The pump P1 supplies the port B1 of the cylinder 5 along the circuit: tank- P(block 2)- B(block 2)-IN(booster 4)-H3(booster 4)- B1. The port A1 is connected to the tank along the circuit: A1-H1(booster 3)- DV(booster 3)- IN(booster 3)- A(block 2)- T(block 2)-RF1- tank.

The pump P2 supplies the port A2 of the cylinder 6 along the circuit: tank- check valve CV2-A2. The port B2 is connected to the tank along the circuit: B2- check valve CV3- valve PRV (fully open)- tank.

6. Summary

The research aims to identify the amplitude and frequency of pulses of minibooster type oscillating pressure intensifiers, in order to integrate them on low-pressure pumping units, to supply small-sized hydraulic cylinders, able to move large loads with relatively constant travel speed over the entire stroke.

The working methods applied make use of: technical data presented in the catalogues of the minibooster manufacturer; numerical simulation and experimental identification to determine the amplitude and frequency of the pulses.

This paper presents the first part of the research, which includes: a preliminary model of numerical simulation of the dynamic operation of a minibooster; an experimental test stand for a low-pressure pumping unit, equipped with two miniboosters, able to determine the amplitude / frequency of booster pulses, and also their impact on the displacement of a hydraulic cylinder with load on the entire stroke.

The research will continue with the development of the stand, performance of experimental tests and completion of the numerical simulation model.

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