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CONCEPT OF A HYDRAULIC CONTROL SYSTEM WITH ONE SIGNAL LINE

In the paper a concept of a digital hydraulic control system with increased data transmission capacity through a single hydraulic line is presented. The proposed transmitter-receiver system was subjected to preliminary simulation of its operation in *FluidSIM Hydraulics*.

Key words: hydraulics, hydraulic control, simulation

1. INTRODUCTION

Hydraulic control systems are commonly used in many hydraulic power transmission systems. Generally speaking, hydraulic control techniques can be divided into continuous (analogue) and digital. Examples of continuous control by varying both pressure and flow are conventional control systems of positive-displacement units [Stryczek 2003] and more complicated Load Sensing systems [Szydelski 1999]. In most of these methods the main carrier of information is the level pressure which generally varies continuously in a given control circuit. A digital hydraulic signal is in most cases, the same as in electronic systems, a binary signal and is used for controlling devices such as directional control valves for electronic signal amplification. On/off systems are advantageous from the practicality point of view as they enable using of Boolean algebra and implementing the electric control portion in integrated circuits that are highly reliable, fast acting and relatively immune to interferences.

In binary hydraulic control the high and low states are ascribed to specific, constant pressure levels. The logic 0 is represented by low pressure, most often return

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pressure. The logic 1 is represented by a wide pressure range with the lower limit defined by the functional characteristics and the upper limit defined by the supply pressure. The binary control systems are in most cases limited to single-bit signals. For receivers requiring continuous control and for controlling greater numbers of receivers electric systems are used, specifically various network interfaces. Having the advantages of quick response and high level of reliability they are, however, not immune to large variations of supply voltage which may be caused by external interference, such as strong electromagnetic pulse.

Moreover, there are limitations on using electric control systems in areas with a high likelihood of occurrence of hazardous atmospheres. This paper describes a concept of a digital hydraulic control system featuring an increased data transmission capacity via a single hydraulic line for distances not exceeding a few dozen metres which is a typical length of hydraulic systems operated in various appliances and systems. Longer response time of pneumatic control (as compared to electronic control) limits its application to systems with receivers not requiring high control speeds.

2. OVERALL CONFIGURATION OF THE PROPOSED SYSTEM

A characteristic feature of the proposed control system is its ability to transmit information to multiple receivers sited within the above-mentioned radius via a single control line. The general configuration of the system with one receiver is presented in Fig. 1. The input control signal can be generated manually, mechanically, pneumatically or hydraulically while on the path between the transmitter and the receiver the control signals are exchanged by hydraulic fluid only. The transmitter system, called transmitter A is connected with the receiver, called receiver B through signal line C. The transmitter supplied by system E1 converts the input signal, manually generated with buttons 1 to digital pressure signals with the same sign and of specific and constant over time pressure p_s. For each of the n buttons one input signal is ascribed with the corresponding pressure value p_i, where: $i = 1 \ldots n$. Example of a system with one transmitter is presented in Fig. 1. However, the system can support connection of multiple transmitters connected at any point along the signal line. The pressure signals are directed to the receiver via a hydraulic signal line. The power capacity of the supply system E1 depends on the range of control pressure used, on the number of receivers, on the distance between the receivers and the transmitter and on the required signal transmission speed. In the receiver block the pressure signal is received by the system No. 2, amplified on the system No. 3 and the fluid power (pressure) is transferred from generator E2 to actuator D. The pressure generation system supports also the operation of the receiver system No. 2.

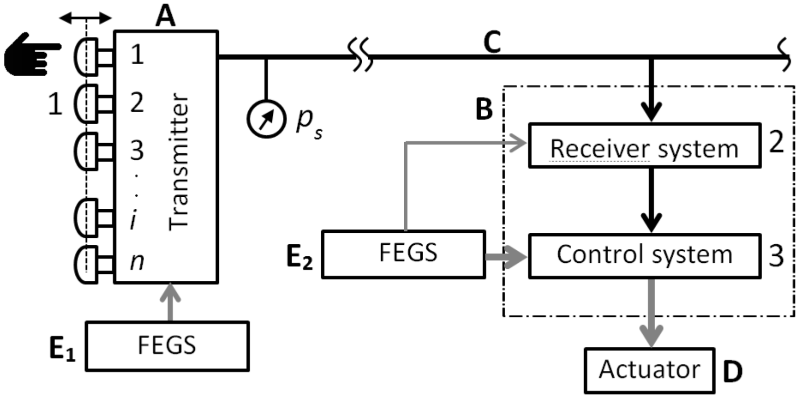

Fig. 1 General configuration of the proposed hydraulic control transmitter and receiver system: A, B – hydraulic transmitter and receiver, C – hydraulic signal line, D – actuator, $E_{1,2}$ – fluid energy generation system, 1 – signal buttons, 2 – receiver system, 3 – control system, p_s – signal line pressure

In the Fig. 2 three main configurations of the proposed system comprising one transmitter and multiple receivers is presented. In a distributed configuration (Fig. 2a) the distances between the receivers are large and it takes the longest for the input signal to reach receiver *n*. In the ring configuration b) the signal line is looped which enables reduction of the hydraulic pressure losses and shortening of the time to reach the most remote receivers. In the concentrated configuration c) the receivers spaced at small distances yet the transmitter-receiver distance is large. The above configurations can be used in combination.

There are no limits as to the type of fluid energy generation system, as long as it is immune to strong electromagnetic interference. Taking into account potentially high consumption of energy by actuators self-igniting IC engines are envisaged as the source of power. This does not preclude the use of other sources of power, especially for signal pressure generation and also for starting the IC engine. To ensure the required stability of operation of transmitter-receiver devices the viscosity of the fluid flowing through the circuit should be as low as possible and, more importantly, it should be independent of the operating temperature. Mineral oil whose viscosity varies considerably over the temperature may fail to satisfy this requirement. On the other hand, using emulsion of more or less constant viscosity in the whole system will limit application of the hydraulic drive itself. Therefore, it would be optimal to separate the transmitter-receiver circuit and the actuation circuit and fill them with different fluids.

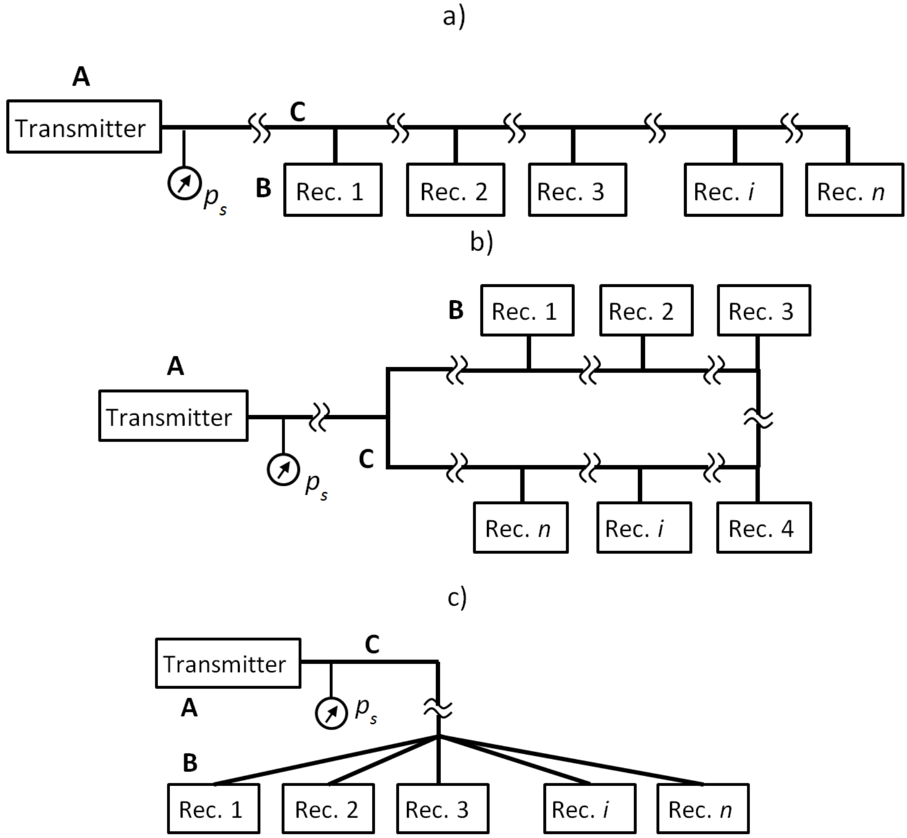

Fig. 2 Main configurations of hydraulic transmitter-receiver systems: a) network (distributed), b) ring, c) radial, A – transmitter, B – receiver, C – signal line, p_s – signal line pressure

3. IMPLEMENTATION OF THE PROPOSED HYDRAULIC CONTROL SYSTEM WITH ONE SIGNAL LINE

In the Fig. 3 the hydraulic diagram of the transmitter consistent with the patent claim presented [Frąckowiak, zgłoszenie patentowe nr P.420408]. The system includes four external connections (ports): pressure port P1, return port T2 and two signal ports S3. The transmitter comprises four directional control valves 12 (n = 4), 5/2 bistable, switched manually from "0" to "1" with hydraulically held control signal and hydraulically from "1" to "0" with the dominant signal from the right hand side, 4/2 monostable directional control valve 13 operated manually with hydraulically held control signal, two check valves 17 and 18 and the following regulating valves: throttling valve 19, pressure reduction valve 15, pressure switch-on valve 16 and hydraulic accumulator 20.The value of pressure $p_s \in (p_1, p_2, p_i \dots p_n)$ ascribed to each of the n input signals is set with the pressure reduction valves 14. From the supply port 1 the fluid flows through the high-pressure path 4 to the pressure reduction valves 14 which on the work paths 7 reduce the supply pressure p_z to the preset values of p_i after which the fluid is directed to the pressure ports P of directional control valves 12. In zero position of the directional control valves 12 and 13 the signal path is connected through work paths 7 with return path 5 and the signal pressure p_s is about the same as the return pressure p_T. By switching an i-th directional control valve 12 to position "1" the reduced pressure path 6 becomes connected through the work path 7 with the signal path 8 thus increasing pressure p_s to the value p_i preset on the i-th pressure reduction valve 14. Simultaneously the fluid is directed to the following paths through the path P-A of the i-th directional control valve 12: control path 10 – thus keeping the directional control valve in position "1" and through paths 15 and 16 to the control path 9 – thus generating X2 stop signal. Pressure p_{x2} of signal X2 acting on the spool faces of all the directional control valves 12 generates a force that prevents manual switching of the other directional control valves to position "1". It is assumed that pressure p_{X2} limited by the reducer valve 15 does not exceed 0.8 *MPa* and the pressure in the reduced pressure paths 6 satisfies the condition $p_i > 1$ *MPa*. The side surfaces of spools of directional control valves 12 were designed so that for the control signal X1 > X2. The pressure switch-on valve 16 preset at $p_{z2} = 1$ MPa prevents uncontrolled switching of the i-th directional valve 12 to zero. Without the pressure switch-on valve 16 during generation of pressure p_s the pressures p_{x1} and p_{x2} would reach levels at which the resulting force would switch the directional control valves to zero position by acting on different surface areas of the sides of spools of the directional control valves 12. The pressure switch-on valve 16 operating in combination with the pressure reduction valve 15 and the hydraulic accumulator 20 decreases the rate of pressure rise from p_{x2} to the value of 0.8 MPa in path 8 and thus enables avoiding the above-described problem. The directional control valves 12 are returned to zero hydraulically by manually switching the directional control valve 13 from position "0" to position "1" with the signal kept hydraulically by the control signal X transmitted through path 11. In positon "1" of directional control valve 13 the signal path is connected with the return path 5 through return path A-P. At that time through path B-T of directional control valve 13 the fluid flowing from the cut-off i-th directional control valve is directed to the control paths 9 with a time delay depending on the capacity of accumulator 20 and adjusted throttle area 19. After the delay time the value of pressure p_{x2} increases in the control paths 9, returning to zero position the i-th directional control valve 12 followed by 13. Owing to the time delay the fluid returns from the signal circuit between transmitter A and receiver B through only one path A-P of the directional control valve 13, thus minimising the flow resistance and the cut-off time of receivers B. Without this delay the fluid would drain from the signal circuit C through paths A-T of all directional control valves 12 connected in series, thus increasing the flow resistance and the cut-off time of the receivers B. In order to reduce the capacity of accumulator 20 a reducer valve 15 was provided to reduce the pressure p_r in control paths 9. Moreover, reduction of pressure p_r enables increasing the throttle area of valve 19 thus reducing fluid cleanness requirements. The directional control valves 12 in zero position are connected in series by paths A and T, this resulting in priority of response during actuation. If i-th directional control valve 12 is actuated all the valves from i+1 to n downstream of the valve in question will not supply the signal path 8.

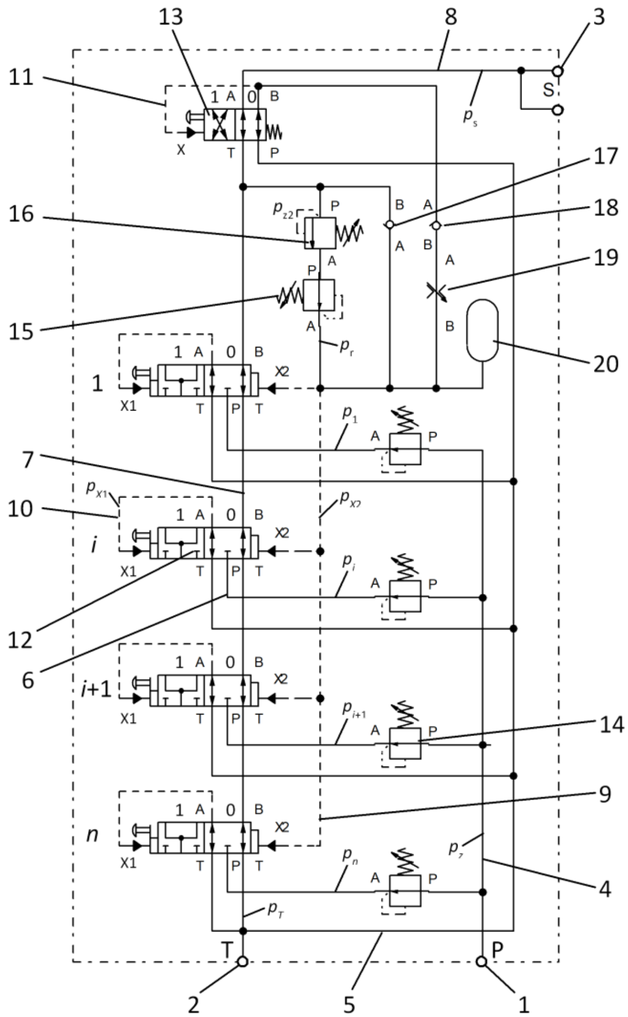

Fig. 3. Hydraulic diagram of the transmitter [Frąckowiak, zgłoszenie patentowe nr P.420408]

In turn, each directional control valve 12 located upstream of the *i*-th valve in question has a priority to supply signal path 8, with *i*-2 valve preceding valve *i*-1. The time needed for pressure p_s to reach the preset level p_i depends primarily on: the number of receivers and their power input, the hydraulic resistance of the flow paths of directional control valves 12 and 13, pressure reduction valves 14, flow paths 4, 6, 7 and 8 and the hydraulic resistance, volume and stiffness of the signal circuit C between the transmitter A and the receiver A and also the pressure generator flow rate of system E1. In turn the rate of decrease of pressure p_s will depend primarily on the adjusted throttle area of throttle valve 19, directly related to the volume, stiffness and hydraulic resistance of the signal circuit C, flow paths 8 and 5 and the hydraulic resistance of the A-P path of directional control valve 13.

In the Fig. 4 the hydraulic diagram of the receiver as per the patent claim [Frąckowiak, zgłoszenie patentowe nr P.420407]. The receiver has five ports: pressure port P 1, return port T 2, control port X 3 and two signal ports S 4 for connecting subsequent receivers with any range of preset pressure p_s presented. Besides, two hydraulic circuits can be identified: signal circuit and control circuit. The function of the signal circuit is to receive pressure signal p_s from the transmitter of preset, specifically selected pressure range after which the control circuit elements are activated. The signal circuit comprises the signal path 9, switch-on paths 10 and 11, check valves 14 and 15, pressure switch-on valves 16 and 17 and two 3/2 monostable directional control valves 18 and 19 hydraulically controlled by pressure signals p_{X1} and p_{X2}. In the control circuit pressure signal p_s is generated on port X 3 and it can be used both to operate the actuator and for transmitting information. This circuit comprises low pressure supply paths 12, pilot signal path 13, 3/2 monostable directional control valve 20 - hydraulically controlled by pressure signal p_{X3} and pressure supply and rate of rise regulation systems. The supply system comprises high pressure supply paths 5 and 6, return path 7, accumulator 25, filter 26, pressure reducer 27 and check valves 24 and 28 and the rate of rise regulation system comprises throttle valve 21, check valve 22 and pressure accumulator 23. The signal and control circuits are separated from each other and, as such, they can be filled with different hydraulic fluids. The control circuit can be also supplied from a separate system or from the supply system of the unit controlled by the above- described receiver. After the transmitter has generated specific pressure signal p_s the fluid is directed from the signal line to one of the two ports S 4 of the receiver. If there are subsequent receivers connected to the signal line, they are connected in series using the second port S 4. In the last receiver connected in series, the second S port is blocked. The signal circuit in the receiver operates as follows: the directional control valve 18 is switched to position 1 allowing for the flow of supply stream from path 5 to the pilot signal path 13 only when the value of signal pressure p_s falls within the range preset with the pressure switch-on valves 16 and 17. The lower and upper limits are set on valves 16 and 17 respectively. If the pressure value is lower than the preset limit valve 16 will not open and the directional control valve 18 will remain in the zero position cutting off supply to the pilot signal path 13. The control signal will not appear also when the pressure exceeds the upper limit. This results in opening both valves (16 and 17) and directing the fluid from the signal path 9 to the flow opening paths 10 and 11. Next pressure signals p_{X1} and p_{X2} are generated, both directional control valves are switched to position 1 thus cutting off the flow path from low pressure supply path 12 to pilot signal path 13. Conversely, if the level of pressure p_s in the signal path 9 falls within the preset range then only the directional control valve 18 is switched to position "1" directing the fluid from the high-pressure supply path 5 to the low-pressure supply path 12 and finally to the pilot signal path 13. When pressure signal pX3 appears in path 13 the directional control valve is switched to position "1", the supply fluid flows from the high pressure supply path 6 to the direct control path 8 and control pressure p_X appears on port X 3. The pressure rate of rise regulation system is required when more than one receiver is coupled with the transmitter. Taking into account unavoidable delay of the pressure signal on the signal line during the time when pressure rises from p_s to the value in the preset range the directional control valves 18 are switched in all receivers for which the preset level of pressure p_s is lower than the range of pressure of the receiver to be activated. In order to avoid undesired appearance of momentary control signals X3 in pilot signal path 13 during that time, the throttle valve 21 extends the charge time of hydraulic accumulator 23 and decreases the rate of rise of control pressure p_X in the pilot signal path 13 until the directional control valves 19 have switched to "1". Then in all the above-mentioned receivers the pilot signal path is connected with the return path 7 and the pressure accumulator 23 is discharged to the level of return pressure p_T through the

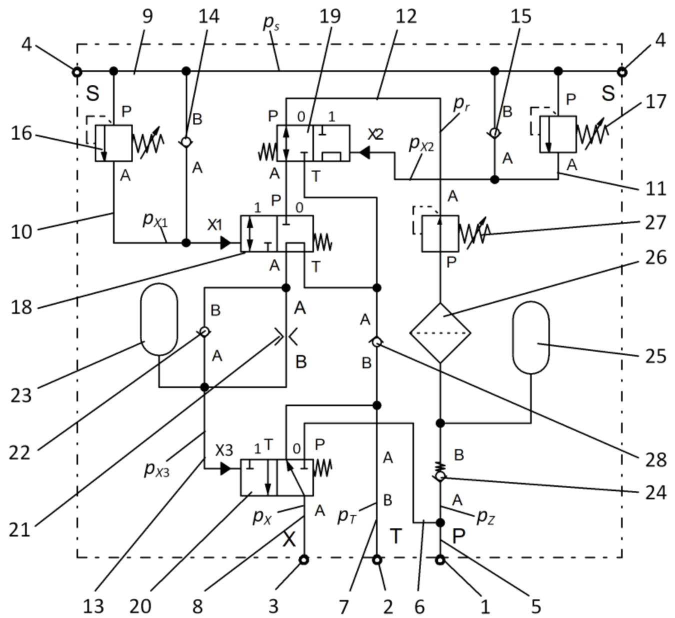

Fig. 4. Hydraulic diagram of the receiver

check valve 22, preventing uncontrolled appearance of control signal p_{X3} in the pilot signal path 13 of the directional control valve 20. The reducer valve 27 fixes the pressure in the low pressure supply path 12 at the level of p_r providing a relatively constant time-delay independent on the receiver supply pressure p_Z. Moreover, by lowering the reducer valve setpoint it becomes possible to increase the flow restriction gap of the throttle valve 21 thus reducing fluid cleanness requirements of the pressure rate of rise regulation system. The required cleanness of the fluid in the control circuit is ensured by filter 26. The check valve 28 protects the system from the effects of incorrect connection of the supply line and controlled devices to the receiver ports while valve 24 and accumulator 25 mitigate the effects of momentary oscillations of the control pressure p_{X3} in the flow path 12 which may appear during switching of hydraulic actuator supplied from the supply source E2, the same as receiver B.

4. SIMULATION OF THE SYSTEM OPERATION

In order to verify functioning of the above-described systems a simulation was carried out in *FluidSIM Hydraulics* for a system comprising one transmitter and six receivers connected according to the diagram presented in Fig. 2a. The simulation study was preceded by defining the parameters of all the system components. This included determination of the hydraulic resistance values of valves and capacity adjustment of accumulators. Moreover, some changes were implemented in the system design and a model was defined to represent the signal line. The simulation input values were taken to represent the actual values and performances of the components which could potentially be used to build the proposed systems. The component selection method will be covered by another paper yet to be drawn up. In the Fig. 5 a fragment of the simulated system comprising six directional control valves 12n and six receivers connected with the transmitter presented. The parameters of the signal lines C were adopted at the values corresponding to ca. 10 *m* estimated length. The supply flow rate of transmitter A was $Q = 10\ dm^3/min.$ and the switching pressures of the receivers were in the range of 2÷16 MPa. The system of each receiver was divided into three modules: B2 – signal receiving module, B3 – controlling module and D – actuator module. The required increase of the stiffness of springs in the directional control valves 13n, 18o and 19o was obtained by providing each of them with an additional control path and connecting pressure reduction valves ZR on these paths. This enabled by-passing the restriction of fixed default stiffness of springs. The transmitter return port 2 was provided with a pressure relief valve ZM which maintains in the signal line C a minimum overpressure of 0.3 MPa.

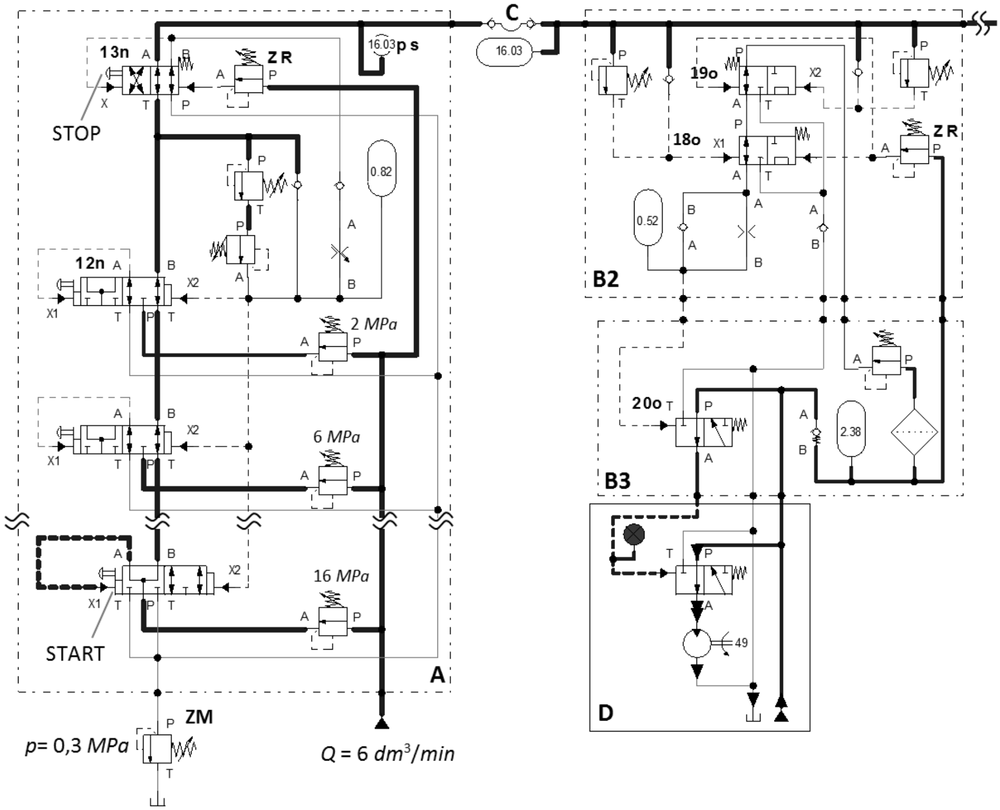

Fig. 5. Diagram of the simulated transmitter-receiver system

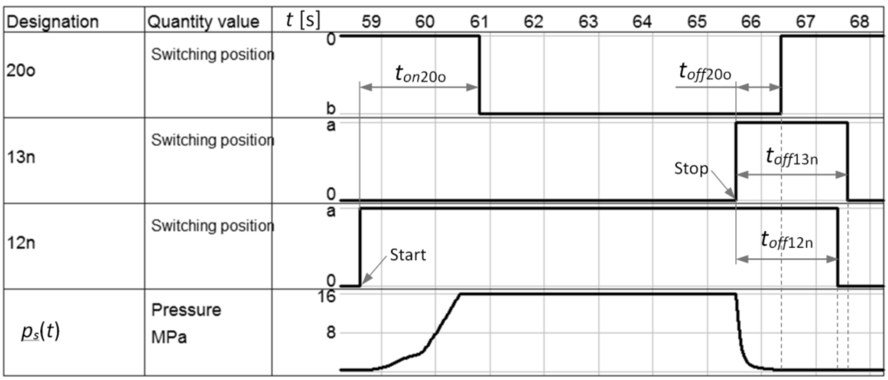

Fig. 6. Results of simulation of the transmitter/receiver system for generated pressure of p_s = 16 MPa

Presentation of the simulation output is limited to selected curves of pressure p_s variation over time in the signal line C and the delay times for switching of valves 12n, 13n and 20o for the generated pressure of p_s = 16 MPa. These times are of utmost importance since the sequence of switching of these valves is critical for correct functioning of the system. Switching of valve 12n to position "1" for a short time should trigger switching of a specific vale 20o to position "1" and switching of valve 13n to position "1" should trigger switching sequence to zero position of valves 20o, 12n and 13n. This sequence is kept irrespective of the value of pressure p_s and the sequence in which the receivers are connected on the signal line. The valve switching times are defined by the variation of p_s pressure over time. Both the rate of rise of pressure to the preset value of p_s and the rate of its decrease to 0.3 MPa depend primarily on the flow resistance, volume and stiffness of the hydraulic circuits. Hence, with a reduced supply flow rate Q the rate of rise of pressure p_s is smaller than its rate of decrease. Blow are the valve switching times obtained for the pressure range of p_s = 2÷16 MPa: t_{on20o} = 1.06÷2.21 *sec.*, t_{off20o} = 0.65÷0.83 *sec.*, t_{off13n} = 1.83÷2.07 *sec.*, t_{off12n} = 1.77÷1.88 *sec.*

5. CONCLUSIONS

The simulation results demonstrate the technical feasibility of the proposed concept of hydraulic control system in which the control and status signal are transmitted from one transmitter to multiple receivers through a single signal line. The next phase of research, including both simulation and test stand experiments will provide a more accurate estimate of the values of hydraulic parameters of the analysed systems and will provide a foundation for the prototyping phase.

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KONCEPCJA HYDRAULICZNEGO UKŁADU STEROWANIA Z JEDNYM PRZEWODEM SYGNAŁOWYM

Streszczenie

W pracy przedstawiono koncepcję cyfrowego sterowania hydraulicznego, które cechowałoby się zwiększoną objętością informacji, przesyłaną zdalnie przy wykorzystaniu jednego przewodu hydraulicznego. Zaproponowany układ nadawczo-odbiorczy poddano wstępnej symulacji pracy w programie *FluidSIM Hydraulics*.

Słowa kluczowe: hydraulika, sterowanie hydrauliczne, symulacja