MATEC Web of Conferences **254**, 03001 (2019) https://doi.org/10.1051/matecconf/201925403001
MMS 2018

Simulation study of the hydraulic transmitter-receiver system

Damian Frąckowiak[1]

[1] Chair of Basics of Machine Design, Poznan University of Technology, Piotrowo Street 3, 60-965 Poznan, Poland

Summary. The paper presents a hydraulic transmitter receiver system which is characterized by the ability to remotely send information utilizing a single hydraulic line. The system was subject to computer simulation in the software *Fluid-SIM Hydraulics,* and based on the obtained measurement results the influence of the parameters of its components on the correct operation of the entire system was determined.

Keywords: hydraulics, hydraulic control, simulation

1 Introduction

Hydraulic control is commonly employed in numerous power hydraulic systems. In general, these solutions can be divided into continuous and digital. An example of a continuous amplifier system utilizing both pressure and volumetric methods may be the classic setting systems for displacement units [1], as well as more complex arrangements such as Load Sensing systems [2]. In the majority of these applications, the key information is the pressure value, which is usually continuous in the particular control circuit. Conversely, digital hydraulic amplifier systems are usually limited to binary, single-bit signals. If the receivers call for continuous control, or if a larger number of devices needs to be controlled, electrical systems are usually employed, together with different network interfaces. The electrical systems show an undeniable advantage in operating speed and reliability; however, they remain susceptible to large fluctuations in power supply voltage, which may occur with external interference in form of a strong electromagnetic pulse. Moreover, electrical amplifier systems have limited application in areas with significant fire and explosion hazards. Hence, the concept of digital hydraulic control was established, which would be characterized by an increased information volume, transmitted remotely via a single hydraulic line, at a distance of several dozen meters, which is within the range of the hydraulic installations commonly found in various systems and setups.

2 Construction and principle of operation

The distinguishing property of the suggested control concept is the ability to transmit information to numerous receivers at the above mentioned distance, utilizing one signal line. The general structure of such a solution for a single receiver setup is shown on Fig. 1. The input control signal can be generated manually, whereas the transmission of control signals between the transmitter and receiver systems occurs hydraulically. The transmitting component called Transmitter A is connected to the receiving component called receiver B with signal line C. The transmitter is powered by the system E_1 and changes the manually generated transmitted signal, by means of buttons 1, into pressure-based digital signals with one digit and a specific pressure value of p_s, which is continuous in time. For every one of the n buttons, a single transmitted signal is assigned, with corresponding pressure p_i, where: $i = 1 \ldots n$. Fig. 1 presents an arrangement with only one transmitter, whereas in an actual application more can be used, and can be also connected to the signal line in any location. The pressure signals are transmitted via hydraulic signaling system to the receiver. The supplied flow at E_1 is dependent on: the range of utilized pressure, number of receivers, distances between the receivers and the transmitter and the required speed of signal transmission. In the receiver block, the pressure signal is received by system 2 and amplified in system 3, the pressure energy from generator E_2 is transferred to actuator D. The pressure generator also assists in the operation of receiver system 2.

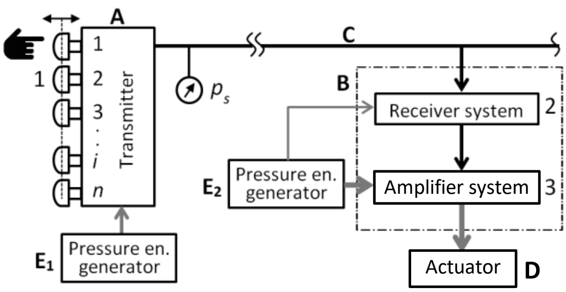

Fig. 1. General construction of the hydraulic transmitter-receiver system: A, B – hydraulic transmitter and receiver, C – hydraulic signal line, D – actuator, $E_{1,2}$ – pressure energy generators, 1 – signal buttons, 2 – receiver system, 3 – amplifier system , p_s – pressure in signal line

An example design of transmitter-receiver system was presented in detail in papers [3, 4]. Due to the comprehensive nature of this material, the present paper only provides a general principle of operation of these devices. Based on the simulation diagram shown on Fig. 2, it is possible to provide a general description of the construction and principle of operation of the examined transmitter-receiver system. The generation of pressure signal p_s in the signal line C is achieved by means of flow dividers 12n. The pressure value $p_s \in (p_1, p_2, p_i \ldots p_n)$ assigned to each of the n transmitted signals is set with reduction valves 14n. After engaging the i-th divider 12n, pressure p_s is generated and (in order to ensure proper operation of the system) other 12n dividers are blocked. The hydraulic block entails generating control signals X2 at dividers 12n, so that it is not possible to override them manually. The pressure of this system is determined by the reduction valve 15n. Subsequently, the signal arrives at the B2 receiver system for all the receivers connected to signal line C, and subsequently to the amplifier system B3 only for the receivers in which the pressures set by valves 16o and 17o fall in the range of p_s – 0.5-p_s [MPa]. The signal can be further used for control or information purposes. If pressure value p_i falls in the set range, the divider 18o is overridden, and the control signal is generated at terminal X3 and transmitted further to divider 20o, which generates the proper control or information signal. In the opposite case, dividers 18o and 19o are set in position preventing signal generation at terminals X3 and subsequently at X. Cancelling of the transmitted signal is achieved by pressing the control button at divider 13n. In order to ensure stable operation of the device, both at the transmitter and the receiver, delaying systems were employed. The delaying system in the transmitter, constituting: check valves 17n, 18n, connecting valve 16n, flow regulator 19n and accumulator 20n introduces a delay in the signal X2 while generating pressure p_s. This avoids automatic shutoff of the dividers 12n, which can occur if they are engaged with a low stream value of Q_z powering the system. Moreover, this ensures that the proper shutoff sequence is observed for dividers 12n, 13n, 18o and 19o. On the other hand, the delaying system employed in the receiver consists of the following valves: check valve 21o and throttle valve 21o as well as an accumulator 23o, it prevents the temporary shutoff of receivers which are not initialized at the moment. The reducer valve 27o lowers the pressure at terminal X3 and maintains its value regardless of the supplied pressure from generator E_2. Moreover, the reduction of pressure allows to reduce the flow cross section in the throttle valve 21o, and therefore to reduce the sensitivity of the delaying system to impurities.

3 Design used in simulation

The correct operation of the transmitter-receiver system was tested in *FluidSIM Hydraulics* simulation software. The designed system consists of a transmitter fitted with six 12n dividers and six receivers interconnected with ten meter sections of flexible signal line reinforced with a single steel braid. Obtaining the correct results from the simulation depends on assuming proper parameter values for individual system components.

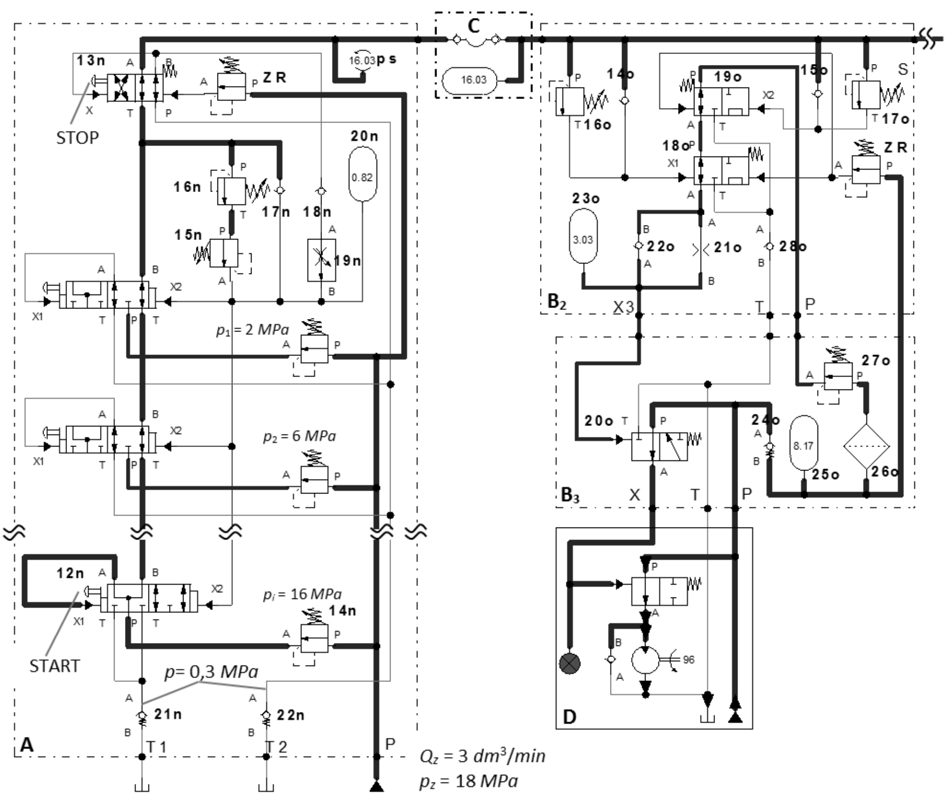

Fig. 2. Diagram of transmitter-receiver system used in the simulation, where: A – transmitter system, B_2 – receiver system, B_3 – amplifier system, C – signal line, D – actuator system, no. of dividers 12n and receivers $n = 6$

Both for the receiver and the transmitter, one needs to specify the hydraulic resistance for every valve, set pressure values, adjust the accumulator capacities and model the signal line. The hydraulic diagram of the simulated transmitter-receiver system is shown on Fig. 2. For the purpose of the simulation, several changes were introduced in the system in comparison to the initial design. The outflow conduit of the transmitter was fitted with check valves 21n and 22n, which introduce an overpressure in the signal line p_s = 0.3 MPa. To ensure the system can operate correctly at elevated drain line pressure, it is required to increase the spring tension at dividers 13n, 18o, and 19o, which was achieved by introducing an additional hydraulic control generating a p_{z3} = 0.3 MPa signal. The transmitter is connected with the receiver with the signal line consisting of a section with specific resistance value R_{hp} and accumulator with volume of V_p. The assumed initial value of flow powering the transmitter is Q_z = 3 dm^3/min.

3.1 Valve hydraulic resistance

The assumed hydraulic resistance values are determined by several requirements. It is assumed that the system should transmit signals from transmitter to receiver in as short amount of time as possible and use as little energy as possible. The latency between the transmitter and receiver depends primarily on distance, and therefore it is affected primarily by hydraulic resistance values of all the system components as well as the power of the generator. The assumed resistance values should furthermore be realistic (from the standpoint of engineering and technology), the weight and capacity of devices is also relevant and should be minimized where possible. The resistance value of receiver components along the flow line powering the signal conduit assumed the principle that the pressure drop in the control line should not exceed 3-5% of supplied pressure p_z [1]. For the maximum assumed value of signal pressure $p_s = p_z$ = 16 MPa in the current example, the pressure drop should therefore be kept in the boundary of Δp = 0.48-0.8 MPa. In the examined system, the following components are placed along the flow path: valve 14n, 6 valves 12n and valve 13n. Accounting for the transmitter as a single, complex valve, the pressure drop at every one of the above valves should be equal to $\Delta p_i = \Delta p/(n+2)$, where n is the number of 12n dividers. Therefore, Δp_i on every component should be kept in the range of: 0.06-0.1 MPa, and the hydraulic resistances, assuming that the maximum supplied flow is Q_z = 12 dm^3/min, R_h = 0.00042-0.00069 MPa/(dm^3/min)^2. It is therefore assumed that the resistance of valves 12n, 13n and 14n is equal to R_h = 0.0005 MPa/(dm^3/min)^2. Check valves 21n and 22n should be characterized by as low resistance values as possible, to allow for the correct sequence of initializing the valves 18o, 12n and 13n, as well as the correct shutoff speed of valve 13n. The influence of resistance of these valves on the operation of the system is further discussed in chapter 4. Simulation testing assumes that $R_{h21\mathrm{n}} = R_{h22\mathrm{n}}$ = 0.005 MPa/(dm^3/min)^2. The valves 15n, 16n and 17n should also be characterized by low hydraulic resistance, because of the engagement speed of valves 12n. Too high resistance of valves 15n and 16n causes slow buildup of pressure p_{x2} in lines 9n which causes a delayed engagement of the hydraulic block over the disengaged valves 12n. On the other hand, too high resistance of valve 17n does not allow to quickly reduce the pressure in this line, and therefore the hydraulic block is engaged for a longer time. The flow rate at regulator 19n was set to Q_r = 1.5 dm^3/min, therefore at maximum pressure p_s = 16 MPa the resistance at the section between the power supply and accumulator 20n should not exceed 0.0065 MPa/(dm^3/min)^2. For the earlier assumed hydraulic resistance values for valves 12n, 13n and 14n, the resistances for valve 18n and regulator 19n should be, respectively $R_{h18\mathrm{n}} = R_{h19\mathrm{n}} \approx$ 0.00125 MPa/(dm^3/min)^2. The resistances of valves 14o-17o depend on the volume of control chambers of dividers 18o and 19o. As the volume increases, the resistance value should become lower. Due to the fact that *FluidSIM* software assumes negligibly small volumes of control chambers, the simulation assumes exceptionally large resistance values of these valves. The flow through dividers 18o, 19o is bi-directional. When generating the pressure signal X3, the medium flows via paths P-A and the flow duct resistance values along these sections may be larger, so as to assist the operation of the throttling valve 21o. On the other hand, the paths A-T should be characterized by low resistance values as it affects, together with the placement of valves 22o and 28o in this branch, the discharge speed of accumulator 23o; consequently, this affects the shutoff of control divider 20o. Unfortunately, also in this case the simulation software does not account for the possibility to differentiate resistance values for specific flow paths, and therefore the simulation assumes a single resistance value for dividers 18o and 19o R_h = 0.005. At the throttling valve 21o, it was assumed that the opening diameter is 1 mm, at pressure reduced to 3 MPa, this makes for a flow intensity of $Q_D \approx 3$ dm^3/min and resistance $R_{h21o} = 0.35$. On the other hand, components 24o and 27o assume that the resistance is lower by an order of magnitude from R_{h21o}, and for the filter 26o it was selected based on the principle that the pressure drop should not exceed 0.05 MPa [1]. Table 1 shows the preliminary assumed resistance values for all the components of the transmitter-receiver system.

Table 1. Assumed preliminary values for the components of transmitter and receiver

Component no.	**Hydraulic resistance R_h [MPa/(dm^3/min)^2]**
12n, 13n, 14n, 15n, 16n, 17n	0.0005
18n, 19n, 20o, 26o	0.001
18o, 19o, 22o, 28o	0.005
24o, 27o	0.035
14o, 15o, 16o, 17o	0.1
21o	0.35

3.2 Valve opening pressure

The output pressure of reducer valves 14n in the transmitter was set in the range of p_i = 2-16 MPa, with setting adjustment every 1 MPa. The lower range is a result of limitations of the *FluidSIM* software, which are discussed in greater detail in subchapter 3.4. The upper range is arbitrary and is only limited by design and technology employed in the system. The check valves 21n and 22n, while the transmitter is disengaged, maintain an overpressure of p_T = 0.3 MPa in the signal line. Such pre-induced tension in the line allows for a quicker generation of the set pressure value p_s. On the other hand, the assumed pressure value p_T is a compromise between the ability to quickly generate pressure p_s, and the construction limitations of dividers 12n. Due to the fact that these dividers , feature a non-symmetrical control signal (the side area ratio of pistons controlling the spool in *FluidSIM* software is: φ = 2.135) it is not possible to balance the axial force affected on the spool, and therefore the force value F_s required for a manual override is proportional to the pressure p_T. For the assumed values: p_T = 0.3 MPa and the piston controlling the spool d = 6 mm the force value is as high as $F_s \approx 10$ N. Assuming that the pressure at terminal X2 set with the reducer valve 15n is equal to p_{X2} = 0.8 MPa, the force blocking the spool in divider 12n is equal to only F_b = 40 N. This value is too low, however, in an actual system, the ratio φ can be reduced, this allows, together with an additional increase of diameter d, to achieve a larger value of F_b and at the same time, a smaller value of F_s. The increase in F_b value can also be obtained by increasing the pressure p_{X2}, however, this limits the lower range of pressure p_s, hence the assumed value of p_{X2} = 0.8 MPa. The opening pressure of connecting valve 16n equal to 1 MPa stems from the nature of pressure increase p_s, which is discussed in detail in chapter 3.5. In the receiver system, the connecting valves 16o and 17o are set for opening pressure of, respectively,: $p_n - 0.5$ and p_n. The lower pressure boundary is caused by pressure at terminal X1 and divider 18o which is required for its override. The pressure primarily depends on the tension of the pressure setting the spool. The minimum possible value in *FluidSIM* is 0.53 MPa. The reducer valve 27o limits and stabilizes the pressure at $p_{X3} = 3$ MPa.

3.3 Accumulator parameters

As mentioned previously in chapter 2, the accumulator 20n has an indirect influence on the correctness of system operation, stability of operation of dividers 12n as well as the pressure p_s reduction speed to minimum value. Insufficient volume does not allow to achieve the required preservation of signal X1 in dividers 12n in situations when the flow powering the transmitter is too low in relation to the volume of signal line conduits. On the other hand, too large volume causes longer control time. Preliminary simulation tests for assumed resistance and pressure values of the components allowed to estimate the range of accumulator volume $V_{20n} = 0.2\text{-}0.3$ dm^3, and for further testing the value $V_{20n} = 0.3$ dm^3 was assumed. The receiver system contains two accumulators, 23o and 25o. The accumulator 23o together with throttling valve 22o introduce a time delay between engaging the dividers 18o and 20o. This delay value needs to be adapted to the speed of increase of pressure p_s in the signal line. On the one hand, it should be as short as possible in order not to unnecessarily increase the receiver response time, and on the other hand, it should be long enough not to cause disturbances in form of momentary shutoffs of dividers 20o in all receivers where the pressure range p_s is set lower in relation to the pressure range of the initialized receiver. This delay is directly related to the line volume, its rigidity, and flow powering the transmitter. It relates directly to the hydraulic resistance of the throttling valve 21o working together with the accumulator 23o as well as the pressure set by reducer valve 27o. Therefore, the volume V_{23o} is a parameter value that can be assumed or adjusted. In the examined case, it is assumed that the parameter value is constant $V_{23o} = 0.02$ dm^3, and the required time delay is set by the throttling valve 21o. Both in the accumulator 23o and 20n, it was assumed that the initial charging pressure is $p_0 \approx 0$ MPa. The parameters of accumulators 25o should be determined on an individual basis as they depend on the on the flow powering the system of actuator D. Their presence become significant when the flow powering the actuator's system is relatively small ($Q_D < 3$ dm^3/min) and there is a danger of interference occurring in the delaying system. Due to the fact that in simulation testing $Q_D = 80$ dm^3/min, the effect of the accumulator is practically irrelevant. The study assumes that the accumulator volume is $V_{25o} = 0.3$ dm^3, and its initial pressure value is $p_0 = 0.1$ MPa.

3.4 Signal line model

In order to account for actual latency between the transmitter and receiver in the simulated system, one needs to define the length, volume as well as the replacement substitute flexural modulus for the liquid and signal line. Due to the fact that for the hydraulic lines available in the *FluidSIM* software library it is only possible to define the resistance value, a hydraulic accumulator was added to the standard connection to obtain the required time delay. The replacement system is shown on Fig. 3, however it makes for a major simplification regarding the actual line and does not account for the nature of pressure changes occurring in the signal line. These differences are shown on Fig. 4, which demonstrates the change of pressure after switching the control valve in the actual circuit and the one simulated in the software. The different character of the pressure increase in the simulated line results from the use of gas accumulator with progressive pressure change during charging, which will cause an increase in the time of maintaining the relatively low pressure p_s. Fig. 4 shows that the increase in pressure p_s to the value approx. 2 MPa progresses relatively slowly, therefore the time delay established initially for the actual line in its delay system may prove insufficient.

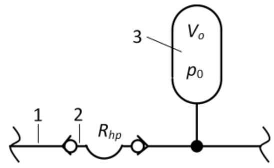

Fig. 3. Replacement system for the signal line, where: 1 – connection not introducing loss or change of volume, 2 – line with defined hydraulic resistance, 3 – hydraulic accumulator, R_{hp} – hydraulic resistance of the line, V_o – delaying accumulator volume, p_0 – initial pressure in accumulator

Considering the stable operation of the transmitter and receiver, it is therefore required to increase the power supply flow to the system, or increase the time delay by changing the volume of delaying accumulator 23o together with the resistance value of throttle valve 21o in the receiver. However, in order not to significantly modify these parameters, the assumed lower range of pressure p_s in the simulated system should not be lower than $p_{s\min} = 2$ MPa. If this condition is not met, unstable system operation may occur, which always manifests itself by momentary engagement of the receiver set to pressure value $p_s < p_{s\min}$, regardless of which receiver was initialized at that time.

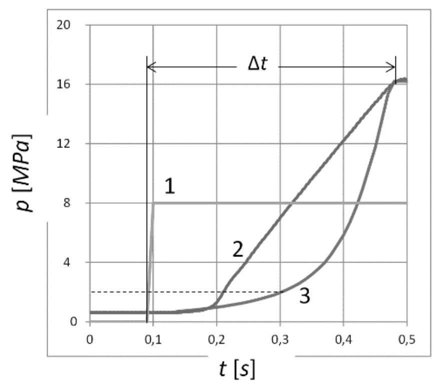

Fig. 4. Change of pressure value p_s in the signal line after switching the valve, where: 1 – electrical forcing signal, 2 – example pressure change achieved during bench testing, 3 – pressure change in the line achieved during computer simulation in *FluidSIM*, Δt – delay in pressure increase

Although the suggested physical model only reflects the actual object in a limited way, it is possible to accurately define the time of increase of set pressure, eventually it is this value that decides if the specific receiver is switched on. It was therefore assumed that, from the standpoint of preliminary simulation testing, such model is sufficient. The delay caused by the expansion of the signal line and liquid compressibility is a well-known phenomenon. The paper [5] suggests an experiential method to determine the pressure wave speed in hydraulic lines, it allows to approximate (for the replacement modulus flexural modulus of the considered line type $B_{zp} \approx 350\text{-}590$ MPa and pressure range $p_s = 2\text{-}16$ MPa) the speed value as $c_0 = 600\text{-}800$ m/s, and the resultant delay (for line length 9 m) to be $\Delta t = 0.011\text{-}0.015$ s. This time value however is only a partial constituent of the final delay which occurs in the examined transmitter receiver system, as it does not account for the delay at valve 12n as well as the time required to increase the pressure p_s from the minimum value of 0.3 MPa.

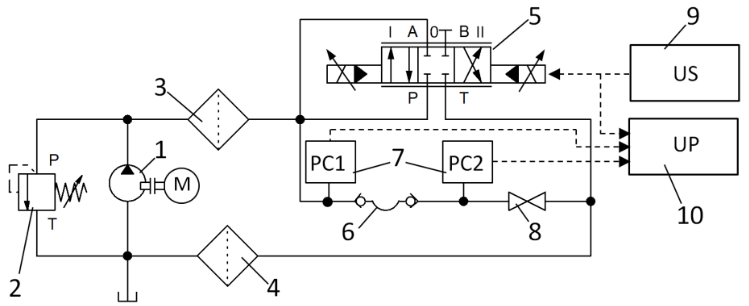

Fig. 5. The diagram of the measurement system for testing the hydraulic line, where: 1 – pump with motor, 2 – safety valve, 3, 4 – filters , 5 – servo valve, 6 – tested line, 7 – pressure converters, 8 – shutoff valve, 9 – power supply system and control for the servo valve, 10 – measuring system

Therefore, in order to determine the actual delay times, accounting for all the transitory processes, we carried out testing of the hydraulic line on a testing station with design as provided on Fig. 5. For testing, a flexible hydraulic line with single steel reinforcement braid (6), with internal diameter d_w = 10 mm and length l_o = 13.8 m was employed. The pressure p_s in the tested line (in the range of 2-16 MPa) was generated via a servo valve (5), utilizing the setting range „II" of its spool. The system was powered by a continuous flow of Q_z = 7.58 dm^3/min. The results were measured with converters (7). The example result provided on Fig. 4 was achieved with the following parameters: set pressure p_s = 16.3 MPa, initial pressure p_0 = 0.45 MPa, temperature of the medium t_c = 50^0C, kinematic viscosity ν = 41 mm^2/s. Delay change Δt for the entire examined scope of pressure p_s is shown on Diagram 2 of Fig. 6. Due to the fact that the scope of simulation tests also includes systems for different Q_z values, it is required to establish the delay value with account for the change in power supply flow. Assuming the formula describing the flow caused by liquid compressibility and elasticity of line [6], omitting its resistance value, the approximate time of pressure increase can be calculated from the formula:

$$\Delta t = \frac{60 \cdot (V_p + V_f) \cdot \Delta p}{B_z(p_s) \cdot Q_z} + \Delta t_s \text{ [s]}, \tag{1}$$

where:
Q_z [dm^3/min] – supplied flow
V_p [dm^3] – volume of all lines in which pressure p_s is generated
V_f [dm^3] – volume of filter (3) in the supply line
$\Delta p = p_s - p_0$ [MPa] – change of pressure in the signal line
Δt_s [s] – servo valve switching time, Δt_s = 0.010 s [7]
$B_z(p_s)$ [MPa] – the replacement volumetric flexural modulus of the line, accounting for the liquid compressibility, line expandability and filter as in [6]:

$$B_z(p_s) = \frac{B_{zo}(p_s) \cdot B_{zp}(p_s) \cdot (V_f + V_p)}{V_p \cdot B_{zo}(p_s) + V_f \cdot B_{zp}(p_s)} \text{ [MPa]}, \tag{2}$$

$B_{zo}(p_s)$ – replacement flexural modulus of the volumetric filter casing and hydraulic oil,
$B_{zp}(p_s)$ – replacement flexural modulus of volumetric flexibility of the line and hydraulic oil.

Calculated based on the formula (2), the flexural modulus value in the pressure range p_s = 2-16 MPa is $B_z(p_s)$ = 291-566 MPa. Diagram no. 1 presented on Fig. 6 shows progression of the pressure increase time in the signal line calculated according to formula (1). The results were obtained for the following data: Q_z = 7.58 dm^3/min, V_p = 1083.8 dm^3, V_f = 421.3 dm^3, Δp = 1.55-15.55 MPa. The differences between the results obtained from calculations and from testing for the range 3-16 MPa do not exceed 10%. Therefore, it was decided to use (in transformed form) the formula (1) for modeling the signal line. Omitting the filter volume, the delay time can be calculated from the formula below:

$$\Delta t(\Delta p, Q_z) = \frac{V_p \cdot \Delta p}{B_{zp}(p_S) \cdot Q_z} + \Delta t_r \text{ [s]}, \tag{3}$$

where:
Δt_r – switch time of divider 12n, (Δt_r = 0.02 s – this value is forced by the software)

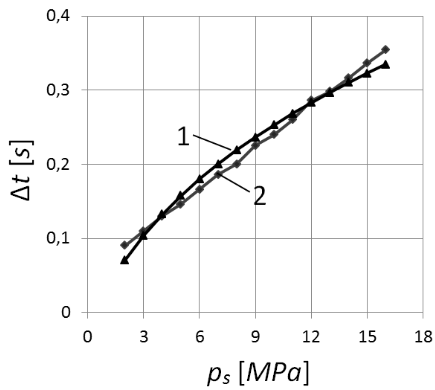

Fig. 6. Time of pressure increase in the signal line, where: 1 – values calculated from formula (1), 2 – values obtained in bench testing

The hydraulic resistance of the signal line was determined from the formula:

$$R_{hp} = 1.67 \cdot 10^{-5} \cdot \frac{\nu \cdot \rho \cdot l_o}{Q_z \cdot d_w^4} \text{ [MPa/(dm}^3\text{/min)}^2\text{]}, \tag{4}$$

where:
ν [mm^2/s]– kinematic viscosity
ρ [kg/m^3]– the density of the working medium
d_w [mm]– internal diameter of the hydraulic line, l_o [m] – length of the hydraulic signal line
For the calculations, it was assumed that: ν = 41 mm^2/s, ρ = 890 kg/m^3, d_w = 10 mm, l_0 = 10 m, p_0 = 0.3 MPa, Δt_r = 20 ms. In order to determine the pressure increase time, for the values for p_s and Q_z assumed in the simulation software, the line resistance R_{hp} was calculated with formula (4), and subsequently, by simulating the system provided on Fig. 3 for p_0 = 0.3 MPa the appropriate value of volume V_o of the delaying accumulator needs to be established so that the required delay value Δt is achieved, as calculated from formula (3).

3.5 System simulation

Example results of simulating the transmitter-receiver system carried out using the parameters established earlier are presented on Fig. 7. Regardless of the pressure value p_s and the placement sequence of receivers in the signal line, in a correctly working system, the following sequence of engaging the flow dividers need to be observed: after momentary switching of valve 12n to position “1” the specified divider 20o is switched to setting “1”, next, after the divider 13n is set to position “1” the dividers 18o, 20o, and next 12 n and finally 13n are switched to setting “0”. After this sequence is finished, it is possible to generate a new signal p_s. If the system parameters are set correctly, the proper order of the sequence will always be maintained with shutoff times $t_{off13n} \geq t_{off12n} \geq t_{off20o} \geq t_{off18o}$. Otherwise, there is a risk that the user generates a different signal pressure p_s in the time when the initialized divider 20o did not return to setting "0", and the hydraulic block is already disengaged. An example system response with improperly set parameters can be seen on the simulation provided on Fig. 7b.

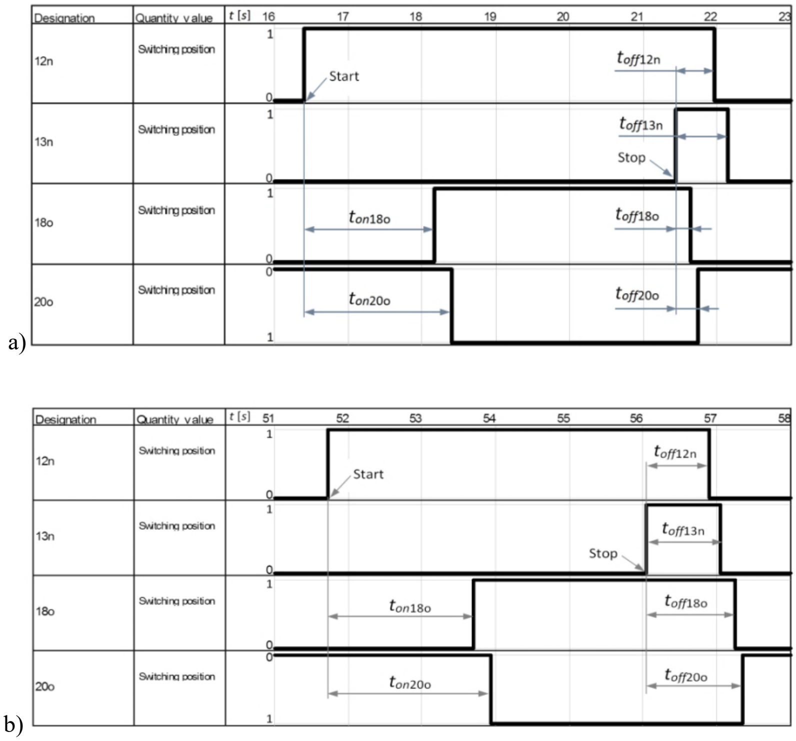

Fig. 7. Example simulation results for the operation of the transmitter-receiver system, operating: a) correctly, b) incorrectly

4 The influence of the transmitter-receiver parameters on the correctness of system operation

The preliminary simulation testing reveal that the transmitter-receiver system is functioning correctly, on the condition that the provided parameters are correct. In order to determine their influence on the correctness of the operating parameters of the system, was carried out a simulation for different values of selected parameters. Out of over 37 parameters, the testing analyzed only the parameters with material influence on the changes occurring during system operation. This stems from the fact that some of the parameter values were calculated (e.g. valve resistance for 12n-14n, or the parameters of the signal line); other parameters, due to the working characteristics of the components (to which the discussed parameters are related) are not relevant for the tested model (e.g. valves 14o-17o), or finally those with predictable effect when combined with other parameters (e.g. resistance for valves 18o, 19o and 21o connected in series). In the course of the study, the influence of the following parameters was analyzed: signal pressure p_s, supply flow Q_z, resistance of valves: 15n, 16n, 21n, 22n, 18o, 19o, 21o, 22o and 28o and accumulator volume V_{20n}.

4.1 The influence of signal pressure p_s and supply flow Q_z

The results obtained from simulation were analyzed in the range of signal pressure p_s = 2-16 MPa, while keeping the assumed values for all other parameters. Based on the testing results it was observed that together with the increase in pressure p_s the engaging time t_{on20o} = 2.38-6.14 s (≈157%) increases almost linearly and it can be formulated as $t_{on20o}(p_s) = 0.268p_s + 1.96$ [s]. The engaging time t_{off13n} changes in the range of 0.8-2.7 s (≈ 242%), whereas the value change can be approximated as a function $t_{off13n}(p_s) = 0.928 \cdot \ln(p_s) + 0.244$. On the other hand, the increase in supplied flow in the range of Q_z = 3-15 dm^3/min allows to reduce the t_{on20o} time by approx. 49% at pressure 2 MPa and by 77% at 16 MPa. The time t_{off13n} was reduced by approx. 12% at p_s = 2 MPa, whereas at 16 MPa, it remained mostly unchanged. Therefore, the increase in supplied flow causes a decrease in the difference in engage and disengage time of the receiver, in particular the time t_{off13n} at maximum p_s.

4.2 The influence of selected resistance values in the system

The resistance value of the examined valves was decreased by two or three orders of magnitude (change of flow diameter of approx. 210-460%) compared to the initial value established in Chapter 3. The range of pressure adjustment p_s = 2-16 MPa, and supplied flow Q_z were kept unchanged (Q_z = 3 dm^3/min).

The change of resistance value of valve 15n in range R_{h15n} = 0.0005-0.5 MPa/(dm^3/min)^2 at p_s = 2 MPa causes a longer engaging time t_{on18o} by approx. 200%, t_{on18o}=2.5-7.7 s, and at p_s = 16 MPa the change is negligibly small (approx. 0.16%). Shutdown times t_{off13n} for R_{h15n} = 0.0005 and at p_s = 2 MPa are relatively short t_{off13n} = 0.8 s, and with the increase in resistance to R_{h15n} = 0.5 MPa/(dm^3/min)^2 they are practically unchanged (increase ≈ 3.7%). At maximum pressure p_s and minimum resistance, together with the increase of resistance to 0.5 the time t_{off13n} = 2.37 s, shows an increase by approx.16%.

A similar nature of change in transmitter-receiver response times is observable when adjusting the resistance of valve 16n. For minimum pressure p_s = 2 MPa and changing the resistance to R_{h16n} = 0.5 MPa/(dm^3/min)^2 a time increase is observed for t_{on16n}, of 730%. At p_s = 16 MPa, the changes are very small and amount to approximately 1.7%. The shutoff times t_{off13n} at minimal resistance increase only to a very small degree (up to 4.5%) for the entire range of pressure values p_s.

The increase of resistance for valve 16n to the value R_{h16n} = 0.5 MPa/(dm^3/min)^2 causes disturbances which, when engaging a specific receiver, manifest as short-term shutoff of all other receivers with p_s value set as lower (≈2-5 MPa) in comparison to the pressure of the initialized receiver. During the cancelling of signal p_s, the proper sequence of engaging the valves 12n, 13n, 18o and 20o is maintained. The increase of resistance for both the valve 15n and 16n therefore causes a decrease in response time of the receiver for lower pressure values p_s, which is caused by the longer charging time of accumulator 20n after exceeding the set pressure on valve 16n equal to 1 MPa. In this situation, the supplied flow Q_z is divided. One part is directed to the accumulator 20n, the other reaches the line and due to the high resistance of valves 15n and 16n causes a relatively slow increase in pressure until the accumulator is charged. When the resistance of examined valves becomes relatively low, the entire flow Q_z is first directed to accumulator 20n, and after it becomes charged, the entire flow reaches the signal line and allows to obtain the required speed of pressure increase p_s, until the value equal to 0.8 MPa is exceeded. Hence, in the range of set pressures p_s = 2-16 MPa the speed of this increase is sufficient to prevent the characteristic, short-term shutoffs from occurring.

The increase in resistance of valve 21n to the maximum value examined during testing, regardless of pressure p_s, does not cause a noticeable change in the engaging time of valve 20o, whereas the change of shutoff times of valve 13n is noticeable. For pressure $p_s = 2$ MPa, in relation to the initial value $t_{off13\mathrm{n}} = 0.69$ s the time increases by approx. 220%, whereas at $p_s = 16$ MPa, the observed extension is by 130%. In the entire range of resistance value change, no disturbances in system operation were observed. The latency stems from the fact that after generating pressure at terminals X2 causing shutoff of divider 12n, and subsequently discharge of accumulator 20n by: valve 17n, all dividers 12n as well as the check valve 21n. With increased resistance, the blocking pressure at terminal X of valve 13n will be maintained longer.

Changing the resistance of valve 22n causes the engagement time of valve 20o along the entire range of pressures p_s to increase only slightly, the increase of $t_{on18\mathrm{o}}$ for $R_{h22\mathrm{n}} = 0.005\text{-}0.5$ MPa/(dm^3/min)^2 does not exceed 2.5%. Whereas shutoff time $t_{off13\mathrm{n}}$ increases to 17%, regardless of the value of signal pressure. In the range of increased resistance of valve 22n, there are visible interferences in system operation, manifesting themselves by failure to keep the proper sequence when engaging the valves 12n, 13n, 18o and 20o during the cancelling of signal p_s (the times $t_{off13\mathrm{n}} > t_{off12\mathrm{n}} < t_{off20\mathrm{o}} > t_{off18\mathrm{o}}$). This disturbance is caused by a decrease in the speed of pressure discharge at the signal line. This speed is insufficient to ensure that the shutoff of divider 18o is effected before the shutoff of divider 12n, which occurs after charging (in the assumed time) of accumulator 20n.

In the receiver system, the change of resistance of dividers 18o, 19o and check valves 22o and 28o were examined. During the generation of signal X3, the resistance of divider 18o does not have any major influence, as it is lower by nearly two orders of magnitude than the resistance of the throttle valve 21o. As mentioned in subchapter 3.2, the result of lowering this value is increasing the charging time of accumulator 23o. When cancelling the signal X3, the medium flow is primarily from accumulator 23o through divider 18o and check valves 22o and 28o, and therefore, the change of resistance in the three components can be examined collectively. For the purpose of simplification for simulation testing, only the resistance value of valve 28o was changed in the range of $R_{h28\mathrm{o}} = 0.005\text{-}0.5$. For pressure value $p_s = 2$ MPa, the increase in resistance causes an increase in time $t_{off20\mathrm{o}}$ by 130% at the maximum. The critical value $R_{h20\mathrm{o}}$ from the point of view of the correct engagement sequence of the valves is $R_{h20\mathrm{o}} \approx 0.29$ MPa/(dm^3/min)^2, as if the value is exceeded, the time $t_{off20\mathrm{o}} > t_{off12\mathrm{n}}$, which is a symptom of incorrect system operation. For pressure $p_s = 16$ MPa with $R_{h28\mathrm{o}} = 0.5$, the change is only by 35%, and the critical value is observed only at $R_{h20\mathrm{o}} \approx 2.86$. It is therefore concluded in the testing that too large increase in the total resistance value of components 18o, 19o, 22o, 28o causes disturbance in the operation of the transmitter-receiver system, in particular this applies to the lower range of pressures p_s.

Both the resistance of the throttle valve 21o and the volume of accumulator 23o are not parameters which directly determine the delay between the engaging of valves 18o and 20o. Assuming constant volume $V_{23\mathrm{o}}$, the delay time will only depend on the resistance value $R_{h21\mathrm{o}}$. The range of this value is $R_{h21\mathrm{o}} = 0.035\text{-}3.5$ MPa/(dm^3/min)^2. For maximum pressure $p_s = 16$ MPa, in range of $R_{h21\mathrm{o}} = 0.035\text{-}0.05$, the system does not operate in a stable manner as the characteristic momentary disengagement of dividers 20o, which was discussed in subchapter 3.3, is observed. The critical values for resistances $R_{h21\mathrm{o}}$ are: 0.29 at pressure $p_s = 2$ MPa and 0.09 at $p_s = 4$ MPa. From the value $p_s = 7$ MPa and above, a stabilization occurs at approximately 0.06. Therefore, the receivers most sensitive to change are the ones with low range of pressure values ($p_s = 2\text{-}4$ MPa). The increase of resistance to $R_{h21\mathrm{o}} = 3.5$ serves to increase the time delay by approx. 8.5% compared to its initial value $t_{on20\mathrm{o}} \approx 6\ s$ at $R_{h21\mathrm{o}} = 0.35$.

4.3 The influence of volume of accumulator 20n

In the course of simulation testing, the volume of the accumulator 20n was changed in the range of V_{20n} = 0.05-0.5 dm^3. At the volume V_{20n} < 0.07 dm^3 the transmitter does not operate in a stable way, which manifests itself in the previously discussed phenomenon of premature shutoff of dividers 12n. At the range of V_{20n} = 0.07-0.15 dm^3, especially for the lowest pressure values, the transmitter operates in a stable manner; however, the system does not operate correctly in connection with the receiver as the proper shutoff sequence of dividers 12n, 13n, 18o and 20o is not observed. The shutoff times in this case are $t_{off13n} < t_{off12n} < t_{off20o} > t_{off18o}$. With the value range V_{20n} = 0.2-0.5 dm^3 the system operates correctly. At p_s = 2 MPa the engaged time t_{on20n} increases from 1.67 s to approx. 3.53 *s* (≈111%), whereas for p_s = 16 MPa t_{on20n} = 5.6-6.65 s. (≈19%). The shutoff times t_{off13n} at p_s = 2 MPa are relatively short and are equal to approximately 0.5 s for V_{20n} = 0.2 dm^3, and for V_{20n} = 0.5 dm^3 they become longer by approx. 125%. For p_s = 16 MPa and V_{20n} = 0.2 dm^3 t_{off13n} = 1.68 s, and for V_{20n} = 0.5 dm^3 there is a noticeable increase at over 115%. The most optimal range of V_{20n} values from the standpoint of correct system operation and achieving the lowest possible reaction times is therefore in the range of approximately 0.2-0.25 dm^3. Above this range, the engaged times for receiver and shutoff times for the transmitter are increased. Moreover, larger accumulator volume causes an unjustified increase in device dimensions. One needs to point out that similarly to the delay mechanism in the receiver, it is also possible to alter the flow value Q_r at the regulator 19n instead of the accumulator volume.

5 Conclusion

The obtained simulation results allow to conclude that the presented concept of hydraulic control mechanism for multiple devices utilizing a single signal line is possible to realize. Furthermore, the results obtained from the simulation allow to evaluate, in the broad range, the influence of parameters of the transmitter-receiver system on its operation. The obtained knowledge will allow to prepare a method of selecting system parameters allowing for an easier estimation of the hydraulic component parameters in the prototype construction achieved at later stages of the study.

References

1. S. Stryczek, *Napęd hydrostatyczny – układy*. (WNT, Warszawa 2003)
2. Z. Szydelski, *Pojazdy samochodowe – Napęd i sterowanie hydrauliczne*. (WKŁ, Warszawa,1999)
3. D. Frąckowiak, *Hydrauliczny nadajnik ciśnieniowy*. Zgłoszenie patentowe nr **P.420408**
4. D. Frąckowiak, *Hydrauliczny odbiornik ciśnieniowy.* Zgłoszenie patentowe nr **P.420407**
5. A. Figiel , Z. Kuźma, O. Mackiewicz, *Pośredni sposób określania prędkości propagacji fal ciśnienia w przewodach hydraulicznych*, Hydraulika i Pneumatyka **5/2015**, 16-21 (2015)
6. M. Guillon, *Teoria i obliczanie układów hydraulicznych.* (WNT, Warszawa 1966)
7. Strona internetowa: www.mooge.com , broszura informacyjna – Moog servovalve 772 series.