HUMAN CAPITAL
NATIONAL COHESION STRATEGY

Wrocław University of Technology

EUROPEAN UNION
EUROPEAN
SOCIAL FUND

THE DEVELOPMENT OF THE POTENTIAL AND ACADMIC PROGRAMMES OF WROCLAW UNIVERISTY OF TECHNOLOGY

Automotive Engineering

Michał Stosiak, Ph.D. Eng.

Testing of vehicle elements and assemblies

Testing of the brake system elements

Project co-financed by European Union within European Social Fund

Introduction

Automotive brake systems use the force of hydraulic pressure to apply the brakes. Because automotive brakes use hydraulic pressure, we need to study some basic hydraulic principles used in brake systems. These include the principles that fluids cannot be compressed, fluids can be used to transmit movement and force, and fluids can be used to increase force.

LAWS OF HYDRAULICS

Automotive brake systems are complex hydraulic circuits. To better understand how the systems work, a good understanding of how basic hydraulic circuits work is needed. A simple hydraulic system has liquid, a pump, lines to carry the liquid, control valves, and an output device. The liquid must be available from a continuous source, such as the brake fluid reservoir or a sump. In a hydraulic brake system, the master cylinder serves as the main fluid pump and moves the liquid through the system. The lines used to carry the liquid may be pipes, hoses, or a network of internal bores or passages in a single housing, such as those found in a master cylinder. Valves are used to regulate hydraulic pressure and direct the flow of the liquid. The output device is the unit that uses the pressurized liquid to do work. In the case of a brake system, the output devices are brake drum wheel cylinders **(Figure 1)** and disc brake calipers.

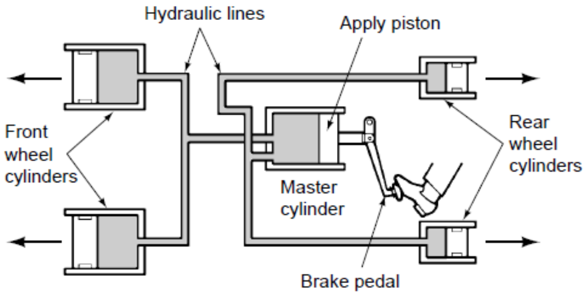

Figure 1. The master cylinder is an apply piston, working as a pump, to provide hydraulic pressure to the output pistons at the wheel brakes.

As can be seen, hydraulics involves the use of a liquid or fluid. Hydraulics is the study of liquids in motion. All matter, everything in the universe, exists in three basic forms: solids, liquids, and gases. A fluid is something that does not have a definite shape; therefore, liquids and gases are fluids. A characteristic of all fluids is that they will conform to the shape of their container. A major difference between a gas and a liquid is that a gas will always fill a sealed container, whereas a liquid may not. A gas will also readily expand or compress according to the pressure exerted on it **(Figure 2)**. A liquid will typically not compress, regardless of the pressure on it. Therefore, liquids are considered noncompressible fluids. Liquids will, however, predictably respond to pressures exerted on them. Their reaction to pressure is the basis of all hydraulic applications. This fact allows hydraulics to do work.

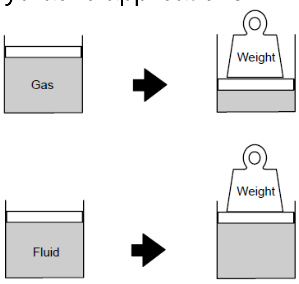

Figure 2. Gases are compressible, but liquids are not.

Pascal’s Law

More than 300 years ago a French scientist, Blaise Pascal, determined that if you had a liquid-filled container with only one opening and applied force to the liquid through that opening, the force would be evenly distributed throughout the liquid. This explains how pressurized liquid is used to operate and control the brakes on a vehicle. The action of the brake pedal on the pistons inside the master cylinder pressurizes the brake fluid and the fluid is delivered to the various wheel brake units **(Figure 3)**.

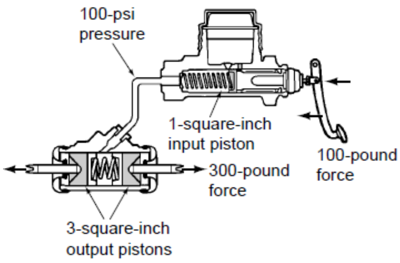

Figure 3. The mechanical force exerted on the brake pedal is transferred hydraulically to provide an increased mechanical force at the wheel brake unit.

Pascal constructed the first known hydraulic device, which consisted of two sealed containers connected by a tube. The pistons inside the cylinders seal against the walls of each cylinder and prevent the liquid from leaking out of the cylinder and prevent air from entering into the cylinder. When the piston in the first cylinder has a force applied to it, the pressure moves everywhere within the system. The force is transmitted through the connecting tube to the second cylinder. The pressurized fluid in the second cylinder exerts force on the bottom of the second piston, moving it upward and lifting the load on the top of it. By using this device, Pascal found he could increase the force available to do work, just as could be done with levers or gears. Pascal determined that force applied to liquid creates pressure or the transmission of force through the liquid. These experiments revealed two important aspects of a liquid when it is confined and put under pressure. The pressure applied to it is transmitted equally in all directions and this pressure acts with equal force at every point in the container.

Interesting fact: Pascal’s work is known as Pascal’s Law. Pascal’s Law says that pressure at any one point in a confined liquid is the same in every direction and applies equal force on equal areas. One of the most important results of Pascal’s work was the discovery that fluids may be used to increase force. Pascal was the person who first demonstrated the relationships of pressure, force, and motion and the inverse relationship of motion and force. In an automobile, Pascal’s Laws are not applied just to the brake system. These same hydraulic principles are at work in the hydraulic system of an automatic transmission. Pascal’s Laws are even at work in the movement of liquid fuel from a tank to the fuel injection system on the engine.

Fluid Characteristics

If a liquid is confined and a force applied, pressure is produced. In order to pressurize a liquid, the liquid must be in a sealed container. Any leak in the container will decrease the pressure. The basic principles of hydraulics are based on certain characteristics of liquids. Liquids have no shape of their own; they acquire the shape of the container they are put in. They also always seek a common level. Therefore, oil in a hydraulic system will flow in any direction and through any passage, regardless of size or shape. Liquids are basically incompressible, which gives them the ability to transmit force. The pressure applied to a liquid in a sealed container is transmitted equally in all directions and to all areas of the system and acts with equal force on all areas .As a result, liquids can provide great increases in the force available to do work. A liquid under pressure may also change from a liquid to a gas in response to temperature changes.

Fluids Can Transmit Movement

Liquids can be used to transmit movement. Two cylinders of the same diameter are filled with a liquid and connected by a pipe as shown in **Figure 4**. If you force piston A downward, the liquid will push piston B upward. Because piston A starts the movement, it is called the apply piston. Piston B is called the output piston. If the apply piston moves 10 inches, the output piston also will move 10 inches. This principle works not only for one output piston, but for any number of output pistons. The principle that motion can be transmitted by a liquid is used in hydraulic brake systems. A master cylinder piston is pushed when the driver applies the brakes. The master cylinder piston is the apply piston. The brake fluid in the master cylinder is connected by pipes to pistons in each of the car's front and rear wheel brake units. Each of the wheel brake pistons is an output piston. They move whenever the master cylinder input piston moves.

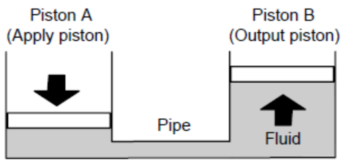

Figure 4. Fluid can transmit motion through a closed system

Mechanical Advantage with Hydraulics

Hydraulics is used to do work in the same way as a lever or gear does work. All of these systems transmit energy or force. Because energy cannot be created or destroyed, these systems only redirect energy to perform work and do not create more energy. **Work** is the amount of force applied and the distance over which it is applied. **Force** is power working against resistance; it is the amount of push or pull exerted on an object needed to cause motion. We usually measure force in the same units that we use to measure weight: pounds or kilograms. **Pressure** is the amount of force exerted onto a given surface area. Therefore, pressure equals the applied force (measured in pounds or kilograms) divided by the surface area (measured in square inches or square centimeters) that is receiving the force. In customary English units, pressure is measured in pounds per square inch (psi). In the metric system it can be measured in kilograms per square centimeter, but the preferred metric pressure measurement unit is the pascal. The pressure of a liquid in a closed system such as a brake hydraulic system is the force exerted against the inner surface of its container, which is the surface of all the lines, hoses, valves, and pistons in the system. Pressure applied to a liquid exerts force equally in all directions. If the hydraulic pump provides 100 psi, there will be 100 pounds of force on every square inch of the system **(Figure 5)**.When pressure is applied to a movable output piston, it creates output force.

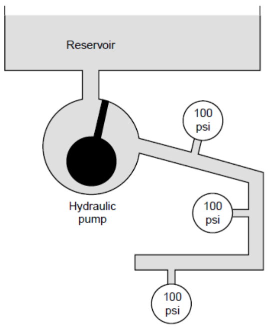

Figure 5. While contained, the pressure of a liquid is the same throughout the container.

If the system included a piston with an area of 30 square inches, each square inch would receive 100 pounds of force. This means there would be 3,000 pounds of force applied to that piston **(Figure 6)**.The use of the larger piston would give the system a mechanical advantage or increase in the force available to do work. The multiplication of force through a hydraulic system is directly proportional to the difference in the piston sizes throughout the system. By changing the sizes of the pistons in a hydraulic system, force is multiplied, and as a result, low amounts of force are needed to move heavy objects. The mechanical advantage of a hydraulic system can be further increased by the use of levers to increase the force applied to a piston

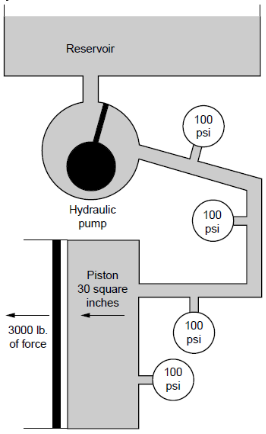

Figure 6. One hundred psi on a 30-square-inch piston generates 3000 pounds of force

In **Figure 7**, input piston A is smaller than output piston B. Piston A has an area of 20 square inches; in the example, we are applying 200 pounds of force. Therefore,

$$\frac{200\ pounds(F)}{20\ square\ inches\,(A)} = 10\ psi(P)$$

where F is force, A is area, and P is pressure.
If that same 200 pounds of force is applied to a piston of 10 square inches, system pressure is 20 psi because

$$\frac{200\ pounds(F)}{10\ square\ inches\,(A)} = 20\ psi(P)$$

Therefore, pressure is inversely related to piston area. The smaller the piston, the greater the pressure that is developed.

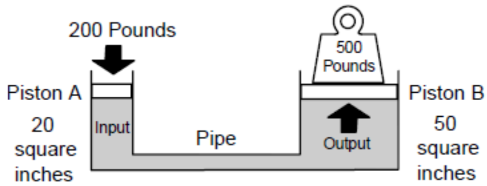

Figure 7. A hydraulic system also can increase force

Let us apply the 10 psi of pressure in the first example to an output piston with an area of 50 square inches. In this case, output force equals pressure times the surface area:

$$P \times A = F \tag{1}$$

Therefore, 10 psi of pressure on a 50-square-inch piston develops 500 pounds of output force:

$$10 \times 50 = 500$$

Brake systems use hydraulics to increase force for brake application.
Figure 8 shows a hydraulic system with an input piston of 10 square inches. A force of 500 pounds is pushing on the piston. The pressure throughout the system is 50 psi:
$500(F)/10(A) = 50(P)$

pressure gauge in the system shows the 50-psi pressure. There are two output pistons in the system. One has 100 square inches of area. The 50-psi pressure in the system is transmitted equally everywhere in the system. This means that the large output piston has 50 psi applied to 100 square inches to deliver an output force of 5000 pounds:

$$100\, square\, inches \times 50\ psi = 5000\ pounds$$

The other output piston in Figure 8 is smaller than the input piston with a 5-square-inch area. The 5-square-inch area of this piston has 50-psi pressure acting on it to develop an output force of 250 pounds:

$$5\, square\, inches \times 50\ psi = 250\ pounds$$

In a brake system, a small master cylinder piston is used to apply pressure to larger pistons at the wheel brake units to increase braking force. Importantly, the pistons in the front brakes have a larger surface area than the pistons in the rear brakes. This creates greater braking force at the front wheels to overcome the weight transfer created by momentum during braking.

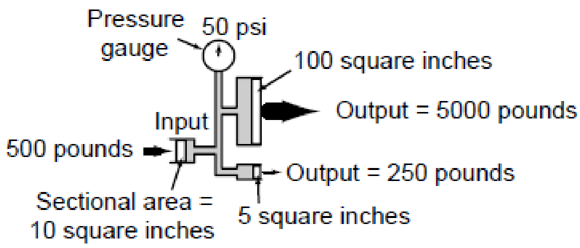

Figure 8. Different-sized output pistons produce different amounts of output force from the same hydraulic pressure.

Hydraulic Pressure, Force, and Motion

Although the force available to do work is increased by using a larger piston in one cylinder, the total movement of the larger piston is less than that of the smaller one. When output force increases, output motion decreases. If the 10-square-inch input piston moves 2 inches as it applies 50 psi to the 100-square-inch output piston, that output piston will move only 0.2 inch as it applies 5000 pounds of output force **(Figure 9)**.The ratio of input motion to output motion is the ratio of the input piston area to the output piston area, and you can use this simple equation to calculate it: The result from dividing the area of the input piston (A1) by the area of the output piston is multiplied by the stroke of the input piston or

$$(A1 - A2) \times S\ (the\ input\ stroke) = M\ (the\ output\ stroke) \tag{2}$$

or

$$\frac{10\, square\, inches\ (input\ piston)}{100\, square\, inches\ (output\ piston)} = \frac{1}{10} \times 2\, inches\ (input\ stroke) = 0.2\, inch\ output\ motion$$

If the output piston is larger than the input piston, it exerts more force but travels a shorter distance. The opposite also is true. If the output piston is smaller than the input piston, it exerts less force but travels a longer distance. Apply the equation to the 5-square-inch output piston in Figure 9:

$$\frac{10\, square\, inches\ (input\ piston)}{5\, square\, inches\ (output\ piston)} = \frac{2}{1} \times 2\, inches\ (input\ stroke) = 4.0\, inches\ output\ motion$$

In this case, the smaller output piston applies only half the force of the input piston, but its stroke (motion) is twice as long.

These relationships of force, pressure, and motion in a brake system are easily observed when you consider the force applied to the master cylinder's pistons and the resulting brake force and piston movement at the wheels. Wheel cylinder pistons move only a fraction of an inch to apply hundreds of pounds of force to the brake shoes, but the wheel cylinder piston travel is quite a bit less than the movement of the master cylinder piston. Disc brake caliper pistons move only a few thousandths of an inch but apply great force to the brake rotors.

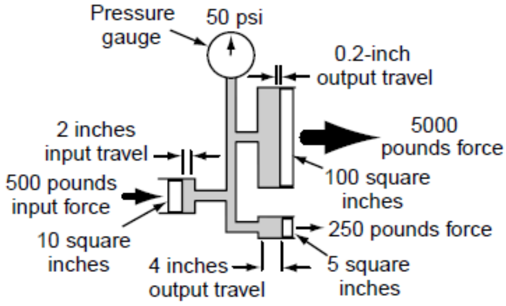

Figure 9. As output force increases, output travel (motion) decreases

This demonstrates how the use of hydraulics provides a mechanical advantage similar to that provided by the use of levers or gears. Although hydraulic systems, gears, and levers can accomplish the same results, hydraulics is preferred when the size and shape of the system are of concern. In hydraulics, the force applied to one piston will transmit through the fluid, and the opposite piston will have the same force on it. The distance between the two pistons in a hydraulic system does not affect the force in a static system. Therefore, the force applied to one piston can be transmitted without change to another piston located somewhere else. A hydraulic system responds to the pressure or force applied to it. The mere presence of different-sized pistons does not always result in fluid power. The force or pressure applied to the pistons must be different in order to cause fluid power. If an equal amount of pressure is exerted onto both pistons in a system and both pistons are the same size, neither piston will move; the system is balanced or is at equilibrium. The pressure inside the hydraulic system is called **static pressure** because there is no fluid motion.
When an unequal amount of pressure is exerted on the pistons, the piston receiving the least amount of pressure will move in response to the difference between the two pressures. Likewise, the fluid will move if the size of the two pistons is different and an equal amount of pressure is exerted on the pistons. The pressure of the fluid while it is in motion is called **dynamic pressure**.

HYDRAULIC BRAKE SYSTEMS

Engineers must consider these principles of force, pressure, and motion when designing a brake system for any vehicle. If an engineer chooses a master cylinder with relatively small piston areas, the brake system can develop very high hydraulic pressure, but the pedal travel will be extremely long. Moreover, if the master cylinder piston travel is not long enough, this high-pressure system will not move enough fluid to apply the large-area caliper pistons regardless of pressure. If, on the other hand, the engineer selects a large-area master cylinder piston, it can move a large volume of fluid but may not develop enough pressure to exert adequate braking force at the wheels. The overall size relationships of master cylinder pistons, caliper pistons, and wheel cylinder pistons are balanced to achieve maximum braking force without grabbing or fading. Most brake systems with front discs and rear drums have large-diameter master cylinders (a large piston area) and a power booster to increase the input force.

HYDRAULIC BRAKE FLUID

The liquid used in a hydraulic brake system is brake fluid. The specifications for all automotive brake fluids are defined by Society of Automotive Engineers (SAE) Standard J1703 and Federal Motor Vehicle Safety Standard (FMVSS) 116. Fluids classified according to FMVSS 116 are assigned United States Department of Transportation (DOT) numbers: **DOT 3, 4, and 5**. Basically, the higher the DOT number, the more rigorous the specifications for the fluid. These specifications list the qualities that brake fluid must have, such as:

- Free flow at low and high temperatures.
- A high boiling point (over 400°F or 204°C).
- A low freezing point.
- Ability to not deteriorate metal or rubber brake parts.

- Ability to lubricate metal and rubber parts.
- Ability to absorb moisture that enters the hydraulic system.

Choosing the right fluid for a specific vehicle is not based on the simple idea that if DOT 3 is good, DOT 4 must be better, and DOT 5 better still. The domestic carmakers all specify DOT 3 fluid for their vehicles, but Ford calls for a heavy-duty variation that meets the basic specifications for DOT 3 but has the higher boiling point of DOT 4. Import manufacturers are about equally divided between DOT 3 and DOT 4. DOT 3 and DOT 4 fluids are polyalkylene-glycol-ether mixtures, called **polyglycol**. The color of both DOT 3 and DOT 4 fluid ranges from clear to light amber. DOT 5 fluids are all silicone based because only silicone fluid—so far—can meet the DOT 5 specifications. No vehicle manufacturer, however, recommends DOT 5 fluid for use in its brake systems. Although all three fluid grades are compatible they do not combine well if mixed together in a system. Therefore, the best rules are to use the fluid type recommended by the manufacturer and never mix fluid types in a system.

Brake Fluid Boiling Point

The most apparent differences among the three fluid grades are the minimum boiling points as listed below:

	DOT 3	DOT 4	DOT 5
Dry boiling point	401 ^oF (205 ^oC)	446 ^oF (230 ^oC)	500 ^oF (260 ^oC)
Wet boiling point	284 ^oF (140 ^oC)	311 ^oF (155 ^oC)	356 ^oF (180 ^oC)

The boiling point is important because heat generated by braking can be transmitted into the hydraulic system. If the temperature rises too high, the fluid can boil and form a vapor in the brake lines. The stopping power of the system then will be reduced. As a result, the brake pedal can go to the floor and the vehicle will not stop. The dry boiling point is the minimum boiling point of new, uncontaminated fluid. Because brake fluids are hygroscopic, their boiling points decrease due to water contamination after the fluid has been in service for some time. Brake systems are not completely sealed, and some exposure of the fluid to air is inevitable.

Other Brake Fluid Requirements

A high-temperature boiling point is not the only requirement brake fluid must meet. Brake fluid must remain stable throughout a broad range of temperatures, and it must retain a high boiling point after repeated exposure to high temperatures. Brake fluid must also resist freezing and evaporation and must pass specific viscosity tests at low temperatures. If the fluid thickens and flows poorly when cold, brake operation will suffer. Besides temperature requirements, brake fluid must pass corrosion tests. It also must not contribute to deterioration of rubber parts and must pass oxidation-resistance tests. Finally, brake fluid must lubricate cylinder pistons and bores and other moving parts of the hydraulic system.

Reservoir

All hydraulic systems require a reservoir to store fluid and to provide a constant source of fluid for the system. In a brake system, the reservoir is attached to the top of the master cylinder, although some vehicles might use tubing to connect the reservoir to the master cylinder. Brake fluid is forced out of the pan by atmospheric pressure into the master cylinder and returned to it after the brake pedal has been let up.

Venting

In order to allow the fluid to flow into the master cylinder, the reservoir has an air vent that allows atmospheric pressure to force the fluid into the master cylinder when a low pressure is created by the movement of the pistons. The vent is positioned above the normal brake fluid level in the reservoir and keeps atmospheric pressure at the top of the fluid.

VACUUM AND AIR PRESSURE PRINCIPLES

A law of nature defines the role of **atmospheric pressure** on the operation of a brake system. The law simply states that whenever a high pressure is introduced to a lower pressure, it moves to equalize the pressures. In other words, something that has a high pressure will always move toward something that has a lower pressure. The force at which the higher pressure moves toward the lower pressure is determined by the difference in pressures. When the pressure is slightly lower than atmospheric, the force is low. When there is a large difference, the higher pressure will rush into the lower and the force will be great. In the world of automotive technology, any pressure that is lower than atmospheric pressure is called a **vacuum**. Atmospheric pressure **(Figure 10)** is the pressure of the air around and on us and has a value of approximately 14.7 psi at sea level. When we are at higher elevations, there is less air above and on us and therefore the pressure of the atmosphere is less, but that air is still considered atmospheric pressure, and any pressure less than that is a vacuum.

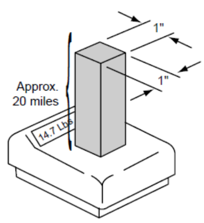

Figure 10. A square-inch column of air the height of the earth's atmosphere exerts 14.7 pounds of pressure on the Earth's surface at sea level.

When the pistons inside a master cylinder move, the volume of the piston's cylinder changes. When the volume decreases, the pressure increases. When the piston moves back to its original location, the pressure is lower and atmospheric pressure pushes fluid from the reservoir into the cylinder. The relationship of vacuum and atmospheric pressure is used in most power brake systems to provide a power assist for the driver **(Figure 11)**. The rush of high pressure toward an area of vacuum causes an increase in force, much like a lever.

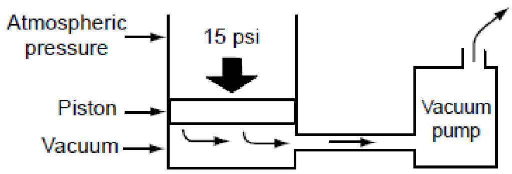

Figure 11. Vacuum (low pressure) works with atmospheric pressure to develop force.

Summary

- In a hydraulic brake system, the master cylinder moves brake fluid through the system. The lines used to carry the liquid may be pipes, hoses,or a network of internal bores or passages in a single housing, such as those found in a master cylinder. Valves are used to regulate hydraulic pressure and direct the flow of the liquid. The output devices are brake drum cylinders and disc brake calipers.
- Hydraulics is the study of liquids in motion.
- Liquids are considered noncompressible fluids.
- Pascal's Law says that pressure at any one point in a confined liquid is the same in every direction and applies equal force on equal areas.
- If a liquid is confined and a force applied, pressure is produced. If the pressure on the fluid is applied to a movable output piston, it creates output force.
- In a brake system, a small master cylinder piston is used to apply pressure to larger pistons at the wheel brake units to increase braking force.

- Most brake systems with front discs and rear drums have large-diameter master cylinders (large piston area) and a power booster to increase the input force.
- DOT 3 and DOT 4 fluids are polyglycol mixtures. The color of both DOT 3 and DOT 4 fluids ranges from clear to light amber.
- Although the performance requirements of DOT 3 and 4 fluids are different, FMVSS 116 requires that the grades of fluid be compatible with each other in a system; however, mixing different types of fluid in a system is not recommended.
- All hydraulic systems require a reservoir to store fluid and to provide a constant source of fluid for the system.
- The relationship of vacuum and atmospheric pressure is used in most power brake systems.

Tasks to execute

1. Forces and velocities calculating. **.** Build an hydraulic system according to scheme presented on fig. 12.

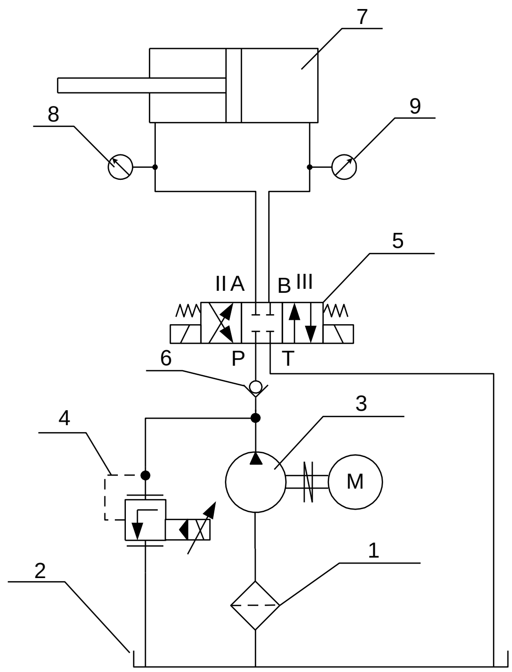

Figure 12. Scheme of test system: 1 – filter, 2 – tank, 3 – fixed displacement pump, 4 – proportional relief valve, 5 – 4/3 directional control valve with “on/off” solenoids, 6 – check valve, 7 – double acting, single piston rod hydraulic cylinder, 8,9 - manometers

For system presented at fig. 12 calculate actual and maximal force at piston rod during extension and return of the cylinder. Moreover calculate velocities for extension and return of the cylinder.

$$F_{\max} = p_{\max} \cdot A \tag{3}$$

$$F_{actual} = p_{actual} \cdot A \tag{4}$$

$$v_i = \frac{Q_p}{A_i} \quad (5)$$

where: F_{max} – maximal force at piston rod, p_{max} – maximal pressure in system, F_{actual} – actual force at piston rod, p_{actual} – actual pressure in system, v_i – cylinder velocity, Q_p – pump capacity, A_i – cylinder active area.

2.1. Next test step - pipes length (6) is equal to L_1 = 1000 mm.

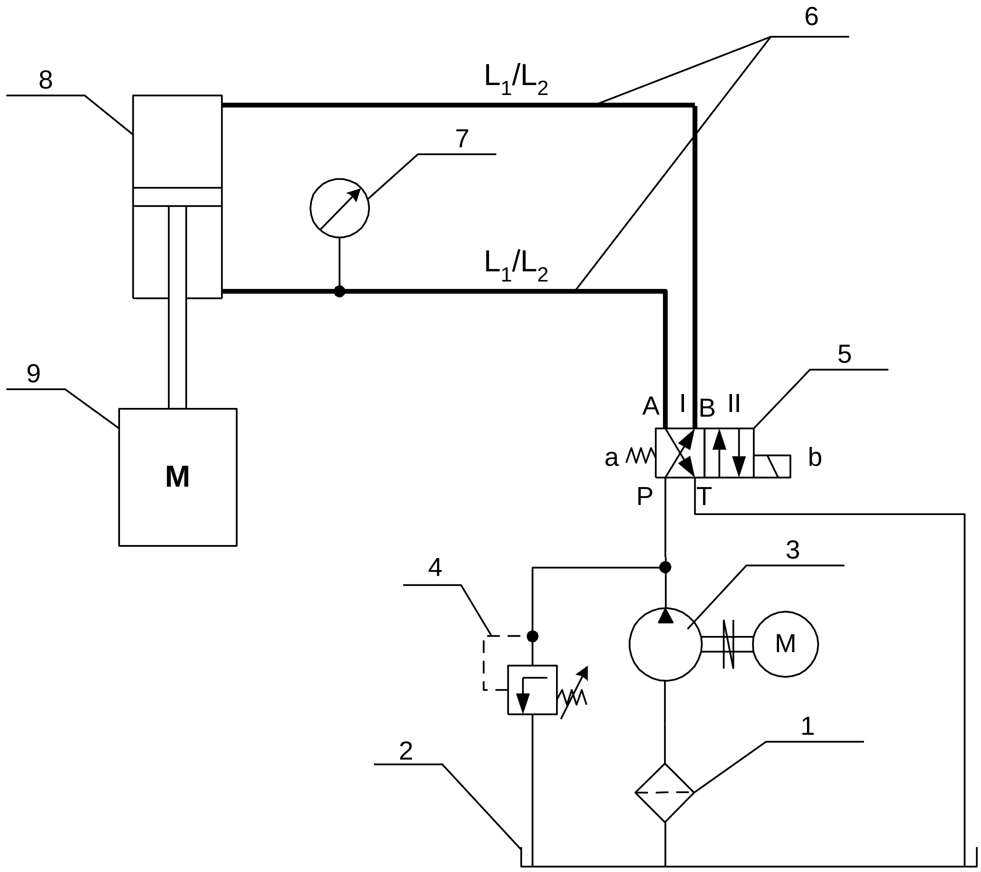

Figure 13. Scheme of test system: 1 – filter, 2 – tank, 3 – fixed displacement pump, 4 – safety valve, 5 – 4/2 directional control valve with “on/off” solenoids, 6 – flexible pipes (length L_1 = 1000 mm, length L_2 = 2000 mm), 7 – pressure transducer, 8 – double acting, single piston rod hydraulic cylinder, 9 – external load (30 kg).

An electrical circuit of solenoid is operated by a monostable button normally opened. A spring keeps valve spool in position I. The closure of the electrical circuit of solenoid b causes the cylinder to move up. Ports P and B are connected now. Ports A and T are connected now too. During the system start pressure is acquired by pressure transducer 7. Now pressure ripple can be observed and the coefficient of dynamic surplus can be calculated. Coefficient of dynamic surplus is described by the formula:

$$\varphi_d = \frac{p_{\max} - p_{st}}{p_{st}} \tag{6}$$

where: p_{max} – pressure ripple, p_{st} – stable pressure.

Capacitance of flexible pipes 6 can be calculated:

$$C_V = \frac{V}{B} \tag{7}$$

where: V - volume of oil in pipes, B – substitute bulk modulus (for flexible pipes ≈750 MPa).

2.2. Next test step - changes pipes length to L_2 = 2000 mm. An electrical circuit of solenoid is operated by a monostable button normally opened. A spring keeps valve spool in position I. The closure of the electrical circuit of solenoid b causes the cylinder to move up. Ports P and B are connected now. Ports A and T are connected now too. During the system start pressure is acquired by pressure transducer 7. Now pressure ripple can be observed and the coefficient of dynamic surplus can be calculated. Capacitance of flexible pipes 6 (length L_2) can be calculated too.

3. Next valve 5 is replaced by a proportional directional control valve, according to the scheme presented in fig. 13.

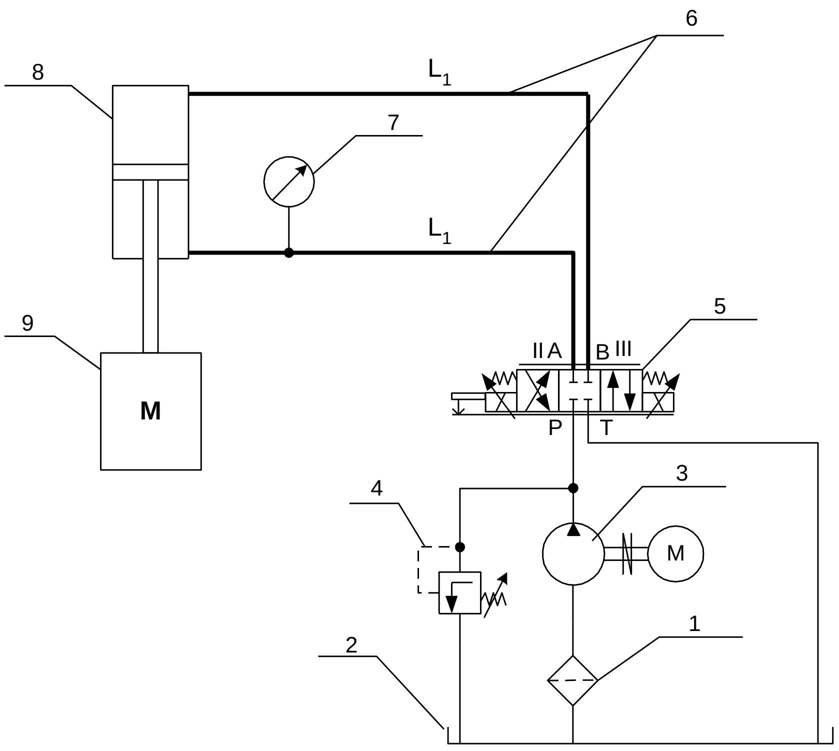

Figure 13. Scheme of test system: 1 – filter, 2 – tank, 3 – fixed displacement pump, 4 – safety valve, 5 – 4/3 proportional directional control valve, 6 – flexible pipes (length L_1 = 1000 mm), 7 – pressure transducer, 8 – double acting, single piston rod hydraulic cylinder, 9 – external load (30 kg).

Spool of valve 5 is operated by proportional solenoids, so spool displacement is proportional to input current. Moreover an electronic amplifier which collaborates with proportional solenoids is equipped with "rampenzeit" knob to adjust the value of time delay of electrical control signal. It is an efficient tool to shape transient processes in hydraulic systems (starting or stopping hydraulic cylinder). During system operation pressure transducer 7 measures pressure run. Now pressure ripple can be observed and the coefficient of dynamic surplus can be calculated.

4. Reduction of pressure ripples using hydraulic accumulator.

Next test step covers building the system with an accumulator according to the scheme presented in fig. 14.

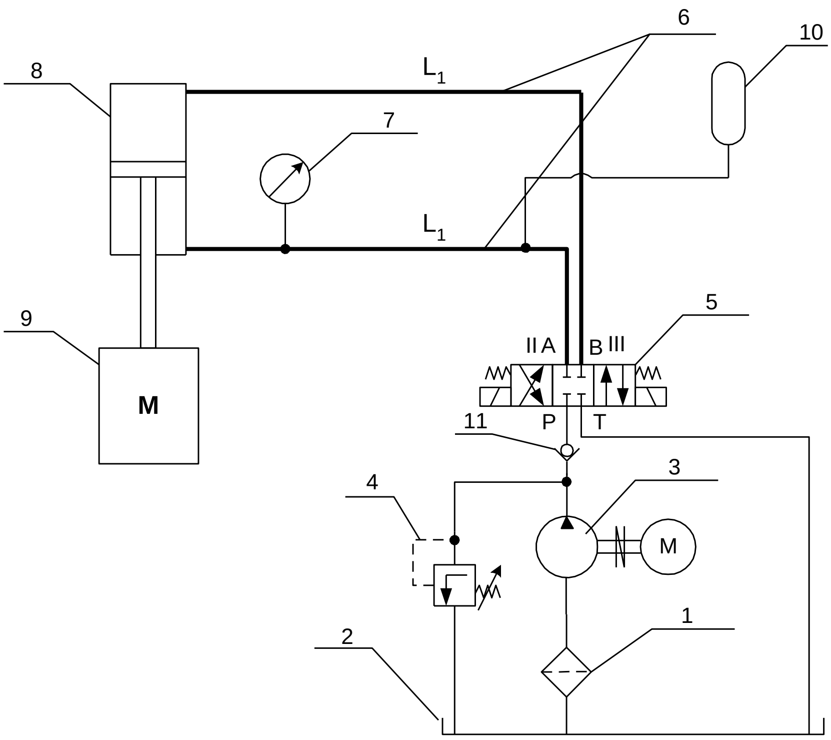

Figure 14. Scheme of test system: 1 – filter, 2 – tank, 3 – fixed displacement pump, 4 – safety valve, 5 – 4/3 directional control valve with "on/off" solenoids, 6 – flexible pipes (length L_1 = 1000 mm), 7 – pressure transducer, 8 – double acting, single piston rod hydraulic cylinder, 9 – external load (30 kg), 10 – bladder accumulator, 11 – check valve.

Electrical circuits of solenoids are operated by monostable buttons normally opened. Springs keep valve spool in neutral position. The closure of the electrical circuit of solenoid b causes the cylinder to move up. Ports P and A are connected now. Ports B and T are connected now too. In the first phase the accumulator is being charged. Next the hydraulic cylinder moves up softly. Pressure change can be observed. Pressure ripple is reduced.

Conclusions should cover comparison dynamics states of considered systems (figures 11, 12, 13, 14) with the help of coefficient of dynamics surplus φ_d and discussion about practical rules of pressure pulsation and pressure ripples reduction. Results of the reduction should be well understood. Moreover conclusion should cover maximal force and velocities of hydraulic cylinder and methods of their control.

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Project co-financed by European Union within European Social Fund