1. Ivan KOSTUCHENKO[1], 2. Oleh LEVCHENKO[1], 3. Dmytro KOSTIUK[1]

Igor Sikorsky Kyiv Polytechnic Institute (1)
ORCID: 1. 0009-0008-2179-6673; 2. 0000-0002-7620-9009; 3. 0000-0001-5407-1443

doi:10.15199/48.2024.09.33

SLA 3D Printing in Mini Electrohydraulic Systems

***Abstract**. This article is devoted to an analytical engineering study of the practicality of using 3D printing for the manufacture of hydraulic components, in order to solve problems related to the weight, size and complexity inherent in traditional hydraulic elements. The research aims to demonstrate the feasibility of using 3D printing to achieve simplified design and increase efficiency. The article presents samples of hydraulic elements printed on a 3D printer, which reflects the practical feasibility of this approach.*

***Streszczenie.** Artykuł ten poświęcony jest analitycznym badaniom inżynierskim dotyczącym praktyczności wykorzystania druku 3D do produkcji elementów hydraulicznych, w celu rozwiązania problemów związanych z masą, rozmiarem i złożonością charakterystycznych dla tradycyjnych elementów hydraulicznych. Badania mają na celu wykazanie wykonalności wykorzystania druku 3D w celu uproszczenia projektowania i zwiększenia wydajności. W artykule przedstawiono próbki elementów hydraulicznych wydrukowane na drukarce 3D, co odzwierciedla praktyczną wykonalność takiego podejścia. (**Drukowanie 3D SLA w miniaturowych systemach elektrohydraulicznych**)*

Keywords: 3D printing, hydraulics, robotics, hydraulic cylinder, directional control valve.
Słowa kluczowe: Druk 3D, hydraulika, robotyka, siłownik hydrauliczny, zawór kierunkowy.

Introduction

Recent developments in additive manufacturing, particularly SLA (Stereolithography) 3D printing, holds immense potential in the creation of hydraulic robots, offering a streamlined approach to design and production. By consolidating multiple components into a single, multipurpose part [1], 3D printing simplifies the overall structure, fostering efficiency in both manufacturing and functionality. The method's ability to produce lightweight yet robust structures contrasts favorably with traditional metal construction, resulting in reduced weight and manufacturing costs [2]. Additionally, the inherent advantage of utilizing hydraulic actuators in 3D-printed robotic systems further enhances their energy performances [3].

SLA 3D Printing has some significant advantages. It offers unparalleled precision and resolution, making it ideal for constructing intricate components essential for micro-scale hydraulic and pneumatic systems. The method allows for the creation of complex geometries with high accuracy, enabling the production of miniaturized yet efficient hydraulic components [4].

In general, hydraulic systems have a number of significant advantages compared to other technical areas of industry. These include the possibility of creating extremely large static forces, the possibility of simple implementation of linear and rotary motion, compact dimensions, as well as many options for the ability to adjust the output characteristics of the actuator, such as force and velocity [5].

Since most hydraulic systems are designed specifically to obtain high forces on actuators, the working pressure in these systems is quite high and reaches about 300-400 bars. If there is no need for high forces, such as in robotics, the working pressure can be significantly reduced (up to 2-3 bar), which in turn allows the use of various polymer materials instead of metal for the production of hydraulic system elements [6].

Methodology and mathematical model

Technology of SLA 3D Printing can be used in field of robotics and industrial automation. The capabilities of this technology have been harnessed in the development of robotic systems. For determination the geometric dimensions of the hydraulic cylinder, certain calculations of its design had to be performed. Knowing the required force on the piston rod of the hydraulic cylinder and applying the nominal working pressure for such type of hydraulic systems, the piston effective area of the hydraulic cylinder can be determined:

$$S = \frac{F}{P} \tag{1}$$

where: S – piston effective area, m^2; F – force on the rod, N; P – nominal working pressure in the hydraulic system, Pa.

From the resulting effective area of the piston, the diameter of the piston can be found and standard diameter of piston rod can be chosen. By choosing a piston rod diameter of hydraulic cylinder was used the effective area ratio of 1.33.

$$D = \sqrt{\frac{4 \cdot S}{\pi}} \tag{2}$$

$$d = D \cdot \sqrt{1 - \frac{1}{\psi}} \tag{3}$$

where: D – piston diameter, m; d – piston rod diameter, m; ψ – area ratio coefficient.

In addition to the nominal working pressure for the pump station also must be determined the flow rate of the working fluid in hydraulic system. Flow rate of the working fluid depends on the effective area of the piston and the velocity of its movement and it can be defined as follows:

$$Q = S \cdot V = S \cdot \frac{L}{t} \tag{3}$$

where: Q – flow rate, m^3/s; V – velocity of cylinder piston, m/s; S – piston effective area, m^2, L – working stroke, m; t – movement time, s.

After performing all the necessary calculations and determining the geometric dimensions of the elements of the hydraulic cylinder, a drawing of these elements was made for further printing. By simplifying and minimizing the number of elements of the hydraulic cylinder, 3 main structural elements have been highlighted, such as a sleeve with inlet pipes, a front cover and a piston with a piston rod. In the elements of the hydraulic cylinder, which have contact surfaces, appropriate grooves were also provided for the installation of standard seals, which are used for this type of devices.

As a result, a hydraulic cylinder was printed with a simplified design, which consists of only three main parts, and also were added three standard rubber seals. These include the seal between the sleeve and the front cover of the cylinder, the piston seal and the seal of the rod cover on the surface of the rod. (Fig.1).

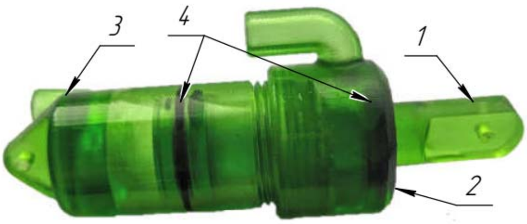

Fig. 1. Printed hydraulic cylinder: 1 – piston rod combined with the piston; 2 – cover with a thread and connecting pipe; 3 – sleeve with fastening, thread and connecting pipe; 4 – rubber seals inserted into the grooves.

In order to implement the possibility of controlling the created hydraulic cylinder, was also made a decision to develop a new simplified design of the hydraulic control directional valve, with the possibility of its manufacture using 3D printing technology.

The design of this valve was based on the design of existing hydraulic servovalves with a control cascade of the flapper-nozzle type valve. The advantages of this design of the hydraulic control directional valves are its high speed and accuracy of regulation, as well as the largest amplification factor. For this purpose was proposed a simplified design of the control cascade of the servovalve, which is adapted for printing from polymers (Fig. 2).

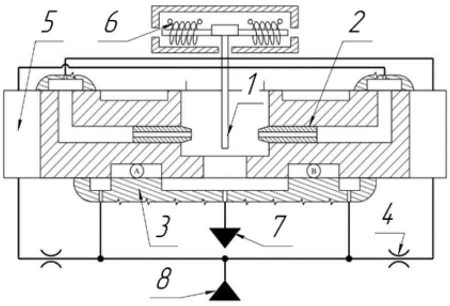

Fig. 2. Design of servovalve control cascade (flapper-nozzle type): 1 – flapper, 2 – spool with nozzles, 3 – body of directional control valve with fluid inlet and outlet ports, 4 – throttle valve, 5 – control chambers, 6 – solenoid coil, 7 – drain line, 8 – working fluid supply line.

In design of directional control valve with flapper-nozzle control cascade, part of the working fluid is constantly supplied to the nozzles of the control cascade. This working fluid, passing through two non-adjustable throttles, is supplied to two nozzles from opposite sides. In the case when the flapper is in the middle position between two nozzles, the pressure in both working chambers is the same due to the same hydraulic resistance. Moving the flapper to one of the sides leads to pressure increase in one of the working chambers and a simultaneous pressure decrease in the opposite working chamber and switching of the hydraulic directional control valve. Combination of two constant throttles with two nozzles and a flapper forms a certain hydraulic bridge shown in Figure 3.

To simplify the problem, it is possible to find the flow rate of the working fluid that will be used for control in the equilibrium position in the pressure chambers. For the type of directional control valve we have chosen, this state will correspond to absolutely any static position of the flapper (we will not take into account quick switches). In this position, the flow rate passing through both control branches will be the same.

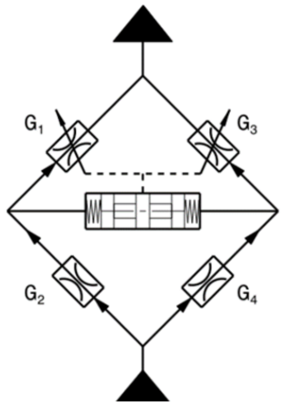

Fig. 3 Diagram of a hydraulic bridge

The description of these processes is quite cumbersome, so are usually used formulas for turbulent flow with correcting coefficients:

(4) $$Q_{dr} = \mu_{dr} \cdot f_{dr} \cdot \sqrt{\frac{2}{\rho} \cdot \left(P_{PS} - P_{DCV}\right)}$$

where: μ_{dr} – fluid internal friction coefficient; ρ – working fluid density, kg/m^3; f_{dr} – hydraulic cross-sectional area, m^2; Q_{dr} – throttle flow rate, m^3/s; P_{PS} – pump station pressure, Pa; P_{DCV} – directional control valve pressure, Pa.

We can determine a certain value of hydraulic resistance as the square of multiplication of the fluid internal friction coefficient and the area of the hydraulic cross-section:

(5) $$G_{dr} = \left(\mu_{dr} \cdot f_{dr}\right)^2$$

This allows us to consider hydraulic circuit as an electric circuit, where Q_{dr}^2 will be an analog of current, $1/G_{dr}$ – analog of resistance, and $2 \cdot P/\rho$ will be an analog of voltage.

In particular, it is possible to use the following formula to calculate the resistance of the control branch:

(6) $$G_{cr} = \left(\frac{1}{G_{nr}} + \frac{1}{G_{dr}}\right)^{-1}$$

where: G_{cr} – control line resistance, G_{nr} – resistance of the flapper-nozzle.

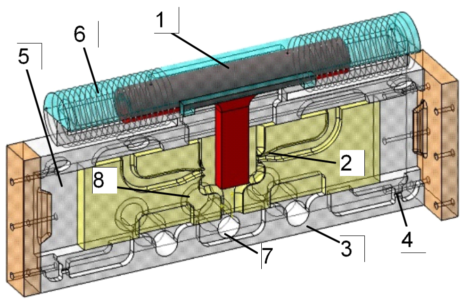

Fig. 4. Design of directional control valve: 1 – flapper, 2 – spool with nozzles, 3 – valve body with fluid inlets and outlets, 4 – throttling constrictions, 5 – control cavities, 6 – solenoid coil, 7 – drain line , 8 – fluid supply line.

Design of the 3D-printed directional control valve (Fig. 4) involves the creation of two solenoids to control the position of the flapper. Winding of the coils will be wound directly on the shutter body glued with photopolymer. The core will be inserted into the central axis of the groove, in the model of which a hole is provided for this. In this way, we will get a compact pair of solenoids in a hermetically glued housing, where the gluing seam is made of the same material as the housing itself.

To design the coils, we are interested in the pulling force of the rod, as well as the inductance and resistance of the coil, which will be used to calculate the control circuit (Fig. 5) of the arm robot. The calculation is carried out as follows.

Flapper retraction force:

$$F_{sl} = \frac{\mu_0 \cdot \mu_r \cdot (\pi \cdot R_c \cdot Z_c) \cdot (N \cdot I)^2}{(R_c - R_i)^2} \tag{7}$$

where: F_{sl} – force created by the solenoid, N; μ_0 – magnetic permeability of free space; μ_r – relative permeability of the metal; R_c – radius of the coil, m; R_i – radius of the metal core of the insert, m; Z_c – length of the coil, m; N – number of turns, pcs; I – electrical current, A.

Inductance of such coil will be determined as:

$$L_{sl} = \frac{\mu_0 \cdot \mu_r \cdot \pi \cdot (N \cdot R_c)^2}{Z_c} \tag{8}$$

The resistance of the solenoid coil can be determined by knowing the specific resistance of the used material and the length of the wire.

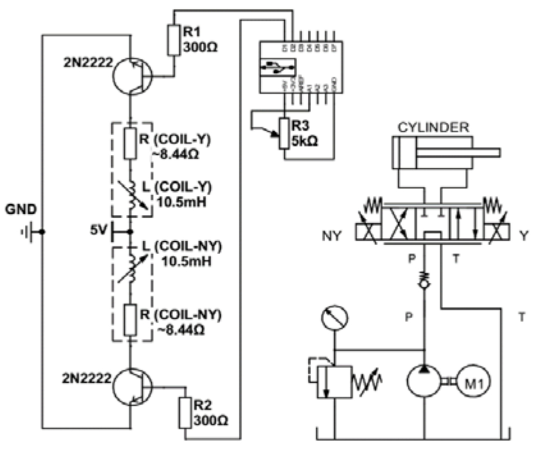

Fig. 5 Schematic diagrams: a) electric, b) hydraulic

The schematic image presented in Fig.5 shows a typical connection scheme of one hydraulic cylinder in the robot drive, it implements an electrical scheme for controlling solenoid coils using transistors. Since the power of non-industrial controllers such as Arduino, Raspberry, ESP32 is quite small, it does not allow direct power consumers to be connected to the NIC, as this can lead to overloading of the control port and damage to the controller. Therefore, it is necessary to use an amplifier, in this example, the 2N2222 transistor was used due to its availability and reliability in combination with good technical characteristics. The power of the coil in this case was 1.6W. For more powerful coils can be used MOSFET transistors, which will have a more complicated connection scheme. Potentiometers fixed on the hinges of the limbs were also used to determine the position of the robot's limb, as an inexpensive and accessible limb bending angle sensor.

The hydraulic diagram of the robotic arm consists of seven printed hydraulic cylinders, each of which is connected to a separate distributor with a corresponding pair of solenoids and elements of electrical amplification. Hydraulic diagram of one of the cylinders is presented in Figure 5(B). Five cylinders control the movements of the fingers. The other two are responsible for the movement of the wrist and biceps. The system is powered by a single pumping station (2.25 l/min) and controlled by a single Arduino controller that can be replaced by a Raspberry Pi pico if more computing power is needed.

Discussion of the obtained results

A stereophotographic SLA printer with an accuracy of 48 microns was used to manufacture the parts of hydraulic equipment, like hydraulic cylinder, directional control valve etc. The maximum accuracy of this method can currently reach 15 microns and tends to increase every two years.

The components, which were produced, are fully functional, their great advantage is speed and ease of manufacture. The printing process took only a few hours and this technology radically shortens the entire manufacturing cycle from development to the finished system. The cost of manufacturing one cylinder is very cheap, which is a serious advantage compared to cylinders produced of metals. It is possible to make different hydraulic parts from different photopolymers that have slightly bright properties, such as flexibility, wear resistance and hardness. There are also specialized ceramic polymers that after printing can be fired in a furnace and the resulting material will have increased wear and heat resistance.

However, it is worth noting certain disadvantages of this method in the manufactured parts and methods of combating them. The main problem of this production method is the quality of the obtained surfaces, which directly depends on the orientation of the components during printing. As it turned out, the best surfaces will be at a perpendicular orientation to the plane of polymerization of the 3D printing layers (vertically). At an inclined orientation, a defect of a stepped (layered) structure appears which will have a certain roughness depending on the height of the layer and the angle of inclination.

Another defect observed when printing thin-walled surfaces, such as cylinder liners, is deformation of the form (boxing) associated with thermal relaxation of bonds between the chains of polymer structures, the defect can be corrected by heating and aligning the part. The angle of inclination during printing plays a significant role in the appearance of this defect.

Post-treatment of important surfaces plays a key role. The methods include: grinding, polishing and varnishing of surfaces. It is possible to varnish with special photopolymer varnishes that polymerize from ultraviolet light and have similar or even better wear-resistant properties than the material from which the element was printed. In all these methods of processing and manufacturing, it is important to correctly calculate the amount of tolerance of the elements, taking into account the type of processing.

A significant problem is also the impossibility of working at high working pressures due to the extremely low strength of the material from which the hydraulic equipment is made, as well as the difficulty of sealing the moving elements of the equipment.

By designing hydraulic cylinder seals, it is very important to use rubber seal rings that are specifically designed for hydraulic cylinders. For our tasks, we have used ordinary hydraulic sealing rings. The high tension of the side surfaces of these seals resulted in the cylinder head gasket being too large and creating a lot of friction at rest.

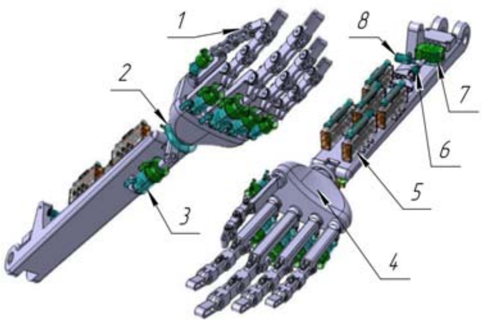

Fig. 6 Robotic arm: 1 – finger movement cylinder, 2 – palm rotary drive, 3 – palm tilt cylinder, 4 – palm, 5 – hydraulic servo distributors, 6 – collector, 7 – pump, 8 – tank.

Finally, it should be noted that SLA 3D printing at home should be carried out in a well-ventilated, specially separated room or a separate room. During polymerization, formaldehyde vapors are released, so the presence of a goggles and respirator is mandatory. The proposed 3D printing technology can be applied not only to actuate a robotic arm, as shown in Figure 6, but also in other industries where there is no need to create large efforts, such as pharmaceuticals, food industry, medicine, etc.

Conclusion

As a result of the work two basic elements were developed and adapted to 3D printing: a hydraulic cylinder and a servovalve. Based on the comments on the features of the production of hydraulic components on the SLA printer, it can be identified that the fast production cycle and low cost make this method very attractive for prototyping robotic systems, including hydraulic ones. Also, the ability to combine many system elements into one compact design can be decisive for technical solutions where compactness and weight play key roles.

Most of the disadvantages of this method lie in the quality of the obtained surfaces. Most of these surface imperfections can be easily corrected with additional processing. At the same time, the surface tolerance control condition is easily fulfilled in an iterative way thanks to the fast manufacturing cycle, which can be carried out directly by the engineer at the workplace. If you need more strength and durability of the materials, you can choose another photopolymer with the required properties. In the absence of satisfactory photopolymers, the developed model can be printed with a laser metal powder method on an industrial SLM printer, which is many times more expensive, but allows printing strong parts made of steel, aluminum, various alloys, and titanium.

***Authors**: master student Ivan Kostuchenko, e-mail: 1vankostuchenko2604@gmail.com; PhD, Associate Prof. Oleh Levchenko, e-mail:olehlevch@gmail.com; PhD, Associate Prof. Dmytro Kostiuk, e-mail:kostiukdv@ukr.net. Igor Sikorsky Kyiv Polytechnic Institute, Beresteyskiy str. 37, buiding #1, Kyiv, Ukraine, 03057.*

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