Improvement of the Pneumo–hydraulic Amplifier for Press Machines: Design and Parameter calculation

M. Polishchuk
Associate Professor
National Technical University of Ukraine
Department of Information Systems and Technologies
Ukraine

M. Tkach
Associate Professor
National Technical University of Ukraine
Department of Information Systems and Technologies
Ukraine

Y. Kornaga
Professor
National Technical University of Ukraine
Department of Information Systems and Technologies
Ukraine

Pneumohydraulic pressure amplifiers are widely used in mechanical engineering. Using a pneumohydraulic amplifier makes it possible to minimize the size of the presses while simultaneously multiplying their technological effort. A significant disadvantage of the classical method of force multiplication is the low speed of movement of the working bodies of technological equipment under a hydraulic drive.

The article proposes a fundamentally new design of a pneumohydraulic amplifier, in which a high-speed pneumatic cylinder carries out the idling of the technological tool, and force multiplication is carried out only at the stage of the working stroke, which allows many times to increase the performance of the amplifier. This effect is achieved by using a movable hydraulic chamber. The engineering formulas and diagrams presented in the article for calculating the parameters of a new pneumohydraulic amplifier allow engineers to adapt the amplifier to various technological conditions. The economic effect when using the proposed amplifier design is achieved by multiplying the productivity of the press equipment.

Keywords: *hydraulic amplifier, pneumatic press, force multipli–cation, hydraulic transformer*

1. INTRODUCTION

The classical method of multiplication of the techno–logical force of the press drive is known, which is based on the conversion of the low pressure of the compressed air of the pneumatic cylinder into the high pressure of the liquid of the working hydraulic cylinder. According to this method, compressed air is supplied to the piston cavity of the pneumatic cylinder, and the piston of the same cylinder displaces liquid from the hydraulic cavity of a smaller section into the cavity of a larger section. As a result, the piston of the hydraulic cylinder is subjected to increased fluid pressure (eg engine oil). The value of pressure increase can reach several tens, which is the main advantage of pneumohydraulic drives.

However, a significant disadvantage of this method is the low speed of movement of the technological tool of the pressing equipment. This is because as an idle, i.e., the approach of the tool to the object of processing, and the working stroke by the amount of processing are carried out under the action of a force on the rod of the hydraulic cylinder, the movement speed of which is an order of magnitude less than that of the pneumatic actuator. It is known that when performing such techno–logical operations as riveting, punching, embossing, assembly of press joints of parts, and similar operations, the working stroke of the tool is many times less than the idle stroke also necessary for installing a techno–logical tool. Therefore, the force multiplication until the application of the technological load significantly slows down the action of the press drive.

The fundamentally new design proposed below (Patent UA 113679) of the pneumohydraulic amplifier multiplies the technological force only at the stage of the technological operation, and a high-speed pneumatic drive implements the idling. With such a separation of movements, the productivity of the press equipment is greatly increased.

2. PREREQUISITES AND MEANS FOR SOLVING THE PROBLEM

Currently, there are many technical solutions for wor–king force multipliers. As a rule, they are based on the conversion of low pressure of the medium at the inlet of the system into a high pressure of the liquid at the outlet of the devices. So, for example, the classical method of force multiplication is known [1]. According to this method, compressed air is supplied to the piston cavity of the pneumatic cylinder, and the liquid is displaced from the hydraulic cavity of a smaller section into the cavity of a larger section of the cylinder by the rod of the same cylinder. As a result, the piston of the hydraulic cylinder is subjected to increased engine oil pressure. However, in such devices, the output link of the multiplier makes the entire path under the action of a

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Correspondence to: M. Polishchuk, Associate Professor
National Technical University of Ukraine, Department
of Information Systems and Technologies, Ukraine
E-mail: borchiv@ukr.net
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hydraulic cylinder, the movement speed of which is an order of magnitude less than that of a pneumatic drive.

Research [2] presents a theoretical substantiation of the main parameters of a pneumohydraulic impulse drive with a jet control system for micro tool movements on metal-cutting machines. In these studies, pneumohydraulic converters are made as pneumatic membrane cylinders of one-way force action with return springs, the rods of which are simultaneously plungers of hydraulic cylinders with working cavities. This solution is quite acceptable for micro-movements. However, implementing pneumohydraulic converters in the form of pneumatic membrane cylinders limits the idle and working stroke of the amplifier, which is a significant drawback in contrast to the technical solution proposed in this article. The paper [3] presents the results of an experimental study of the "nozzle-shutter" mechano-pneumatic converter and a pneumatic power amplifier created on its basis. This problem was solved using differential hydraulic cylinders with cross-connection of their piston and rod cavities, and compensation for the difference in supply and consumption of compressed air is provided using pneumohydraulic accumulators. However, these studies are limited mainly to developing a power amplifier control system and do not offer technical solutions to increase the amplifier's performance. Studies [4] provide an opportunity for mathematical modeling and experimental testing of pneumohydraulic systems in which single-level and two-level pneumohydraulic springs. The results of these studies are very useful for transport devices when the mechanisms have a small amplifier stroke. But they do not contain recommendations for designing pneumohydraulic amplifiers for pressing process equipment with a large stroke of the process tool.

The study's results [5] contribute to an increase in the service life of the pneumohydraulic amplifier due to the improvement of the sealing rings; however, based on the classical principle of the amplifier, which, as noted above, has a low performance.

Methodological recommendations for modeling pneumohydraulic amplifiers for mobile equipment are also known [6]. Here, the increase in transmitted power occurs due to the energy supplied using liquid or compressed air under pressure from a pumping station or a hydraulic accumulator. However, in this academic work, a classical power amplification scheme is used, i.e., without increasing the speed of the technological force multiplier. In studies [7], a method for theoretical modeling of hydraulic amplifiers was proposed in order to obtain quantitative and qualitative indicators of the structural components of amplifiers and their elements, but without taking into account the gain and its effect on the speed of the amplifier. Unlike other research works [8], the pneumohydraulic amplifier consists of three cylinders, with hoses connecting the first two cylinders. However, in the aggregate, the proposed scheme of the pneumohydraulic multiplier is classical. It does not contribute to an increase in the speed of movement of the working cylinder at idle, in contrast to the design proposed in this article. The papers [9, 10] present the results of studies on using pneumohydraulic amplifiers in-vehicle clutch mechanisms. However, in these works, classical multiplier schemes are used, the speed of which depends on the speed of the engine oil flow, which limits their speed.

Thus, the above analysis of studies shows that the problem of increasing productivity remains relevant. Next, consider the design solutions of pneumohydraulic amplifiers.

A perfect method of force multiplication is the method of sequential pneumatic and hydraulic amplification [11]. This method includes two consecutive stages: the operation of the amplifier at low pressure when compressed air is applied to the working fluid through an intermediate medium and the second stage is the operation of the amplifier at high pressure. Thus, in contrast to the previous technical solution, the speed of the pneumohydraulic drive is increased. However, because the flow rate of a liquid (for example, engine oil) is an order of magnitude lower than the speed of compressed air, increasing the speed of a drive of this type remains relevant.

It was also known as the Hydraulic pressure transformer [12], which contains three consecutive cylinders: pneumatic, hydraulic, and again pneumatic. At the first stage (i.e., during the idling period), the tool is brought to the object of processing using the second of the indicated pneumatic cylinders, and simultaneously, under the action of a spring-loaded piston, the liquid is displaced from the first chamber into the cavity of the hydraulic cylinder. In the second stage of work, i.e., when applying technological effort to the processing object, the multiplication of technological effort is carried out dozens of times. The device and principle of operation of the pressure amplifier [13] and hydropneumatic pressure transformer [14] are similar. The difference between the last two technical solutions from the source [12] is the absence of a spring on the piston, which separates the first pneumatic cylinder from the hydraulic cavity. And the displacement of liquid in the process of pneumohydraulic amplification is carried out under a pneumatic drive.

Compared with the technical solution of the source [11], the last three devices [12-14] make it possible to increase the speed of the drive since the passage of the idle distance is carried out due to the action of the pneumatic drive of the second stage. However, simultaneously, the liquid is simultaneously displaced in the process of pneumohydraulic amplification from one cavity to another, which is accompanied by hydraulic friction, and hence the braking of the pneumatic drive. In other words, the performance of the drive amplifier is reduced due to the limitation of the hydraulic flow rate, which is a significant drawback of the described technical solutions. This is also confirmed by the fact that if the hydraulic flow is given the speed of a pneumatic drive, such negative phenomena as liquid cavitation and increased wear of hydraulic seals will occur, which is unacceptable.

There is also a method of multiplication of technological effort [15]. According to this method, the multiplier contains two cylinders of large and small diameters, which are rigidly connected to each other and have a common working rod. This rod is connected to the piston of the large cylinder, more precisely, to the amplifier in the form of a diaphragm drive. This property, in contrast to previous technical solutions, makes it possible to eliminate the limitation on the speed of the idle drive, which, of course, increases the speed of the pneumohydraulic amplifier. However, the presence of a constant rigid connection between the cylinders of the idle and working stroke drives limits the technological capabilities of the amplifier since when the size of the processing object changes (for example, rivets, cutting depth, embossing, etc.), both of these cylinders cannot change position relative to each other.

The use of pneumohydraulic amplifiers is very diverse. They are used in mechanical engineering for force multiplication of clamping devices [16] or in the automotive industry for clutch mechanisms [17]. The use of technological force multipliers in the deformation of various materials is very promising [18, 19]. It is also advisable to use pneumohydraulic amplifiers to assemble high-precision press joints [20]. However, in any case, force multiplication should be carried out only at the stage of performing a power operation without using the idle distance of the technological tool. Thus, increasing the speed of the pneumohydraulic force multiplier remains relevant.

3. FORMULATION OF THE PROBLEM

To increase the productivity of pressing machines, it is necessary to create a pneumohydraulic pressure amplifier with the application of technological effort only at the stage of performing a power operation, i.e., at the stage of the working stroke, and idling is carried out using a high-speed drive. In other words, it is necessary to increase the speed of the working force multiplier while eliminating the effect of hydraulic friction on the speed of movement of the idle drive, i.e., tool supply drive to the working area. At the same time, to ensure a multiple (tens of times) increase in the technological effort of the operation being performed. In addition, it is necessary to develop analytical relationships and diagrams for calculating force multiplier parameters, allowing engineers in the field to design similar devices for different process conditions.

4. SOLUTION OF THE PROBLEM UNDER CONSIDERATION

The technical novelty of the proposed engineering solutions lies in the fundamentally new design of the pneumohydraulic amplifier [21], and graphical and analytical dependencies display the scientific novelty for calculating the parameters and modeling the specified technological module. The main motivation of this research is the creation of a pneumohydraulic amplifier, which has a higher performance when performing pressing operations.

4.1 The design of the pneumohydraulic amplifier

Figure 1 shows a 3D model of a hydraulic amplifier. The main difference in its design is the presence of a movable chamber, which houses a hydraulic cylinder filled with machine oil. A stationary pneumatic cylinder with piston 1 is installed in the amplifier housing for idling, i.e., supply of a technological tool to the processing object. Rod 1 of piston 1 enters the hydraulic chamber and through piston 2, and rod 2 acts on the object of processing. Moreover, compressed air is supplied under piston 2 to return piston 2 to its original position after performing a technological power operation. Another difference between the amplifier and traditional designs is the locking mechanism for the movable chamber to stop the chamber in a given position depending on the magnitude of the stroke, i.e., displacement of the movable hydraulic chamber by the amount of application of the multiplier force.

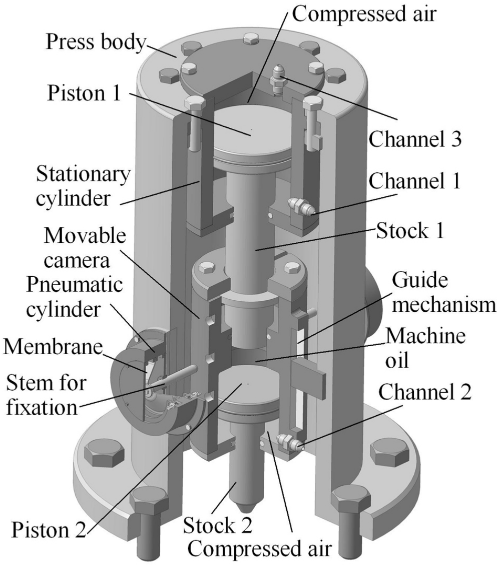

Figure 1. The design of the pneumohydraulic amplifier (the 3D model in the quarter section)

In this case, the mechanism for fixing the movable hydraulic chamber (cylinder) is made as a diaphragm pneumatic cylinder. When compressed air is supplied to the membrane of this drive, its rod fixes the hydraulic chamber in a predetermined position, depending on the magnitude of the application of the multiplication force. To evenly distribute the fixing force of the hydraulic chamber, it is desirable to install three diaphragm locking cylinders on the amplifier body at an angle of 120 degrees in the horizontal plane. In addition, the housing of the movable hydraulic chamber has a guiding mechanism in the direction of the translational movement of the hydraulic chamber. It excludes the possibility of its rotation around the axis of the amplifier housing. For a better understanding of the design, Figure 2 shows the front view of the amplifier in ¼ section of its case. As can be seen from this figure, the diameter of the hydraulic multiplier cylinder is D_1, piston 1 of the stationary pneumatic cylinder has a diameter of D, and its rod has a diameter of d. These last two parameters d and D, determine the pressure amplification factor in the hydraulic chamber.

Figure 2 also shows the holes in the body of the movable hydraulic chamber for stopping it with a diaphragm actuator retainer. There can be many of these holes, depending on the distance to the point of application of the animation force to the processing object. The diameter of rod 2 is not of fundamental importance and is determined only by the strength of the amplifier mechanism. A technological tool is placed on rod 2.

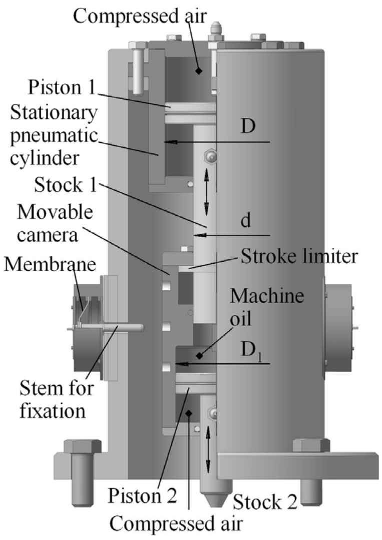

Figure 2. Frontal view of the pneumohydraulic amplifier (1/4 section)

4.2 Operation process of the amplifier

Figure 3 shows the stages of operation of a pneumohydraulic amplifier using the example of rivet deformation for two arbitrary parts. In the initial position "A", the piston of the stationary pneumatic cylinder with a diameter *D* is in the upper position. Its rod with a diameter d through a lock is rigidly connected to the body of a movable hydraulic chamber with an inner diameter D_1. This hydraulic chamber is filled with engine oil.

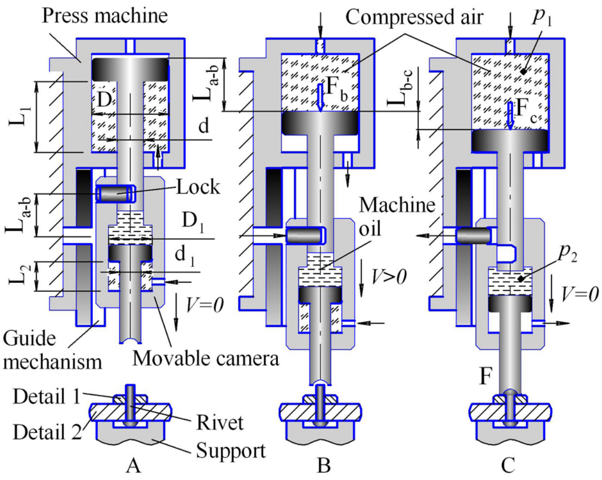

Figure 3. Stages of movement of the pneumohydraulic amplifier

By supplying compressed air with pressure p_1 to the upper cavity of cylinder *D*, its piston moves to the idle stroke value L_{a-b} (stage "B") with the idle force:

$$F_b = F_c << F$$

where: $F_b = F_c = \dfrac{\pi D^2}{4} p_1$; *F* - technological effort. A rod with a diameter *d*, connected by a lock to the hydraulic chamber D_1, moves the chamber by the same amount with speed $V > 0$, i.e., by the amount of idling until the tool contacts the rivet. Further, at the command of the control system, the lock latch using a diaphragm pneumatic actuator (see also Figure 2) disengages from a rod with a diameter *d* and engages with the amplifier housing, i.e., fixes the position of the hydraulic chamber D_1 relative to the amplifier housing (stage "C"). As a result, the rod with a diameter d displaces the engine oil into chamber D_1 and passes the distance of application of the technological force, namely: L_{b-c}.

In this case, the compressed air under piston D_1 is released into the atmosphere. As a result of the displacement of machine oil from the cavity with a diameter *d* into the cavity with a diameter D_1, the technological force F increases many times with a gain factor. Upon completion of the operation, in this case, the rivet deformation, compressed air is supplied under piston *D* and piston D_1. As a result, the elements of the amplifier return to their original position, "A". Then the cycle repeats.

Thus, due to the movement of the movable hydraulic chamber at the idle stage L_{a-b} under the action of a high-speed pneumatic drive and fixation of this chamber at the stage L_{b-c}, the amplifier's performance is significantly increased. This becomes possible because, according to the new technical solution, the speed of the engine oil outflow is no longer the speed limiter of the high-speed pneumatic cylinder. And only at this stage L_{b-c} there is a pressure p_2 multiplication in the hydraulic chamber with a diameter D_1 and, as a result, a multiple increase in the technological force *F*.

5. CALCULATION OF AMPLIFIER PARAMETERS

The method for calculating the parameters of a pneumohydraulic amplifier is necessary for engineers who create press equipment for performing technological power operations, such as riveting, rolling, pressing parts, punching, stamping and stamping, and similar power operations. According to the formulation of the problem, increasing the speed of the working force multiplier is necessary. In this case, it is necessary to exclude the influence of hydraulic friction on the speed of movement of the idle drive, i.e. drive for bringing the tool to the working area, while ensuring a multiple (tens of times) increase in the technological effort of the operation being performed, namely when:

$$F >> F_b \text{ or } F = kF_b, \tag{1}$$

where: F, F_b – respectively, the force of the working and idle movement of the tool (see Figure 3); *k* – is the amplification factor (force multiplication), as a rule $k = 10...40$. It is also necessary to ensure the fulfillment of the conditions for high performance of the operation:

$$V_{a-b} >> V_{b-c} \text{ when } L_{a-b} >> L_{b-c}, \tag{2}$$

where: V_{a-b}, V_{b-c} – the speed of movement of the technological tool in the areas of idle and working strokes, respectively; L_{a-b}, L_{b-c} – the values of the idle and working movements of the tool (see Figure 3).

5.1 Method for calculating the parameters of the amplifier

The method for calculating the parameters of the technological force multiplier is as follows. Initially, it would help if you calculated the gain:

$$k = \left(\frac{D}{d}\right)^2 \qquad (3),$$

where: D – is the diameter of the pneumatic cylinder piston; d – is the diameter of the pneumatic cylinder rod. Then the pressure of the liquid (machine oil) in the hydraulic cylinder of the multiplier will be:

$$p_2 = p_1\left(\frac{D}{d}\right)^2 \qquad (4)$$

Consequently, the technological effort of the operation will reach the value:

$$F = \frac{\pi D_1^2}{4} p_2 K_1 K_2 K_3 = \frac{\pi D_1^2}{4} p_1 \left(\frac{D}{d}\right)^2 K_1 K_2 K_3 \qquad (5)$$

where: D_1 – the diameter of the piston of the hydraulic cylinder; p_1 – pressure of compressed air in the pneumatic cylinder; p_2 – engine oil pressure in the hydraulic cylinder; K_1 – volumetric efficiency of the entire drive, $K_1 = 0.95$; K_2 – is the mechanical efficiency of the multiplier, $K_2 = 0.95$; K_3 – is the mechanical efficiency of the hydraulic cylinder, $K_2 = 0.9$. Pneumatic cylinder stroke at the stage of technological power operation:

$$L_{b-c} = l\left(\frac{D}{d}\right)^2 \frac{n}{K_1} \qquad (6)$$

where: l – the necessary movement of the hydraulic cylinder rod to perform the technological operation; n – is the number of hydraulic cylinders (if there are several). It is expedient to present function (6) in a different form:

$$l = L_{b-c}\frac{K_1}{n} \Big/ \left(\frac{D}{d}\right)^2 \qquad (7)$$

Then it becomes more obvious that the allowable value of the technological movement of the working tool is inversely proportional to the gain. Compressed air consumption for the full cycle of moving the working tool will be:

$$Q = \frac{\pi D^2}{4}(L_{a-b} + L_{b-c}) + \frac{\pi(D^2 - d^2)}{4} L_1 + \\ +2\frac{\pi(D_1^2 - d_1^2)}{4} L_2 \qquad (8)$$

where: L_{a-b} – the value of the idle stroke of the tool at the stage of its approach to the working area. This parameter shows that at the stage of idling, force multiplication is not carried out, which significantly improves the performance of the technological module; L_1 – length of the pneumatic cylinder D rod part (see Figure 3); d_1 – diameter of the hydraulic cylinder D_1 rod; L_2 – length of the rod part of the lower pneumatic cylinder.

5.2 Analysis of the numerical parameters of the amplifier

Figure 4 shows the dependencies of the multiplication factor k of the technological force on the diameter D of the pneumatic cylinder of the amplifier for various values of the diameter d of the pneumatic cylinder rod. As can be seen from these graphs, as the diameter of the rod, which displaces engine oil into the hydraulic cylinder, increases, the gain decreases. For reasons of proportionality of the design ratios of the diameters of the piston and the rod of the pneumatic cylinder, it is recommended to limit the values of the multiplication factor in the range $k = 15 \ldots 35$, which will fully ensure the efficient operation of the pneumohydraulic amplifier, depending on its technological purpose.

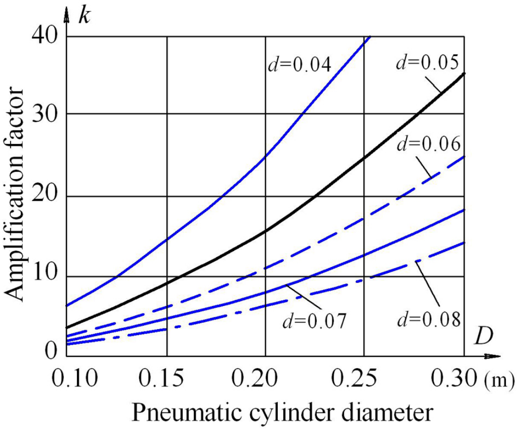

Figure 4. Dependence of the amplification factor *k* on the diameter of the pneumatic cylinder *D* (where *d* is the diameter of the pneumatic cylinder rod, m)

Figure 5 shows the dependence of the technological force F (i.e., the force after multiplication) on the diameters of the piston D and rod d of the pneumatic cylinder, provided that the diameters of the pneumatic and hydraulic cylinders $D = D_1$ of the multiplier are equal.

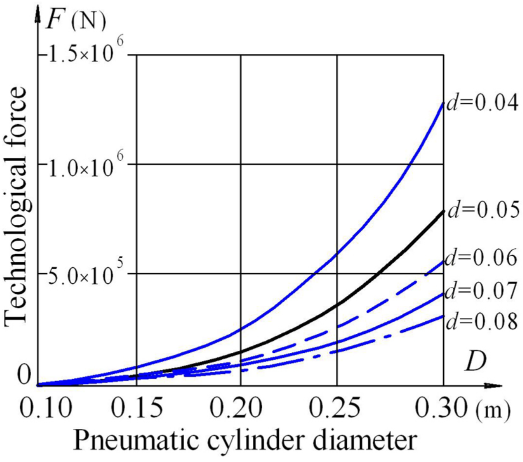

Figure 5. The dependence of the technological force *F* on the diameters of the piston *D* and rod *d* (m) of the pneumatic cylinder of the amplifier (at $D = D_1$)

As can be seen from the graphs in Figure 5, the values of the working forces after the multiplication are quite significant, which is typical for the conditions of mechanical engineering. For the production conditions of instrumentation, it is recommended to take the ratio of the diameters of the pneumatic and hydraulic cylinders within $D_1 = (0.25, \ldots 0.50)D$. This ratio of diameters will allow you to create compact multiplier designs.

Figure 6 shows the dependence of the value of the technological displacement l of the tool (i.e., the rod of the hydraulic cylinder) on the gain k for various values of the displacement of the pneumatic cylinder L_{b-c} (m) rod at the stage of multiple increases in the working force at $n = 1$, see function (7). Obviously, with an increase in the gain (force multiplication), the technological movement of the working tool decreases.

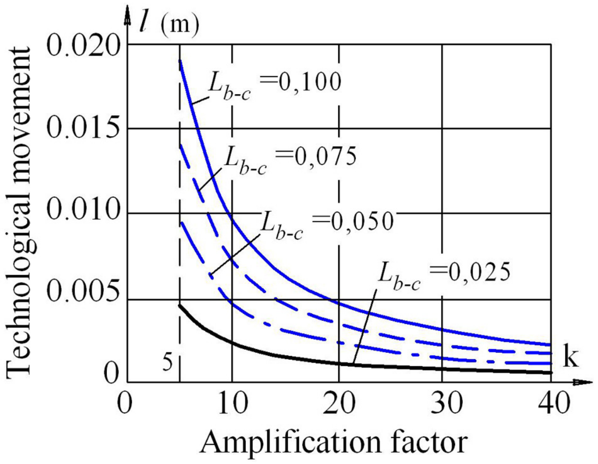

Figure 6. Dependence of technological displacement *l* of the hydraulic cylinder rod on the amplification factor *k* at the stage of multiplication of the technological force

Therefore, for various technological operations, the appropriate amplification factor should be taken into account. For example, to install bearings on a shaft with a press fit, technological displacement values in the range $l = 0.015 \ldots 0.040$(m) are sufficient. To do this, it is necessary either to increase the movement of the pneumatic cylinder rod or to reduce the amplification factor. And for such operations as the deformation of rivets, technological displacement in the range $l = 0.005 \ldots 0.010$(m) is sufficient. For other technological operations, it is enough to change the values of the function's parameters (7) and, based on the technological movement of the tool specified by the assembly, either increase the movement of the pneumatic cylinder rod or change the multiplication factor of the labor force.

6. RESULTS AND DISCUSSION

In contrast to the technical solutions discussed above [2–5], in the proposed new design of the working force multiplier, the idle motion, when the tool approaches the processing object, and the working stroke, when the technological force is applied (after multiplication) are divided into two stages. This became possible due to the presence of a movable hydraulic chamber, alternately connected to the pneumatic cylinder rod at the idle stage and the pneumohydraulic amplifier body at the stage of working technological effort. Therefore, the speed of the hydraulic drive of the multiplier does not limit the speed of movement of the high-speed pneumatic drive.

The execution of the mechanism for fixing the hydraulic chamber relative to the multiplier body in the form of a diaphragm pneumatic drive is not mandatory. Other drives for fixing the hydraulic chamber are also possible, for example, in the form of an electromagnetic, electric, or hydraulic drive of the locking mechanism.

The technical implementation of the new method of multiplication of technological forces allows the modification of drives, which contributes to the application of the proposed method in various areas of industrial production.

7. CONCLUSION

In this article, the authors proposed a fundamentally new design of a pneumohydraulic amplifier, the main difference of which is the presence of a moving hydraulic chamber of the multiplier. The proposed method of technological force multiplication, due to the presence of a movable hydraulic chamber and the possibility of its alternate fixation relative to both the leading link at the idle stages of the multiplier and relative to the fixed body at the stage of the technological operation, provides an opportunity to significantly increase the speed and expand the technological capabilities of the force multiplier.

The results of modeling the functioning of the new pneumohydraulic amplifier illustrate its industrial applicability when used in various production conditions. The developed analytical and graphic dependences of the design parameters of the multiplier of working technological forces allow for the multivariate design of such devices. However, the new multiplier can provide the greatest effect in the mass production of industrial products when the need for high productivity is the dominant factor.

Ultimately, due to the passage of the idle speed of the technological tool at high speed (i.e., without multiplication of the labor force), the proposed multiplier can significantly increase the productivity of the press equipment.

DECLARATION OF CONFLICTING INTERESTS

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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УНАПРЕЂЕЊЕ ПНЕУМО-ХИДРАУЛИЧКОГ ПОЈАЧАЛА ЗА МАШИНЕ ЗА ПРЕСОВАЊЕ: ПРОЈЕКТОВАЊЕ И ПРОРАЧУН ПАРАМЕТАРА

М. Полишчук, М. Ткач, И. Корнага

Пнеумохидраулични појачивачи притиска се широко користе у машинству. Коришћење пнеумохидрауличног појачала омогућава да се минимизира величина преса уз истовремено умножавање њиховог технолошког напора. Значајан недостатак класичне методе множења силе је мала брзина кретања радних тела технолошке опреме под хидрауличним погоном.

У чланку се предлаже фундаментално нови дизајн пнеумохидрауличког појачала, у којем пнеуматски цилиндар велике брзине обавља радни ход технолошког алата, а множење силе се врши само у фази радног хода, што омогућава вишеструко повећање перформансе појачала. Овај ефекат се постиже коришћењем покретне хидрауличне коморе. Инжењерске формуле и дијаграми представљени у чланку за прорачун параметара новог пнеумохидрауличног појачала омогућавају инжењерима да прилагоде појачавач различитим технолошким условима. Економски ефекат при коришћењу предложеног дизајна појачала постиже се множењем продуктивности опреме за штампу.