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STRUCTURAL-PARAMETRIC SYNTHESIS OF HYDRO-MECHANICAL DRIVE OF HOISTING AND LOWERING MECHANISM OF PACKAGE-FORMING MACHINES

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Виконано аналіз роботи піднімально-опускних механізмів пакетоформуючих машин та синтез структури гідромеханічного привода. Теоретично досліджено режим роботи гідромеханічного привода із гідрогазовим акумулятором. Сформульована цільова функція мінімізації витрат енергії при кроковому заповненні акумулятора. Експериментально підтверджено, що стискання газу в акумуляторі піднімально-опускного механізму описується адіабатою. Визначено гіпотетичний показник політропи. Визначено параметри гідропривода, що забезпечить мінімум цільової функції мінімізації витрат енергії

Ключові слова: піднімально-опускний механізм, гідромеханічний привод, акумулятор, пакетоформуюча, потенціальна енергія

Выполнен анализ работы подъемно-опускных механизмов пакетоформующих машин и синтез структуры гидромеханического привода. Теоретически исследован режим работы гидромеханического привода с гидрогазовым аккумулятором. Сформулирована целевая функция минимизации затрат энергии при шаговом заполнении аккумулятора. Экспериментально подтверждено, что сжатие газа в аккумуляторе подъемно-опускного механизма описывается адиабатой. Определен гипотетический показатель политропы. Определены параметры гидропривода, это обеспечит минимум целевой функции минимизации затрат энергии

Ключевые слова: подъемно-опускной механизм, гидромеханический привод, аккумулятор, пакетоформирующая, потенциальная энергия

1. Introduction

Lifting and lowering mechanisms are an integral part of any modern machine for formation and disassembly of transport packages. Package disassembling machines with hoisting and lowering mechanisms implement the ways of disassembling a package "from bottom" and "from top" with subsequent cargo delivery. During designing of a hoisting and lowering mechanism, it is impossible to consider it separately form the structural totality of all mechanisms of package-forming or package-disassembling machines. Preset productivity, quality of package formation, physical-mechanical properties of cargo, assembly of all mechanisms and much more are conditions imposing a limit on generally accepted criteria for designing this type of machinery.

A tendency of development of package-forming machines is compliance with the generalized efficiency criterion. This criterion includes power consumption parameters. Hoisting and lowering mechanisms consume up to 70 % of power of the entire package-forming machine. That is why the search for rational structures of a drive of a hoisting and lowering mechanism and ways of minimizing power consumption is a relevant task in the field of packaging machinery. This is especially true for package-forming machines with a hydromechanical drive. There is a need for mounting such drives during formation of transport packages, weighing more than 10 kN.

2. Literature analysis and problem statement

In the course of implementation of the packing method "from top to bottom", cargoes are accumulated on the platform of a hoisting and lowering mechanism. This involves layered or piece-by-piece stacking of cargoes with serving in horizontal direction. The platform motions downwards step-by-step. The number of motions corresponds to the number of layers in a transport package. Loading increases discretely at every step of the motion by magnitude equal to the weight of a cargo layer. In machines, which operate by principle of package formation "from bottom to top", the platform provides lifting of cargo layers in the vertical direction. Loading on the platform also increases discretely as layers accumulate. In source [1], configurations of possible types of hydromechanical drives with accumulating devices were explored, but without offering mathematical substantiation of calculation models.

A drive of a hoisting and lowering mechanism can be electromechanical, hydromechanical or pneumo-mechanical, but in paper [2], advantages and disadvantages of these drives were not indicated. In modern examples of package-forming machines, designed for transport packages weighing more than 10 kN, hydromechanical drives are widely used [3], but there is no information on conducting industrial experimentation.

Today, selection of the structure and parameters of elements of a drive of hoisting and lowering mechanisms is carried out by the commonly accepted technique of calculation of a hydraulic drive [4]. The presented calculation technique essentially complicates selection of a drive with accumulating devices. During a discrete increase in loading on the platform in the process of transport package formation, pressure in pistol cavity of a cylinder increases. After completion of the operation of transport package formation and its withdrawal from the platform, the platform rises unloaded. In other words, operation of a hoisting and lowering mechanism makes it possible to use potential energy of cargoes that are being packed. The obtained results of papers [5] do not cover research in loading of the drive at various stages of the technological cycle. The most extensive description of the mathematical model of the process of cargo formation with the use of a hydromechanical drive is given in article [6]. The experimental studies, described in this source, make it possible to estimate power consumption of a drive, but only with one kind of loading on the operating sector. The possibility of accumulation of potential energy is conditioned by the packing technology. This is a feature of hoisting and lowering mechanisms of package-forming and package-disassembling machines. The need for extension of mathematical models [7] and performing research in this direction is caused by the necessity to additionally study information on the influence of the structure and elements of a hydro drive on operation of hoisting and lowering mechanisms and find ways of minimizing power consumption at step-by-step loading of a drive.

Research into directions of improvement of hydraulic and pneumatic machines using accumulating systems [8] is not energetically perfect due to a decrease in efficiency of pressurizers due to interaction between solid and liquid particles and rapid wear of the moving elements of the proposed structure. In terms of influence of compressibility of fluid in accumulating systems [9], hydraulic and pneumatic machines should be considered as one class of machines that have common features in implementation of operation processes. Under adverse conditions of operation of working bodies of the pumps, it is necessary to make the optimal choice between pumps of different shapes and structures of accumulating systems [10]. Under these conditions, it is necessary to install additional pressurizers or to use additional units for working fluid filtering. Technical systems [11], in which compressible and non-compressible working media are a necessary part of the performed operation process, which are different by operation principle and structural implementation, require expansion of mathematical modeling in direction of determining of energy consumption. The proposed mathematical models [8] for transport modules with hydromechanical drives require checking for validity of obtained calculation results. Energy regeneration system for hybrid hydraulic transport modules [12] revealed that approximately 41 % of potential energy can be regenerated in case of introduction of a battery. On the other hand, it is a widely acknowledged [13] that many of hydraulic systems for prevention of hydraulic pulse and overloading are equipped with hydraulic batteries. Hydro-gas batteries are used in drives of hoisting and lowering mechanisms of package-forming machines, which requires new technical solutions for energy efficient systems.

3. The aim and objectives of the study

The aim of present research is to select rational structures and search for the ways of minimizing energy consumption during formation of transport packages on the platform of a hoisting and lowering mechanism with a hydromechanical drive.

To accomplish the set goal, the following tasks had to be solved:

– to explore the structure and operation mode of a hydromechanical drive of a hoisting and lowering mechanism for a package-forming machines;

– to state mathematically the problem of minimizing the energy of a power station battery;

– to prove experimentally the assumptions, made during mathematical modeling and to determine a hypothetical polytropic index at step-by-step battery filling.

4. Analysis of the structure and operation principle of a hoisting and lowering mechanism with a hydromechanical drive

As cargo layers accumulate, and, accordingly, pressure in the hydro cylinder increases, the platform lowers step by step under the influence the force of its own weight and a cargo on it. The fluid from the cylinder enters the liquid cavity of a battery. Pneumo-hydro batteries are widely used nowadays [5], that is why it is appropriate to apply this type of batteries for a hoisting and lowering mechanism of package-forming machines as well.

Motion control (fluid consumption) is performed by the appropriate controlling equipment. After formation of a transport package is completed, pressure in the battery reaches its maximum value, and energy, accumulated in it, also reaches the highest values. Then an empty platform rises at the expense of this energy at connection with of a cylinder piston cavity from the fluid cavity of a battery. Along with this, it is important to note that the weight of the platform is commensurate with the weight of one cargo layer, and a transport package includes some of them (5…7) [8, 9]. Therefore, energy consumption for platform lifting will be lower than energy, accumulated in the battery after a package formation cycle. Only a part of the fluid volume in the battery is used to provide serviceability of a hoisting and lowering mechanism, while residual energy can be consumed, for example, in launching modes of other mechanisms (mechanism of pallet removal from the pallet pack) of the machine. To solve the set problem, it is proposed to construct a drive of a hoisting and lowering mechanism of a package-forming machine by the following scheme (Fig. 1) with the use of the hydro-gas battery NTR 0.35 [13]: maximum operating pressure up to 250 bars, operation temperature (–20...+80 °C). In the presence of an elastic element (gas) and significant weight, accordingly, inertia of the piston can cause its self-oscillations. Oscillations are transmitted to all components of the hydraulic system through working fluid.

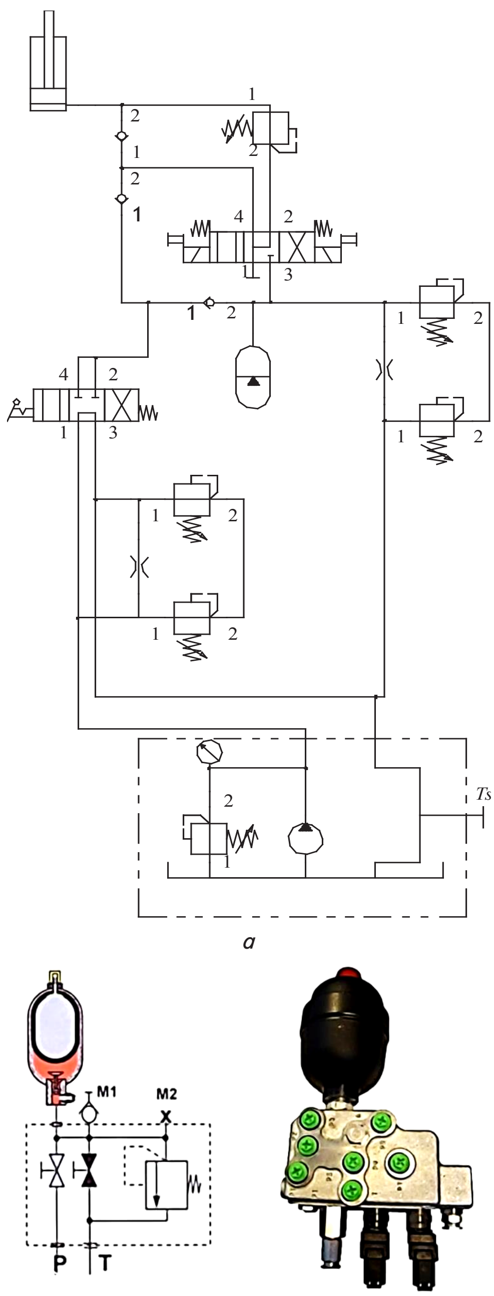

Fig. 1. Schematic of a hydraulic drive and a battery of a hoisting and lowering mechanism: *a* — schematic of a hydraulic drive of a hoisting and lowering mechanism with hydro-gas battery; *b* — schematic and general view of hydro-gas battery with security unit

Such self-oscillations can be the cause of fatigue destruction of individual elements. At low negative temperatures, there can be loss of pressurizing in the place of piston fit in the cylinder, which leads to gas leakage. These shortcomings were eliminated in batteries, where fluid and gas media are isolated from one another by rubber dividers.

In such batteries, gas pressure is transferred directly to the surface of working fluid. Gas and fluid pressures are equal. The use of inert nitrogen as working gas prevents the contact with air oxygen for rubber dividers, which significantly increases service life.

The use of air is not desirable, because at pressures of 1.4–1.6 MPa it becomes explosive (Diesel effect) [8]. That is why nitrogen gas is used. The amount of working fluid, fed to the battery, and gas pressure determine energy storage (energy intensity) that can be fully or partially used at battery discharge with pressurizing of working fluid to the circuit of the hydraulic system. A rubber divider must have such dimensions and the shape that at battery discharge (pressurizing of working fluid to the hydro system), folds could not be formed and stretching would be within acceptable limits.

Scientific papers [9, 10] contain results of research in hydraulic drives with the use of accumulating devices at constant values of loading. Given the special operation modes of hydraulic devices in a hoisting and lowering mechanism of package-forming machines (step-by-step change of loads), the recommended design techniques introduce significant differences compared to actual processes.

5. Research into operation mode and minimal energy consumption in a hydromechanical drive of a hoisting and lowering mechanism

During designing of hoisting and lowering mechanisms, at the stage of technical proposals, i. e. at the stage of selection of types and dimensions of hydraulic equipment (the cylinder and the battery), we face a multiple problem that is necessary to solve by the optimal design method. While studying operation and energy consumption of the battery, it is appropriate to accept such assumptions: gas for battery charging has the properties of an ideal gas, gas compression is between extreme cases – isothermal and adiabatic [4].

Taking into account actual properties of gas essentially complicates computations [5, 6]. We also selected the range of values of working pressure (5–10 MPa) and temperature (5–30 °C), at which a hoisting and lowering mechanism functions. This assumption is sufficiently substantiated and practically expedient.

Condition of gas in the gas cavity can be described by equation:

$$P_1 V_1^n = P_2 V_2^n, \quad (1)$$

where n is the polytropic index $(1 \le n \le 1{,}4)$.

Index n depends on many factors, such as duration of gas compression, initial and final values of pressure, heat exchange, battery design and other factors, and characterizes the operation mode of the battery under actual conditions. That is why it is necessary to determine the polytropic index experimentally by modeling the technological cycle of a hoisting and lowering mechanism operation.

Fluid during step-by-step lowering of the loaded platform is throttled. This provides limits and stabilization of consumption, and accordingly, speed and motion duration of the platform.

Throttle damping factor leads to the fact that oscillatory processes in a hydromechanical drive virtually do not exist [7].

In addition, existence of the distributor with the closed neutral position in the line between the cylinder and the battery generally excludes the impact of residual oscillations on the battery.

The full volume of the gas cavity of the battery is equal to:

$$V_0=V_G+V_P, \tag{2}$$

where V_G is the gas volume; V_P is the fluid volume.

With regard to expression (1), pressure in the gas cavity can be determined:

$$P_G=\frac{P_1V_1^n}{\left(V_0-V_\text{P}\right)^n}. \tag{3}$$

Initial state of gas is determined by pressure of the previous battery charging P_0. That is:

$$P_G=\frac{P_0V_0^n}{\left(V_0-V_\text{P}\right)^n}. \tag{4}$$

In subsequent studies, we will omit indices *p*, 0, considering pressure only of gas and fluid volume in correspondent cavities of the battery.

After each platforms' step-by-step motion downwards and gas compression, there occurs technological downtime of the mechanism, which is caused by the operation of cargo layer formation.

Throughout this time, pressure in the gas cavity of the battery decreases isochronally through heat exchange with the environment. Then the magnitude of pressure drop ΔP_V can be determined [5]:

$$P_V=P_2\left[1-\left(\frac{P_1}{P_2}\right)^{\frac{n-1}{n}}\right], \tag{5}$$

where P_1 is the initial gas pressure; P_2 is the final gas pressure.

Subsequently, we will assume that steady temperature in the hydraulic system is equal to gas temperature during previous battery charging, that is why at the moment if its connection to the system, pressure change does not occur.

Expression (5) corresponds to full scattering of heat, released at polytropic gas compression, in the environment

Pressure drop at one step-by-step platform lowering can be determined:

$$P_V=\frac{P_0V_0^n}{\left(V_0-\dfrac{V_\text{H}}{m}\right)^n}\left[1-\left(\frac{V_0-\dfrac{V_\text{H}}{m}}{V_0}\right)^{n-1}\right], \tag{6}$$

where V_H is the volume of cavity of the cylinder with the bigger area of the piston; *m* is the number of steps, which equals to the number of cargo layers in the package.

Relation (V_H/m) is the volume of fluid, which fills the battery at correspondent motion downwards of the loaded platform.

Pressure in the gas cavity at the end of the technological downtime is determined:

$$P_{21}=P_2-P_V=\frac{P_0V_0^n}{\left(V_0-\dfrac{V_\text{H}}{m}\right)^n}. \tag{7}$$

Expression (7) indicates that final value of pressure during downtime or initial value at the next compression depends on polytropic index and corresponds to isothermal process when n=1. Under actual conditions, there is no complete heat exchange, because actual technological downtime is not long (5–20 s) and depends on performance of a package-forming machine. Along with this, it is rather difficult to take into account magnitude of pressure drop analytically, because the system depends on many factors – ambient temperature, battery design, and others.

Fig. 2 shows the process of battery filling with subsequent supply of fluid to the cavity of the cylinder with the piston area smaller than in the battery, the capacity of which will be denoted as *k*. Hypothetical polytropic index n_1 can be connected with polytropic index of gas compression at step-by-step motion at the expense of coefficient of operation mode of battery *k*, which is a slightly smaller that unity $n_1=kn$.

Mathematical modelling of the process, described above, was conducted according to cyclically-modular approach with the use of known empirical dependences for individual components of the module in the form of a logical-functional model. Processing of results of modeling of operation processes and numerical calculations were performed with application of the software package MathCad 14.0.

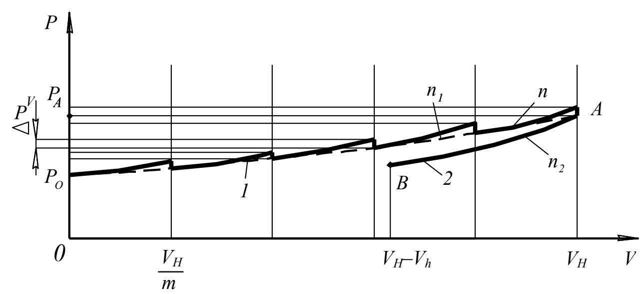

Fig. 2. Dependence of pressure P in gas cavity of the battery on volume of fluid cavity *V*: 1 — hypothetical polytrope that describes the process of battery filling with fluid; 2 — adiabat of fluid supply in the pump mode at n_2=1.4

Point A in Fig. 2 corresponds to gas state on completion of a cycle of step-by-step filling with fluid, and coordinates are derived from equation:

$$P_A\left(V_0-V_\text{H}\right)^n=P_0V_0^{n1}. \tag{8}$$

On complete filling of fluid cavity and some downtime, the battery supplies fluid to the cavity of the cylinder with the smaller piston area, then the platform rises to the initial upper position. At this point, it is not possible to throttle fluid in order to limit the motion speed. Rapid process of gas expansion is adiabatic with index n_2=1,4 [8]. Coordinates of point B determine state of gas on completion of battery operation in the pump mode, in which certain volume of fluid is still under pressure. Residual energy can be used to power other hydraulic engines of machines, which reduces established power station capacity.

Along with this, during designing of a hoisting and lowering mechanism, it is impossible to determine exactly, when residual energy will be used, i. e., how long it will take after completion of adiabatic gas expansion. Within the period of time, determined by the sequence of operations of mechanisms of a package-forming machine, temperature in the gas cavity increases and isochoric increase in pressure will occur as a result of heat exchange. Magnitude of residual energy will somewhat increase its value (with a decrease in entropy of the whole system), which is impossible to calculate at this design stage.

In this case, it is appropriate to state such problem – to select rational parameters of a hydromechanical drive, which minimize values of energy, consumed by the battery when fluid is fed to the cylinder.

Fig. 2 shows battery operation in the pump mode – the area under the section of adiabat AB:

$$W = \int_{V_H - V_h}^{V_H} \left(p - \Delta P_P\right) dV, \qquad (9)$$

where ΔP_P is the pressure losses in distribution element of the battery, for example in the piston ($\Delta P_P = \xi \cdot P$); ξ is the coefficient of pressure losses, ξ=0,015...0,07 [9].

After substitution of equation of gas state at point A in expression (9)

$$P_A = \frac{P_0 V_0^{n1}}{\left(V_0 - V_m\right)^{n1}} \text{ and } P_A V_A^{n2} = PV^{n2},$$

we will obtain

$$W = \int_{V_H - V_h}^{V_H} \frac{P_0 V_0^{n1}}{\left(V_0 - V_H\right)^{n1}} \frac{\left(V_0 - V_H\right)^{n2}}{\left(V_0 - V\right)^{n2}} (1 - \xi) dV. \qquad (10)$$

After integration, we will obtain the form of objective function

$$W = \frac{P_0 V_0^{n1}}{0,4} \left(V_0 - V_H\right)^{1,4 - n1} \times$$
$$\times \left[\left(V_0 - V_H\right)^{-0,4} - \left(V_0 - V_H + V_h\right)^{-0,4}\right](1 - \xi). \qquad (11)$$

To provide serviceability of a hoisting and lowering mechanism, it is necessary that pressure P_{max} in static state in the cavity of the cylinder with the piston of bigger area should be higher than or equal to pressure in fluid cavity of the battery at maximum loading of the platform, located in the extreme lower position. That is:

$$P_{max} \ge P_A \left(1 + \xi\right)$$

or

$$\frac{F_{ymax} S}{V_H} \ge \frac{P_0 V_0^{n1}}{\left(V_0 - V_H\right)^{n1}} \left(1 - \xi\right), \qquad (12)$$

where F_{ymax} is the maximal value of force at the cylinder rod; S is the piston stroke.

Reliable functioning of the mechanism while lifting the empty platform to a specified level is provided by pressure P_{min} in the cavity of the cylinder with smaller piston area. That is:

$$P_{min} \ge P_B \left(1 - \xi\right)$$

or

$$\frac{F_{ymax} S}{V_h} \ge \frac{P_0 V_0^{n_1} \left(V_0 - V_H\right)^{1,4 - n_1}}{\left(V_0 - V_H + V_h\right)^{1,4}} \left(1 - \xi\right). \qquad (13)$$

Expressions (12) and (13) contain magnitude of piston stroke S. This magnitude is pre-set. Thus, doubled magnitude of piston stroke equals to platform motion, which corresponds to the height of the transport package and the technological gap between the surface of the platform and the surface of the package delivery mechanism.

Thus, mathematical statement of the problem of minimizing battery's energy, which is determined when fluid is fed to the operation hydro cylinder can be written down as:

$$\min_{V_0, V_H, V_h, P_0} \left\{ W \frac{P_0 V_0^{n1}}{0,4} \left(V_0 - V_H\right)^{1,4 - n1} \left[\left(V_0 - V_H\right)^{-0,4} - \left(V_0 - V_H + V_h\right)^{-0,4}\right](1 - \xi) \right\},$$

at limits:

$$\frac{F_{ymax} \cdot S}{V_H} \ge \frac{p_o \cdot V_o^{n_1}}{\left(V_o - V_H\right)^{n_1}} (1 + \xi);$$

$$\frac{F_{ymin} \cdot S}{V_h} \le \frac{p_o V_o^{n_1} \left(V_o - V_H\right)^{1,4 - n_1}}{\left(V_o - V_H + V_h\right)^{1,4}} (1 - \xi);$$

$$V_0 < V_{0i};\ V_H < V_0;\ V_h < V_0,$$

where V_0 is the volume of gas cavity of the battery, which correspond to values of recommended range.

To verify accepted assumptions and to determine hypothetical polytropic indices at step-by-step battery filling, the authors carried out experimental research. They used the standard hoisting and lowering mechanism of the floor loader with a flexible traction body and the hydraulic drive, designed according to the schematic in Fig. 1. The experiment was conducted with imitation of the actual operation mode at step-by-step motion of the platform under the influence of packaged cargo. The stop time after each motion of the platform was selected from actual performance of the machine. At pre-set motion step of 120 mm, by preliminarily analyzed dimensions of packaged cargo, at double pulley block, the cylinder's rod moved by 60 mm. Under these conditions, fluid volume in the chamber of the cylinder was 0.302 dm^3.

Measurements were carried out in two extreme positions of the throttle, which corresponds to the lowest speed of the platform of 0.03 m/s and to the highest speed of 0.38 m/s. Maximum speed was limited to accepted values of dynamic loads at switching of the distributor. At critical values, the cargo layer in the package disintegrated. Total time of one step-by-step platform motion downwards and that of the stop was accepted as t=20 s.

Fluid volume of fluid, coming from the cylinder to the battery within one step motion, is V=0.302 dm^3. The volume of the gas cavity of the battery V=2.5 dm^3. Magnitude of platform motion at each step was accepted as constant, which is why the volume of fluid that enters the battery, is a constant value. Given the fact that in logarithmic coordinates [8], graph of dependences between P, V, V_0, P_0 and n_1 is a straight line, equation for determining of hypothetical polytropic index n_1 will be written down as follows:

$$Y = a - n_1 x,$$

where

$$Y = lnP; x = \ln\left(1 - \frac{V}{V_0}\right); a = lnP_0. \qquad (14)$$

To measure values of pressures of fluid in the hydro cylinder and in fluid cavity of the battery, laboratory complex Module of discrete-analog type Easyport USB (D:HW-EASYPORTUSB-D16A-INTERFACE)/Festo/Germany was used When carrying out measurements, a change in the studied parameters in time at each step-by-step motion of the platform was registered with the help of oscillograms. The volume of the sample of experimental values was 25. Table 1, 2 show some data on results of the conducted experimental research at platform motion under various critical speed modes.

Table 1

Experimental data of a change in fluid pressures in hydro cylinder and in battery at V_{min}=0,03 m/s

No.by order	P_1, MPa	P_2, MPa	$\ln P_1$	$\ln P_2$	ΔP, 0,1 MPa	V, dm³	$\ln(1-(V/V_0))$	t, s
1	10	11.5	2.303	2.442	0	0.302	−0.129	4.2
	11	15	2.398	2.708	0.5	0.604	−0.277	4
	14.5	20	2.674	2.996	0.5	0.906	−0.45	4.2
	19.5	25.5	2.97	3.239	0.5	1.208	−0.65	3.4
	25	34.5	3.219	3.541	1.5	1.51	−0.926	4
2	10	12	2.303	2.485	0.5	0.302	−0.129	2.4
	11.5	13.5	2.442	2.603	0.5	0.604	−0.277	4
	13	18	2.565	2.89	0.5	0.906	−0.45	4.2
	17.5	23	2.862	3.135	1	1.208	−0.65	3.4
	22	34	3.091	3.526	1.5	1.51	−0.926	4.2
3	10	11.5	2.303	2.44	0	0.302	−0.129	2
	11.5	13.5	2.442	2.603	0.5	0.604	−0.277	4
	13	16.5	2.565	2.803	0.5	0.906	−0.45	4.2
	16	22	2.773	3.091	1	1.208	−0.65	3.4
	21	33.5	3.045	3.512	2	1.51	−0.926	4

Table 2

Experimental data of a change in fluid pressures in hydro cylinder and in battery at V_{max}=0.38 m/s

No.by order	P_1, MPa	P_2, MPa	$\ln P_1$	$\ln P_2$	ΔP, 0,1 MPa	V, dm³	$\ln(1-(V/V_0))$	t, s
1	10	11.5	2.303	2.442	0.5	0.302	−0.129	0.28
	11	15	2.398	2.708	0.5	0.604	−0.277	0.32
	14.5	18	2.674	2.89	0.5	0.906	−0.45	0.32
	17.5	23	2.862	3.135	1	1.208	−0.65	0.32
	22	33	3.091	3.497	1.5	1.51	−0.926	0.4
2	10	12	2.303	2.485	0.5	0.302	−0.129	0.28
	11.5	14	2.442	2.639	0.5	0.604	−0.277	0.32
	13.5	17.5	2.603	2.862	0.5	0.906	−0.45	0.32
	17	23	2.833	3.135	1	1.208	−0.65	0.32
	22	32.5	3.091	3.481	1.5	1.51	−0.926	0.4
3	10	11.5	2.303	2.442	0	0.302	−0.129	0.28
	11.5	14.5	2.442	2.674	0.5	0.604	−0.277	0.32
	14	18	2.639	2.89	0.5	0.906	−0.45	0.32
	17.5	22.5	2.862	3.114	1	1.208	−0.65	0.32
	21.5	31.5	3.068	3.45	2	1.51	−0.926	0.4

According to data in Table 1 for the second sample, the actual process of a change in fluid pressures in logarithmic coordinates is presented (Fig. 3).

$$\ln \Delta P_1 = \ln P_{21} - \ln P_{12} = \ln \frac{P_{21}}{P_{12}};$$

$$\ln \Delta P_2 = \ln \frac{P_{22}}{P_{13}};$$

........................;

$$\ln \Delta P_i = \ln \frac{P_{2i}}{P_{1,i+1}}, \qquad (15)$$

where i=1,..., l.

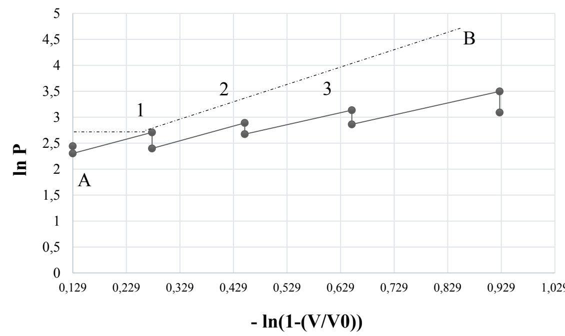

Fig. 3. Actual process of stepwise filling of battery with fluid

Having used equation (14) and research results (Table 1, 2), the authors determined the value of a hypothetical polytrope of step-by-step filling of the hydro-gas battery. For the considered range of speeds of platform motion, polytropic index is within n_1=1.23...1.27. In this case, a higher value corresponds to a slower speed at one step of motion.

6. Discussion of results of study of operation of hoisting and lowering mechanism of package-forming machine

Based on the synthesis and analysis of the operation modes of a hoisting and lowering mechanism of a package-forming machine, it was established that to minimize energy consumption at cyclic filling, it is necessary to apply hydro-gas accumulating devices. To provide effective energy saving, the system of pressure regulators was introduced to the scheme of control of a hydromechanical drive. In existing examples of package-forming machines with alternating loads, cyclic step-by-step loading is not intended in the course of operation. It does not provide a possibility to minimize energy consumption for the most important part of a package-forming machine – a hoisting and lowering device. To determine parameters of a hydraulic drive, operation modes of hydro-gas battery were modeled, and objective function of minimizing energy consumption was formulated. Experimental studies were carried out in order to verify this function and above assumptions in the calculation model.

Results of experimental research allow us to determine coordinates of straight line AB (Fig. 3). For average relative rate of filling the battery cavity with fluid V_{ave}=0.033 m/s, index n_g is within 1.391...1.437. At this rate of filling the battery cavity with fluid, gas compression process can be described with an adiabat with index n_g=1.4. This proves the assumptions, made in the theoretical part of the research. Similar results were also obtained at a higher speed of platform motion.

Theoretically stated problem of minimization of energy consumption by a hydro-gas battery is a problem of nonlinear programming and it is solved using the numerical multi-step zero-order method [10] at the following source data: n_1=1.25 (experimentally obtained value of hypothetic polytropic index); V_0=2.5 dm^3, $F_{y\max}$=26 kN, $F_{y\min}$=5.7 kN, coefficient of pressure losses ξ=0.05, piston stroke S=0.5 m.

Values of parameters that provide the minimum of objective function at the following limits were acquired: pressure of previous battery charging P_0=2.6 MPa, volume of the cylinder cavity V_H=1.5 dm^3. Value of tolerance for magnitude P_0 is limited by expressions (12), (13). To obtain the desired value of this magnitude tolerance, it is necessary to increase and to decrease, respectively, values of $F_{y\max}$ and $F_{y\min}$ in inequalities of limits.

Validity of theoretical assumptions (Fig. 2) on verification of dependence of pressure P in the gas cavity of the battery on volume of fluid cavity V was proved by obtained experimental results (Fig. 3).

Search for new technical solutions to minimize energy consumption in drives of package-forming machines requires improvement of hydromechanical control systems. One of the main obstacles in development of hybrid hydro-gas systems is insufficiently highlighted step-by-step cyclic loading of the entire hydraulic drive. The obtained research results for a package-forming machine with a hoisting and lowering hydraulic mechanism and the proposed accumulating device significantly differ from the existing ones.

Development of technical design of an accumulating device, provision of control of pressure drops in the system of a hydraulic drive, improvement of hoisting and lowering mechanisms of package-forming machines, development of complex control systems with feedback are directions of development of this research.

7. Conclusions

1. The structure of a hydromechanical drive with the hydro-gas battery for a hoisting and lowering mechanism of a package-forming machine was proposed. Due to throttling of fluid motion from the hydro cylinder to the battery, accumulation of potential energy at step-by-step loading of a hoisting and lowering mechanism was provided. Operation modes of hydro-gas battery as a part of a hoisting and lowering mechanism were theoretically studied. Objective function of minimization of energy consumption by a hydraulic drive was formulated.

2. We experimentally proved adiabatic mode of gas compression in the battery at pre-set speeds of platform motion: $V_{\min}$=0.03 m/s, $V_{\max}$=0.38 m/s. This proves accepted assumptions in the theoretical part of the research.

3. We experimentally determined hypothetical polytropic index of step-by-step filling of the hydro-gas battery, which for pre-set speeds is within n_1=1.23...1.27, according to values of speed extrema ($V_{\min}$=0.03 m/s, $V_{\max}$=0.38 m/s). For basic original parameters of package-forming machines, parameters of a hydraulic drive, which provide minimum of objective function in terms of energy consumption by the battery, were determined.

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