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Method of Compact Ground Launching Devices Shape Formation for Unmanned Aerial Vehicles

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Abstract. The purpose of this paper is to develop a method for forming the shape of compact ground launching devices (GLDs) unmanned aerial vehicles (UAVs), which includes three stages.

Firstly, the choice on the basis of the theory of dimension and similarity of the closest analogue of the design object based on world experience gained in this field. Secondly, the creation of a comprehensive model of the working process of GLD and a universal method for its numerical implementation. Thirdly, the solution to the problem of optimizing the dynamic characteristics of GLD.

At the described stages of the formation of the shape of an GLD UAV, a statistical analysis of the technical perfection of known analogues of UAV launch systems, methods of the theory of similarity and dimension in mechanics, methods of numerical simulation of the working process, and also methods of conditional parametric optimization are used. The undoubted importance of the problem of the equivalent development of the components of the UAS, consisting of an aircraft and a launch system (catapult). The traditionally non-priority status of GLD in the general cycle of the complex design program is also known. A systematic solution to this problem lies in the mainstream of creating common approaches, one of which is contained in this article. The proposed method of forming the appearance of compact GLDs UAV can be extended to a wide class of starting systems containing a thermal expansion machine and a mechanical component. In the presented form, the method is not applicable to systems of air, aerodrome and manual launch of UAVs. A method has been developed for the formation of the shape of GLD based on the energy relations of the criterion type between useful functions and the corresponding costs, with subsequent verification numerical studies of the launch processes based on specially created technology of a computational experiment, as well as optimization of the dynamic characteristics of GLD. The method of forming the shape of compact GLD is universally applicable to any type of catapults, regardless of the type of transmission and drive, since many particular forms of organization of the working process are generalized using the criteria of energy perfection, a comprehensive physical and mathematical model and normalization of the starting overload.

Keywords: shape formation, ground catapult, similarity criteria, mathematical model, performance optimization

1. INTRODUCTION

General trends in the informatization and robotization of the techno sphere based on the ongoing miniaturization of the radio electronic element base entail the rapid development of unmanned aerial systems (UAS) with a focus on the intensive growth of functionality without increasing the scale factor. The condition for the harmonious development of technical systems, including the UAS, implies a comparable level of perfection of the constituent elements, providing the necessary synergistic effect. However, in the process of designing the complex, this condition is far from always fulfilled with inevitable damage to the quality of the final product. For example, the low priority of the perfection factor of ground launching devices (GLDs) for light unmanned aerial vehicles (UAVs) of an aircraft type entails a deterioration in speed characteristics, range, mobility, operational suitability, cost of the complex, etc.

The above considerations make it possible to draw a conclusion about the importance of the problem of ensuring the high-quality design of GLD (catapults) as part of the UAS. A systematic solution to this problem lies in the mainstream of creating common approaches and design methods presented below.

Work on the development of compact expansion machines, which includes three successive stages. Design on the basis of world experience, accumulation in this area on the basis of the theory of size and similarity [1]. At the second stage, the complex model of GLD and the method for approximate solution of the corresponding system of equations are configured on the basis of universal technology for the numerical simulation of the complex of thermogasdynamic and mechanical processes in expansion heat machines [2]. At the third stage, the solution of the problem of parametric optimization of the dynamic characteristics of the GLD is found [3].

At the described stages of the formation of GLD UAV appearance, a statistical analysis of the technical perfection of known analogues of UAV launch systems, methods of the theory of similarity and dimension in mechanics, methods of numerical simulation of gas-thermodynamic processes in thermal expansion machines, as well as methods of conditional parametric optimization are used.

A family of unified methods has been developed to form the appearance of GLDs, based on the criterion energy relations between useful functions and the costs of their production, with subsequent numerical studies of the launch processes based on the particular configuration of the universal technology of a computational experiment for parametric optimization of the dynamic characteristics of GLDs.

The family of methods for forming the appearance of compact GLDs is universally applicable to any type of thermal expansion machines and transmissions due to the generalized mapping of the variety of forms of organization of the work process by the criteria of energy excellence, a complex physical and mathematical model and the principle of normalization of starting overload.

2. CLASSIFICATION AND GENESIS OF GROUND CATAPULTS

Catapults as throwing machines have been used by mankind throughout history – from the wars of the first generation, where only edged weapons were used, and to modern wars of the fifth generation, where high-precision systems are used. For a long period of history (over several centuries), catapults were not used at all in conflicts, since the appearance of gunpowder (the beginning of the wars of the second generation) made the use of low-powered mechanical installations inappropriate.

The catapults found a new life as ground launching devices (GLDs) – systems for the forced dispersal of an aircraft (manned or unmanned) vehicle on a shortened section of the trajectory. However, in the last century, the term catapult was actually associated only with deck-mounted steam catapults, and mainly powder accelerators were used to launch unmanned aerial vehicles (UAVs) [4]. The turning point at the beginning of this century was the miniaturization of on-board equipment, which made it possible to create full-fledged UAVs weighing several kilograms [5]. The desire to reduce the cost of unmanned aerial systems (UAS) as a whole, the developers refused multimode UAVs and excluded take-off using the runway. Thus, the use of external energy, that is GLD (catapult), has become an uncontested way of introducing single-mode and / or high-speed UAVs into flight [6]. Currently, there is no established standard classification of external UAV flight input systems, however, systematization by the start method looks logical:

1. hand;
2. from a carrier;
3. with a booster;
4. from a catapult.

Manual start due to the limited muscular effort of a person is applicable for a very limited class of micro-UAVs (UAV “FQM-151” AeroVironment). Basically, starting from an external carrier is used at the stage of testing heavy free-flying models (FFM) or heavy UAVs. As a carrier may be considered as a vehicle (UAV “Pchela-1” SRI PSP KhAI), helicopter (UAV “SLM-22” SRI PSP KhAI) or airplane (UAV “BQM-34A” Ryan Aeronautical). Launching using rocket boosters is a legacy of the UAS of the first generations and shifts the energy balance of UAVs in the field of aeroballistic missiles (UAV “Tu-243 Reis-D” DB Tupolev). A catapult launch means acceleration of a UAV along a portion of a guide of a limited length. Extensive ejection type GLD class it is advisable to group according to the principle of creating traction drive forces:

1. mechanical:
   - inertial;
   - rubber;
   - gravitational;
2. on a “cold” working fluid:
   - pneumatic;
   - vacuum;
   - steam;
3. on a “hot” working fluid:
   - liquid propellant gas generator;
   - solid propellant gas generator;
   - jet trolleys.

Mechanical catapults do not have the potential for modernization due to the low energy of mechanical drives [7]. In this regard, mechanically-driven pumping facilities are beyond the scope of thematic interest due to their insufficient power density. The first engineer to create a “real” (in the modern sense) catapult for the FAU-1 projectile was Werner von Braun. For a long time, this scientific and technical groundwork remained unclaimed and for almost the next 70 years completely ordinary installations appeared – the results of spontaneous evolution of species. Currently, there are several well-known companies systematically engaged in the development and manufacture of GLD in Europe [8]: Robonic Ltd Oy (Finland) и Aries Ingenieria Y Sistemas (Spain). The author considers the installation of SuperWedge by The Insitu Group Inc. (USA) to be the pinnacle of engineering in the class of low-powered GLD, and among GLD of medium power – R12P of the Rotor company (Russia).

3. MAIN FACTORS DETERMINING SHAPE OF GLD

Under the face is understood the principle of operation, the design of the GLD and its parametrization of the workflow, i. e., a set of relative parameters that uniquely determine the safe start of the UAV and, as a result, the performance characteristics. Today it can be stated that the appearance of the GLD for launching light UAVs has fully formed. Regardless of the design, the ground catapult has the following main nodes:

1. drive;
2. transmission;
3. guide;
4. energy source.

Based on the utilitarian logic, regardless of the type of GLD, its useful function $\overline{\Pi}_U$ is the kinetic energy that the UAV should give the catapult in the conditions of limiting the starting overload:

$$\overline{\Pi}_U = \{V_{0\,\min}, m_{UAV}\},\ n_X(x) < n_{X\,\max},\ \forall x \in L \tag{1}$$

where: $V_{0\,\min}$ – minimum initial UAV velocity;

m_{UAV} – UAV mass launched;

$n_{X\,\max}$ – maximum permissible starting overload.

Thus, the matrix of parameters $\{V_{0\,\min}, m_{UAV}, n_{X\,\max}\}$ will uniquely determine the appearance of GLD. A comparative analysis of the functional perfection of well-known GLD samples is carried out on the basis of the “rule of standards” [9]. In accordance with the rule, a non-negative number is assigned to each object of technology, and then the level of perfection is determined by comparing these numbers. The appearance of GLD is normalized with the help of dimensionless criteria of transport (energy, speed, mass, etc.) perfection.

3.1. Criteria of similarity of transport systems with GLD

Similarity criteria are understood as dimensionless numbers composed of dimensional physical parameters that determine the considered physical phenomenon. Similarity criteria can be obtained formally on the basis of the π-theorem using the dimension search algorithm [10], derived from the basic conservation laws by their dimensionlessness or by the analytical method in the form of process efficiency [11]. Consider a simplified UAV launch model, but fully reflecting the physics of the process, which includes the equations of conservation of momentum (for catapults) and energy (for accelerators), as well as the initial conditions:

$$\begin{cases} m_{UAV}\dfrac{dV}{dt} = F - m_{UAV}g(f\cos\theta + \sin\theta); \\ m_F H_U \xi = \dfrac{m_{UAV}V^2}{2} + m_{UAV}gL\sin\theta; \end{cases} \qquad (2)$$

$$V\Big|_{t=0} = 0;\ x\Big|_{t=0} = 0;\ \left.\frac{dV}{dt}\right|_{t=0} = 0 \qquad (3)$$

where: *x* – UAV coordinate on the guide;

V – UAV flight velocity;

g – gravitational acceleration;

m_p – fuel starting accelerator mass;

ξ – completeness of fuel combustion coefficient;

θ – angle of inclination of the guide;

f – sliding friction coefficient;

H_u – calorific fuel value.

To reduce the system of equations to dimensionless form, for each dimensional parameter, the equation records its relation to primary physical quantities, i.e., *L*, *V*, *m*, *g*, *t* (for example, it is written H_u/gL at a value H_u), and then the first equation is reduced by $m_{UAV}\cdot g$ and the second – by the amount $m_{UAV}\cdot V^2$:

$$\begin{cases} \Pi_1 n = \Pi_2 - (f\cos\theta + \sin\theta); \\ \Pi_3\Pi_4\xi = \Pi_5 - \Pi_6\sin\theta, \end{cases} \qquad (4)$$

where: $\Pi_1 = \dfrac{V}{tg}$, $\Pi_2 = \dfrac{F}{m_{UAV}g}$, $\Pi_3 = \dfrac{m_F}{m_{UAV}}$, $\Pi_4 = \dfrac{H_U}{V^2}$, $\Pi_5 = \dfrac{V^2}{2Lg}$, $\Pi_6 = \dfrac{gL}{V^2}$ – primary similarity criteria.

In addition to the special criteria of similarity $\Pi_{1...5}$ obtained in the criterion analysis, generally accepted criteria can be used: starting overload (*n*), Mach number (*M*), compactness of GLD (*λ*), etc. Further, special criteria for energy perfection are derived as a combination of criteria $\Pi_{1...5}$.

$$K_{LD} = \frac{\Pi_5}{\Pi_2} + \Pi_2 \sin\theta = m_{UAV} \frac{V^2 + 2m_{UAV} gL \sin\theta}{2FL} \tag{5}$$

$$K_{BP} = \frac{1}{2\Pi_4\Pi_3} + \frac{\Pi_6}{\Pi_4\Pi_3} = m_{UAV} \frac{V^2 + 2m_{UAV} gL \sin\theta}{2m_F H_U} \tag{6}$$

where K_{LD} and K_{BP} – criteria for energy excellence pneumatic catapult and powder boosters

3.2. GLD Shape Formation

The obtained similarity criteria are analogues of efficiency, that is, they express the beneficial effect on the cost of obtaining it in equivalent terms [12]. Criteria allow to carry out systematic assessments of the perfection of the functional properties of GLDs (transport, speed, energy) of various types like [13]. The information for the formation of criteria (5) and (6) is the technical characteristics of GLD available in available bibliographic sources. Imagine the set of GLD N with their characteristic characteristics in the form of an information vector $\vec{c}_i = \{c_i^1, ..., c_i^M\}$ (l = 1…M), then the rule of norms for them will be written as $K_i = \left\|\vec{c}_i\right\|$ (i = 1…N). As a result, the task of finding the best GLD formally reduces to establishing inequalities:

$$K_\alpha \overset{>}{\underset{<}{}} K_\beta\,;\ \alpha \in [1, N]\,;\ \beta \in [1, N]\,;\ \alpha \neq \beta \tag{7}$$

Below are expert assessments of the energy excellence of GLDs of various types based on the well-known performance characteristics (Table 1) in the “K-n” criterion space (Figure 1).

The graph demonstrates the inverse dependence of the criteria energy perfection from the starting overload and, at the same time, a decrease in energy excellence with increasing power of GLD. Statistical processing of a given sample of the performance characteristics of ground catapults provides a distinct linear type separation of samples in order of increasing drive power of the pumping station: mechanical – pneumatic – pyrotechnic.

Table 1. Performance Characteristics of Catapult Type GLD

No	GLD and UAV	Type of GLD	m [kg]	V [m/s]	L [m]	n [g]	K
1	KZO	Starting accelerator	161	40	12	16	0.437
2	Stroy-P (“Pchela-1”)	Jet trolley	138	35	9	14	0.509
3	BAE Sys. (“Phoenix”)	Pneumatic hydraulic	140	33	8	12	0.595
4	HESA (“Ababil”)	Pneumatic	83	30	7.5	10	0.631
5	KGM-6S (“Albatros”)	Inertial	26	25	7	6	0.792
6	KBPS M-10-2 (“Oko”)	Rubber	5	13	3	3.5	0.878

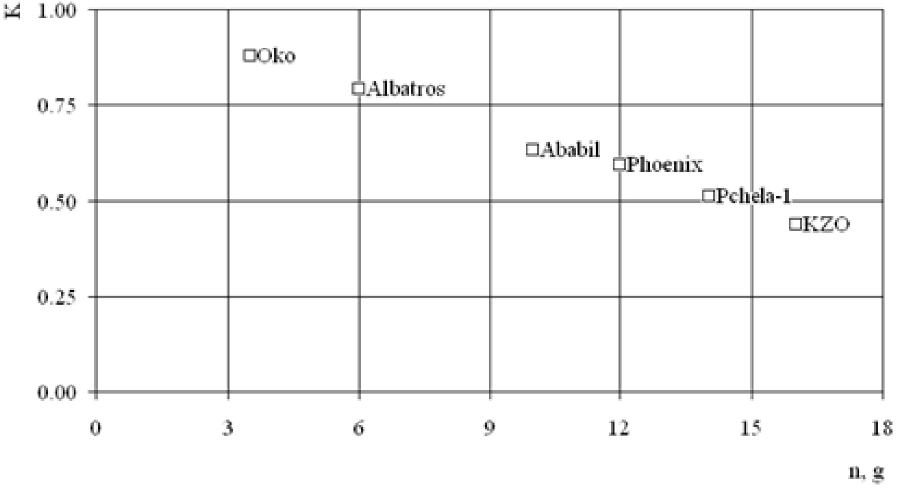


Fig. 1. Perfection Energy Estimation for Various Types of GLDs in Criterial Space of Functions “K-n”

Criterion (6) indicates the low energy perfection of pyrotechnic GLDs (“Pchela-1”, “KZO”). In combination with the unmasking signs of launch, the need to obtain a launch license, the scope of this type of UAV flight entry systems is narrowing.

A high level of energy excellence is demonstrated by mechanical GLDs (“Albatros”, “Oko”), this is due to the fact that purely mechanical drives and transmissions have generally higher effective efficiency. The limitation for their widespread use is the low starting overload and, as a consequence, the growth of the dimensions of the guide.

3.3. Numerical Modelling of Work Processes in GLD

As part of the formation of the appearance, after assessing the energy perfection of GLD taking into account world design experience, the next step is to conduct advanced numerical studies of work processes in GLD. An adequate display of the completeness of a fast-moving process in a pumping station requires the use of a complex drive model in an unsteady spatial setting with moving boundaries, the position of which is determined by the conjugate dynamics of the moving parts.

The mathematical description of GLD model is based on the conservative form of writing the system of equations of spatial non-stationary inhomogeneous flow in Cartesian coordinates [14], consisting of equations of conservation laws:

1. masses:
   - mass as a whole;
   - concentration;
   - entropy;
2. pulse:
   - in direction of the axis OX;
   - in direction of the axis OY;
   - in direction of the axis OZ;
3. energy.

The universal form of writing the system of equations of the 3D model, which allows to manifest a unified compositional structure of the model, in vector-matrix terms has the following representation [15]:

$$\frac{\partial \overset{\Rightarrow}{F}}{\partial t} + \sum_{j=1}^{3} \frac{\partial \overset{\Rightarrow}{\Phi}}{\partial x_j} = \sum_{n=1}^{M_M} \left(\frac{\partial \rho}{\partial t} \frac{\overset{\Rightarrow}{F}}{\rho} \right)_n + \sum_{m=1}^{M_C} \overset{\Rightarrow}{\Delta}_m \tag{8}$$

where:

$\overset{\Rightarrow}{F} = \rho \left\{ 1,\ \omega,\ S,\ \vec{w},\ \varepsilon^0 \right\}$ – vector matrix of local processes;

$\overset{\Rightarrow}{\Phi} = \vec{e}_j \Phi_j = \overset{\Rightarrow}{F} w_j + p \left\{ 0,\ 0,\ 0,\ \delta_{1,\,j},\ \delta_{2,\,j},\ \delta_{3,\,j},\ w_j \right\}$ – vector matrix of convective processes;

$\vec{e}_j$ – unit vectors of the rectangular coordinate system;

$\overset{\Rightarrow}{\Delta}_m = \left\{ 0,\ \frac{\partial}{\partial x}(\rho\omega),\ \frac{\partial}{\partial x}(\rho S),\ \vec{f},\ \frac{\partial}{\partial x}\left(\rho\varepsilon^0\right) \right\}$ – vector matrix of “free” features;

$\vec{f} = \{ f_1, f_2, f_3 \}$ – mass force field vector;

ρ – density;

S – entropy;

ω – mass concentration of the component (fresh charge of gas or combustion products);

$\varepsilon^0 = \varepsilon + w^2/2 = C_V T + w^2/2$ – total internal energy;

$\iota^0 = \varepsilon^0 + \frac{p}{\rho} = \iota + w^2/2 = C_p T + w^2/2$ – enthalpy in full terms;

M_M – total number of substantial features;

M_C – total number of “free” features.

The closing conditions of the system of equations are the initial and boundary conditions, the thermal and caloric equations of state of an ideal gas, the equations of the dynamics of moving boundaries (9), and also the relations that determine the intensities of the features.

To solve the subsystem of equations (8), which takes into account only the change in the “autonomous” flow, the finite-difference scheme of S. K. Godunov modified for the boundary cells of the computational subdomain is used [16]. The intensities of the exchange processes between cells and at the cell boundaries are found from the solution of well-known self-similar problems.

The set of dominant factors of the workflow is modelled by the application of the features of the type of sources-drains of material substances of two types: those associated with mass transfer, and “free” ones. The solution of the problem of gas dynamics in geometric regions of complex shape is also constructed using the method of features in the form of a “gas-thermodynamic mask”. To display the topological properties of the object of study in the computational domain, a system of masks of three types is specified:

1. thin-walled:
   - full permeability;
   - partial permeability;
2. guide cosines:
3. volumetric.

Dissipation in the working process of the drive of the pumping unit is reproduced by normalizing the approximating viscosity (Ambrozhevich, 1998), which can be considered as a one-parameter model of turbulence. To ensure a correspondence between physical and approximate viscosity, system (8) contains an “excess” equation of entropy transfer.

The mechanical sub model of the moving parts of the transmission of the pumping unit, coupled with thermo-gas-dynamic conditions at the internal boundaries, is described by the second-order Lagrange equation. The differential equation describing the movement of the mobile units of the pumping station in general will look like a second-order equation with one independent variable:

$$a[F(t)]\ddot{s} = d[P(t)] \tag{9}$$

where a[$F(t)$] and d[$P(t)$] – well-known functions of the geometric, inertial and dynamic characteristics of the mobile parts of the GLD, which determine the traction force; s – coordinate of the movable mechanism.

To conduct a computational experiment, a software package in C++ was developed that consists of three modules: a mask generator, a mathematical core, and an animation shell. The 3D model for generating masks is imported in the STL format from any CAD application. In the graphical shell, each scalar field corresponds to its own shade within the allotted colour tone (pressure – blue, temperature – red, number M – lilac, charge concentration – yellow).

In Figure 2 presents one of the phases of the GLD working cycle modelled using the author's technology of a numerical experiment [17].

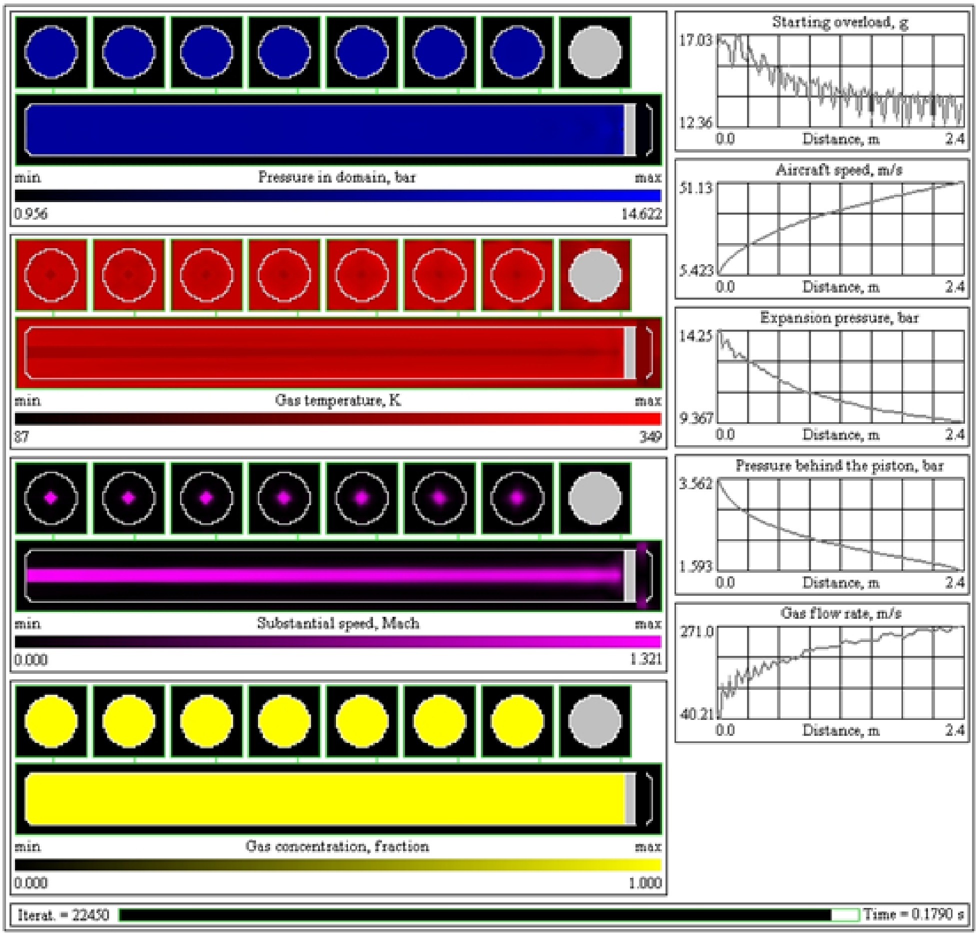


Fig. 2. States of Physical Fields and Dynamic Characteristics of Pneumatic Pump

The calculation results have the representation of a virtual test bench in the form of colour maps of physical fields synchronized in the phases of operation in the drive of the pumping station and graphs of the transmission integral characteristics.

4. OPTIMIZATION OF DYNAMIC CHARACTERISTICS OF GLD

Regardless of the type of GLD, its useful function is the kinetic energy E_{LD} that UAV needs to report. However, it is possible to perform work on accelerating UAV of a certain mass m_{UAV} to a given speed $V_{0\ min}$ in different sections of the length of the guide L.

The determining overload of the acceleration section is the starting overload acting on UAV, which in turn depends on the characteristics of the avionics and structural strength [18].

Optimization of the dynamic characteristics of an injection pump is understood as obtaining a constant law of starting overload n_x = const, which will allow UAV to give a predetermined initial speed at the minimum possible acceleration area and to obtain a more compact design.

GLD with optimal dynamic characteristics will be as compact as possible, thus, the target function of the optimization problem is the minimum guide length $L \to \min$. The efficiency criterion, on the basis of which the best of the options can be identified, is the degree of completeness of the work performed to accelerate UAV, which is an analogue of the efficiency and is calculated by the formula:

$$\kappa = \frac{A_{act}}{A_O} = \frac{\int_0^L n_X(x) g dx}{n_{X\max} g L} = \frac{n_{X\,mid}}{n_{X\max}} \tag{10}$$

where:

A_{act} and A_{max} – actual and maximum possible work on moving UAV along the guide;

$n_{X\ mid}$ – average value of the starting overload with the actual regressive law of its change;

$n_{X\ max}$ – maximum permissible starting overload, maintained at a constant level in an ideal process.

Among the many parameters of GLDs, one can single out the controlled ones – those that have the greatest impact on the performance criterion. It is advisable to leave the general controlled parameters (start angle, cylinder volume, diameter of the pneumatic line, etc.) fixed due to the weak effect on κ.

Private controlled parameters are inherent in a particular direction of improving the characteristics of the pumping facilities, among which it is advisable to single out measures aimed at upgrading the transmission and / or catapult drive:

$$\overline{\Pi} = \left\{\overline{\Pi}_{T}, \overline{\Pi}_{D}\right\} = \left\{ \begin{matrix} y(x) \\ \alpha_0 \\ \dots \end{matrix} \right\}, \left\{ \begin{matrix} s_i \\ d \\ \dots \end{matrix} \right\} = \mathrm{var} \tag{11}$$

where:

$\overline{\Pi}_{T}$ and $\overline{\Pi}_{D}$ – private controlled transmission and drive parameters;

y(*x*) – plane profile equation of the copier;

α_0 – initial angle of inclination of the working elements of the variator;

t_i – moments of operation of additional electric cranes;

d – the diameter of the quick-release valve, *i* = 1, 2, 3.

The optimization problem (12) is reduced to finding the value of the controlled parameter $\overline{\Pi}^{*}$ at which the constant law of the starting overload is realized and the maximum value of the duty cycle of the diagram is achieved $\kappa\left(\overline{\Pi}^{*}\right) \to 1$. The set of feasible solutions $\overline{\Pi}^{*} \in D$ is set by the system of restrictions of the form of inequalities (13) for the starting overload $n_{X\,\max}(x)$, the speed of the UAV $V_{0\,\min}$ entering the flight and the initial cylinder pressure p_{OB}:

$$\kappa\left(\overline{\Pi}^{*}\right) = \max_{\Pi\text{ч} \in D} \kappa\left(\overline{\Pi}\right) \tag{12}$$

$$\begin{cases} n_X(x) \le n_{X\,\max} = \mathrm{const}, \ \forall x \in L; \\ V_0 \ge V_{0\,\min} = \mathrm{const}; \\ p_{0\,B} \le 2 \text{ MPa.} \end{cases} \tag{13}$$

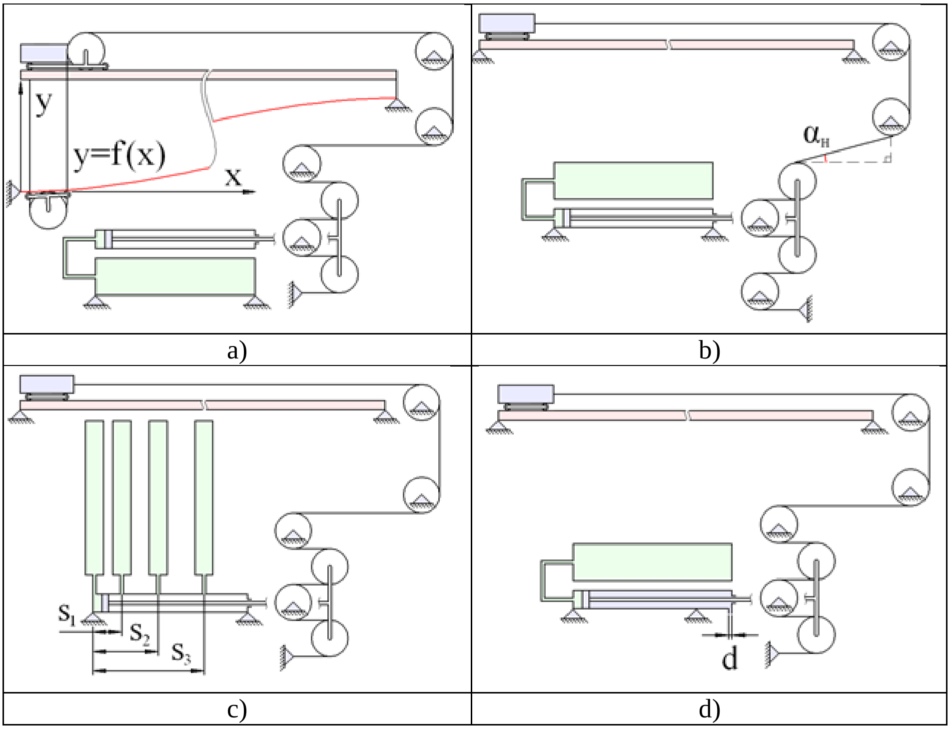
It is proposed to solve the problem of finding the best values of the controlled parameters of GLD using the search method that uses the previous information to build an improved solution, i. e., in the iteration process. To record the desired point of the next iterative step, the increment of the vector $\Delta\overline{\Pi}^{k}$ of controlled parameters is used, which is defined as the product of the step of the parameter *h* and the search direction $\alpha^k > 0$ and is predefined:

$$\overline{\Pi}^{k+1} = \overline{\Pi}^{k} + \Delta\overline{\Pi}^{k}, \ k = 0, 1, \dots, \tag{14}$$

where $\Delta\overline{\Pi}^{k} = h\alpha^{k}$ and $\alpha^{k} \in R$.

It is proposed to solve the problem of finding the best values of the controlled parameters of GLD using the search method that uses the previous information to build an improved solution, i. e., in the iteration process. Consider the main directions of modernization of pneumatic GLD. It should be noted that the standard GLD consists of a pneumatic linear engine and a multisliding mechanism with a constant gear ratio.

1. transmission upgrade:
   - use of variator pulley type (Figure 3 a);
   - use of variable-speed variators (Figure 3 b);
2. drive upgrade:
   - reusable supply of a working fluid along the cylinder (Figure 3 c);
   - management of the law of change of back pressure (Figure 3 d).



a) b)

c) d)

Fig. 3. Some Modernization Methods of GLD Due to Use of: a) Copier Type Variator; b) Variator of Polyspast Type; c) Reusable Supply of Working Fluid; d) Changes in Law of Counter pressure

Among the above-mentioned modernization methods for high-capacity power plants, it is advisable to modernize the drive (Figure 3 c, d), in particular, to control the law of resistance to the main link.

The main idea of the principle is to obtain the law of change of counter-pressure equidistant to the law of change of expansion pressure so that the resulting force remains constant throughout the work cycle:

$$F(x) = [p_P(x) - p_\Pi(x)]S = \text{const}, \ \forall x \in L \tag{15}$$

where:
$p_P(x)$ – instantaneous value of expansion pressure;
$p_\Pi(x)$ – instant value of back pressure behind the piston;
S – the area of the piston;
$F(x)$ – traction effort of GLD.

In a conventional pneumatic cylinder, a quick pressure relief valve lowers the back pressure behind the piston to atmospheric pressure $p_\Pi(x) = p_0 = 1$ bar, as a result of which the traction force corresponds qualitatively to a change in the expansion pressure. It is proposed by injecting air into the piston space of the cylinder and partially clamping the valve section to obtain a regressive backpressure law that is equidistant to the regressive expansion law.

The controlled parameter in the optimization problem is the diameter of the venting hole of the quick pressure relief valve (d), which uniquely sets the creep law and, as a result, the dependence of the change in traction force, all other things being equal. The optimization task of GLD is reduced to finding the set of admissible values of the controlled parameter $d_i^* \in D$, in which the completeness of the thrust cyclogram acquires the maximum value $\kappa(d_i^*)$ with restrictions (13):

$$\kappa(d_i^*) = \max_{d_i \in D} \kappa(d_i) \tag{16}$$

Below are the results of optimizing the dynamic characteristics of a pneumatic catapult (Figure 4, a and b).

The search for the optimal value of the valve diameter was carried out in several iterations with a step of 1/4 inch, starting from 1 inch, and subsequent normalization of the law of change in the starting overload. The analysis shows that the optimal option is with a diameter of a pressure relief valve of 1.5 inches, since this achieves the maximum possible value of the coefficient $\kappa = 0.96$. Comparison of the calculated integral dynamic characteristics of the standard pumping station (pos. № 1) and the modernized (pos. № 2) indicate the best filling of the overload diagram (by 18 %) by the end of the working cycle (shaded area). Due to the compensation of the overload drop, it is possible to reduce the acceleration section of UAV by 20 % with a guarantee of achieving the necessary initial GLD speed.

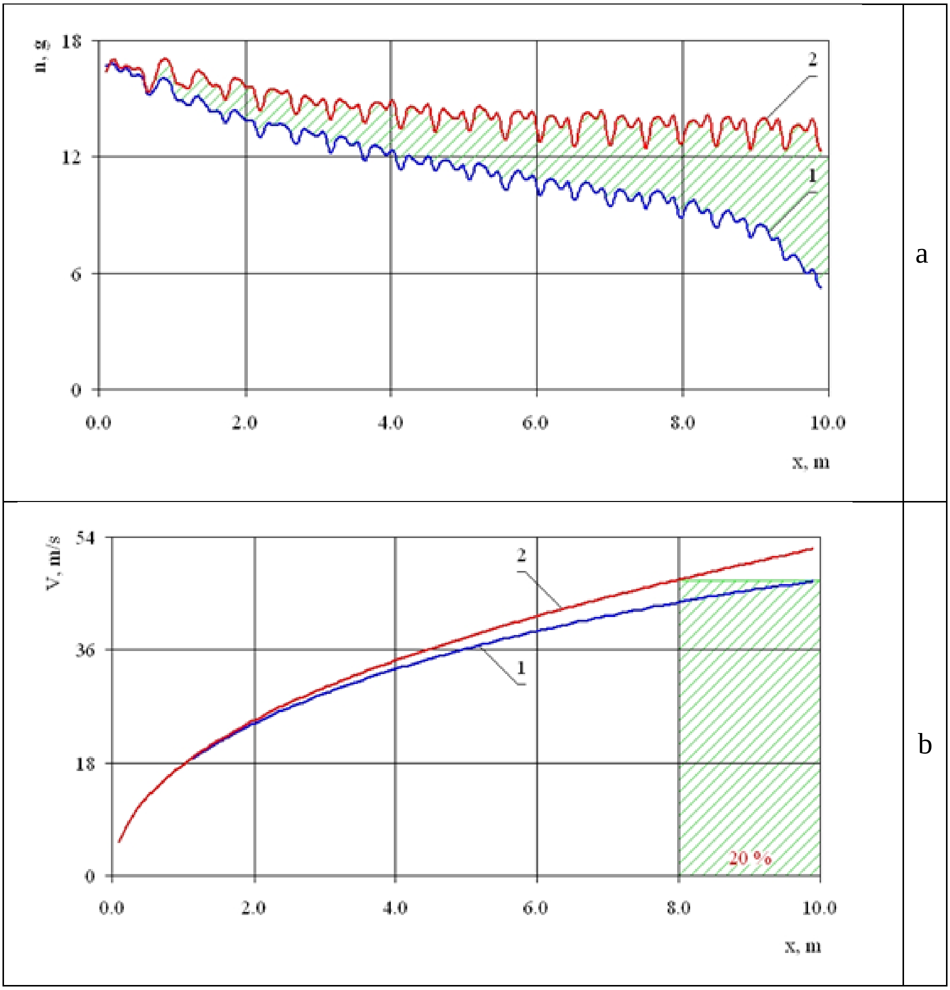


Fig. 4. Comparison of Dynamic Characteristics of Optimized and Standard Pumping Stations: a) Change in Overload; b) Speed Gain

In general, it is possible to state some difficulties in achieving a constant law of changing the starting overload with one-parameter control. In particular, for the considered option (Figure 4), in addition to the diameter of the pressure relief valve, it is advisable to control the initial level of backpressure in the piston cylinder space.

5. CONCLUSIONS

The proposed innovative toolkit allows minimizing the technical risk at the early most critical stages of the design of GLD as part of the general task of achieving the specified tactical and technical characteristics of UAS including launch overload, flight launch speed, UAV take-off weight, range, operational suitability, etc.

The abovementioned capabilities are provided by formalizing the design process of GLD formed by a determinate sequence of stages: shaping the appearance on the basis of theory and dimension in a specific criterion space → configuring a private numerical model of the object based on the general technology of a computational experiment → minimizing the length of the guide based on the proposed integral indicator of the completeness of perfect work during acceleration UAV.

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