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MATCHING OF DRIVE AND VARIATOR CHARACTERISTICS OF GROUND PNEUMATIC CATAPULT

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Abstract. *The article represents a method of providing a permanent starting overload of pneumatic ground launching device through the modernization of flexible transmission. We show fundamental differences and the main advantages of the investigated polyspast in relation to the cam variator type. Initial and final values of the angle of inclination of the polyspast rope to ensure equal force on the unmanned aerial vehicle in the starting torque and exit from the guide were received. The main gas-thermodynamic and dynamic parameters in the expansion drive machine of catapult were provided.*

Keywords: launching device; maximum allowable launching acceleration; polyspast; unmanned aerial vehicle; variator

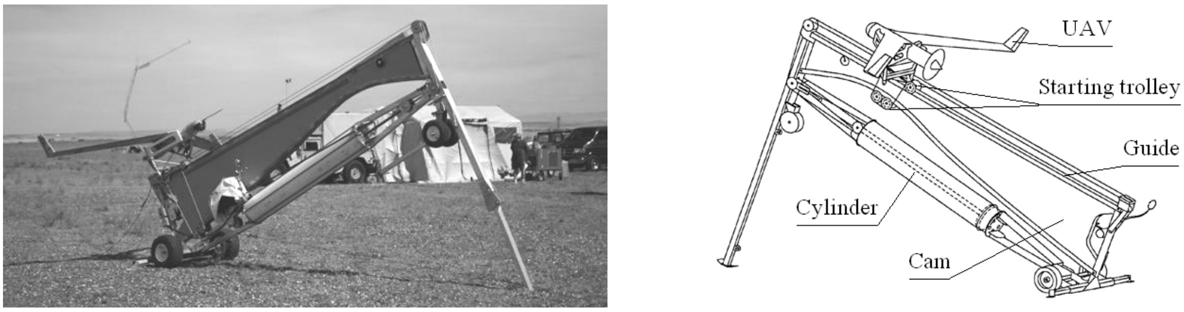
1. Introduction

One of the most important factors, determining the functional properties of unmanned aircraft systems, is the process of aircraft input into the flight and the conditions of its tactical implementation. Ground launching devices (GLD, catapults) with pneumatic drive and flexible transmission are wide spread currently. Catapults of this type tend to decrease pressure expansion [1] as the gas flows from the air pressure accumulator (APA) or balloon. Known flexible transmission, stepped and differential polyspast mechanisms, in their turn, have a constant gear ratio and can not compensate the abovementioned fall of effort.

Most preferred is a permanent law of tractive effort creating, which allows: first, to reduce the length of the guide GLD in order to obtain a more compact design; secondly, to exclude single throw overload at launching trolley breakaway, transmitted eventually to the construction of an unmanned aerial vehicle (UAV). In this connection in this paper we propose a method for matching the drive of GLD and transmission in order to get the law traction effort nearly constant [2] instead of disadvantageous regression one.

2. Analysis of Researches and Publications

One way to implement permanence efforts of pneumatic GLD is to use transmissions with a cam variator type [3], but it leads to a significant complication of the kinematic transmission scheme. In addition, such devices do not allow to dump the launching trolley after the descent of the UAV with a guide, which requires additional complexity of construction due to the need to implement a trolley braking in front a dead point. Fig. 1 shows a pneumatic catapult SuperWedge [3] with a cam variator type that implements the permanent law of tractive effort and used to launch from the surface of the UAV ScanEagle.



а *б*

Fig. 1. GLD SuperWedge with cam variator type manufactured by The Insitu Group Inc. [3]:
a) full-scale specimen; b) the basic structural elements

Relying on the abovementioned construction, the simple variator in class of polyspast transmissions may be implemented on the basis of a cam with sloping rectilinear guide. Further simplification of the kinematic scheme leads to the fact that additional shaped guide, which plays the role of the cam, in this case, is redundant and can be replaced by an equivalent polyspast system. In such a catapult changing force on the trolley with UAV will be directly proportional to the trigonometric functions of the angle of the rope.

This diagram does not require any additional trolleys which move along the profile of the cam and has twice as little of pulleys. Modernization of the classic catapult in a more perfect one is carried by drive axis down displacement to the distance $l_{\Pi} tg\alpha_{H}$ (where l_{Π} – piston stroke), which is inherently not a costly exercise with valid pneumatic GLD.

Of this kind polyspast type variator compensates the pressure drop and allows to provide some constancy acting efforts on UAV [4]. In contrast to the cam variator type (Fig. 1), the proposed scheme allows to dump trolley after the descent of the UAV with a guide. The main part of the transmission, except for the free end of a rope that connects with the start trolley, is under the guide and provides a sufficiently high compact construction.

3. Statement of the Objective

Fig. 2 shows a diagram of the polyspast mechanism of the catapult with variable gear ratio. The purpose of the study is reduced to finding such variator parameters that would ensure presented in Table 1 starting characteristics of UAV. This is only possible by ensuring a constant law of tractive effort, as in the standard configuration catapult (with regressive law) the rate of descent of the UAV does not exceed 25 m/s, which is not enough to secure input into the flight (without stalling and subsidence) of this type of aircraft.

Table 1. General integral characteristics and parameters of pneumatic GLD mode in starting conditions

№№	The physical parameter	The numerical value
1	The initial pressure in the APA, atm	7
2	The length of the guide, m	3
3	The weight launched UAV, kg	25
4	The maximum allowable starting overload, units	not more than 5
5	The initial input speed flying UAV, m/s	not less than 30
6	The multiplicity polyspast mechanism	4

4. Project tools

In the task of creating a new type of high-level excellence GLD fundamental condition of the adequacy of project funds design object is the account of the interaction of the expansion engine and transmission. Therefore, to obtain the dynamic characteristics of the catapult on the basis of the proposed variator requires the use of complex conjugate thermal gas and mechanical models like [5].

Consider the structure of the spatial, non-uniform, non-stationary gas-dynamic process sub-model in the pneumatic drive. The process of motion of a multi-component Environment in external and internal areas of the computational domain is characterized by a basic set, consisting of two thermodynamic parameters (p, T), one of the kinematic (w) and a parameter turbulence model (S), that appears in the model matrix of the state of the physical fields:

$$\Pi\left(\vec{x}, t\right) = \left\{p, T, \vec{w}, S\right\}\left(\vec{x}, t\right), \tag{1}$$

where t – time; $\vec{x} = \{x_1, x_2, x_3\}$ – coordinate vector; p – pressure; T – temperature; $\vec{w} = \{w_1, w_2, w_3\}$ – velocity vector; S – entropy.

The mathematical description of the model is based on a conservative form of writing equations of spatial flow in a Cartesian coordinate system. The compact form of the equation of the law of conservation of mass, momentum and energy is of the form:

$$\frac{\partial \bar{F}}{\partial t} + \vec{\nabla} \vec{\Phi} = \sum_{n=1}^{M_M} \left(\frac{\partial \bar{F}}{\partial t}\right)_{(n)} + \sum_{n=1}^{M_C} \bar{\Delta}_{(n)}, \tag{2}$$

where $\bar{F} = \rho\left\{1, S, \vec{w}, \varepsilon^0\right\}$ – streamed vector; ρ – density; ε^0 – the internal energy of the parameters of the adiabatic braking; $\vec{\Phi} = \sum_{k=1}^{3} \vec{i}_k \bar{\Phi}_k$ – convective vector; $\vec{i}_k$ – orts Cartesian coordinate system; $(...)_k$

– index directions in space; $(\ldots)_n$ – the group index features; M_M – the total number of groups of SD conditioned from the transfer of substantional; M_C – the total number of groups of «free» SD; $\overline{\Phi}_k = \overline{F}w_k + p(0, 0, 0, 0, 0, \delta_{1,k}, \delta_{2,k}, \delta_{3,k}, w_k)$ – projection of the vector $\vec{\overline{\Phi}}$ on the coordinate axes; $\overline{\Delta}_{(n)} = \left\{0, \frac{\partial(\rho S)}{\partial t}, \vec{f}, \frac{\partial(\rho\varepsilon^0)}{\partial t}\right\}_{(n)}$ – vector-matrix «free» source-drain (SD); $\vec{f} = \{f_1, f_2, f_3\}$ – the vector of the field of mass forces.

Such a model is formally reduced to the evolutionary problem for the solution of which the family of finite difference schemes [6] on a regular time grid is used. The prevailing thermogasdynamic component model is presented in terms of the method of the form features of SD mass, momentum and energy, than leads to uniformity of the mathematical description of the factors of different physical nature. Dissipative properties of currents are imitated by rationing of approximation viscosity [6], which can be considered as a one-parameter model of turbulence.

The boundary value problem is reduced to finding the grid approximation $\overline{\Pi}$ for all $\{x_1, x_2, x_3\} \in \Omega$ and $t \in [0, t_k]$, where t_k – finite time of process. The conditions composition of the unambiguity of the solution of a system (2) consists of thermal and caloric equation of ideal gas state, of the additive thermal properties of the medium, the equations Mayer, initial and boundary conditions

$$\overline{\Pi} = \overline{\Pi}\left(\vec{x}, 0\right), \ \vec{x} \in \Omega ; \tag{3}$$

$$\overline{\Pi} = \overline{\Pi}\left(\vec{x}, t\right), \ \vec{x} \in \Gamma, \ \forall\Gamma , \tag{4}$$

as well as the relations determining the intensity of SD:

$$\left(\frac{\partial \overline{F}}{\partial t}\right)_\beta = f_\beta\left(\overline{\Pi}, \vec{x}, t\right), \ \beta = 1, \ldots, M_M ;$$

$$\overline{\Delta}_\gamma = f_\gamma\left(\overline{\Pi}, \vec{x}, t\right), \ \gamma = 1, \ldots, M_C .$$

Thermogasdynamic expansion engine model is presented in the computational domain size of 24×24×170 cells with spatial increments of 5 mm (Fig. 3). Thin-walled construction elements (cylinder) are displayed by the mask surface, and bodily (piston) – by solid one. Submodel process flow of the working fluid into the cylinder is defined by features such as SD, localized at the site of supply pneumatic line, the intensity of which is subordinated to the integral of the Euler.

The dynamics of system moving links (piston and rod, block pulleys and trolley with UAV) is shown the mechanical submodel. Universal form of describing the dynamics of transmission GLD is Lagrange's equation of sort II in generalized coordinates. On the basis of its differential equation, which in turn is a condition for closing (2) and describes the position of the moving links of the system, is given by:

$$c_1(\alpha)\ddot{s} + c_2(\alpha)\dot{s} + c_3(\alpha)s = c_4[\alpha, F(t)], \tag{5}$$

where $c_1(\alpha)$, $c_2(\alpha)$, $c_3(\alpha)$, $c_4[\alpha, F(t)]$ – given functions of basic characteristics of mobile links GLD; s – coordinate of the moving mechanism; α – angle variator rope; $F(t)$ – driving power.

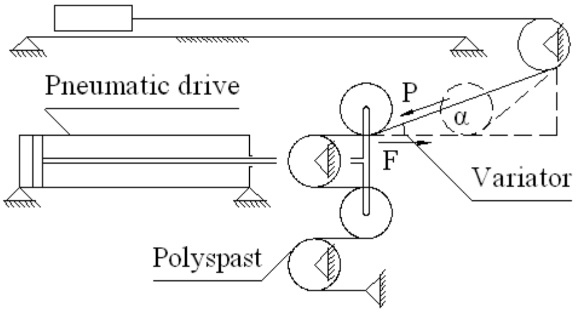


Fig. 2. The variator-polyspast that implements law $P(t) = 4F(t)\sec\alpha$

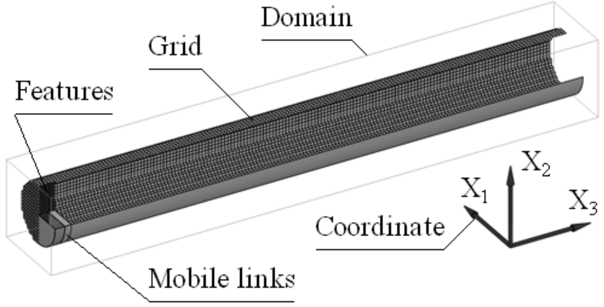


Fig. 3. The structure of the complex conjugate model pneumatic GLD

In view of the unwieldiness of private forms (3) further exposition is limited by indication of changes the gear ratio law according to the principle of operation of the variator. In the case of 4-fold polyspast using effort acting on the UAV is directly proportional to the tractive force of pneumatic drive and inversely proportional to the cosine of the angle of inclination to the longitudinal axis of rope (Fig. 2):

$$P(t) = \frac{4F(t)}{\cos\alpha} = 4F(t)\sec\alpha .$$

5. The method of GLD characteristics matching

Because of the specific kinematic scheme catapult initially provides a law of tractive effort which is different from traction unprofitable regression. However, to get the best starting conditions UAV must solve the problem of matching the characteristics of the drive (the degree of regression) and transmission (gear ratio). To ensure sufficient valve rod travel we specify the range of variation of the angle of inclination of rope to 20°, and then only a variable geometry parameter of considered transmission at a constant length of stroke is the initial angle of the rope to the guide α_H.

Consequently, the control parameter in the problem of best dynamic characteristics of catapult of this design is the initial value of the angle of rope α_H. Performance criteria, allowing quantitatively evaluate the design solution is the speed of descent of the UAV with a guide V_0. The objective function is to work to disperse UAV along the guide $A(\alpha_H)$, which will be the maximum only in providing constant traction catapult $P(t) = \text{const}$.

Thus, the problem of conditional parametric optimization reduces to finding the initial value of the angle of rope α_H, at which the maximum value of the work to disperse the UAV in conditions of longitudinal starting overload n_X restricted by permissible value $n_{X\,ПД}$:

$$A(\alpha_H) = \max A(\alpha_H) \text{ at } n_X \neg > n_{X\,ПД} .$$

Search of the optimal configuration was carried out in several iterations based on a number of angles of inclination of rope in increments of 3° beginning with 10° (Table 2). Each iteration is a solution of equations system (2) with initial and boundary conditions (3) and (4) which close the equations of transmission (5). The criteria for determining the best configuration of GLD are the initial velocity of the UAV, the average overload and ratio completeness of doing work [7].

When changing the angle of rope in the range of 15°...39° maximizes the rate of descent UAV 30,6 m/s, which is possible in the case of the minimum regression law traction, which corresponds to the execution of 98% of the maximum possible expansion work.

Table 2. Integral indicators GLD at different inclination angle rope

№№	The physical parameters	The iteration number				
		0	1	2	3	4
1	The initial angle of rope, °	0	10	13	16	19
2	The average overload, g	3,59	3,90	3,92	3,95	4,00
3	The initial velocity UAV descent from the guide, m/s	29,1	30,3	30,3	30,5	30,6
4	The traction coefficient of completeness	0,88	0,95	0,96	0,97	0,98

6. The results of numerical studies

For the solution of evolutionary problem programming language Visual Fortran developed a software package that allows in analog form to submit results of the calculation. Fig. 4 shows a phase section of the final workflow stage: physical parameter fields in the cylinder and the main integral characteristics of GLD.

Analysis of color charts of physical fields (Fig. 4) allows to reveal processes that have a key influence on the performance of GLD. The color map of pressure fields shows uniformity of the parameters in the whole volume of expansion engine. The local increase in temperature of the environment due to deceleration of the flow is observed, which leads to an increase in the speed of propagation of disturbances and increased oscillations, which follows from the corresponding fields of temperature. Physical fields of concentration of air from the balloon talk about a satisfactory filling of the cylinder fresh charge. Slices fields of Mach numbers demonstrate continuous generation by a moving piston of outgoing discharge compression waves and their distribution inside the cylinder.

Fig. 5-8 presents the dynamic characteristics of under review air GLD with polyspast mechanism with the properties of the variator. The position of the curve on the graph matches the number of the next iteration (see Table 2), the dashed line (zero iteration – pos. 0) denotes the parameters of the catapult without variator. Cyclogram of acting on the UAV overload (Fig. 5, pos. 4) gives an indication of the fact that the proposed variator effectively compensates its fall at the end of the operating cycle. The velocity diagram (Fig. 6, pos. 4) indicates that achieving a maximum speed of descent of the UAV (30,6 m/s) on the guide length of 3 m with the variator with variable gear ratio and the impossibility of achieving it in standard configuration of GLD (29,1 m/s). Ceteris paribus, in order to achieve the desired start parameters in the classical drive is necessary to increase the guide 10%, that is 0,29 m.

Fig. 7 shows that the change of the angle of inclination of a rope is made in a narrow range of angles (20°), which allows to eliminate sagging of rope and the attendant negative effects. The dependence of gear ratio of changing mechanism (Fig. 8) indicates that the variator is raised and the gear ratio is close to unity at the initial time when the pressure in the APA is sufficiently high and transmission properties change is not required.

7. Conclusions

The result of matching characteristics of the drive and transmission was GLD configuration with the angle of inclination of a rope in the range 19°…39°, provides a nearly constant overload starting law (~4 g) and the desired input speed of the UAV in flight (30 m/s) to a minimum overclocking guide area (3 m). Proposed polyspast variator with gear ratio $w = 4\sec\alpha$ of type unlike cam, although not perfectly provides permanent law of tractive effort, is more acceptable due to the constructive simplicity of implementation.

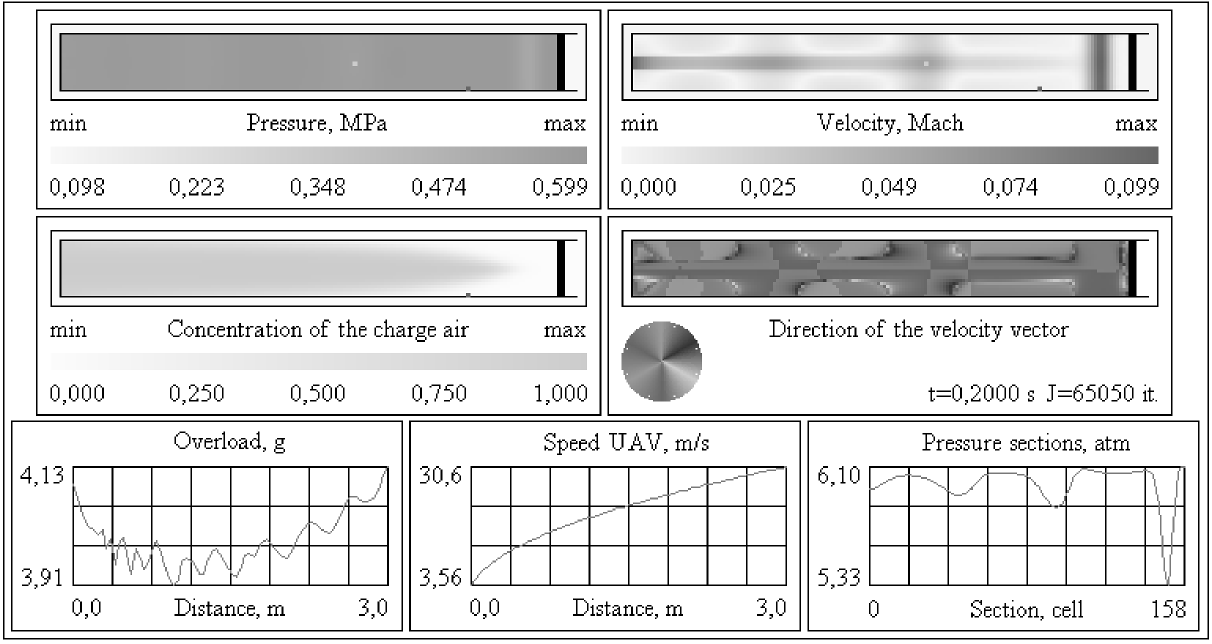


Fig. 4. End the filling phase of the air cylinder and descent UAV guide

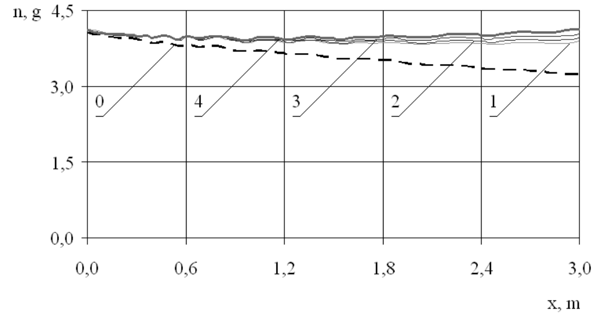


Fig. 5. Start an overload acting on the UAV

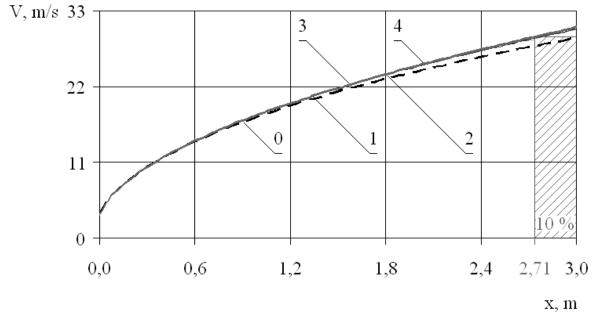


Fig. 6. Change the speed of the UAV while driving on guide

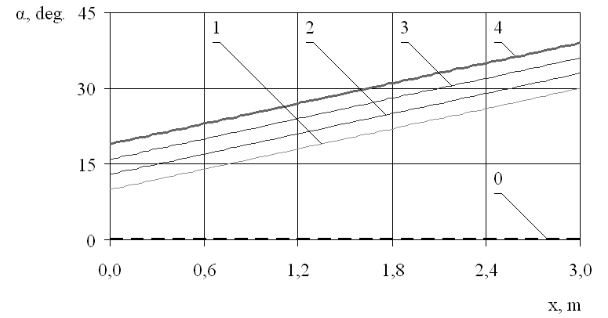


Fig. 7. The angle of inclination to the longitudinal axis of a rope drive

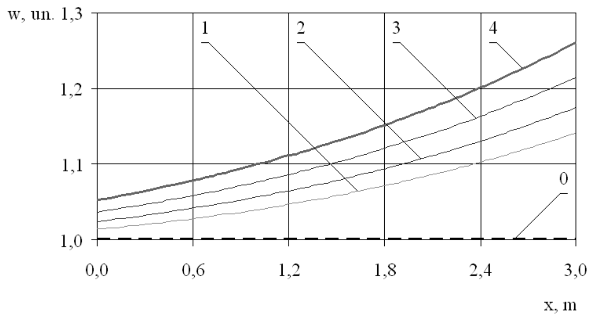


Fig. 8. The value of the transmission gear ratio

The main disadvantage of the proposed device is that the polyspast variator unlike cam can not be adjusted to the characteristics of pneumatic drive, since the law of change the gear ratio is uniquely determined by a trigonometric function of the angle of inclination of a rope (α).

The obtained results allow you to position this type of transmission in the class GLD to launch light UAVs weighing up to 25 kg with limited overload to 4,5 g, due to the presence of an extended free area between the of a rope pulleys, endangered breaking wave of variator kinematic links.

In order to match the characteristics of pneumatic drive and transmission of GLD, the complex conjugate thermogasdynamic and mechanical model are designed. The method of implementation of the program on high level programming language is designed, also a number of numerical experiments for different drive configurations were held.

The problem of obtaining the best parameters in the case of unchanged point of rope binding is further simplified because preassigned boundary values of rope angle of slope completely define the geometry of polyplast that provides a solution without going through multiple iterations.

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В. О. Середа. Узгодження характеристик привода та варіатора наземної пневматичної катапульти

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Викладено спосіб забезпечення постійного стартового перевантаження пневматичного наземного пускового пристрою за допомогою модернізації гнучкою трансмісії. Вказано принципові відмінності та основні переваги досліджуваного поліспаста по відношенню до варіатору копірного типу. Отримано початкове й кінцеве значення кута нахилу троса поліспаста, що забезпечують рівність зусилля яка діє на безпілотний літальний апарат у момент зрушування і сходу з направляючої. Наведено основні газотермодінамічні та динамічні параметри розширювальної машині приводу катапульти.

Ключові слова: безпілотний літальний апарат; варіатор; гранично припустиме стартове перевантаження; поліспаст; пусковий пристрій

В. А. Середа. Согласование характеристик привода и вариатора наземной пневматической катапульты

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Изложен способ обеспечения постоянной стартовой перегрузки пневматического наземного пускового устройства посредством модернизации гибкой трансмиссии. Указаны принципиальные отличия и основные преимущества исследуемого полиспаста по отношению к вариатору копирного типа. Получены начальное и конечное значения угла наклона троса полиспаста, обеспечивающие равенство усилия, действующего на беспилотный летательный аппарат в момент страгивания и схода с направляющей. Приведены основные газотермодинамические и динамические параметры в расширительной машине привода катапульты.

Ключевые слова: беспилотный летательный аппарат; вариатор; полиспаст; предельно допустимая стартовая перегрузка

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