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V. Sereda

National Aerospace University – Kharkiv Aviation Institute, Kharkiv

PNEUMATIC CATAPULT DAMPER MODEL

The problems of using standard pneumatic equipment in ground catapults for launching unmanned aerial vehicles are considered. A scheme for upgrading the catapult's power cylinder to reduce the speed of the moving system to an acceptable speed is proposed. A comprehensive gas-dynamic and mechanical model of a starting device is described. Software has been developed to present the calculation results in the form of an interactive test bench. The results of calculating the dynamic characteristics of a pneumatic catapult are presented. The conclusion is made about the possibility of using standard power cylinders with a number of improvements in pneumatic catapults.

Keywords: *ground catapult, power cylinder, pneumatic damper, mathematical model.*

Introduction

The use of powerful ground launching devices (GLDs, catapults) to give the initial speed to unmanned aerial vehicles (UAVs) with a high specific load on the wing looks uncontested [1–3]. Catapults with significant energy include installations where expansion machines (pyrotechnic or pneumatic) are used as the drive [4–6]. However, the difficulties associated with obtaining permits for the use of pyrotechnic products by medium or small businesses make pneumatic low pressure catapults more attractive.

The most responsible and expensive element of the pumping station is a power pneumatic cylinder, therefore high demands are placed on it for reliability and providing the necessary resource. The best solution for a company developing powerful GLDs is to produce cylinders for a given size and force. However, the main obstacle to the manufacture of unique elongation cylinders is the provision of the required surface cleanliness of 0.8–1.6 Ra on special honing machines. The latter can be an insurmountable obstacle for companies with a limited machine park, and ordering such a cylinder from third-party enterprises can exceed the cost of the finished product by several times.

Commercially available standard pneumatic cylinders of well-known manufacturers Festo, Camozzi, Norgren, etc., have a limit on the speed of movement of the rod (maximum 1.1 m/s) [7–9]. The limitation applies primarily to the elastic damper in the cylinder cover, which is not designed for large shock loads. Thus, the use of standard cylinders is possible only if there is an additional damping system for pumping stations with high-speed chain hoists (over 6) and a not-so-high UAV flight speed (up to 50 m/s). The article presents a shock damping scheme using standard equipment and a spatial inhomogeneous non-stationary model of a pneumatic damper.

Statement of basic materials

Damping circuit

In the framework of the standard element base for the GLD pneumatic system, the simplest way to constructively implement shock damping at the end of the operating cycle is to use an additional pressure relief valve. In addition to the main valve (RV2), which is connected to the rear cover of the cylinder (Fig. 1), the additional (RV1) is connected to the front cover of the cylinder, that is, from the side of the stem. The valves operate in the following sequence: until the UAV descends from the guide, the valve RV2 is open and the valve RV1 is closed, then when passing the damping section, the valves switch.

Switching of valves occurs automatically at the moment of approach of the piston (with built-in permanent magnet) and reed switch, the position of which is set taking into account the delay in operation of electric cranes. When the reed switch is closed, the main electric crane (EC) is also turned off and it is closed by a spring. After start-up, both valves are disconnected from the power supply and closed by a spring, then the mobile system returns to its original state with the help of a manual dispenser (MD).

Settlement Instrumentation

The critical parameters of the damping system are the length of the braking section (the position of the reed switch) and the diameter of the passage section of the pressure relief valves RV1 and RV2. To obtain these parameters, it is necessary to solve the optimization problem by the gradient search method. However, the current state of the problem of formalizing the selection of optimization criteria is at the stage of production [10].

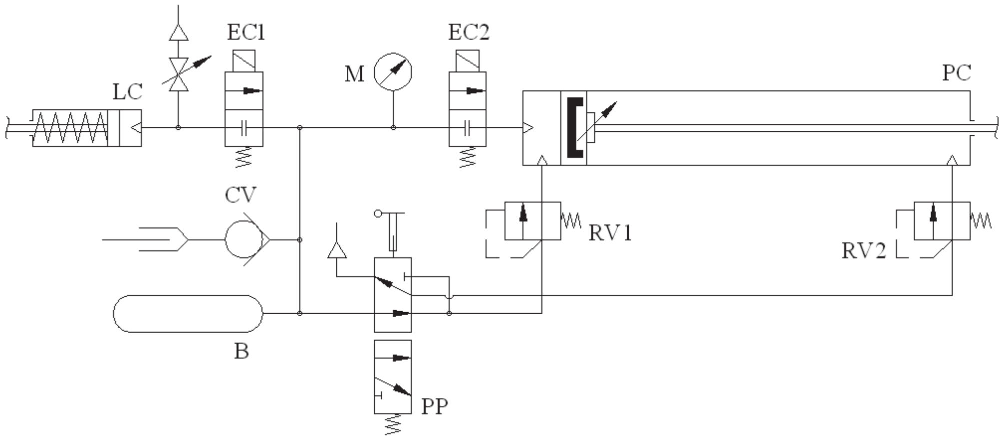

Fig. 1. Wiring diagram for pneumatic catapult:
LC – lock cylinder; PC – power cylinder; MD – manual dispenser; B – balloon;
M – manometer; CV – check valve; EC – electric crane; RV – pressure relief valve

The approaches to the "gradient" search are subjective, as they are determined by the experience, traditions of schools and the intuition of the developer. Therefore, we can only talk about an "interactive" research mode with full automation of the steps for solving a direct gas-dynamic problem. Thus, a spatial inhomogeneous non-stationary complex model of GLD is needed, in which the gas-dynamic and mechanical submodels are interfaced. The system of equations of the gas-dynamic model in a vector-matrix form in a cylindrical [11] coordinate system has the form:

$$\frac{\partial\left(\rho\overline{P}\right)}{\partial t}+\vec{\nabla}\vec{\overline{\Phi}}+\frac{1}{x_1}\rho w_1\overline{P}=\sum_{n=1}^{M_M}\left(\frac{\partial\rho}{\partial t}\overline{P}\right)_n+\sum_{n=1}^{M_C}\overline{\Delta}_n\;, \quad (1)$$

where $\overline{\Phi}_k=\rho\overline{P}w_k+p\left\{0,0,0,\delta_{i,k},w_k\right\}$,

$\overline{P}=\left\{1,\omega,S,\vec{w},\varepsilon^0\right\}$, $i=1,2,3$ – column flow matrices; $\vec{\overline{\Phi}}=\vec{i}_k\overline{\Phi}_k$, $\overline{\Delta}_n=\left\{0,\frac{\partial(\rho\omega)}{\partial t},\frac{\partial(\rho S)}{\partial t},\vec{f},\frac{\partial\left(\rho\varepsilon^0\right)}{\partial t}\right\}$ – vector matrices of convective and wave factors, as well as "free" sources-drains (SD); $\vec{\nabla}=\vec{i}_k\frac{\delta_{2,k}}{x_1}\frac{\partial}{\partial x_k}$ – Hamilton operator; $\vec{w}$ – speed vector; $\vec{f}$ – mass force field vector; ε^0 – total internal energy; ω – mass concentration of gas charge; S – entropy; x_1, x_2, x_3 – radial, axial and circumferential coordinates; M_M, M_C – total number of substantive and "free" SD.

The convenience of the method of singularities consists in the simple application of factors that are heterogeneous from the point of view of their physical nature and, as a result, give the mathematical model a formal homogeneity and ease of presentation. The conservative form of writing the equations of the laws of conservation of mass, momentum and energy, and the transfer of functions of substantial properties is adequate to the method of singularities, since IP intensities in this case enter the right-hand sides of the equations as terms.

The system of equations of the flow of the medium is closed by the thermal and caloric equations of state, the Mayer relation, the initial and boundary conditions, and the relations that determine the intensity of the SD. The boundary conditions also include the equations of dynamics of the moving parts of the transmission, which determine the position of the piston of the hydraulic control unit:

$$a\ddot{s}=d\left[F(t)\right], \quad (2)$$

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

The heterogeneous physical factors of the model were set in the form of distributed or localized features of the type of SD [12]. SD intensities were determined based on general conservation laws. For example, air velocity w_B from the cylinder was calculated by the Euler integral, from where the set of parameters $\overline{\Pi}=\left\{p,T,w_B,\omega,S\right\}$ to determine the composition of sources simulating air supply to the cylinder (provided the process is isentropic and the velocity pulse is preserved):

$$\frac{\partial\left(\rho\overline{P}\right)}{\partial t}=\frac{\rho Aw}{\Delta V}\left\{1,1,S_B,w_B,0,0,\varepsilon_B^0\right\}, \quad (3)$$

where A, ΔV – the density and volume of the zone of air flow from the cylinder.

To calculate the parameters of the unperturbed flow, we used the integro-interpolation method for representing difference analogues of convective derivatives. Definition of streaming components $\overline{\Phi}^{l+\frac{1}{2}}_{i_1+\frac{\delta_{k,1}}{2}, i_2+\frac{\delta_{k,2}}{2}, i_1+\frac{\delta_{k,3}}{2}}$ (β = –1, 1) on permeable cell walls, the problem of decay of the initial discontinuity was carried out, and on impermeable ones, by solving the problem of the interaction of a uniform gas flow with an obstacle.

To carry out the calculation of GLDs in C++, software was developed in the Code::Blocks environment, which includes a grid generator, a calculation module, and a graphical interface. The software allows you to synchronously display the integrated (mechanical) characteristics of the pumping stations and the state of physical fields in the expansion machine (Fig. 2). The calculation was carried out in one segment of a cylindrical coordinate system on a computational grid with dimensions of 1×20×155 cells with spatial steps along the linear and axial coordinates of 10 mm.

Calculation results

In Fig. 3–6 show the characteristics of the full working cycle of a pneumatic catapult with a pneumatic damper: on the left are the characteristics of the mobile catapult system during acceleration of the load, on the right, after the moment the damper is activated. The calculation was carried out for a pumping station with a tackle mechanism with a multiplicity of 8; the length of the acceleration section of the UAV along the guide was 10.4 m, and the braking of the cart – 0.72 m.

Calculations show that at the moment the UAV descends from the guideway, the mass of the mobile system decreases by an order of magnitude and overload is thrown to 166.71 g (Fig. 3). At the moment of arrival at the extreme dead point, a negative overload of -1771.67 g acts on the mobile system. The speed of the moving system (piston, rod, blocks, etc.) in the inertia braking section increases to 7.13 m/s and then drops to zero (Fig. 4).

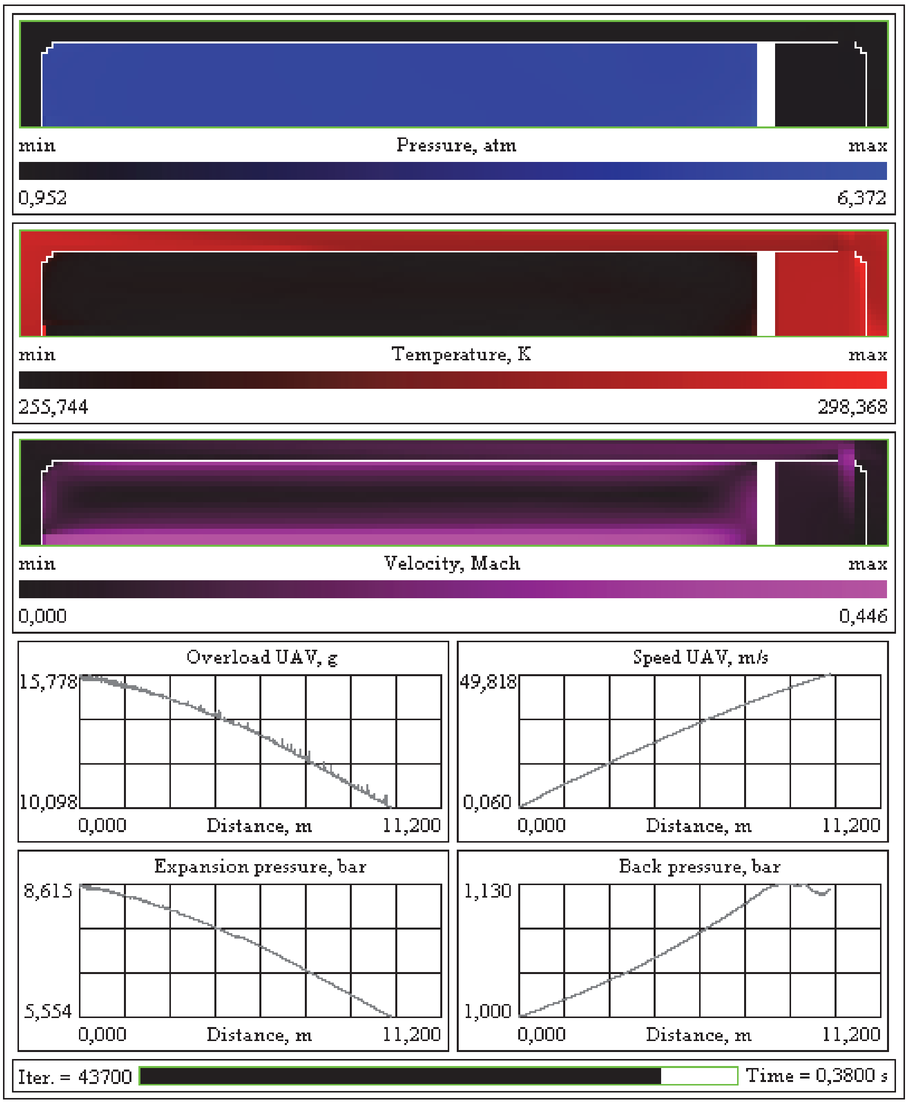

Fig. 2. Temporary sections of the computational domain, demonstrating the state of physical fields in the pneumatic cylinder of the catapult at the end of the acceleration of the mobile system

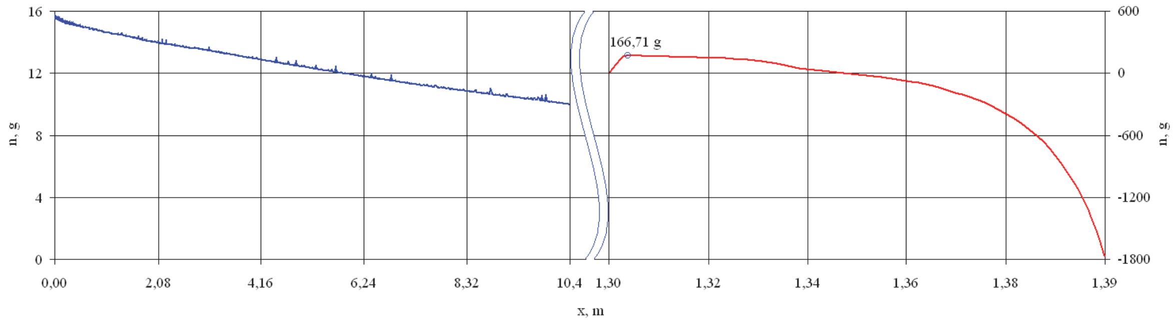

Fig. 3. Starting overload acting on the mobile system

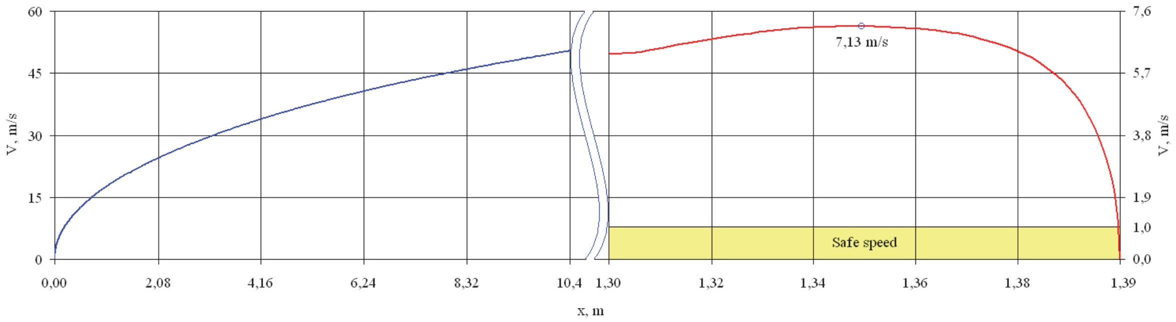

Fig. 4. Changing the speed of the mobile catapult system

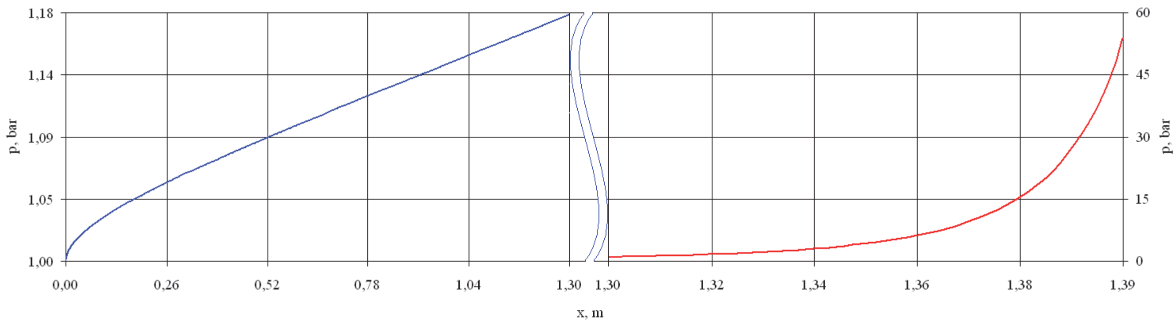

Fig. 5. Pressure in the piston space of the pneumatic cylinder

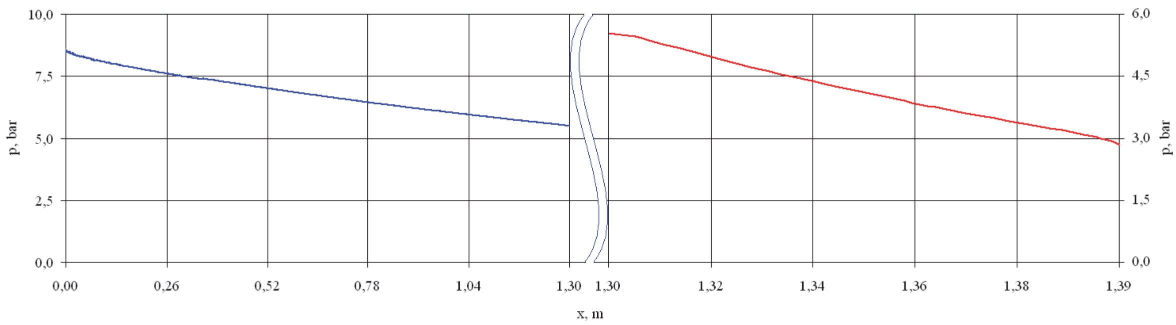

Fig. 6. Expansion pressure in the pneumatic cylinder

A consequence of the described processes is an increase in pressure in a small volume of the piston space to 49.462 bar (Fig. 5) and a drop in expansion pressure to 2.83 bar (Fig. 6) due to the outflow of air from RV1. For this reason, it is necessary to provide for repeated operation of the RV2 valve to relieve pressure from the damping cavity and to prevent the reverse movement of the movable system – a bounce back.

In the cylinder of this expansion machine, no noticeable vibrational phenomena are observed (Fig. 3) due to the low speed of the piston. The small elongation of the cylinder (in this case, 4.6), characteristic of catapults with a high gear ratio, also does not favor the degeneration of weak waves into strong ones. Thus, such GLD pneumatic drives have less expansion losses.

Conclusions

The pneumatic damper fully fulfills its function, reducing the speed of the mobile system to zero at extreme dead center. The described organization of the working process of the catapult makes it possible in principle to use standard pneumatic cylinders as power drives of powerful GLDs. The use of a standard element base reduces the cost of the ground component of the unmanned complex as a whole. However, a negative point in the application of the described scheme is the high requirements for the reliability and accuracy of operation of the pressure relief valves, since the delay in the operation of the valve RV2 can be fatal and lead to destruction of the cylinder cover due to exceeding the permissible piston speed.

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Відомості про автора:

Середа Владислав Олександрович
доктор технічних наук доцент
Національного аерокосмічного
університету ім. М.Є. Жуковського
"Харківський авіаційний інститут",
Харків, Україна
https://orcid.org/0000-0001-5687-4282

Information about the author:

Vladyslav Sereda
Doctor of Technical Sciences Associate Professor
of M. Zhukovsky
National Aerospace University –
Kharkiv Aviation Institute,
Kharkiv, Ukraine
https://orcid.org/0000-0001-5687-4282

МОДЕЛЬ ДЕМПФЕРА ПНЕВМАТИЧНОЇ КАТАПУЛЬТИ

В.О. Середа

На сьогоднішній день пневматичні катапульти є безальтернативним способом введення в політ швидкісних літальних апаратів в цивільному секторі. Технологічні та економічні складнощі при виготовленні силових пневматичних циліндрів катапульт робить доцільним використання стандартного устаткування. Такий шлях можливий тільки з використанням пристроїв, що дозволяють знизити швидкість рухомої системи до допустимої. У статті запропонована схема пневматичного демпфера, що реалізується за допомогою стандартного устаткування, суть якої полягає в синхронному перемиканні клапанів швидкого скидання тиску. Для знаходження тимчасових моментів спрацьовування електрокранів розроблена просторово-неоднорідна нестаціонарна комплексна модель. Наведено систему рівнянь газової динаміки у векторно-матричних термінах і замикаючі умови для її вирішення. Серед замикаючих умов дано опис диференціального рівняння механічної трансмісії, яке визначає положення поршня - рухомої ланки у розрахунковій області. Пропонована модель робочого процесу пускової установки використовує підмножина особливостей типу "джерело-стік", пов'язаних з масопереносом і "вільних". Описано склад авторського програмного комплексу, розробленого для вирішення завдання. Наведено часовий зріз розрахункової області в кінці робочого циклу, що відображає стан фізичних полів в циліндрі і інтегральні характеристики. Представлені результати розрахунку динамічних характеристик пневматичної катапульти. Наведено співвідношення довжини циліндра і ділянки гальмування рухомої системи при заданому рівні тиску в балоні, які можуть бути поширені на геометрично подібні катапульти. Вказані перевантаження і швидкість рухомої системи при русі літального апарату по направляючій і після спрацювання демпфера. Розрахунки показують, що після перемикання клапанів швидкого скидання тиск у запоршневому просторі багаторазово (в 50 разів) підвищується, а в робочій порожнині – знижується. За рахунок цього забезпечується зниження швидкості рухомої системи до безпечного рівня – нижче 1 м/с. Зроблено висновок про можливість застосування стандартних силових циліндрів з рядом доробок в пневматичних катапультах.

Ключові слова: *наземна катапульта, силовий циліндр, пневматичний демпфер, математична модель.*

МОДЕЛЬ ДЕМПФЕРА ПНЕВМАТИЧЕСКОЙ КАТАПУЛЬТЫ

В.А. Середа

Рассмотрена проблематика использования стандартного пневматического оборудования в наземных катапультах для запуска беспилотных летательных аппаратов. Предложена схема модернизации силового цилиндра катапульты для снижения скорости подвижной системы до допустимой скорости. Описана комплексная газодинамическая и механическая модель пускового устройства. Разработано программное обеспечение, позволяющее представить результаты расчета в виде интерактивного испытательного стенда. Приведены результаты расчета динамических характеристик пневматической катапульты. Сделан вывод о возможности применения стандартных силовых цилиндров с рядом доработок в пневматических катапультах.

Ключевые слова: *наземная катапульта, силовой цилиндр, пневматический демпфер, математическая модель.*