Adaptive Air Ejection Device for Catapulting Cargo of the "Guided Air Missile" Type

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***Abstract*—This article presents the results of the development and research of an adaptive air ejection device for catapulting cargo of the "guided air missile" type. The principal diagram of the device based on the use of hydraulic drive pushers and stemming from an approach to controlling the ejection process taking into account the need to ensure safe separation of the payload, is demonstrated. The components of the system's dynamics model are considered using Russian software products of SimInTech and EULER, computer simulation and full-scale experiments, confirming the operational integrity and correctness of the control system algorithms, are carried out.**

Keywords—adaptive air ejection device, guided air missile, dynamics, hydraulics, information technology

INTRODUCTION

Designing launch devices and ejection systems for aircraft missile armament is a complex engineering problem, combining the issues of aerodynamics, gas dynamics, dynamics of elastic and inertial systems, integrity and electrical engineering. The performance and technical specifications of an aircraft and the air-launched weapons (ALWs) mounted on it greatly affect the missile armament (MA) design.

The MA device is an intermediate link between the aircraft and the ALWs, thus, as a general principle, amassing the issues of coordination of various requirements between the aircraft and ALWs, which, of course, imposes conflicting requirements for the ALW transportation and separation system difficult to implement.

These requirements can only be achieved through an integrated approach to the design of MA devices, taking into account the aircraft and ALW specifications, and also in conducting theoretical studies aimed at finding methods for rational fulfillment of the technical specifications requirements and the synthesizing rational structural and kinematic diagrams of the MA device, ensuring the maximum simplicity of the device design. Experimental studies both at the stage of searching for a rational problem solution, and at all further stages of the MA device testing are of great importance in the design.

The integrated design system also provides for the synthesis of individual MA device mechanisms (drives, ejection racks, holdback devices, etc.), forming the structural diagram of the device as a whole. A large part in the designation is assigned to the design development, prototype manufacturing, testing and implementation in line production and commissioning.

An important factor in justifying the air drop method is placement of missiles during their transportation. Missiles are placed on beam holders located outside the aircraft on the wings and fuselage [1-6], or in its cargo compartments [1, 7-9].

If the missiles are placed outside along the fuselage, they are attached to the aircraft directly [4, 5, 10], or in containers [6, 11]. The missiles placed in containers under the wing of an aircraft launch in the direction opposite to the flight path [4, 11], and the missiles placed directly on the aircraft launch in the flight path direction, ensuring a faster target approach, since this does not require time to turn.

Placement of missiles in the cargo compartments during transportation provides the aircraft with the best dynamic characteristics and protects the missiles and the aircraft from external factors. Hence, placing missiles in cargo compartments is considered a step-ahead solution. The patents offer several methods for dropping and launching missiles from a cargo compartment. In order to launch from the aircraft, [1] and [8] use a parachute system linked to the container in which the rocket is placed. The design feature is that containers are launch devices. At the same time, the container and the main parachute of [8] have holes for letting the missile pass through at launch. The method of launching a missile from an aircraft includes using an auxiliary parachute, pulling the container with the missile out of the cargo compartment, pulling the main parachute system out, orienting the missile launcher and starting the missile engine. Moreover, a distinctive feature of [8] is that during the launch of the main parachute, the launch device is directed along the upward vertical, and then the missile engine is started, followed by the missile passing through the holes of the launch device and the dome of the main parachute system.

This method of missile launch ensures the reliability of the launch and its independence from random effects.

The disadvantages of this control method include the complexity of the control system, launch device orientation and stabilization, as well as a longer launch time compared to the missiles launched directly from the aircraft.

The method of dropping missiles from a group compartment proposed in [7] involves using a special container in the aircraft, housing one or more missiles, bombs, or unmanned aerial vehicles, which makes it possible to drop them from the aircraft both with no extraction device and by pushing them out.

The use of a container with adaptability to the placement of various cargoes, both identical and varying in size and purpose, provides flexibility of operation.

The disadvantages of this method include the need for a large capacity of the cargo compartment and the use of special devices for transporting the cargo along the guides to the location of drop or ejection, complicating the design compared to conventional ejection devices used in existing aircraft.

The identified methods of missile pushing and launching from an aircraft, including through the use of the cargo compartment, are methods implemented in ejection devices [2, 3]. The method capable to adapt to the effects of external factors, is considered the most modern from the viewpoint of the engineering level of control in the field of aerospace equipment drive systems. It allows to secure the necessary parameters for the safe separation of the missile in all combat flight modes of the aircraft independently and to a high precision, without obtaining preliminary data on the aerodynamic loads affecting the drop object. This method is implemented in the beam holder device [4].

The method includes analysis of relevant external aerodynamic effects, changes in the mass / inertia data of the drop object, rigidity of the suspension elements and drive controls: explosive-operated drive being a gas hydraulic source, and two follow-up hydraulic drives of hydraulic pushers with linear acceleration pick-ups.

However, this method lacks adaptive control of the angular and linear velocity of the missile during ejection. The angular velocity of the missile is constant in all flight modes, and the linear velocity does not have the maximum allowable constraint.

The lack of adaptive control of these parameters can lead to instability in the stabilization system. Therefore, the method of adaptive control of the angular and linear velocities of the missile during the drop process considered in this article and its implementation are new, increasing the reliability of launch.

Appearance of the Adaptive Air Ejection Device

In terms of the executive part implementation, the challenge in constructing an adaptive air ejection device (AAED) lies in the need to control the high power required to ensure the parameters necessary for the separation of the product, such as linear and angular velocities and the required separation time, measured in tens of milliseconds. In cases where the executive part of the AAED is hydraulic pushers and the medium is hydraulic fluid under pressure, the above requirements result in the need to develop special electrohydraulic control devices with tremendous response speed.

The requirements for response speed and power of the special electrohydraulic control device, in terms of the feasibility of its physical implementation, are the most critical from the viewpoint of its impact on the technical appearance of the developed AAED. The AAED specifications are as follows:

- required linear velocity at the end of the pusher stroke - 6 meters per second;
- providing angular payload velocity in the range of $|\omega_z|$ = 15…40 degrees per second;
- payload all-weight - 800 kilograms (reduced mass to the front pusher is 0.6 ... 0.8 of the all-weight);
- current overload (assisting) - up to 5 units for a mass of 800 kilograms and up to 9 units for a mass of 200 kilograms.
- pusher piston stroke is limited to 0.2 meters.

The executive part of the AAED are two hydraulic pusher cylinder. Due to the differentiation of the push and brake cavities of the cylinder, ensuring the minimum dimensions of the pusher, an estimated calculation of the piston rod diameter was carried out to determine the permissible area of the brake cavity of the hydraulic cylinder, which defines the diameter of the piston in the push cavity as 5 centimeters, and 2.5 centimeters in the brake cavity.

The hydraulic pusher cylinders are powered by the built-in pyrohydraulic (PH) or gas hydraulic (GH) power source. High speed pusher drives (HSPD) structurally consist of a hydraulic cylinder moving the payload, an electrohydraulic flow control device designed to control the movement process and a set of sensors necessary for both transmitting information to the control system (CS), and collection of telemetry data on the HSPD status. Fig. 1 shows the principal diagram of the hydraulic (executive) part of the AAED.

In general form, the pusher rod movement is defined as:

$$m \cdot a = F_p - F_b + m \cdot n \cdot g - F_{ex}, \quad (1)$$

where m – weight of the product reduced to the pusher, F_p – hydraulic force developed in the upper cavity of the pusher, F_b

– hydraulic force developed in the lower (brake) cavity of the hydraulic cylinder, n – G-force, g – gravity acceleration, F_{ex} – total external force.

The required angular velocity is set by the acceleration of one of the pushers in the second half of the stroke. The valve block employs six high-speed discrete flow controllers. The conductivities of flow regulator valves controlled by electromagnets are determined by drill throttles, the cross-sections of which are set to 4 square millimeters.

The structure of the electromagnets is made with no holding coil and a lifter position sensor. The initiation mode is implemented by applying a current pulse of 5 milliseconds to the coil. The holding mode is implemented by applying pulse-width modulation to the coil with a pulse / pause ratio of 25% and a frequency of 5 kilohertz. The lifter is returned to its original position by a spring. In the initial state, the valves are normally closed.

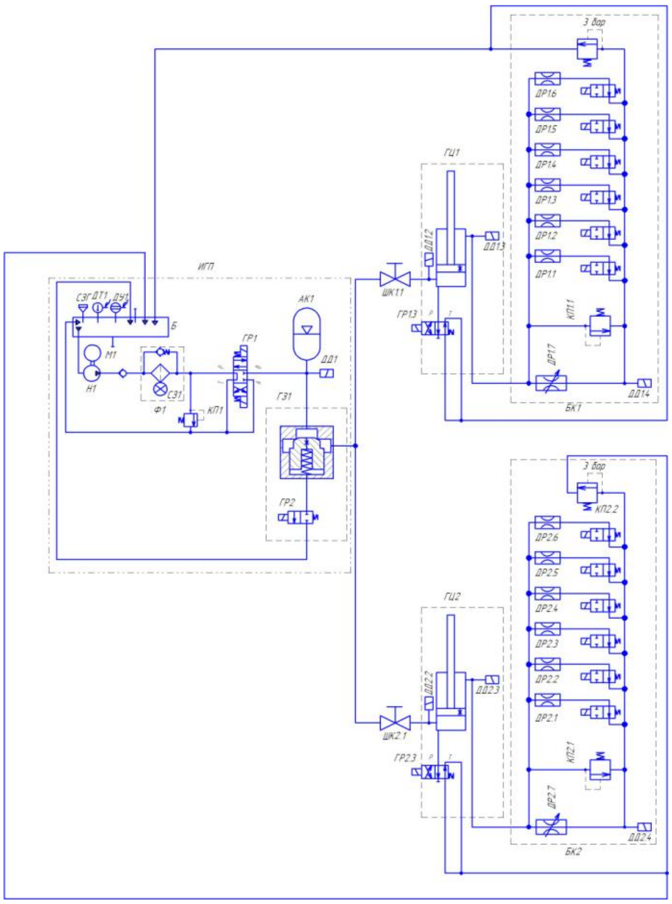


Fig. 1. Principal diagram of the AAED executive part

Based on the diagram presented, a mathematical model was formed and mathematical modeling of the operation of the AAED hydraulic part was carried out.

Tools for Modeling the "Adaptive Air Ejection Device – Guided Air Missile" System

For the purpose of further verification of the system, the modeling implementation involves the utilization of two modeling systems: the dynamic simulation environment of the SimInTech [12] engineering systems and the EULER software complex for automated dynamic analysis of multicomponent mechanical systems [13].

The use of SimInTech is dictated by the need to create a detailed mathematical model of the AAED executive part, presented above in Fig. 1. The mathematical model is designed to determine the processes occurring in the hydraulic units of the AAED, the formation of the operation algorithms of the CS. The structure of the mathematical model is shown in Fig. 2.

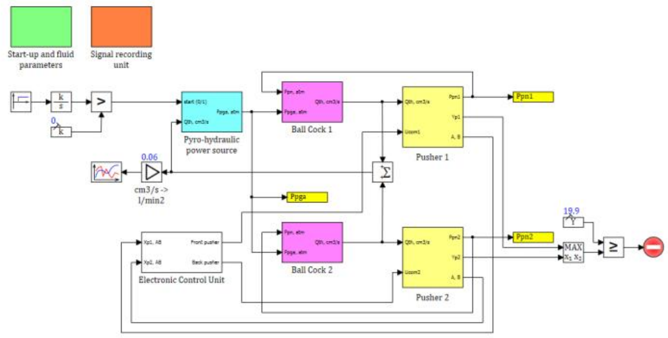


Fig. 2. The structure of the AAED mathematical model

The ignition time of the explosive charge is simulated by the "Step" unit included in the "Pyro-hydraulic power source" sub-model describing the operation of the pyrohydraulic energy source. The pressure of the working fluid is formed at the output of this sub-model, depending on the parameters of the pyrohydraulic energy source and the flow rate of the fluid delivered from the source into the push cavity.

The "ball cock" unit simulating the conductivity of the delivery channels in order to limit the amount of flow entering the input of the hydraulic cylinder, depending on the diameter of the pipes of the delivery channels, is installed between the energy source and each of the hydraulic cylinders.

The "Pusher" sub-model models the movement of the AAED pusher, depending on the flow from the energy source received into the push cavity and the control signal from the "Electronic Control Unit" sub-model.

The signal along the rod is received in the input of the electronic control unit ("Electronic Control Unit" sub-model). In accordance with the laws of control, a control signal to the exact channel of the discrete hydraulic control is formed at the output of this unit (to the corresponding pusher). The discrete hydraulic control consists of a set of 6 electrohydraulic valves of equal and constant conductivity. At start time, the valves are closed, sine the control of the pushers is carried out by means of their acceleration, as noted earlier. Fig. 3 shows the "Electronic Control Unit" sub-model structure.

If the value of the angular velocity increases and is greater than the set value in the process of air drop, the left pusher valves are activated, and in a reverse situation, the right pusher valves are activated. Such regulation ensures the retention of the angular velocity near the set value and, in addition, the increase in the vertical speed of the layout. The structure presented in Fig. 3 involves the following operations:

- calculation of current angular velocity;
- calculation if the difference (misalignment errors) between the given and current angular velocities;
- generation of a release signal based on the comparison of angular velocities;
- deadband area formation;
- calculation the maximum displacement out of two;
- generation of release signals based on the intersection of the threshold value along the stroke of the pushers;
- generation of release signals for turning on/off the valves of the front and rear pushers.

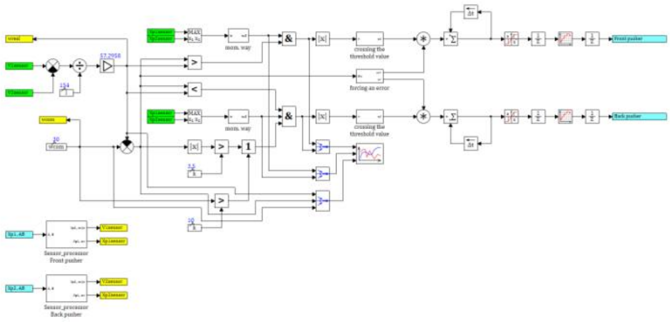


Fig. 3. “Electronic Control Unit” sub-model structure

The sub-models related to the discrete hydraulic control and its digital processor, as well as to the hydraulic accumulator, are located in the “Electronic Control Unit” sub-model. Structurally, the discrete hydraulic control consists of controlled discrete electrohydraulic valves, safety relief valve and an adjustable throttle. The input signal for the hydraulic accumulator sub-model is the flow rate of the working fluid entering it, and the output signal is the pressure in the hydraulic accumulator itself. The modeling assumed that the bracket in the hydraulic accumulator is spring-based.

External conditions, including the working fluid temperature, which determines the density of the fluid (taking into account the dependence of the viscosity of the working fluid on the temperature), the discharge coefficient in the throttles, the magnitude of the external overload affecting the object are set in the “Start-up and fluid parameters” unit.

The “Signal recording unit” is designed for the collection of information on the air drop process: data on payload overloads, pressure, velocities and HSPD movement.

When calculating the mathematical model, a problem solver with a step of 2e-7 was selected. Due to the small step and short lead time, the “Stop calculation” unit was additionally introduced to the mathematical model for stopping the calculation at the end of the useful stroke of the pushers (19.9 centimeters).

The dynamic model of the “AAED – Guided Air Missile (GAM)” system is implemented in EULER taking into account the following requirements:

- Designed to study the kinematics and dynamics of the system.
- Includes the AAED executive part, as well as the GAM separation conditions and operating modes.
- Constitutes a statically determinate system.
- Involves a study of motion both on a plane and in three-dimensional space.
- Takes into account the mass / inertia data (MID) of the AAED and GAM elements.
- Allows to solve the problems of synthesis and analysis of parameters when building an AAED.

The EULER software package is used to implement the following:

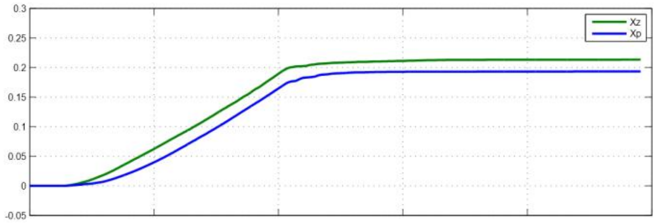
- The model of standard atmosphere in the form of a table of values depending on the current altitude. Based on such table, the following parameters are determined: air temperature, acoustic velocity, atmospheric pressure, medium density, gravitational acceleration.
- The design model for measuring the motion parameters of the carrier aircraft and GAM, constituting a set of sensors for measuring displacements, linear and angular velocities, overloads, and orientation angles in space.
- The dynamic AAED model taking into account the mathematical (executive) model of the device in SimInTech and the geometry of two high-speed pusher drives (HSPD).
- The dynamic GAM models containing information on the mass / inertia and aerodynamic characteristics of the object, the processes of deployment of the folding parts of the flight control surfaces and the operation of the drives of such surfaces during the flight, operation of the propulsion system.
- The dynamic model of the AAED-GAM system configuration, in which the links are specified at the points of missile attachment.
- The testing model of the dynamic AAED-GAM system model, which is the top-level model in the hierarchy of the above models.

Parameterization of the components allows to simulate the operation of the system under various initial conditions: altitude (atmospheric parameters), velocity, and direction vector of the approach flow, function of changing the material velocity over time, current overload, free or forced mode of separation from the AAED (pushers do not work with free separation), active or passive mode of GAM operation (own independent operation systems do not turn on in the passive mode), time for sending the signal to start the payload drop.

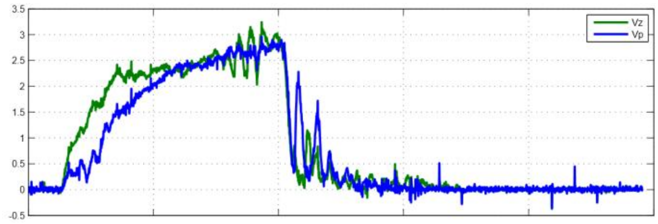
Additionally, the system described in the article was implemented as a test installation, where a simulator device acts as a GAM, which weight can vary from 150 to 200 kilograms, in order to verify the simulation results.

Experimental Testing and Verification

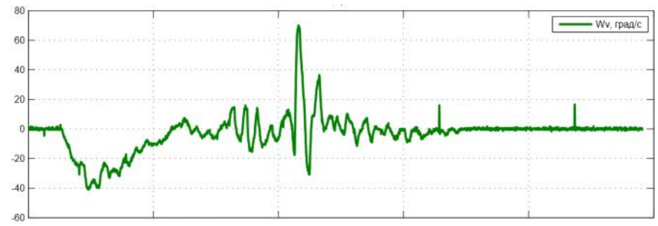
During experimental testing, the general operation of the test installation, charging of the hydraulic accumulator, sending of the control signal to the hydraulic latch, turning on of the control unit, power supply, generation of the control signal to electromagnets were verified. Fig. 4 presents one of the calculated cases, and Fig. 5 shows the results of its modeling.



a)

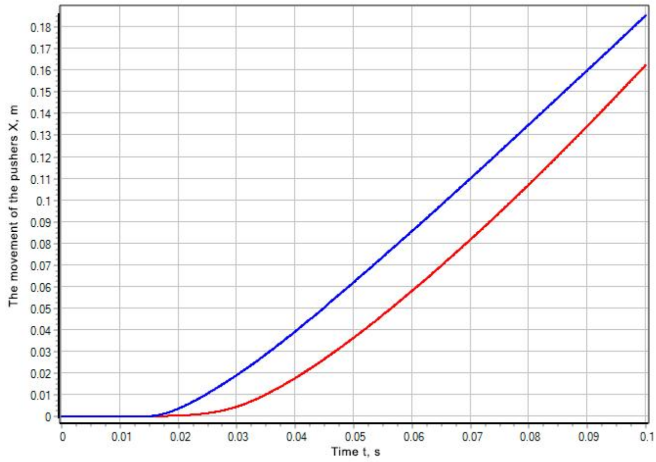


b)

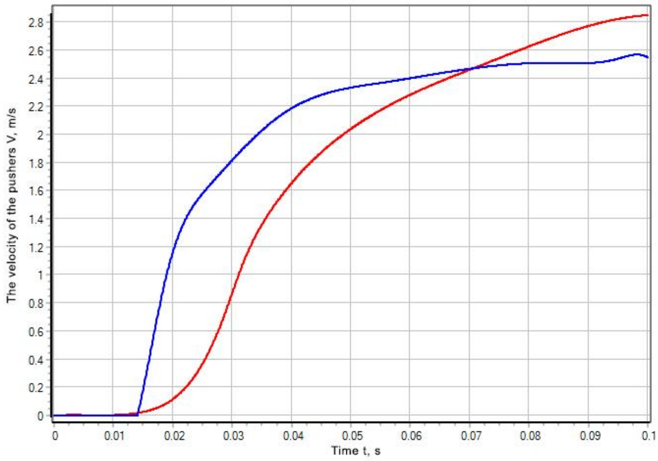


c)

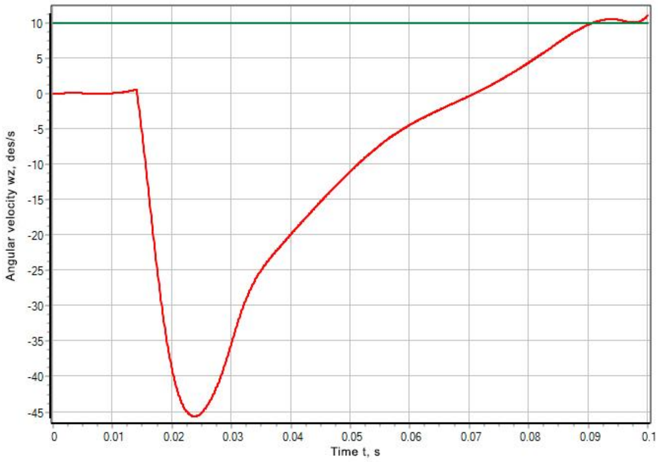
Fig. 4. The results obtained at the test installation: a) movement of pushers in meters (blue - front, green - rear), b) pusher velocities in meters per second, c) angular velocity in degrees per second



a)



b)



c)

Fig. 5. Modeling results: a) movement of pushers in meters (blue – front, green – rear), b) pusher velocities in meters per second, c) angular velocity ind degrees per second (red – current, green – control from the control system)

The results obtained demonstrate good convergence of the mathematical model with experimental characteristics. It should be noted that during mathematical modeling the following factors affecting the convergence of the results were not taken into account:

- location of the beam mount fitting to the guides;
- hydraulic brake cylinder was not taken into account (possible decrease in speed at the end of stroke);
- elasticity of the mount fittings in the mathematical model was not specified due to the impossibility of correct determination of the elasticity and damping coefficients;
- effect of deformation of the walls of the delivery pipelines on the formation of pressure was not taken into account;
- release of the hydraulic lock was taken into account in a simplified model through the pressure rise time constant;
- pressure losses in the delivery channels were not taken into account;
- operation of the brake chamber at the end of the piston stroke was not taken into account, and therefore the processes after separation of the cargo do not correspond to the experimental values and were not considered.

Conclusion

The article describes the need to develop a new method of controlling linear and angular velocities using the example of an adaptive device for cargo ejection. The principal diagram of such a device is presented, based on the use of hydraulic pusher drives, the algorithm for controlling the process of ejection is described taking into account the need to ensure safe separation of the payload using an electronic control unit with discrete flow regulator valves. The components of the dynamic model using SimInTech and EULER are described, the ejection task is simulated using these models, showing good convergence with the results of testing at the test installation.

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