Modeling technique for advanced adaptive aircraft catapult devices

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Abstract. This article represents approaches to the configuration and modeling of adaptive aircraft catapult devices intended for forced separation of aircraft guided missiles from the air vehicle. The creation of such a device is a promising direction of research. The adaptability of such a device lies in the fact that in all air vehicles flight modes, the necessary and safe parameters for separating the air weapons from the carrier are provided. One of the variants of such a device with a hydraulic executive part is considered, its main parameters are determined to meet the requirements for the compartment safety and the possibility of regulating the flow of this process. The computer modeling technique is based on the use of approved information technologies SolidWorks, SimInTech and EULER, which allow solving multiphysics tasks, as well as reducing the full-scale experiments volume due to their use. As a result of comparing the results of mathematical modeling and experimental studies, it was found that the model of the adaptive aircraft catapult devices, developed on the basis of the methodology, describes the processes of payload movement fairly accurately.

1. Introduction

The design of catapult devices for missile armament (MA) of air vehicles (AV) is a complex technical task in which the issues of aerodynamics, gas dynamics, dynamics of elastic-inertial systems and strength are closely related. The military characteristics (MC) of AV and the guided air weapons (AW) suspended on it have a great influence on the design of MA devices. Due to the fact that the MA device is an intermediate link between the AV and the AW, it is necessary during its design to coordinate the various requirements that apply to both the AV and the AW. Often, this leads to contradictory and difficult requirements for the transportation and separation system of AW, the main of which are the following [1]:

- improve the flight technical and operational characteristics of aircraft missile systems (AMS);
- increase the combat capabilities of aircraft missile systems and expand the range of tasks to be solved;
- reduce the type, range of aircraft guided missiles (AGM) and MA devices necessary for arming modern and advanced AV;
- expand the scope of application of unified AGM on modern and advanced AV;
- unify the processes of development and manufacture of aircraft missile systems.

Fulfillment of the above requirements can only be ensured through a systematic approach to the design of MA devices, taking into account the characteristics of AV and AW. Such an approach should include theoretical research aimed at finding rational ways to synthesize MA
devices, ensuring, on the one hand, the effective performance of a combat mission and, on the other hand, maximum simplicity of the device design. Great importance in the design is given to experimental research both at the stage of searching for a rational solution to the assigned task, and at all further stages of testing the MA device. Currently, there is an increase in the share of computer modeling technologies that justify the possibility of reducing the volume of full-scale experiments by replacing them with model ones (from 15–25% at present to 35–50% by 2025).

2. Adaptive aircraft catapult device

A large number of MA installations have been developed for various types of AV and AW, therefore, the unification of MA installations acquires great importance. There are various works on the creation of a unified installation for missiles of one weight missiles of one group, but the most promising direction is the development of a single adaptive MA device for all types of missiles and various types of AV. The adaptability of such a device lies in the fact that in all AV flight modes, the necessary and safe parameters for separating the AW from the carrier are provided. The creation of such device is fundamentally possible and expedient due to the large weight range of the AW. The use of such devices makes it possible to equip an AV simultaneously with AW for various purposes without changing devices. At the same time, the variety of existing mechanical, electrical and pneumohydraulic connections of the device with AW and AV will lead to the complication and overweight of this device type. Despite the obvious shortcomings, the creation of an adaptive aircraft catapult device (AACD) RV will allow:

- improve the flight technical and operational characteristics of aircraft missile systems;
- increase the combat capabilities of aircraft missile systems and expand the range of tasks to be solved;
- reduce the type, range of AGM and MA devices necessary for arming modern and advanced AV;
- expand the scope of application of unified AGM on modern and advanced AV;
- unify the processes of development and manufacture of AMS.

Analysis of works in the area of designing adaptive MA devices indicates that at present the issue of developing AACD design technology is relevant, which makes it possible to scientifically justify the configuration and basic construction characteristics of AACD operating in a closed cycle [2–8].

3. Determination of the parameters of the executive and regulatory AACD parts

The complexity of building a promising AACD from the point of view of implementing its executive part lies in the need to regulate a large amount of power required to provide the required parameters for separating an AW weighing 200–850 kg, such as linear and angular velocities and the required separation time, measured in tens of milliseconds. This process cannot be carried out without preliminary determination of the future AACD parameters [9, 10].

One of the variants of the AACD is a device with a hydraulic executive part (propellant is a hydraulic fluid under pressure). It includes the following elements:

- one built-in power supply (pyrohydraulic or gas-hydraulic);
- two independent fast operating drives-pushers;
- electronic control unit (ECU).

Fast operating drive-pusher (FDP) includes:

- hydraulic cylinder that moves the AW at the attaching points;
- electro-hydraulic flow regulator, which, when joint work with an ECU, creates the required force for load movement;
a set of sensors for transmitting the current velocity values and movement of the pusher rods to the ECU.

It is important to understand that the aforementioned requirements for the parameters and separation time lead to the need to develop special electro-hydraulic flow controllers with colossal speed.

The following basic parameters must be observed for the safe AW separation:

- vertical linear catapult velocity: 5–6 m/s;
- pitch angle: −0.5–0 deg;
- angular pitch velocity: −15–40 deg/s;
- permissible AW overload: no more than 20 units.

As a result of determining the parameters of the executive and regulating AACD parts, the calculated values of the required velocity and force (hydraulic equivalents—fluid flow and pressure) were obtained, as well as the required stroke of the pusher rod, which is 20 cm.

In view of the real difference between the pushing and braking cylinder cavities, which provide the minimum dimensions of the pusher, according to the results of the estimated calculation, the diameters of the piston rod in the accelerating and braking cavities of the hydraulic cylinder are 5 and 2.5 cm [11].

The main feature of a possible version of the basic hydraulic AACD circuit is the use of a set of 6 throttle of the same conductivity in each of the FDP. The required and safe angular velocity is ensured by accelerating one of the pushers in the second half of the stroke. At the initial moment of time the valves are closed.

4. Modeling technique

The systematic approach to design includes computer modeling elements. To use this kind of tools, a modeling technique has been developed based on the use of approved information technologies that form a single integrated information system and allow solving multiphysics issues. The developed technique uses the following technologies:

- computer-aided design system SolidWorks, which is used to determine the geometric and inertial-mass characteristics of AACD and AW;
- environment for dynamic modeling of technical systems SimInTech, in which the executive part of the AACD and work algorithms are implemented;
- software complex for automated dynamic analysis of multicomponent mechanical systems EULER, which implements dynamic models of AACD and AW, as well as their configuration.

4.1. Executive part model

Figure 1 shows the mathematical model of the AACD executive part, executed in the SimInTech environment.

This model is made with the following assumptions:

- elasticity of the attaching points in the mathematical model has not been specified due to the impossibility of correctly determining the elasticity and damping coefficients;
- effect of deformation of the supply pipelines walls on the formation of pressure is not taken into account;
- actuation of the hydraulic lock is taken into account in a simplified way through the pressure rise time constant;
- pressure losses in the supply channels are not taken into account.
For a hydraulic accumulator unit (HA), the input values of the flow rate of the working fluid entering the pushing cavities of the hydraulic cylinders, the output value is the pressure entering the throttle at the inlet. The HA unit directly includes a hydraulic accumulator, a HA throttle and a discharge cavity, which are described by the following equations:

\[
P_{ha}(t) = P_{max} \cdot e^{-\frac{V(t)}{V_0}},
\]

where \(P_{max}\) is the maximum pressure created in the HA, \(V_0\) is the initial liquid volume in the PHA, \(V(t)\) is the liquid volume that entered the pushing cavity of the hydraulic cylinder

\[
Q(t) = \mu(Re) \cdot \sqrt{\frac{T}{\rho}} \cdot S_t \cdot \sqrt{|P_{ha}(t) - P_p(t)|} \cdot \text{sign}(P_{ha}(t) - P_p(t)),
\]

where \(\mu(Re)\) is the flow coefficient, \(\rho\) is the liquid density, \(P_{ha}\) is the pressure created in the HA, \(P_p\) is the pressure at the outlet of the HA injection cavity, \(S_t\) is the throttle window area. The throttle window area change is calculated through the oscillatory link

\[
P_p(Q(t), Q_1(t), Q_2(t)) = \int_0^t (Q(t) - (Q_1(t) + Q_2(t))) \cdot \frac{E_{min}}{V_{cav}} dt,
\]

where \(Q_1, Q_2\) are the flow rates of the working fluid entering the pushing cavities of the hydraulic cylinder; \(E_{min}\) is the minimum modulus of bulk elasticity, \(V_{cav}\) is the compression cavity volume.

The block “Pusher” includes the following components:

- throttle at the inlet;
- throttle in the cylinder;
- a valve block consisting directly of a valve block (six fast operating flow controllers), an adjustable throttle and a safety valve;

**Figure 1.** Mathematical model of the AACD executive part in SimInTech.
• hydroaccumulator (tank);
• piston movement, including a hydraulic force calculation unit, rod and body movement.

The need to use a throttle at the inlet is the possibility of changing the hydraulic conductivity in front of the hydraulic cylinders (limiting the amount of flow entering the hydraulic cylinder, depending on the supply channels pipes diameter). The block is similar in structure to a HA throttle. The input signals are the value of the pressure at the outlet from the HA and the pressure in the pushing cavity of the hydraulic cylinder. The output coordinate is the flow rate of the working fluid entering the pushing cavity of the hydraulic cylinder.

The throttle in the cylinder is used to reduce the rate of pressure rise in the push cavity at start-up, which in fact gives a decrease in the initial overload. The block is similar in structure to a HA throttle. The input signals are the pressures in the pushing and braking cavities.

When implementing the model, a tabular function of the density dependence of the working fluid on temperature and pressure is used.

The block “Valve Block” is a set of six fast operating flow controllers. The conductivity of the flow controllers controlled by electromagnets is determined by the throttle-passages, the fluid on temperature and pressure is used.

Blocks of an adjustable throttle and a straight-through valve are similar in structure to a HA throttle. The input signals are the value of the pressure at the outlet of the hydraulic cylinder’s limit, the amount of flow entering the hydraulic cylinder, the pressure in the hydraulic accumulator and the current at the electrohydraulic amplifier (EHA). The output coordinate is the flow rate of the working fluid entering the hydraulic cylinder.

In general, the equations system can be represented as:

\[
X_s(t) = \begin{cases} 
0, & I_{cha} < 0; \\
\frac{K_{xi}}{T_{cha} \cdot s^2 + 2 \cdot \xi_{cha} \cdot T_{cha} \cdot s + 1} \cdot I_{cha}(t), & 0 \leq I_{cha} \leq I_{cha\text{max}}; \\
X_{s\text{max}}, & I_{cha} > I_{cha\text{max}};
\end{cases}
\]

\[
Q(t) = \mu(Re) \cdot \sqrt{\frac{\sqrt{A_w(X_s(t))}}{\rho}} \cdot \sqrt{|P_{b,c}(t) - P_{ha}(t)|} \cdot \text{sign}(P_{b,c}(t) - P_{ha}(t)),
\]

where \(T_{cha}\) —time constant, \(\xi_{cha}\) —the coefficient of relative EHA damping, \(K_{xi}\) —transmission coefficient according to the position of the valve core (sets the ratio between the maximum valve core stroke and the control current on the EHA), \(X_{s\text{max}}\) —maximum valve core stroke, \(\mu(Re)\) —flow coefficient, \(\rho\) —fluid density, \(A_w(X_s)\) —slot area depending on the valve core stroke, \(P_{ha}\) —pressure in the hydraulic accumulator, \(P_{b,c}\) —pressure in the breaking cavity.

Blocks of an adjustable throttle and a straight-through valve are similar in structure to a HA throttle. The input signals are the value of the pressure at the outlet of the hydraulic cylinder’s braking cavity and the pressure in the hydraulic accumulator. The output coordinate is the flow rate of the working fluid entering the hydraulic cylinder. In a pass-through valve block, the area of the conventional supply window depends on the pressure value.

The operation of a spring hydraulic accumulator (tank) can be represented by an equation system:

\[
x_{p,ha}(t) = \int \int ((P_{ha}(x_{p,ha}(t), x'_{p,ha}(t)) - k_d \cdot x_{p,ha}(t) - k_c \cdot x_{p,ha}(t)) / (A_{p,ha} \cdot m_{p,ha}) \, dt^2;
\]

\[
P_{ha}(x_{p,ha}(t), x'_{p,ha}(t)) = \int_0^t (Q_{in}(t) - A_{p,ha} \cdot x'_{p,ha}(t)) \cdot \frac{E(P_{ha}(t))}{V_{ha}(t)} \, dt;
\]

\[
V_{ha}(t) = V_0 + x_{p,ha}(t) \cdot A_{p,ha},
\]

\[\text{(5)}\]
where \(x_{p,ha}, x'_{p,ha}\) — position and speed of the hydraulic accumulator piston; \(P_{ha}\) — pressure in the hydraulic accumulator; \(k_d\) — damping coefficient (generalized coefficient of viscous friction); \(k_e\) — coefficient of the hydraulic accumulator spring elasticity; \(A_{p,ha}\) — hydraulic accumulator piston surface area; \(m_{p,ha}\) — hydraulic accumulator piston weight; \(E(P_{ha})\) — modulus of the working fluid elasticity; \(V_{ha}\) — hydraulic accumulator volume; \(V_0\) — the initial volume of the hydraulic accumulator.

The input signal is the flow rate of the working fluid entering the hydraulic accumulator, and the output signal is the pressure in the hydraulic accumulator.

Developing hydraulic force is determined by the pressure difference in the pushing and braking cavities of the hydraulic cylinder:

\[
F_{hydro} = F_p - F_b, \tag{6}
\]

where \(F_p\) — hydraulic force developed in the pushing cavity, \(F_b\) — hydraulic force developed in the breaking cavity

\[
\begin{align*}
F_p &= P_{p,c} \cdot A_{p,c}; \\
F_b &= P_{b,c} \cdot A_{b,c},
\end{align*} \tag{7}
\]

where \(P_{p,c}\) — pressure in the pushing cavity, \(P_{b,c}\) — pressure in the breaking cavity, \(A_{p,c}\) — piston effective surface area of the pushing cavity, \(A_{b,c}\) — piston effective surface area of the breaking cavity.

In this case, the pressures in the pushing and braking cavities are determined by the difference in the flow rates entering or leaving the cavities, as well as by the modulus of the bulk fluid elasticity, which depends on the pressure:

\[
\begin{align*}
P_{p,c} &= \int_0^t (Q_{in}(t) - A_{p,c} \cdot V_p(t)) \cdot \frac{E(P_{p,c}(t))}{V_{p,c}(t)} \cdot dt; \\
P_{b,c} &= \int_0^t (A_{b,c} \cdot V_p(t) - Q_{out}(t)) \cdot \frac{E(P_{b,c}(t))}{V_{b,c}(t)} \cdot dt,
\end{align*} \tag{8}
\]

where \(Q_{in}(t)\) — inlet fluid flow rate into the pushing cavity, \(V_p(t)\) — pusher piston speed, \(E(P)\) — bulk modulus, \(V_{p,c}(t)\) and \(V_{b,c}(t)\) — volumes of the pushing and braking cavities of the hydraulic cylinder.

The equation of pusher rod motion with the added weight is described as:

\[
(m_p + M_l) \cdot x'' = F_{push} - F_{brake} - F_{fr} + (m_p + M_l) \cdot n \cdot g - F_{ext}, \tag{9}
\]

where \(F_{fr}\) — force of resistance to motion (viscous and dry friction), \((m_p + M_l)\) — weight of the piston and load (product), \(n \cdot g\) — overload value acting on the product, \(F_{ext}\) — external (aerodynamic) force.

The model also implements the “landing of the actuator rod on the stop” by resetting the integrator, which calculates the speed of the piston when the pusher reaches the limit stroke.

In addition, locking mechanisms are conditionally implemented by fulfilling the condition:

\[
F_d = \begin{cases} 
0, & P_{p,c} \leq P_{min}; \\
F_d, & P_{p,c} > P_{min}.
\end{cases} \tag{10}
\]

The movement of the encasement when pressure is created in the pushing cavity can be described as:

\[
x_b = \int \int \left( \left( (F_{hydro} - F_{fr}) - k_d \cdot x'_b - k_e \cdot x_b \right) / M_b \right) dt^2, \tag{11}
\]
where \( x_b, x_b' \) — position and speed of the drive encasement relative to the fixed point of the pusher encasement attachment; \( k_d \) — encasement damping ratio; \( k_c \) — pusher encasement elasticity coefficient; \( M_b \) — pusher encasement weight.

The control law assumes the following sequence of actions in terms of ensuring a given rotational speed (algorithm “A”):

- data processing from sensors to determine the speed and position of the FDP rods;
- determination of the angular velocity current value;
- comparison of the current angular velocity with the value of the command angular velocity (angular velocity impulse);
- determining the maximum value of one of the two pushers’ displacement and crossing the thresholds along the way (the number of thresholds along the way is six, they are located in the second part of the rod stroke, starting from a stroke value of 100 mm);
- determining the condition for the absolute value of the difference between the current and the specified angular velocity to go beyond the dead zone;
- if all three previous conditions are met, then an enable signal is generated to open one of six high-speed discrete flow controllers (if there is a significant deviation from the command angular velocity, the error is forced by opening two flow regulators).

Additionally, two more algorithms have been created. Algorithm “B”, in general, is similar to control algorithm “A” with the only difference that upon reaching the target angular velocity, all previously open valves on the accelerating pusher are turned off (closed) and half of the closed valves on the opposite pusher open. Algorithm “C”, in general, is similar to control algorithm “B” with the only difference that upon reaching the target angular velocity, all previously open valves on the accelerating pusher are turned off (closed) and half of the closed valves open plus one more valve on the opposite pusher.

4.2. AACD, AW and their configuration

In AACD and AW dynamic model, objects are described in EULER as multicomponent mechanical systems. In the AACD model, the aerodynamic effect of the air environment on the device is described and the time for giving a command to the beginning of the AW separation is formed. The AW model describes the aerodynamic effect of the air environment on the payload, taking into account interference from other elements of the aviation complex (AV and other AWs) and the control of the AW after its separation from the AV. In some AW models, after separation from the AV, the inclusion of their own autonomous functioning systems is provided (disclosure of the folded foil structures and control vanes, the operation of the powerplant).

The configuration model describes the AACD and one of the AWs built up on it. AACD and AW models are used in this model as accessories. In this model, the parameters of the relative AW motion included in the given configuration can be determined and transferred to the corresponding AW model for calculating the aerodynamic interference. The actuator model in SimInTech exchanges data on the values of the force acting on the pusher rods with the equipment model in EULER.

In the initial state, for the formation of the initial conditions of motion, all links of the models are fixed into a single rigid structure. To release them, the models use a special reform (change in the mechanism).

5. Conclusion

As a result of comparing the results of mathematical modeling and experimental studies (figure 2), it was found that the actuator model of the AACD, developed on the basis of the methodology, describes the processes of payload movement with a sufficient degree of accuracy.
Figure 2. Comparison of model and experimental data.

We should note that the movement nature is significantly influenced by such factors as attachment points elasticity (mechanical rigidity), working fluid compressibility (hydraulic rigidity), and can also be influenced by dynamic characteristics of the measurement system, which, obviously, should be more accurately taken into account in the full dynamic model of load movement.

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