Теоретичні основи розробки та експлуатації систем озброєння

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USE OF CRITERIAL ANALYSIS TO ASSESS THE AERO-GAS-DYNAMIC PERFECTION OF SURFACE-TO-AIR MISSILE

The appearance of surface-to-air missiles (SAM) – in general and their control systems – in particular, should be determined by the experience embodied in the most advanced close analogues based on the main interrelated design conditions. These conditions should follow from the given functional purpose of the object: the method of guidance, the range and height of destruction of air targets, the characteristic type of targets, the method of launching the rocket, the construction of control system. A number of dimensionless complexes have been proposed, which, similarly to the efficiency, express the perfection of certain characteristics of missiles: transport, high-speed, high-altitude. As a necessary prerequisite for analyzing the perfection of the embodied technical solutions, a representative array of tactical and technical characteristics of missiles was used. A method for analyzing the aerogasdynamic perfection of known SAM samples and similar objects based on the theory of similarity and dimension with the use of criterion spaces is proposed. A number of examples of the application of the method for obtaining expert assessments to ensure design work at the stage of forming the appearance of missiles as part of the corresponding complexes and systems are given. An attempt was made to comprehend the relevance of the application and the prospects for further promotion of the “popular” today methods of controlling missiles (impulse micromotors), as well as the principles of “hit-to-kill”. The tendency of improving the copied missile samples and the development of the designated class of equipment is revealed.

Keywords: surface-to-air missile, anti-ballistic missile, altitude control motor, aero-gas-dynamic flight controls, criterial spaces, expert assessments.

Introduction

Formulation of the problem. The problem of forming the image of high-tech technical objects of a high level of integration, for some time has firmly entered the applied sections of system analysis. Within this framework, attempts are known to systematically represent the life cycle of a rocket [1] in the state space of the general control theory [2]. Such approaches have been expressed in the form of mathematical programming methods [3] and are based on solving a multicriterial optimization problem [4]. This task is set on the set of design options, but it always assumes the existence of a global efficiency criterion, for the disclosure of which informal logic is applied [1], which devalues all theoretical constructions to the level of a science specimen. Nevertheless, it is possible and quite deterministic choice of basic criteria. To do this, consider the universal methodology of any design, the essence of which lies in certain forms of copying. It always implies the presence of a prototype, in a certain sense, worthy of imitation, or their group. The quantitative assessment of the overall level of excellence (efficiency) of any object

of technology that is necessary for this is not derived in the general case from the existing unsystematic set of information. The generally accepted scientifically based principle of systematization is the method of similarity, based on the physical analogy of the object of design and prototype [5]. In this case, the similarity criteria will be an energy interpretation of the cost-effectiveness ratio, expressing the proportion between the useful work and the cost of its production (equivalent to efficiency) [6]. The disposition of many well-known analogues of the design object is established in the criterion spaces according to the level of their functional excellence with automatic separation of subsets for various purposes.

The aim of the article. Among other things, the purpose of the article is to identify a list of requirements for modern unmanned aircraft vehicle (UAVs) that simulate airborne weapons.

Statement of basic materials

The generalized principle of obtaining expert estimates based on the method of similarity and dimension

The classic compact format of bibliographic in-

formation about the objects of technology is a limited set of tactical and technical characteristics (TTC). In the presence of many of the N objects of technology, each of them is individualized by an inherent information vector: $\vec{c}_i = (c_i^1, \dots, c_i^L)$. For simplicity, assume that the information vectors have the same rank (L), and their components are independent. Based on the rule of the norm of the information vector

$$K_i = \left\| \vec{c}_i \right\|, \quad i = 1 \dots N, \quad (1)$$

the problem of comparative analysis [5] for a given object of technology is formally reduced to the establishment of relations

$$K_\alpha < K_\beta, \quad \alpha, \beta \in [1, N], \quad \alpha \neq \beta, \quad (2)$$

between the criteria determining the ratio of the useful effect and the cost of obtaining it in equivalent terms:

$$K_i = \frac{F\left(\vec{c}_i\right)}{U\left(\vec{c}_i\right)}, \quad (3)$$

where F and U are information vector transformation functions.

Thus, the utilitarian logic of the set of objects of identical functional purpose (3) ensures the establishment of a rule of norms (1) for carrying out a comparative analysis of technical perfection (2). In this article, this methodology has been applied to analyze the aerodynamic perfection of surface-to-air missile (SAM) and anti-ballistic missiles (ABM) ideologically close to them based on the information currently available on the samples currently available.

Criterion complexes for the assessment of aerodynamic perfection of SAM / ABM

In general, the appearance of SAM/ ABM is dictated by the following factors (in the chain of command): aerodynamic scheme $\rightarrow$ layout; control methods $\rightarrow$ flight controls; ways to defeat the target $\rightarrow$ warhead. The aerodynamic shape of missiles is determined by a multivariate complex of heterogeneous factors, adequate to the main design problem – interception with guaranteed reliability of a given type of targets. This complex includes the principles of trajectory control and flight controls implementing them.

Considering that any interception scenario will consist of a standard set of trajectory phases, the necessary structure of the flight controls for their implementation can be derived from the technical solutions adopted for the prototypes. With regard to SAM, the implementation of the only dominant useful function is determined by the triad: the range of action – speed capabilities – altitude. In accordance with (3), the components

of this triad are displayed by the following set of criteria for functional excellence:

– by transport possibilities:

$$K_T = \frac{m_{\Pi H} n g \sqrt{L^2 + H^2}}{(m_C - m_{\Pi H}) H_U}; \quad (4)$$

– by height:

$$K_H = \frac{m_{\Pi H} n g H}{(m_C - m_{\Pi H}) H_U}; \quad (5)$$

– by speed:

$$K_V = \frac{m_{\Pi H} V_{\max}^2}{2(m_C - m_{\Pi H}) H_U}, \quad (6)$$

where, $m_{\Pi H}$, $m_{\Pi A}$ is the mass of the payload and the starting mass of the aircraft;

$n g$ is the characteristic trajectory acceleration; n is the overload; g is the gravitational acceleration;

L is the flight range;

H_U is the conventional net calorific value of the fuel; H is the maximum height of the trajectory;

$V_{\max}$ is the maximum trajectory speed.

Results.

Analysis of the perfection of well-known samples of missiles using criteria spaces

Expert assessments of the main types of functional excellence (4–6) of the 3-4-th generation SAM and ABM based on the well-known TTC [15–17] are presented below in the form of mappings in the semi-criteria “ $K_T - L$ ”, “ $K_H - H$ ” (Fig. 1, 2) and criterial: “ $K_V - M$ ”, “ $K_T - K_H - K_V$ ” (Fig. 3, 4) spaces. Comparison is carried out on the basis of the radius vector $K_0 = \sqrt{K_T^2 + K_H^2 + K_V^2}$ using tetrads, which identify individual objects of the set:

$$\{K_T, K_H, K_V, K_0\}. \quad (7)$$

An exemplary view of the “logical filter” of the disposable information array in order to obtain reference points for shaping the aircraft image is reduced to a sequential processing process: separation of species $\rightarrow$ identification of species with a large modernization resource $\rightarrow$ establishment of an expedient flight controls composition.

Species separation and identification of evolutionary series

According to all criteria, ABM THAAD {0.001, 0.0025, 0.00005, 0.0027}, 53T6 {0.005, 0.0030, 0.00020, 0.0058} and 51T6 {0.010, 0, 0.0035, 0.00040, 0.0106}. It must be assumed that their appearance is determined by a different design paradigm, in which the minimized reaction time for intercepting ballistic targets is a priority function, the starting mass of the ABM is not of paramount importance, and the special or kinetic warheads have a significantly smaller mass than the

usual high-explosive. It is found that Arrow-2 {0.070, 0.0285, 0.00610, 0.076} that is positioned as ABM in its quality of criteria does not differ in any way from the set of typical SAMs.

Ideologically close to ABM are heavy 9M82 family SAMs. High-energy two-stage missiles 9M82 {0.025, 0.007, 0.00195, 0.0260} and its light version 9M83 {0.032, 0.008, 0.00180, 0.0330} due to the reduced accelerator, there are no significant differences in the criterion indicators, which indicates balancing approaches to accelerator design and launch stages. The introduction of the altitude control motor (ACM) in the new version of the 9M82MV missile defense system was a means of providing controllability at elevated elevations up to 35 km, but not in the dense layers of the atmosphere. The main anti-missile functionality of the 9M82 family of missiles of the 9M82 family can be confirmed by its closest analogue of the increased scale – the next generation ABM of the 77N6-H / H1 of the promising S-500 air defense system.

The standard form of missiles is currently associated with the aerodynamic “bearing body” mainly in a single-stage design. Modernization activities in the S-300P → S-400 line of missile-defense systems were carried out, including by radically improving the performance of the missiles without changing the aero-gas-dynamic appearance: 5V55K {0.040, 0.0180, 0.0048, 0.044} → 5V55R {0.060, 0.0190, 0.0040, 0.063} → 5V55U {0.110, 0.0190, 0.0047, 0.112} → 48H6 {0.140, 0.0100, 0.0039, 0.140} → 48N6M / 48N6E2 {0.135, 0.0192, 0.0045, 0.136} → 48N6DM {0.210, 0.0230, 0.0077, 0.211}, which ends with a qualitative leap for the last sample in this model range. In all cases, the predominance of the transport function in range against the background of altitude and speed in the overall energy balance is clearly observed.

The top of the development of this evolutionary series is considered long-range 40N6 / E / E2 {0.220, 0.082, 0.0084, 0.235}, although there is no specific information about their status at the moment in open sources. The exceptionally advantageous disposition of SAM ERINT {0.175, 0.055, 0.017, 0.184} draws attention with a deep separation from analogs, near and far. At that, the presence of ACM belts (by taking into account the overload (4–5)) is unlikely to significantly affect the result.

A unique example is the ship-based Standard Missiles (SM) family. The development of SM occurred around a basic single-stage rocket of a normal aerodynamic scheme with a wide-chord wing of low elongation, the appearance of which provided a transition from the launch from the inclined beam guide to the start from launch canisters: SM-2ER {0.130, 0.0270, 0.00120, 0.133} → RIM-174 SM-6 ERAM {0.280, 0.0260, 0.00175, 0.281} → SM-2MR {0.430, 0.0350, 0.00280, 0.431}. The RIM-161 SM-3 “Orbital Intercep-

tor” completely falls out of the general evolutionary series at a highly unremarkable level of energy perfection {0.0750, 0.0230, 0.00175, 0.0785} due to a fundamentally different functional purpose.

Efficiency of gas-dynamic control

Despite the significant indicators of loss of thrust (up to 40%), the gas rudders have not lost their relevance in the combustible / detachable performance in the class of air-ballistic missiles, including for SAM 3rd generation and above. A classic example of an aircraft with self-sufficient aero-gas-dynamic flight controls of the type of hybrid combination of gas rudders with aero-dynamic rudders can be one of the first 3-D SAM systems of the 5V55K (B-500K) S-300P SAM [10]. The adequacy of the original technical solutions for choosing the aero-gas-dynamic appearance of the 5V55K SAM system is indirectly indicated by the fact that the family of 48N6 missiles for the S-300 / PM / PM1-2 / PMU1-2 / FM and S-400 missiles completely inherited it.

High maneuverability qualities of SAM 48N6DM, as well as any other aircraft with aerodynamic control principle on the passive section of the trajectory, are maintained to altitudes of 25...27 km and sharply deteriorate at 35...37 km, which does not allow intercepting highly maneuverable ballistic and aerodynamic hypersonic objects [10]. The same altitude restrictions are available at SAM 5V55R, 48N6E, MIM-104C, RIM-174 ERAM, and any other non-ACM. Thrust vector control by blowing gas into the supercritical part of the nozzle in the missile defense class is not widely used, but there are still examples. Such a system has been applied to the already mentioned heavy two-stage missile defense system of the S-300V / V4 family 9M82 SAM [10].

In the small-sized version, ACM are used as part of donation systems such as RCIC corrected artillery shells of large calibers and compete with ACAG aerodynamic analogues [8]. According to their appearance, the pulse correction systems, implemented, for example, in the “Cantimetr” projectiles are cal. 152 mm and mines “Smel’chack” cal. 240 mm, close to the propulsion system of kinetic interceptors – suborbital anti-missile stages. RCIC technology provides for correction at the final (20...600 m) segment of the ballistic trajectory [9]. The ACAG aerodynamic systems behave more “sluggishly”: for example, a 152 mm projectile begins a smooth correction of the trajectory 2500 m before the meeting with the target.

There are known interpretations of such a control scheme as applied to the SAM / ABM in order to provide specific trajectory maneuvers in the atmosphere and beyond. For example, the Aster-30 missile {0.060, 0.014, 0.0005, 0.062} of the SAMP-T complex has a solid-fuel ACM located near the center of mass with a

block of 4 slotted nozzles integrated into a cruciform wing. This device implements the principle of combined control PIF-PAF (Pilotage In Force – Pilotage Aerodinamique Fort) [15], according to which the outflow of ACM jets are made for the tail swing of the second rocket stage and do not interfere with the control of the tail aerodynamic control surfaces. ACM is activated approximately 1 s before the meeting with the target, and its thrust is regulated in accordance with the commands of the guidance system.

The same scheme is also used in strictly transatmospheric interceptors. Variant SM SM-3 IA {0.075, 0.023, 0.00175, 0.078} of the “Aegis” air defense and missile defense system (ADS / MDS) contains an additional record light (23 kg) LEAP (Lightweight Exo-atmospheric Projectile) level beyond the atmospheric interception from the thermal homing head. LEAP is equipped with its own solid-fuel 2-pulse 4-nozzle remote control SDACS (Solid Divert Attitude Control System) and combines the functions of a Kinetic Warhead.

ABM THAAD [13–14] consists of a combat stage and a detachable solid-fuel accelerator, and the intermediate compartment is designed for pyrotechnic separation of stages. The combat stage is equipped with a solid propellant rocket motor with a rotary nozzle and gas-dynamic interceptors used to thrust vector control together. On the basis of very vague information, it can be assumed that the interceptors provide for the regulation of the jets of 4 continuous flow control devices. The flexible tail of the rocket, self-adapting to flight conditions, enhances the stabilizing effect under the influence of aerodynamic forces in the process of maneuvering with high overloads.

The maximum speed and overload of the ABM THAAD are 2.5 km/s and 20...30 g, respectively, which, in conjunction with the infrared homing head, allows for the intercept of non-maneuvering ballistic targets with a direct kinetic defeat “Hit-to-kill” (without warhead). Judging by the video material laid out on the net, which captures the energetic maneuvering of the ABM THAAD at a low altitude of the main engine of the combat stage, it means the versatility of the SAM, including in low-flying objects. This example demonstrates the possibility of achieving multi-functionality of SAM / ABM by the complex use of various means of gas-dynamic control, specifying the necessary trajectory forces and moments.

A specific feature of the battery version of the ACM in the form of belts is the discrete nature of operation with a very limited number of cycles. In this regard, the ACM belts are incapable of providing a full trajectory control cycle of the aircraft and can only be used in combination with a continuous action flight control – aero-dynamic, jet, or gas-dynamic. For example, this option is implemented in the gas dynamic control sys-

tem ABM / SAM ERINT complex “Patriot PAC-3”, emanating from the paradigm of kinetic interception.

For obvious reasons, the practical effectiveness of this solution is not known, but on the basis of the small-sized version of the ACM belts, it was developed as promising air-to-air missiles (AAM) / ABM CUDA / SACM-T designed to actively protect fighters from flying missiles by kinetic interception with overload up to 65 g [11]. Given the relatively low maximum speed of small-sized AAM / ABM (no more than 2.5 M) and the need to place on their board active radar seeker, there is no room for warheads, from which the usual American ideology of the new generation of “big” ABM is derived.

The attractiveness of kinetic interception is understandable, however, the expansion of the type of ballistic targets due to the appearance of hypersonic maneuvering aircraft is confidently predicted. Upon reaching operational readiness, the latter will make the next edition of the “air (space) ram” completely unpromising and only heavy intercept equipment with powerful warheads (including “special”) will remain on the scene. Considering that at altitudes of 35...37 km, aerodynamic flight controls become ineffective, in the framework of modernization and advanced design programs, the expediency of implementing ACM is obvious.

The newest modification of the heavy Z-ZRS S-300V4 9M82MV in the control system of the sustainer stage also contains ACM belts located in the center of mass and tail section for maneuvering at the boundary of the atmosphere. A similar solution was repeated in the design of the 77N6-H / H1 missile defense system with the kinetic principle of hitting targets for the promising S-500 air defense missile system. This allows us to solve the problem of intercepting highly mobile ballistic and aerodynamic hypersonic aircrafts, where a massive warhead with a controlled directivity pattern is also given a primary role [12].

Another example is the SAM / ABM 9M96E / E2 SAM-S-400 / C-350E / “Redoubt” ammunition set with a ACM near the center of mass, which allows maneuvers with an overload of more than 20...25 g to (H = 35...40 km) and 65 g (H = 5 km), which is not available analogues with aero-dynamic flight controls. A relatively light rocket 9M96E2 {0.040, 0.010, 0.007, 0.042}, however, has a range of 150 km, and is capable even at the passive trajectory section (at a speed of 700...800 m/s) to turn to a maneuvering target with a high overload (20 g, N = 25 km). These maneuverable properties, active radar homing head and the ability to work on the targeting of external radar station as part of an automated control system (ACS) of the air defense system allow this SAM / ABM to hit (including over-horizon and low-altitude) targets in the “started and forgot”. Thus, from a constructive and functional point of view, technical solutions with ACM are most adequate

to heavy SAMs / ABMs with an extra-atmospheric project section of the trajectory, where aero-dynamic flight controls are not effective by definition. As for missiles with high altitude restriction up to 25-27 km, the expediency of using the air defense system emerges, for example, if it is necessary to sharply target the high-speed maneuvering targets, especially near the surface of the

earth. Such conditions of combat use may be dictated by the conditions for the integration of a separate SAM into the ACS ADS in the external target designation mode.

An analysis of the capabilities and perfection of missile control systems makes a UAV that simulates an airborne weapon too easy a target.

Fig. 1. Evaluation of transport perfection of missiles in semi-criteria space “ $K_T - L$ ”

Source: author's development.

Fig. 2. Estimates of the altitude efficiency of missiles in semi-criteria space “ $K_H - H$ ”

Source: author's development.

Fig. 3. Estimates of the speed perfection of missiles in the criteria space “ $K_V - M$ ”

Source: author's development.

Fig. 4. Disposition of missiles in the test space “ $K_T - K_H - K_V$ ”

Source: author's development.

Conclusions

Thus, the presented apparatus of criterial analysis allows deterministic obtaining of intraspecific comparative assessments, selection of samples by functional groups, identification of the closest analogues for given TTC and other tasks, fundamentally important tasks at the stage of formation of the aero-gas-dynamic appearance of SAM / ABM in the world experience gained in the industry, based on the minimum information available in the public domain. The authors, however, do not try to pass the resulting performance estimates for the ultimate truth. The results presented (Figs. 1–4) should be considered as a product of analytical processing of the well-known “branded” TTC [16–19], possibly promotional, that is not unconditionally reliable. For example, the outstanding positions of the ERINT and 9M96E2 SAM missiles with ACM belts in expert spaces cannot fail to arouse a critical attitude towards

themselves (Fig. 1–4). In fact, the use of ACM belts is most likely not a panacea, but only one of many ways to improve the performance of missiles in the presence of technological resources to ensure an acceptable spread of the characteristics of impulse engines.

At the same time, the effectiveness of the use of non-standard solutions is not quite obvious and expected, and, at first glance, a very moderate trajectory energy. For example, the mobile SAM “Pantsir-S”, despite the radio command principle of targeting the 57E6-E anti-aircraft missile system and the aerodynamic control passive combat stage, in a combat situation, confirmed the ability of interception with a high probability of unguided multiple rocket launcher “Grad” and unmanned aircraft vehicles, that is “uncomfortable” aeroballistics and aerodynamic targets. Based on the analysis, the requirements for maneuverability, speed and altitude for modern UAVs that simulate airborne weapons are quite high.

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ВИКОРИСТАННЯ КРИТЕРІАЛЬНОГО АНАЛІЗУ ДЛЯ ОЦІНКИ АЕРОГАЗОДИНАМІЧНОЇ ДОСКОНАЛОСТІ ЗЕНІТНИХ КЕРОВАНИХ РАКЕТ

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Вигляд зенітних керованих ракет (ЗКР) – в цілому та їх системи управління – зокрема, має визначатися досвідом, втіленим у найбільш досконалих близьких аналогах виходячи з основних взаємопов'язаних умов проектування. Ці умови повинні впливати із заданого функціонального призначення об'єкта: методу наведення, дальності та висоти поразення повітряних цілей, особливостей типу цілей, способу пуску ракети, побудови системи управління. Запропоновано низку безрозмірних комплексів, які аналогічно ККД виражають досконалість тих чи інших характеристик ЗКР: швидкісні, висотні та маневрені. В якості необхідної передумови аналізу досконалості втілених технічних рішень використувався представницький масив тактико-технічних характеристик ЗКР. Запропоновано метод аналізу аерогазодинамічної досконалості відомих зразків ЗУР та подібних до них об'єктів на основі теорії подібності та розмірності з використанням критеріальних просторів. Наведено ряд прикладів застосування методу отримання експертних оцінок для забезпечення проектних робіт на етапі формування вигляду ракет у складі відповідних комплексів і систем. Виконано спробу осмислення доречності застосування та перспективності подальшого просування “популярних” сьогодні способів управління ЗКР (імпульсних мікродвигунів), а також принципів ураження цілей (hit-to-kill). Виявлено тенденцію поліпшення та розвитку зенітних керованих ракет.

Ключові слова: зенітні керовані ракети, протиракетні, органи аерогазодинамічного управління, теорія подібності та розмірності, критеріальні простори, експертні оцінки.

ИСПОЛЬЗОВАНИЕ КРИТЕРИАЛЬНОГО АНАЛИЗА ДЛЯ ОЦЕНКИ АЭРОГАЗОДИНАМИЧЕСКОГО СОВЕРШЕНСТВА ЗЕНИТНЫХ УПРАВЛЯЕМЫХ РАКЕТ

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Предложен метод анализа аэрогазодинамического совершенствования известных образцов зенитных управляемых ракет и подобных им объектов на основе теории подобия и размерности с использованием критеріальных пространств. Приведен ряд примеров применения метода для получения экспертных оценок для обеспечения проектных работ на этапе формирования облика ракет в составе соответствующих комплексов и систем.

Ключевые слова: зенитные управляемые ракеты, противоракеты, органы аэрогазодинамического управления, теория подобия и размерности, критеріальные пространства, экспертные оценки.